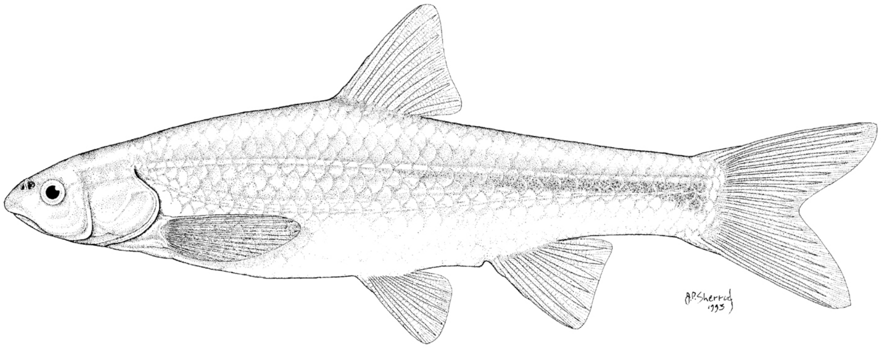
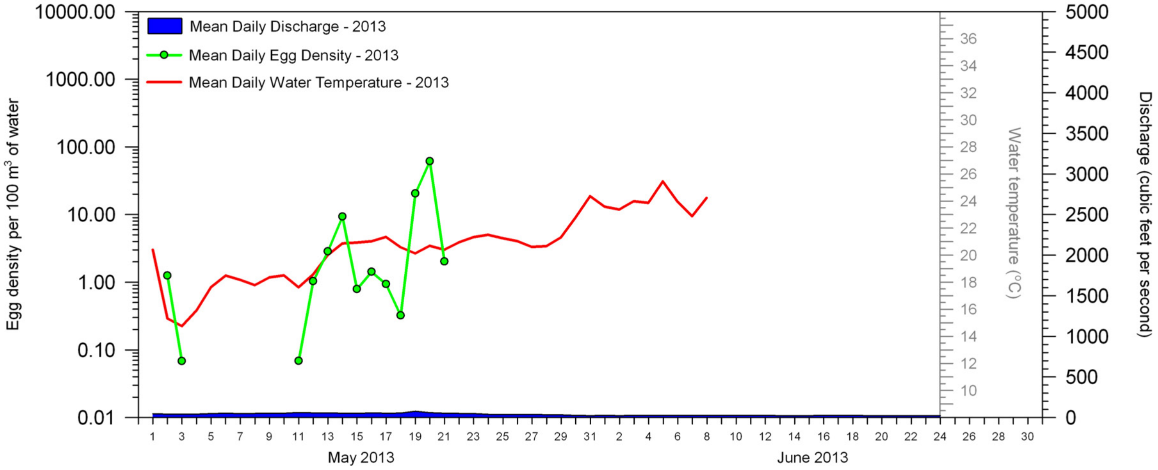
SPATIAL SPAWNING PERIODICITY OF RIO GRANDE SILVERY MINNOW DURING 2013

A MIDDLE RIO GRANDE ENDANGERED SPECIES COLLABORATIVE PROGRAM FUNDED RESEARCH PROJECT





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EXECUTIVE SUMMARY

Systematic monitoring of the reproductive output of Rio Grande Silvery Minnow at multiple sites in the Middle Rio Grande was first conducted in 1999 and has continued annually (except 2005) since 2001. Previous studies demonstrated May and June as the primary period of spawning activity. The 2013 study was a continuation of the long-term monitoring of Rio Grande Silvery Minnow spawning in the downstream-most river reach just upstream of Elephant Butte Reservoir. Additionally, five new sites were added to the study during 2013 (three in the Isleta Reach and two in the San Acacia Reach) in the proximity of the Isleta and San Acacia diversion dams. These sites were established to assess the entrainment of Rio Grande Silvery Minnow eggs into the Middle Rio Grande irrigation canal network and compare the density of eggs in the river with the density of eggs in the canals.

At the long-term monitoring site (San Marcial), daily water temperatures during the initial and peak spawning events were relatively similar among years. In general, mean daily water temperatures ranged from about 18 to 22°C during peak spawning events over the period of study. Mean daily water temperatures ranged between 14.8°C and 21.3°C during spawning in 2013 at the San Marcial Site.

Rio Grande Silvery Minnow mixture-model estimates ($E(x)$), using standardized egg passage rate data (Eggs_P = N [eggs] · 100 · second $^{-1}$) from 2002–2013 at the San Marcial Site, revealed that values of $E(x)$ were highest in 2002 (9.48×10^4) and lowest in 2004 (1.00×10^{-1}). There was a steady decline in $E(x)$ values from 2011–2013. The estimated value of $E(x)$ was significantly lower ($p < 0.05$) in 2013 as compared with 2011.

General linear models of mixture-model egg passage rate estimates (Delta (δ) and Mu (μ)) revealed that variation in μ, as compared with variation in δ, was more reliably predicted by changes in hydraulic variables (allowing for random effects) over the period of study (2002–2013). The top model (δ(Year) μ(ABQ>2,000+random)) received about 18% of the AIC_C weight (w_i) and had a scaled r^2 value of 0.39 ($p < 0.001$). The top three models, which accounted for about 44% of the cumulative w_i, were related to the interaction among μ and hydraulic variables representing elevated spring flows in the Angostura Reach (i.e., ABQmax and ABQ>2,000). No models relating to the interaction among δ, μ, previous year October density data, or previous year flows during irrigation season in the San Acacia Reach received appreciable values of w_i (i.e., no models with w_i > 1%).

Logistic regression modeling of Rio Grande Silvery Minnow egg presence-absence data revealed strong associations with the percentage change in mean daily discharge just prior to egg collection. While the probability of collecting eggs ranged from only 0.13 (Δ discharge = -50%) to 0.33 (Δ discharge = 0%) during periods of declining or stable flows, respectively, the probability of collecting eggs during a 100% increase in flow was 0.84. Further, a substantial increase in flow (e.g., Δ discharge = 200%) was predicted to result in a very high probability of collecting eggs (0.98; LCI > 90%).

Only one egg was collected in all three canal-monitoring sites combined during 2013. Daily egg densities only included a single non-zero value (density = 2.62 eggs per 100 m^3 of water sampled), which was recorded at the Peralta Site. The number of eggs estimated to be entrained into the irrigation system over the duration of the study, from all canal-monitoring sites combined, was 9,676.

Rio Grande Silvery Minnow spawning was documented at all three river-monitoring sites. A total of 1,772 eggs was collected from the three sites with the vast majority collected at the San Marcial Site (n = 1,745). Daily egg densities only included a single non-zero value at Isleta (0.50), ranged between 0.54 and 8.30 at San Acacia, and ranged between 0.07 and 61.00 at San Marcial. However, the estimated egg passage rates at the San Acacia ($E(x)$ = 5.04) and San Marcial ($E(x)$ = 5.11) sites were not significantly different ($p > 0.05$). The number of eggs estimated to be transported downstream over the duration of the study was 2,383 at Isleta, 106,110 at San Acacia, and 151,947 at San Marcial.

The Belen and Peralta canal-monitoring sites were longitudinally comparable to the Isleta river-monitoring site. There was only a single egg collected at the Peralta and Isleta sampling sites and no eggs were collected at the Belen Site. The lack of egg density data from the canal and river monitoring sites in the Isleta Reach during 2013 precluded further statistical comparison among those sites.

The Socorro canal-monitoring site was longitudinally comparable to the San Acacia river-monitoring site. While there were no eggs collected at the Socorro Site, there were 26 eggs collected at the San Acacia Site. The estimated egg passage rate at the San Acacia Site ($E(x)$ = 5.04) was significantly higher ($p > 0.05$) than at the Socorro Site ($E(x)$ = 0.00). However, only a small fraction (often

< 10%) of the water at the Socorro Site originated from San Acacia Diversion Dam during the period of spawning (as documented at the San Acacia Site), which likely explains the difference in egg passage rates between those two sampling sites.

Rio Grande Silvery Minnow spawning intensity appears to be strongly related to some combination of discharge and water temperature conditions. Large increases in flow over a relatively short period seemed particularly related to increased spawning activity in Rio Grande Silvery Minnow. This relationship was especially robust during years when flows in May and June were relatively low, which led to more dramatic increases in flow following spring runoff. Increased flow leads to a series of changes to the physical dynamics of the river (e.g., increased water velocities/depths in some areas and augmented or new “flooded” low velocity habitats in other areas) and changing water chemistry conditions (e.g., increased turbidity and salinity levels) that could be important spawning cues associated with rising flows. While increases in discharge appear to be the primary cue for spawning, water temperature seems to be an important factor as well. Spawning appears to occur over a wide range of mean daily water temperatures (ca. 13 to 26°C) but with the majority occurring over a narrower range of temperatures (ca. 18 to 22°C).

Population trends lend support to the observation that substantial numbers of eggs, and presumably larvae, are being transported downstream every year. In support of these observations, the highest densities of juvenile Rio Grande Silvery Minnow are most frequently found in the southern reaches of the Middle Rio Grande. The few exceptions to this trend (i.e., higher densities of juveniles found in upstream reaches) have almost always occurred following years when flows were very low in the San Acacia Reach, resulting in river drying and loss of fish.

Despite the seemingly large number of Rio Grande Silvery Minnow propagules transported downstream every year, some portion does remain upstream. It is likely that the proportion of individuals retained and successfully recruited upstream is related to the complexity of instream habitat conditions and the long-term availability of nursery habitat. Years with elevated and extended spring runoff conditions appear to create the favorable habitat conditions required for the successful retention and recruitment of early life stages of Rio Grande Silvery Minnow.

The timing, magnitude, and duration of spring flows all seem to be influencing the patterns of spawning periodicity of Rio Grande Silvery Minnow. While a single magnified spawning event often occurs during low flow years, spawning appears to be more protracted during years with higher and extended flows. These later conditions also consistently result in higher densities of Rio Grande Silvery Minnow during October, indicating that a more proactive management of spring flows could be essential to successfully recovering this species.

Rio Grande Silvery Minnow appear to have had a modest spawning effort in 2013 but it is possible that poor recruitment in 2013 (apparently as a result of a truncated spring runoff followed by persistently low summer flows) will translate into decreased numbers of reproductively capable females available to spawn in the spring of 2014. Populations of Rio Grande Silvery Minnow appear to have declined since 2009 and the lack of an adequately high spring runoff (high magnitude over an extended duration) combined with summer drying in 2013 could result in further population declines. The loss of individuals from downstream reaches during river drying events is particularly problematic as these are the areas that most consistently support the highest densities of Rio Grande Silvery Minnow. The successful conservation of Rio Grande Silvery Minnow appears strongly dependent on ensuring appropriate flow and habitat conditions that are timed with the typical spawning and early recruitment phases of this species.

INTRODUCTION

The reach of the Rio Grande between Cochiti Dam and Elephant Butte Reservoir (Middle Rio Grande) has been greatly modified over the last 50 years; this has alternatively led to aggradation, degradation, armoring, and narrowing of the river channel in different portions of the reach (Lagasse, 1985). This section of the river flows through the massive Rio Grande rift and historically resulted in a wide floodplain within the sparsely vegetated Rio Grande valley. Extensive braiding of the river through the relatively linear Rio Grande rift valley was common as it flowed over shifting sand and alluvium substrata; flow in the Middle Rio Grande was generally perennial except during times of severe or extended drought (Scurlock, 1998).

Historically, the Middle Rio Grande was relatively shallow throughout most of the year because of regionally low precipitation levels (Gold and Dennis, 1985) but was subjected to periods of high discharge. Flows were generally highest during the annual spring snowmelt runoff (April–June). However, intense localized rainstorms (monsoonal events that generally occur in July and August) often caused severe flooding and were important in maintaining perennial flow throughout the summer. The cyclic pattern of drought and flooding over mobile substrata likely helped to promote the active interaction between the river and its floodplain. Historically, the Middle Rio Grande was characteristic of a dynamic semi-arid river ecosystem.

The reduced species diversity typical of semi-arid ecosystems was also reflected in the depauperate ichthyofaunal composition of the Middle Rio Grande. Despite the reduced overall species richness of the Rio Grande, the river supported numerous native cyprinids that were endemic to this drainage (Platania and Altenbach, 1998). However, many of the endemic pelagic-spawning cyprinids that historically occupied the Rio Grande basin have been extirpated (Speckled Chub, *Macrhybopsis aestivalis*, Rio Grande Shiner, *Notropis jemezanus*, and Rio Grande Bluntnose Shiner, *Notropis simus simus*) or have become extinct (Phantom Shiner, *Notropis orca*) over the past century (Bestgen and Platania, 1990). Rio Grande Silvery Minnow, *Hybognathus amarus*, is the only extant pelagic-spawning cyprinid in the Middle Rio Grande (Bestgen and Platania, 1991; Platania, 1991).

This group of pelagic-spawning cyprinids shared several life-history characteristics. All were small (generally <90 mm SL), short-lived (ca. 2–5 years), fishes that occupied mainstem habitats. In addition to these shared traits, all five species were members of a reproductive guild of fishes that spawn semibuoyant eggs (Platania and Altenbach, 1998). Reproduction in this guild of fishes is characterized by the production of non-adhesive eggs that, upon expulsion from the female, swell rapidly with water and become nearly neutrally buoyant. Spawning is generally associated with increases in discharge, such as spring run-off or summer rainstorms. The eggs are about 1.6 mm in diameter shortly after spawning but quickly expand (ca. 3.0 mm) and are passively transported downstream during development. Egg hatching time is temperature dependent, but usually occurs in 24–48 hours (Platania, 2000). Recently hatched larval fish are potentially subject to additional passive downstream transport for several days (ca. 3 to 5 days) until development of the gas bladder. This physiological development corresponds with a shift in swimming behavior, as larvae are able to actively avoid higher velocity habitats to some extent.

The 4–7 days necessary for propagules to attain the developmental stage necessary to control their horizontal movements allows for potentially considerable downstream transport of eggs and larvae in the Middle Rio Grande. As has been well documented for other aquatic organisms, it is necessary for at least some portion of the drifting propagules to settle in appropriate nearby low-velocity habitats or move upstream to maintain viable populations (Speirs and Gurney, 2001). Downstream transport distance of the progeny of Rio Grande Silvery Minnow is dependent on a variety of factors including flow magnitude and duration, water temperature, and channel morphology (Dudley and Platania, 2007). Historically, there were no permanent barriers to upstream dispersal of fishes in the Middle Rio Grande. There are currently three instream diversion structures between Cochiti Dam and Elephant Butte Reservoir that act as barriers to upstream movement of fishes and fragment the once continuous range of the Rio Grande Silvery Minnow.

Population monitoring efforts over the past two decades (see Dudley and Platania, 2013) have documented vast changes (i.e., order of magnitude increases and decreases) in the abundance of Rio Grande Silvery Minnow within the fragmented reaches of the Middle Rio Grande. Recent monitoring efforts (Dudley and Platania, 2013) demonstrated that the October density of Rio Grande Silvery Minnow was significantly lower ($p < 0.05$) in 2011 than in recent years (e.g., 2007, 2008, and 2009) but was significantly higher ($p < 0.05$) than in 2002 and 2003 (years with the lowest densities ever recorded). However, October population monitoring efforts in 2012 yielded no Rio Grande Silvery Minnow, which was the first and only sampling effort (in any month) that yielded no individuals of this species since the population monitoring study was initiated in February of 1993.

Systematic monitoring of the reproductive output of Rio Grande Silvery Minnow at several sites in the Middle Rio Grande was first conducted in 1999 (Platania and Dudley, 2000). The 1999 monitoring effort involved collecting and quantifying density of Rio Grande Silvery Minnow eggs at several Middle Rio Grande sites during the relatively short spawning period of this species. Limited Rio Grande Silvery Minnow egg collecting efforts were also conducted at selected sites in the Middle Rio Grande (Platania and Hoagstrom, 1996) and in the Low Flow Conveyance Channel (Smith, 1998, 1999) from 1996 to 1999. These latter samples provide information on the magnitude of reproduction during certain times and for specific sites. However, consistent monitoring throughout the spawning season produces the most reliable measure of the duration and magnitude of Rio Grande Silvery Minnow reproductive output. The first site-specific sampling effort to document the magnitude of the reproductive effort of Rio Grande Silvery Minnow occurred daily throughout May and June 2001 (Platania and Dudley, 2002) at a location near the southern end of the San Acacia Reach of the Middle Rio Grande (River Mile 58.8). Monitoring of the reproductive effort of Rio Grande Silvery Minnow also occurred daily at this site in May and June 2002 (Platania and Dudley, 2003), 2003 (Platania and Dudley, 2004), and 2004 (Platania and Dudley, 2005). More intensive monitoring efforts were conducted from 2006 to 2008 (Platania and Dudley, 2006, 2007, 2008) and resulted in the sampling of the Angostura, Isleta, and San Acacia reaches of the Middle Rio Grande. While monitoring of the Rio Grande Silvery Minnow reproductive effort occurred annually in the Isleta and San Acacia reaches from 2009–2011, only the San Acacia Reach was monitored in 2012–2013.

The spatial spawning periodicity study conducted herein is a continuation of the long-term (2001–2004 and 2006–2013) systematic Rio Grande Silvery Minnow reproductive monitoring research activity. The primary objective of this study is to provide data that will enable characterization of the timing, duration, and magnitude of Rio Grande Silvery Minnow reproduction in the San Acacia Reach of the Middle Rio Grande. Additional objectives include assessing differences in Rio Grande Silvery Minnow spawning magnitude among sampling years; examining the relationships among discharge, fish density, and spawning magnitude; and assessing spatial spawning patterns from multiple canal and river sites in the Isleta and San Acacia reaches. Long-term monitoring of the reproductive effort of Rio Grande Silvery Minnow provides insight to potential factors affecting annual reproductive output, remains necessary for ongoing recovery efforts, and helps facilitate effective management decisions in the Middle Rio Grande.

Institutional Background and Considerations

Monitoring the reproductive effort of Rio Grande Silvery Minnow was identified as a requirement of the 29 June 2001 Programmatic Biological Opinion of the Effects of Actions Associated with the U. S. Bureau of Reclamation's, U. S. Army Corps of Engineers', and Non-Federal Entities Discretionary Actions related to Water Management on the Middle Rio Grande, New Mexico as authored by the U. S. Fish and Wildlife Service. This work was part of an ongoing effort to document changes in the distribution and abundance of the federally endangered Rio Grande Silvery Minnow. This research effort provided an assessment of the reproductive output (eggs) for Rio Grande Silvery Minnow within the Middle Rio Grande and specifically addressed the task: "Evaluate the status and trend of the Rio Grande Silvery Minnow" as identified by the MRGESACP. The Rio Grande Silvery Minnow Recovery Plan (U. S. Fish and Wildlife Service, 2010) also outlined a key research objective (1.1.1 Improve understanding of the relationship between environmental factors and spawning by the Rio Grande Silvery Minnow) that was addressed through this research. This investigation provided an assessment of the relative magnitude of Rio Grande Silvery Minnow spawning effort. This project was also a central component of the Rio Grande Silvery Minnow propagation and genetics research efforts, both requirements of the 29 June 2001 Programmatic Biological Opinion (see "Project Objectives" 2 and 3). In 2002–2003, MRGESACP members met and discussed Rio Grande low flow issues and impacts of the hydrological conditions on Rio Grande Silvery Minnow. The dismal 2002–2003 snow pack in the Rio Grande headwaters meant there would not be a natural spring flow spike in 2003 in the Middle Rio Grande. Personnel from the MRGESACP decided to create an artificial flow spike during mid-May 2002, using reservoir storage, to initiate spawning by Rio Grande Silvery Minnow. As 2003 climatic conditions were similar to those experienced in 2002, an artificial flow spike was also created in the Rio Grande in 2003. Snow pack runoff and ambient flow conditions in 2004 were sufficient enough that, for the first time in two years, an artificial flow spike was not deemed necessary. However, the timing and magnitude of flows have been modified to some degree in most years since 2004 with the intent of inundating within-channel and floodplain habitats to the maximum extent possible.

STUDY AREA

The principal area of interest in the Middle Rio Grande is the reach between the outflow of Cochiti Reservoir and inflow to Elephant Butte Reservoir; this area encompasses the known range of Rio Grande Silvery Minnow in the Middle Rio Grande (Figure 1). Five upstream reservoirs and numerous irrigation diversion dams regulate flow in the Middle Rio Grande. Cochiti Reservoir has been operational since 1973, is located 76 km upstream of Albuquerque, and is the primary flood control reservoir that regulates flow in the Middle Rio Grande. Reach names are taken from the diversion structure at the upstream boundary of that reach of river. In the Cochiti Reach (between Cochiti Dam and Angostura Diversion Dam), the Rio Grande flows through Cochiti, Santo Domingo, and San Felipe pueblos, respectively.

The reproductive effort of Rio Grande Silvery Minnow has, in the past, been sporadically determined at selected collecting localities in the Middle Rio Grande. From 2001 to 2004 and in 2013, sampling efforts were restricted to a single San Acacia Reach collection location. The San Acacia Reach of the Middle Rio Grande is about 56 miles (91 km) long, extending from the apron of San Acacia Diversion Dam to the head of Elephant Butte Reservoir. A wide and braided river channel, sand substrate, high sediment load, and a broad variety of aquatic mesohabitats characterize sections of this reach. Conversely, some segments in this reach are relatively narrow and result in increased water velocity and decreased habitat heterogeneity. The 12-mile (19 km) reach of the Rio Grande downstream of San Marcial Railroad bridge crossing is confined to a channel that is about 50 m wide. Substrate in this segment of the river is predominately sand and braiding of the channel is uncommon except under conditions of relatively low flow.

Given the downstream drift of the eggs, the original location of the collecting activities was selected so as to maximize the number of eggs collected and potentially rescue eggs destined to drift into Elephant Butte Reservoir where, if hatched, larvae would be subjected to a wide array of nonnative predators. This site was located near the downstream-most portion of the San Acacia Reach (River Mile 55.0). The sampling site is downstream of a U. S. Geological Survey stream gaging station located near San Marcial, New Mexico (# 08358400), which is the nearest upstream San Acacia Reach gage. In addition to easy accessibility and favorable river conditions (i.e., wide river channel, current being carried through a single river channel, gently sloped banks, moderate gradient), the only means of vehicle access to this site was gated and could be secured. This area has been sampled annually from 2001–2004 and from 2006–2013.

Additionally, a total of five new sampling sites were added in 2013 for the purpose of assessing spatial spawning patterns in the Isleta and San Acacia reaches. Three sampling sites were added in the Isleta Reach while two sampling sites were added in the San Acacia Reach. In the Isleta Reach, two sampling sites were added in canals (Belen High Line Canal and Peralta Canal) and one site was added in the river just downstream of Isleta Diversion Dam. In the San Acacia Reach, one site was established in the Socorro Main Canal and one in the river just downstream of San Acacia Diversion Dam. These additional sampling sites not only allowed for a more detailed assessment of spatial spawning patterns over a nearly 200 km reach of the Rio Grande but also enabled a direct comparison between canal and river monitoring localities in the two downstream-most reaches of the study area.

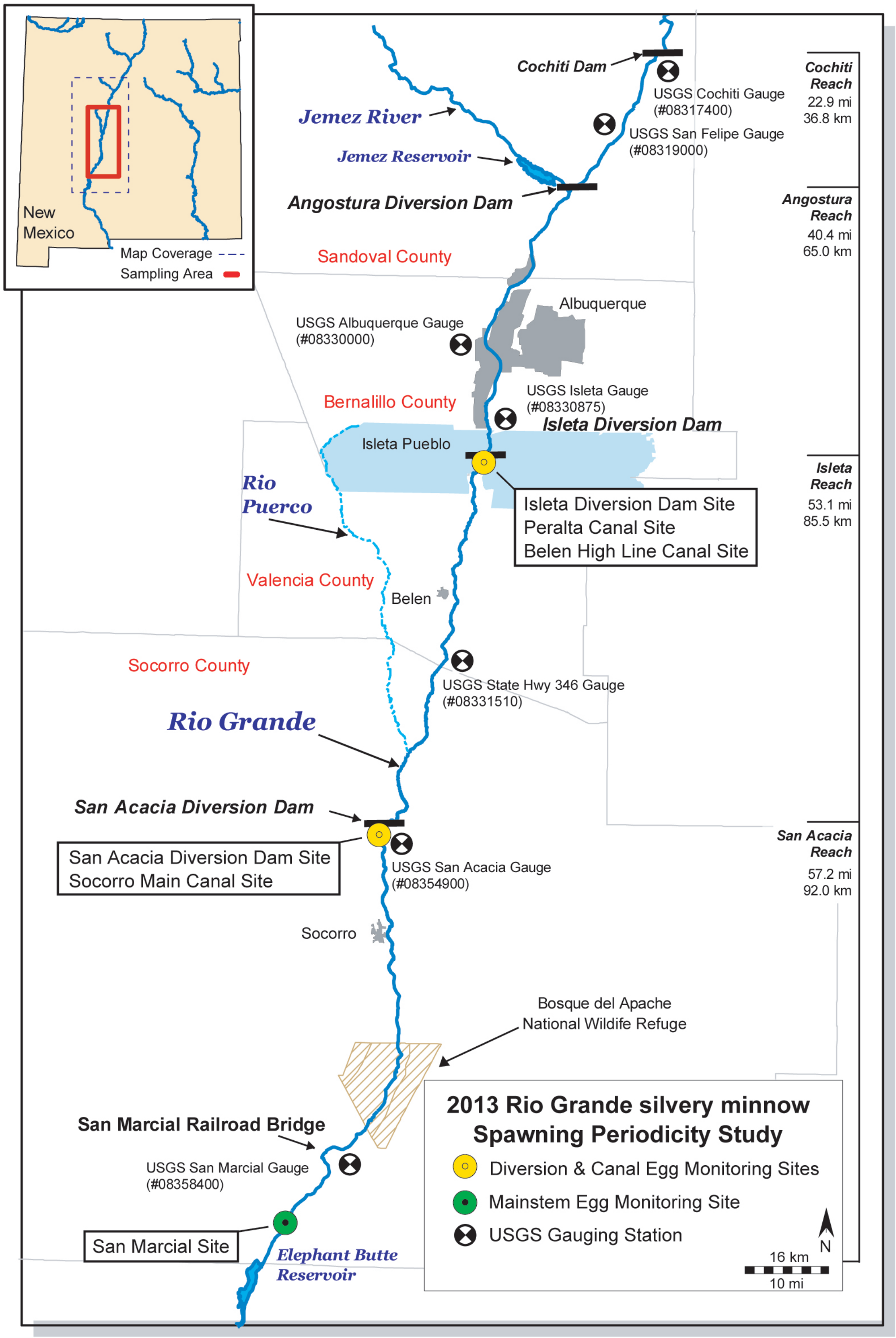

Figure 1. Map of the Middle Rio Grande, New Mexico, and the 2013 study site locations.

MATERIALS AND METHODS

The egg-collecting device, developed specifically for the collection of large numbers of live and undamaged semibuoyant fish eggs (Moore Egg Collector; MEC), was the only sampling apparatus used in this project (Altenbach et al., 2000). Numerous modifications have been made to the collecting gear, since the original publication detailing the construction and operation of the MEC (Altenbach et al., 2000), that have resulted in increased effectiveness and efficiency of the MEC (i.e., greater density per sampling period). Density of Rio Grande Silvery Minnow eggs in the Middle Rio Grande was determined following the sampling protocol described in Altenbach et al. (2000). A mechanical flow meter was attached to the MEC so that volume of water filtered could be calculated and density per unit of water determined. The density of drifting eggs was calculated as the total number of eggs collected · volume of water sampled $^{-1}$ · 100 (i.e., N [eggs] · 100 m^3 water $^{-1}$). The total number of eggs passing a sampling site in one day was estimated by using egg sampling data from the site and flow data from the nearest upstream USGS gaging station (i.e., (number of eggs collected / (volume of water sampled / volume of water available)) · (1440 / number of minutes sampled).

Previous studies demonstrated May and June as the primary period of Rio Grande Silvery Minnow reproductive activity (Dudley and Platania, 2012). The normal sampling regime in 2013 consisted of an intensive daily sampling effort at each sampling site. Eggs were not staged (i.e., determining approximate time from spawning) as this would require substantial laboratory work outside of the current core objectives of this study. Staging eggs would give a general idea of drift time but extrapolating to drift distance would be subject to a series of simplifying assumptions. Also, determining drift distance is a complex modeling exercise of which eggs are only a component (i.e., eggs can be present in the drift for about one day but larvae can be present in the drift for about another three days post-hatching). Two MECs were used at the San Marcial Site and one MEC was used at the other five sampling sites.

Volumetric determination of the number of Rio Grande Silvery Minnow eggs collected, as employed in 2001, lacked the rigor necessary for effective evaluation of the relative level of spawning by this species. Changes initiated in the 2002 sampling protocol were instituted to increase the amount and utility of the information acquired from this research activity. One result was that the sampling protocols incorporated in 2002 included direct counts of all eggs collected. The aforementioned differences in egg density determination between 2001 and post-2001 studies preclude use of 2001 data for quantitative or statistical comparison with data from subsequent years. There have not been changes in the sampling methodology for quantitative determination of egg densities since 2002.

Rio Grande Silvery Minnow egg density values are (in part) dependent on flow conditions thereby precluding unadjusted comparison of inter-annual densities (e.g., higher flow volume will result in lower density since the number of eggs in the water column remains constant). Egg density (i.e., N [eggs] · 100 m^3 water $^{-1}$) was standardized to a downstream passage rate (Eggs_P = N [eggs] · 100 · second $^{-1}$) based on mean daily discharge (Q = m^3 water · second $^{-1}$) to account for these differences, using the formula: Eggs_P = Density · Q. Values of Eggs_P are indicative of the relative spawning intensity among years, corrected for inter-annual differences in flow magnitude. All USGS discharge data presented graphically or analyzed statistically in this report are provisional and subject to change.

Mixture models (e.g., combining a binomial distribution with a lognormal distribution) have been shown to be particularly effective for modeling ecological data with multiple zeros (White, 1978; Welsh et al., 1996; Fletcher et al., 2005; Martin et al., 2005). Long-term Rio Grande Silvery Minnow spawning data during spring (May–June) were analyzed using PROC NLMIXED (SAS, 2013), a numerical optimization procedure, by fitting a mixture model consisting of the binomial and lognormal distributions using the methods outlined in White (1978). Logistic regression and the lognormal model were used to provide estimates of $E(x)$, using egg passage rate data [Eggs_P] during the most common sampling period (1 May to 10 June). Models provided estimates of Delta (δ = probability of absence, i.e., a zero value when present on all sampling days), Mu (μ = mean of the lognormal distribution), Sigma (σ = standard deviation of the lognormal distribution), and $E(x)$ (estimated downstream passage rate of Rio Grande Silvery Minnow eggs). General linear models were used to incorporate covariates to model δ, μ, and σ.

Covariates considered to model egg passage rate data included multiple hydraulic variables (e.g., peak discharge and days > or < a threshold discharge value). Maximum discharge and days exceeding threshold discharge values in 1,000 cfs increments (days > 1,000, 2,000, 3,000, and 4,000 cubic feet per second, cfs) represented the typical range of spring runoff conditions (May–June) at USGS Gage #08330000 (ABQ; Rio Grande at Albuquerque, NM). The onset of lower flows (i.e., first day with discharge < 200 cfs after 1 June), mean daily discharge, and lower threshold discharge values (days < 200 and < 100 cfs) represented some general characteristics of low flow conditions during the previous year's irrigation season (March–October) at USGS Gage #08358400 (SAN; Rio Grande Floodway at San Marcial, NM). Additionally, the estimated density of juvenile and adult Rio Grande Silvery Minnow $E(x)$ from the previous October of each sampling year (Dudley and Platania, 2013) was included as a covariate in the model. Covariate models included both fixed effects models (i.e., the covariate is assumed to explain all the variation in density with only an additive sampling error included in the model) and random effects models (i.e., a normally distributed random error with mean zero and non-zero standard deviation is used to explain deviations around the fitted covariate). The Gauss-Hermite numerical integration was used to integrate out sampling-site random effects in the model.

Goodness-of-fit statistics (logLike = -2[log-likelihood] and AIC_C = Akaike's information criterion [Akaike, 1973] for finite sample sizes) were generated to assess the relative fit of data to various models for all sampling years. Lower values of AIC_C indicate a better fit of the data to the model. Models were ranked by AIC_C values and all models with an AIC_C weight (w_i) > 0.1% were presented. A scaled r^2 value was calculated based on methods outlined in Nagelkerke (1991). Differences among null and alternative models were assessed using a log-likelihood ratio goodness-of-fit test (Zar, 2010).

Logistic regression modeling was used to determine the relationship between the probability of collecting eggs and the percentage change in mean daily discharge (MDday) from two days to one day prior to egg collection. For example, if eggs were collected on day 15, the formula would be (MD14-MD13)/MD13)*100. This was to allow time for the discharge changes occurring at the San Marcial gage to reach the San Marcial Site (ca. 25 km downstream). This metric best represented the approximate change in mean daily discharge that occurred just prior to spawning. Regression models were developed for the San Marcial Site using all data from the period of record. The associated 95% confidence intervals of the modeled regression line were constructed using inverse predictions of discharge across the range of modeled egg collection probabilities (SAS, 2007).

A modified filtering screen to separate drifting debris from Rio Grande Silvery Minnow eggs was developed and tested for the MEC in 2009. The screen was designed to allow the passage of much of the very fine particulate debris while preventing the passage of drifting eggs. Experimental tests revealed that the modified screen was consistently more efficient at sampling a larger volume of water than was the old screen over the same time period (Platania and Dudley, 2009). All MECs were fitted with the modified screen for sampling conducted in 2013.

Two temperature-logging devices (one primary and one backup) were deployed at each study site and recorded hourly water temperatures. The Onset TidbiT v2 water temperature data logger (UTBI-001) used in this study was approximately located in the middle of the water column and attached to a steel post driven into the substrate of the river. This data logger has a published ± 0.21°C level of accuracy over 0°C to 50°C and a resolution of about 0.02°C over the same range of temperatures. The stability (drift) of this device is 0.1°C per year and our typical use (based on battery use and unit failure) generally does not exceed three years. All data were transferred by inserting the data logger into a coupler attached to a HOBO waterproof shuttle, which was then downloaded directly to a computer. Data from the primary and backup data loggers were also compared side-by-side to help further ensure this consistency and identify any potential problems (e.g., outliers). If the data loggers became buried in the substrate or were no longer submerged in the water column, corrective measures were taken and invalid data were not included in further analysis. Hourly water temperature data from the primary data logger were presented in this report as mean, minimum, and maximum daily water temperatures. Data from past spawning periodicity studies were also included for comparative purposes.

RESULTS

Hydrology (2001–2013)

Flows in the Middle Rio Grande have fluctuated dramatically among years since the beginning of this study in 2001 (Figures 2 to 6). A drought that enveloped the study region in 2000 was somewhat interrupted in 2004 by a moderate snow pack and a wetter than normal April. These precipitation events supplemented but did not replenish the already diminished water reserves in upstream reservoirs. Despite the presence of a more normal spring runoff in 2004, elevated flows persisted for only few weeks in May and had declined notably by the beginning of June. Snow pack runoff in 2005 was larger (greater magnitude and duration) than any of the previous four study years (egg sampling was not conducted in 2005). Conversely, flow in the Rio Grande during 2006 (prior to 27 June) was extremely low because of minimal spring snowmelt runoff. Spring flows were markedly higher from 2007 to 2010 as compared with 2006, but returned to very low conditions during the 2011–2013 study periods.

Discharge in the Rio Grande at the San Marcial Railroad Bridge Crossing (USGS Gage 08358400) during the 2013 water year (October–September) closely mirrored the upstream gages, except at a reduced magnitude (Figure 7). From 01 April to 30 June 2013, daily discharge in the Rio Grande at the San Marcial Gage ranged from 18 to 80 cfs (mean = 41.2 cfs, SE = 1.6). There was a small peak on 19 May 2013 (76 cfs) followed by a steady decline in flows throughout the rest of May. The remainder of the spawning season was marked by very low flow conditions and reached the minimum flow of 18 cfs on 28 and 29 June 2013.

Water Temperature (2001–2013)

Comparison of 2001 to 2013 water temperatures at the San Marcial Site during May and June demonstrated only modest differences in mean daily water temperature trends across this period (Figures 8 to 10). However, there were notable day-to-day differences in mean water temperatures among years (e.g., 13.8°C [3 May 2011] vs. 21.7°C [3 May 2007]). The minimum daily water temperatures were consistently the lowest in low flow years (e.g., 2002, 2003, 2006, and 2011–2013). Maximum water temperatures were also consistently the highest during these same years (2002, 2003, 2006, and 2011–2013) as compared with other years of the study. The general trend for minimum temperatures was a slow steady increase through May and June. In contrast, maximum temperatures generally increased slowly in May and then increased rapidly at some point during June (i.e., coinciding with the reduction in flow following spring runoff). There were sometimes notable differences in the day-to-day maximum water temperatures among years (e.g., 18.2°C [19 May 2008] vs. 30.5°C [19 May 2006]) but the difference in day-to-day minimum water temperatures were not as pronounced. The principal reason for these patterns, besides ambient temperature, was the volume of water in the river channel during the respective study periods. The relatively high flows present in 2001, 2004, and 2007–2010 (May to mid-June) served to stabilize water temperatures and minimize diel variation. Conversely, the extremely low flow conditions present throughout most of the spawning period in 2002, 2003, 2006, and 2011–2013 typically resulted in large daily temperature fluctuations.

During 2013, mean daily water temperature at the San Marcial Site fluctuated from about 15°C to 25°C in May but remained above 22°C during the June study period (Figure 10). Temperature extremes (minimums and maximums) followed different trajectories over the course of the study. In general, there was less diurnal fluctuation during May and more diurnal fluctuation during June. This pattern seemed to be mostly reflective of the extremely low flows recorded during June. Maximum daily water temperature exceeded 30°C multiple times during June. Minimum daily water temperature ranged from about 10°C to 20°C from May until mid-June. During the study period, water temperature ranged from a low of 9.6°C (3 May) to a high of 32.9°C (5 June) at the San Marcial Site.

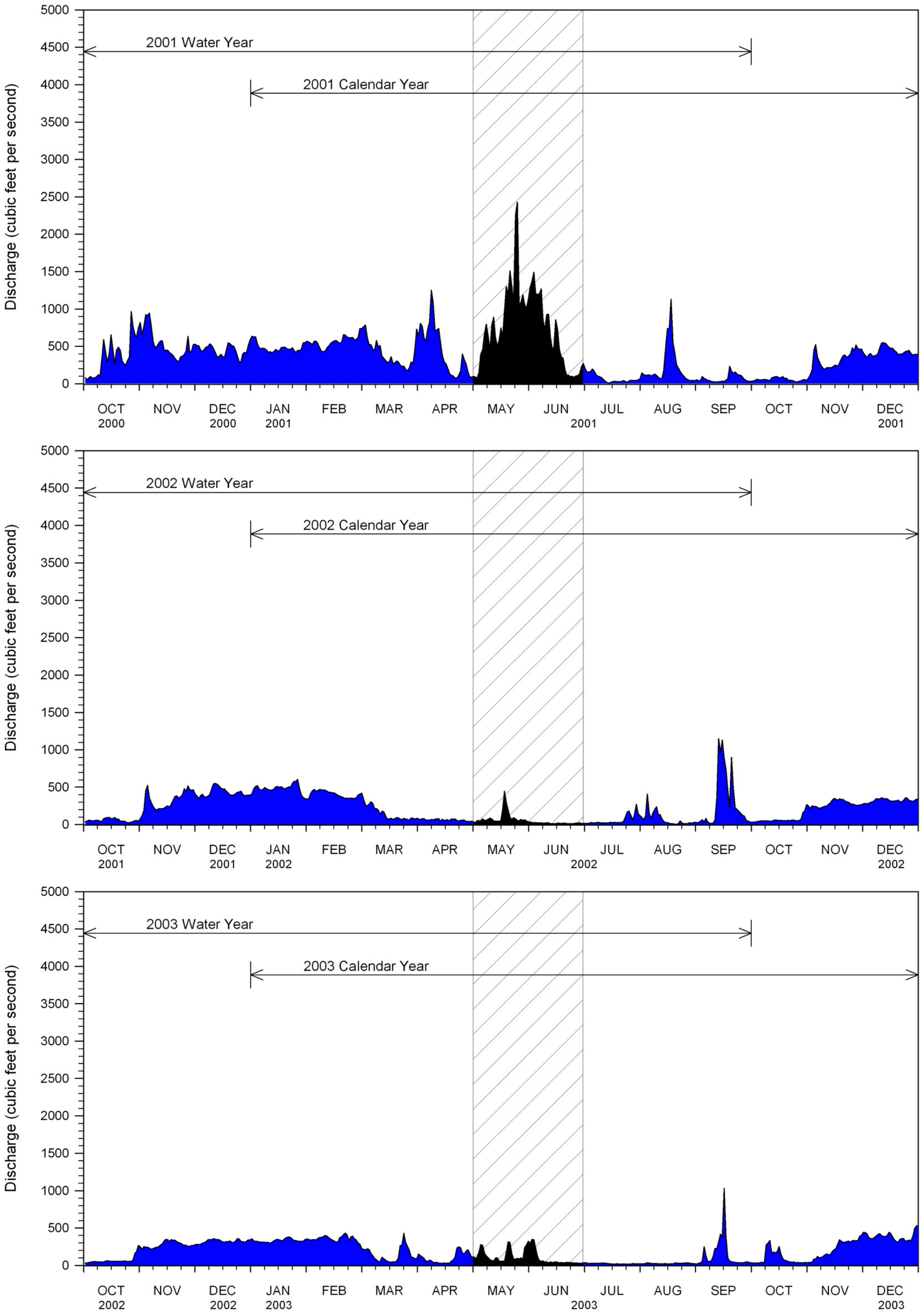

Figure 2. Annual hydrographs of the Rio Grande, New Mexico, at the San Marcial Gaging Station before, during, and after the 2001–2003 Rio Grande Silvery Minnow spawning periodicity study periods. Cross-hatching indicates annual study periods.

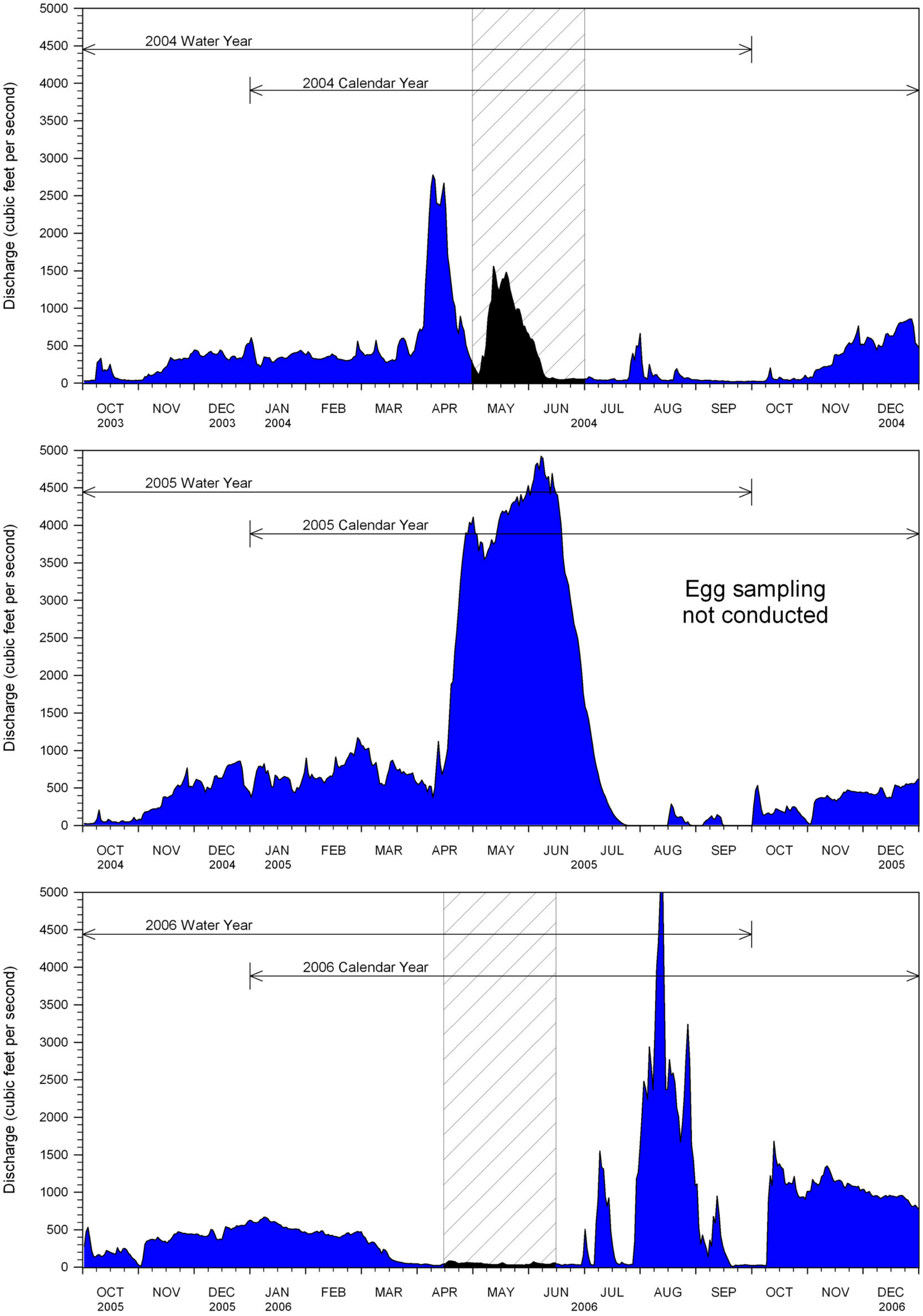

Figure 3. Annual hydrographs of the Rio Grande, New Mexico, at the San Marcial Gaging Station before, during, and after the 2004 and 2006 Rio Grande Silvery Minnow spawning periodicity study periods. Cross-hatching indicates annual study periods. Sampling was not conducted in 2005.

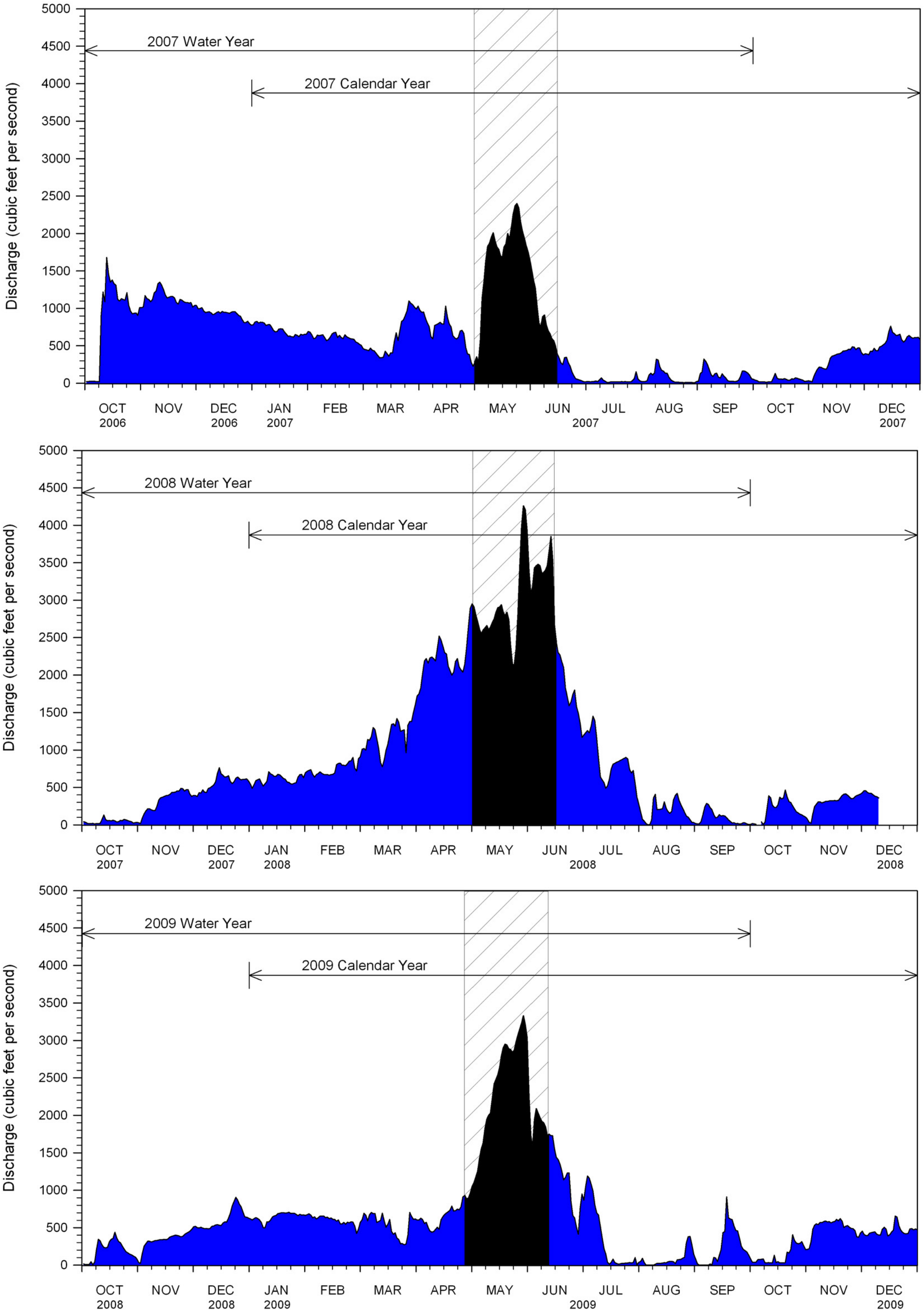

Figure 4. Annual hydrographs of the Rio Grande, New Mexico, at the San Marcial Gaging Station before, during, and after the 2007–2009 Rio Grande Silvery Minnow spawning periodicity study periods. Cross-hatching indicates annual study periods.

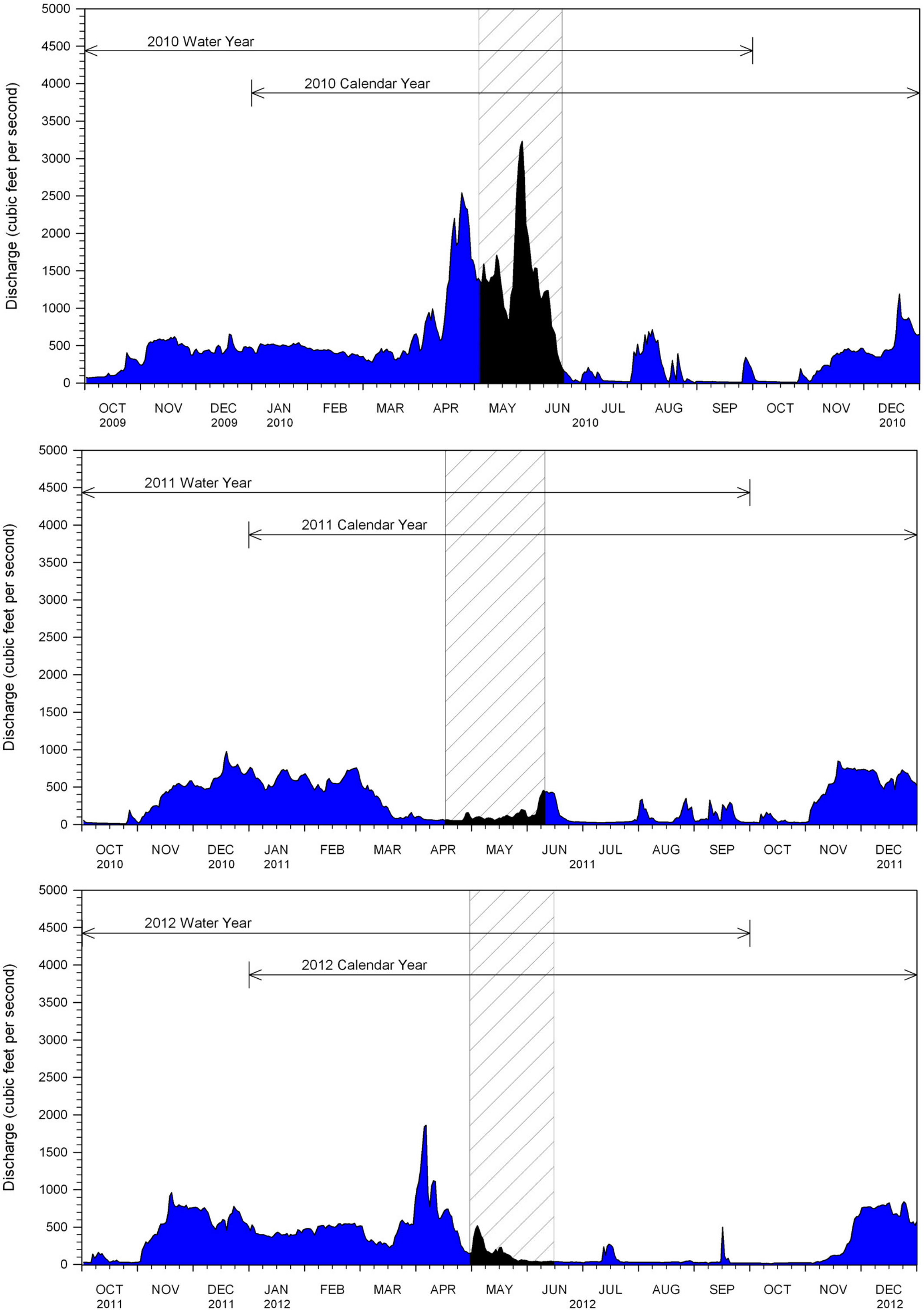

Figure 5. Annual hydrographs of the Rio Grande, New Mexico, at the San Marcial Gaging Station before, during, and after the 2010–2012 Rio Grande Silvery Minnow spawning periodicity study periods. Cross-hatching indicates annual study period.

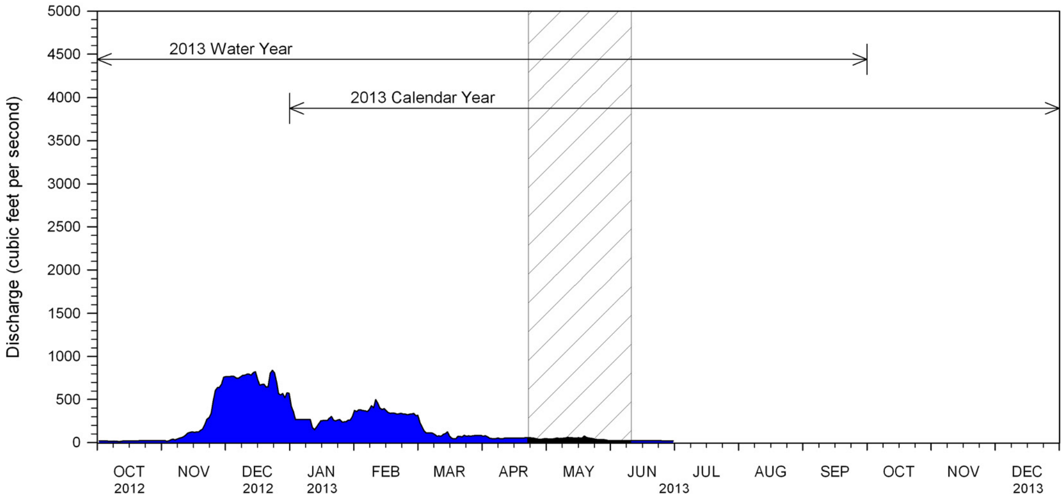

Figure 6. Annual hydrograph of the Rio Grande, New Mexico, at the San Marcial Gaging Station before, during, and after the 2013 Rio Grande Silvery Minnow spawning periodicity study period. Cross-hatching indicates annual study period.

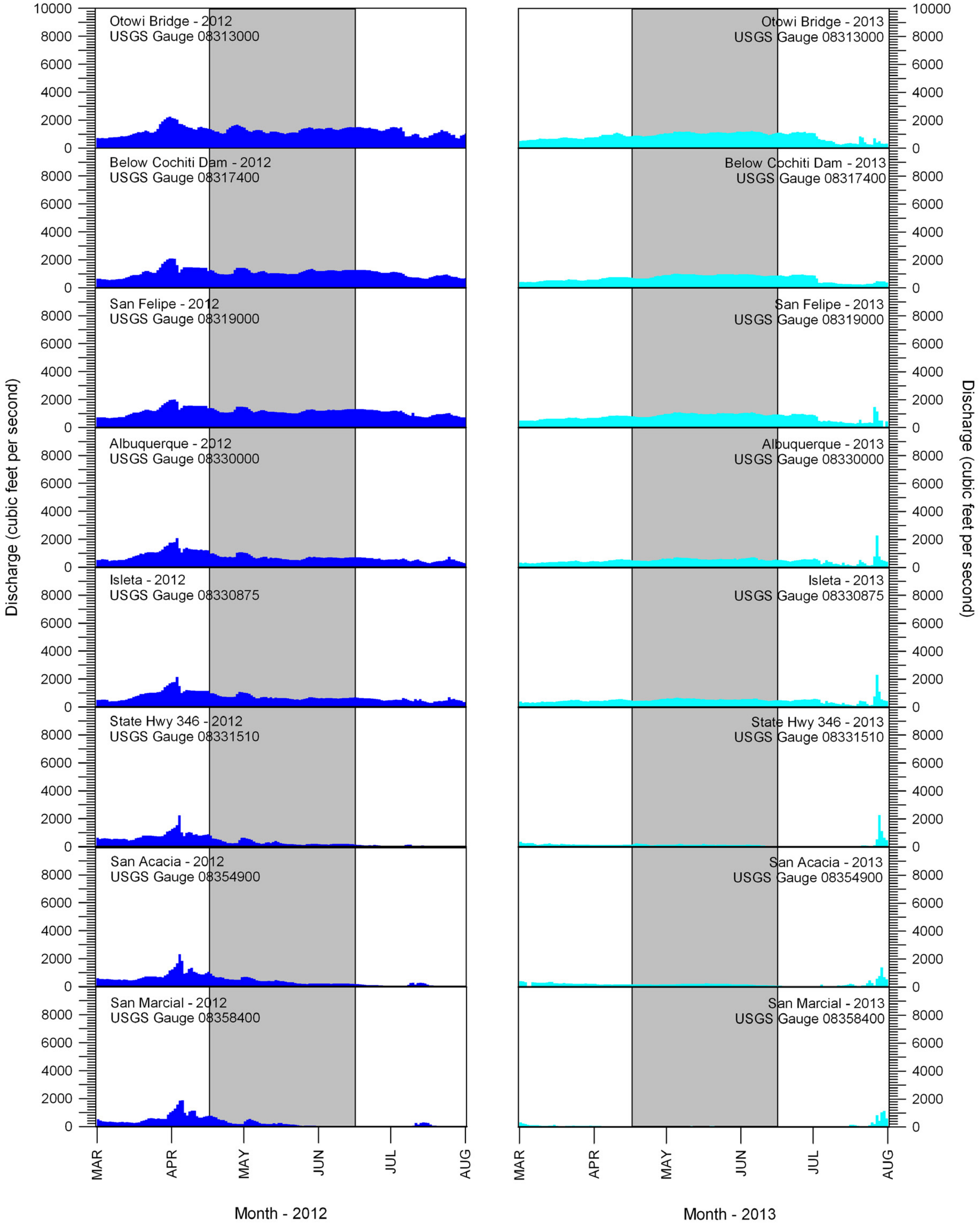

Figure 7. Rio Grande discharge from March–July (2012 and 2013) at seven U. S. Geological Survey Gaging Stations (see Figure 1). The Otowi Bridge gage (not in Figure 1) is provided for reference and gages are ordered from upstream (top) to downstream (bottom). Gray rectangles delineate the peak period of Rio Grande Silvery Minnow spawning activity.

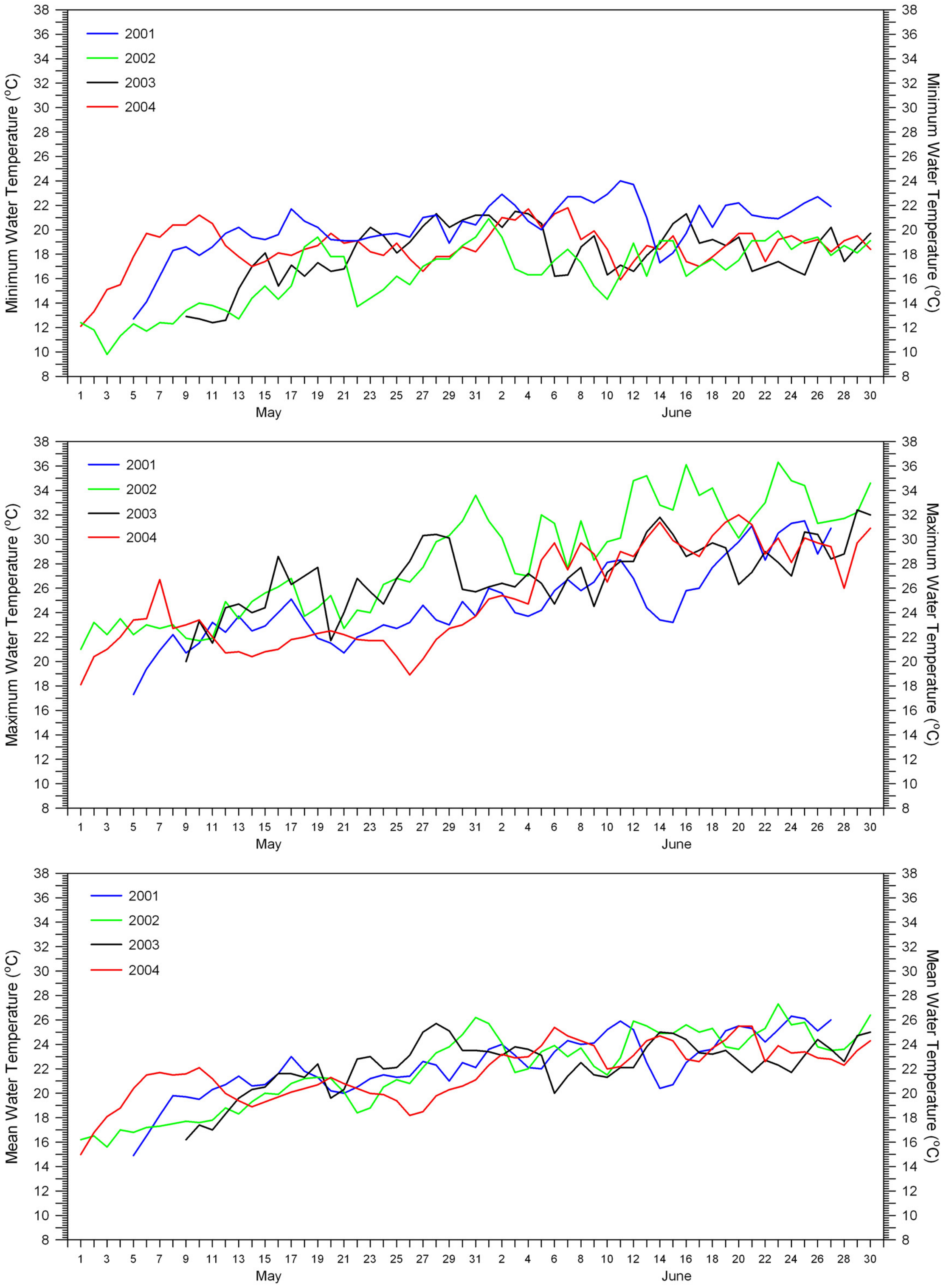

Figure 8. Minimum, maximum, and mean daily water temperatures at the San Marcial Site during the 2001–2004 Rio Grande Silvery Minnow spawning periodicity study periods.

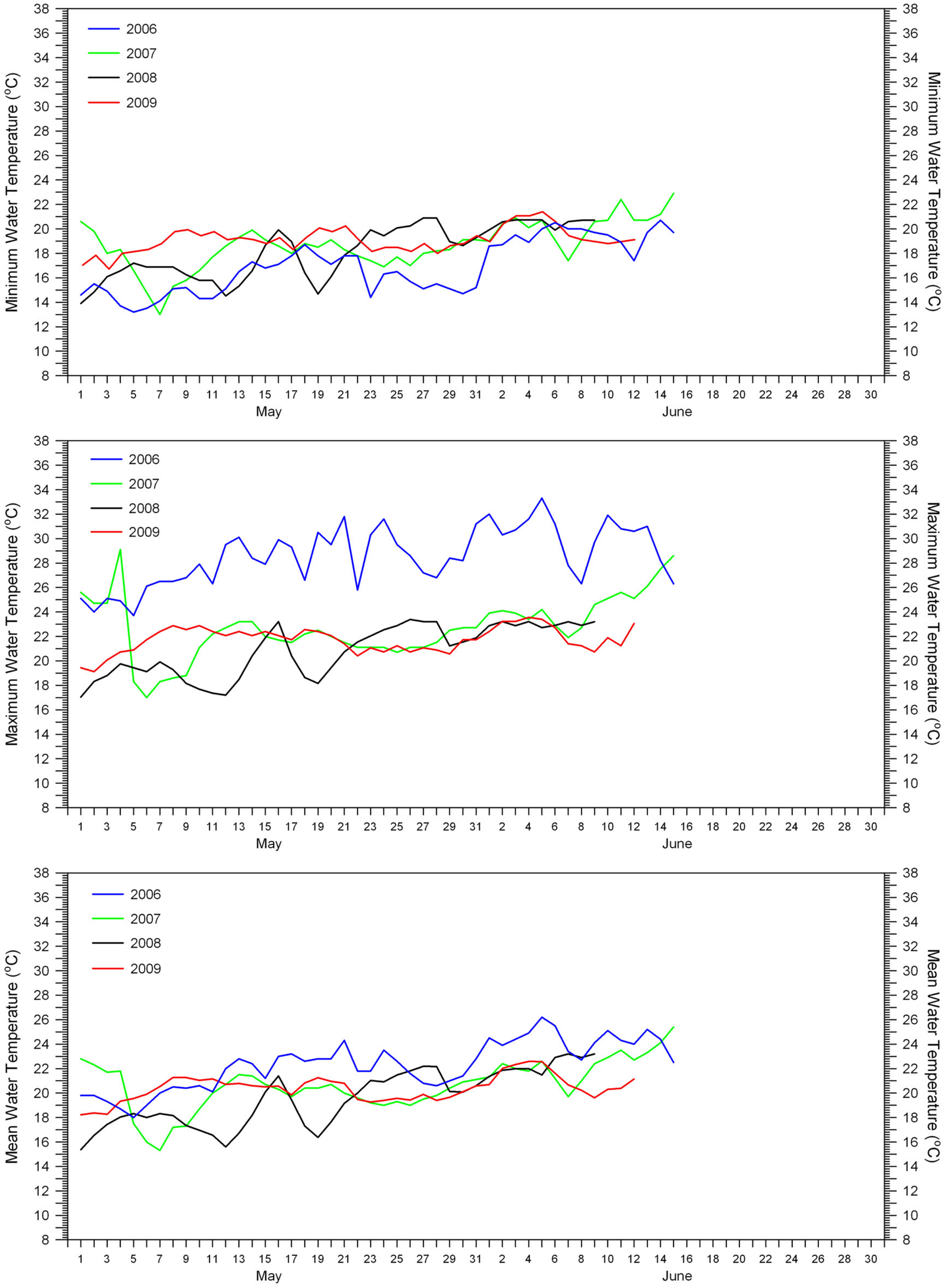

Figure 9. Minimum, maximum, and mean daily water temperatures at the San Marcial Site during the 2006–2009 Rio Grande Silvery Minnow spawning periodicity study periods.

Figure 10. Minimum, maximum, and mean daily water temperatures at the San Marcial Site during the 2010–2013 Rio Grande Silvery Minnow spawning periodicity study periods.

Spawning Periodicity (2002–2013)

Despite substantial inter-annual differences in Rio Grande Silvery Minnow spawning metrics at San Marcial (Table 1), there were several similarities apparent regarding the timing of reproduction among years sampled (2002–2004, 2006–2013; Figures 11 to 15). Based on the results of data taken from all years of the project, there was an extended duration of spawning (ca. April–June). The frequency and duration of spawning were highly variable among years. However, peak spawning consistently occurred during May over the period of record. Two notable exceptions to this pattern occurred in 2006 and 2011, respectively, when peak spawning coincided with elevated flows in early June.

Mean daily water temperatures during the initial and peak spawning events were relatively similar among years. In general, mean daily water temperatures ranged from about 18 to 22°C during peak spawning events. However, spawning also occurred at elevated water temperatures (> 22°C) during years with relatively low flows (e.g., 2003, 2006, 2011, and 2012). Mean daily water temperatures ranged between 14.8°C and 21.3°C during spawning in 2013 at the San Marcial Site.

Rio Grande Silvery Minnow mixture-model estimates ($E(x)$), using standardized egg passage rate data (Eggs_P) from 2002–2013, revealed notable differences among sampling years (Figure 16). Standardized egg passage rates were highest in 2002 (9.48×10^4) and lowest in 2004 (1.00×10^{-1}). There was a steady decline in the densities of eggs collected from 2011–2013. The estimated value of $E(x)$ was significantly lower ($p < 0.05$) in 2013 as compared with 2011. While the estimated value of $E(x)$ was relatively low during 2013, it was still significantly higher ($p < 0.05$) than during 2004.

General linear models of Rio Grande Silvery Minnow mixture-model egg passage rate estimates (Delta (δ) and Mu (μ)) revealed that variation in μ, as compared with variation in δ, was more reliably predicted by changes in hydraulic variables (allowing for random effects) over the period of study (2002–2013). The top model (δ(Year) μ(ABQ>2,000+random)) received about 18% of the AIC_C weight (w_i) and had a scaled r^2 value of 0.39 ($p < 0.001$; Table 2). The top three models, which accounted for about 44% of the cumulative w_i, were related to the interaction among μ and hydraulic variables representing elevated spring flows in the Angostura Reach (i.e., ABQmax and ABQ>2,000). No models relating to the interaction among δ, μ, previous year October density data, or previous year flows during irrigation season in the San Acacia Reach received appreciable values of w_i (i.e., no models with $w_i > 1\%$).

Logistic regression modeling of Rio Grande Silvery Minnow egg presence-absence data revealed strong associations with the percentage change in mean daily discharge just prior to egg collection (Figure 17). The probability of collecting eggs ranged from 0.13 (Δ discharge = -50%) to 0.33 (Δ discharge = 0%) during periods of declining or stable flows. The probability of collecting eggs was predicted to increase rapidly up to approximately a 100% increase in mean daily discharge between days just prior to egg collection. The probability of collecting eggs during a 100% increase in flow was 0.84. While the probability of collecting eggs increased from a 100% to 225% daily increase in flows, the rate of increase was relatively modest. However, a large percentage increase in flow (e.g., Δ discharge = 200%) was predicted to have a correspondingly high probability of collecting eggs (0.98; LCI > 90%).

Spatial Spawning Patterns (2013)

Canal-monitoring sites

Sampling at the canal-monitoring sites was conducted during weekdays from 1 May through 31 May (22 days). The cumulative volume of water sampled at the Peralta and Socorro sites was very similar (2,281.1 m^3 and 2,281.2 m^3, respectively) but notably higher at the Belen site (5,769.5 m^3). Discharge was also higher at the Belen site and sampling occurred over a longer duration there as compared with the other two canal-monitoring sites. The Peralta Site was the only locality where Rio Grande Silvery Minnow spawning was documented (Table 3). Only one egg was collected in all three canal-monitoring sites combined over the study period. Daily egg densities only included a single non-zero value (2.62 eggs per 100 m^3 of water sampled; Figure 18). The egg passage rate could not be estimated for the Peralta Site, using the mixture-model, since only a single value was recorded.

The volume of water sampled at the canal-monitoring sites constituted only a small fraction of the total volume available (ca. 0.5–1.0%). The number of eggs estimated to be entrained into the irrigation

Table 1. Rio Grande Silvery Minnow spawning summary data by year and category (eggs present, eggs absent, percent frequency of occurrence, and maximum daily density) at the San Marcial Site (NS = Not sampled).

Sampling Year	**Eggs Present (Number of Days)**	**Eggs Absent (Number of Days)**	**Percent (%) Frequency of Occurrence**	**Maximum Daily Density (# / 100 m^3)**
2002	6	40	13.0	14,139.43
2003	18	28	39.1	475.63
2004	3	43	6.5	0.09
2005	NS	NS	NS	NS
2006	10	36	21.7	289.33
2007	39	7	84.8	90.13
2008	3	43	6.5	5.10
2009	13	34	27.7	8.05
2010	15	32	31.9	9.47
2011	39	17	69.6	2,334.93
2012	18	30	37.5	466.71
2013	13	37	26.0	61.00

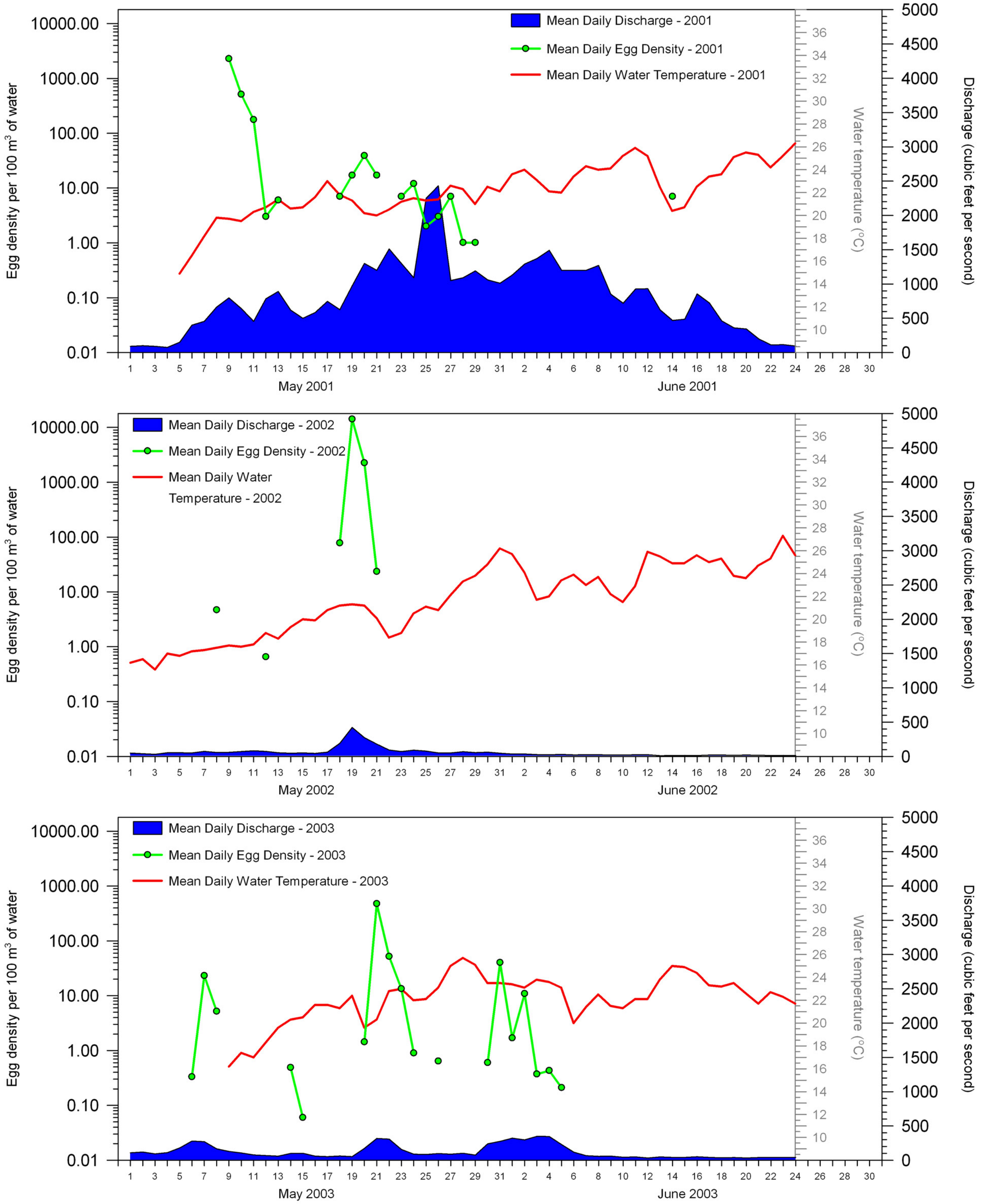

Figure 11. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2001–2003 Rio Grande Silvery Minnow spawning periodicity study periods at the San Marcial Site. Note that the Y-axis for egg density is a log-scale.

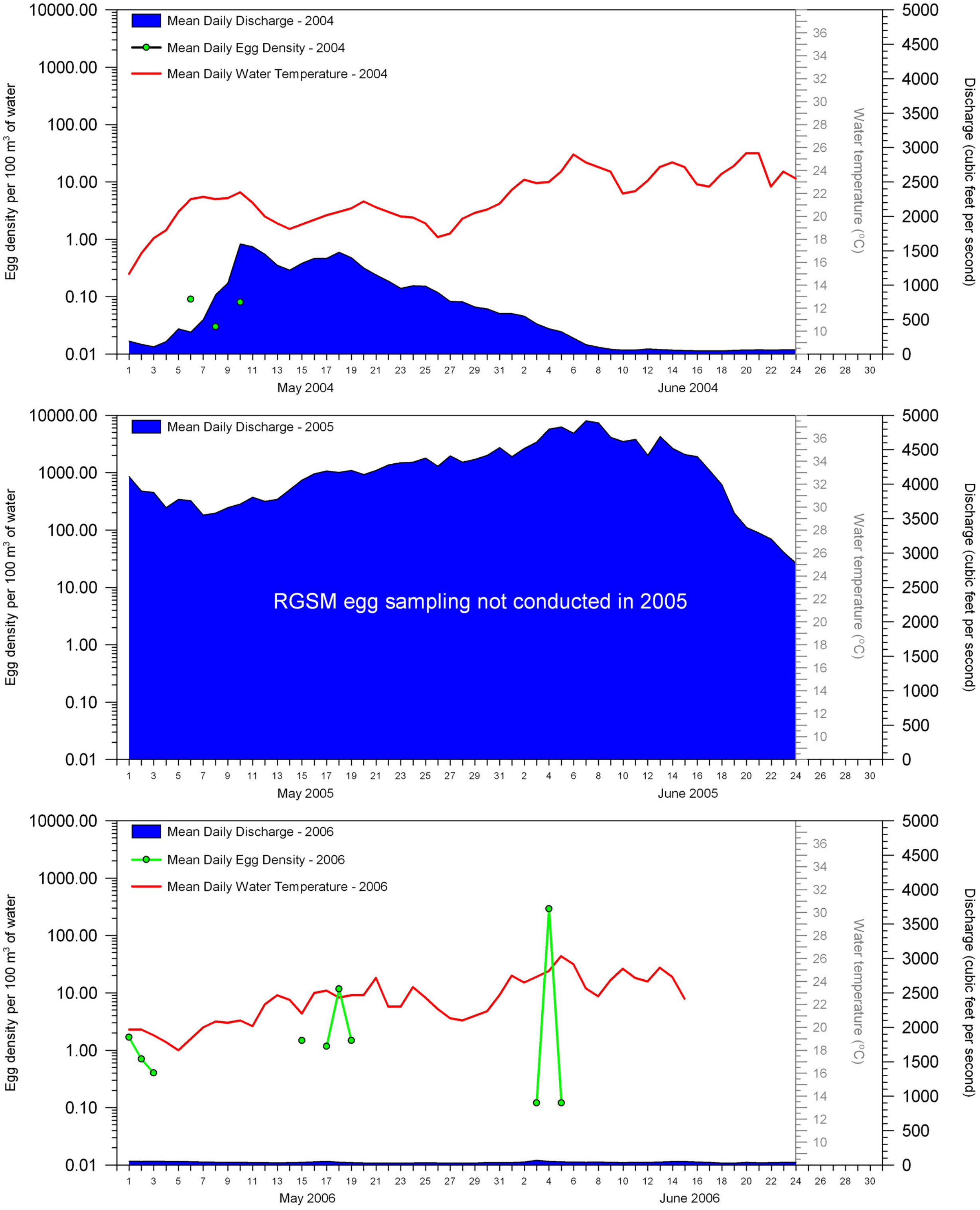

Figure 12. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2004 and 2006 Rio Grande Silvery Minnow spawning periodicity study periods at the San Marcial Site. Note that the Y-axis for egg density is a log-scale.

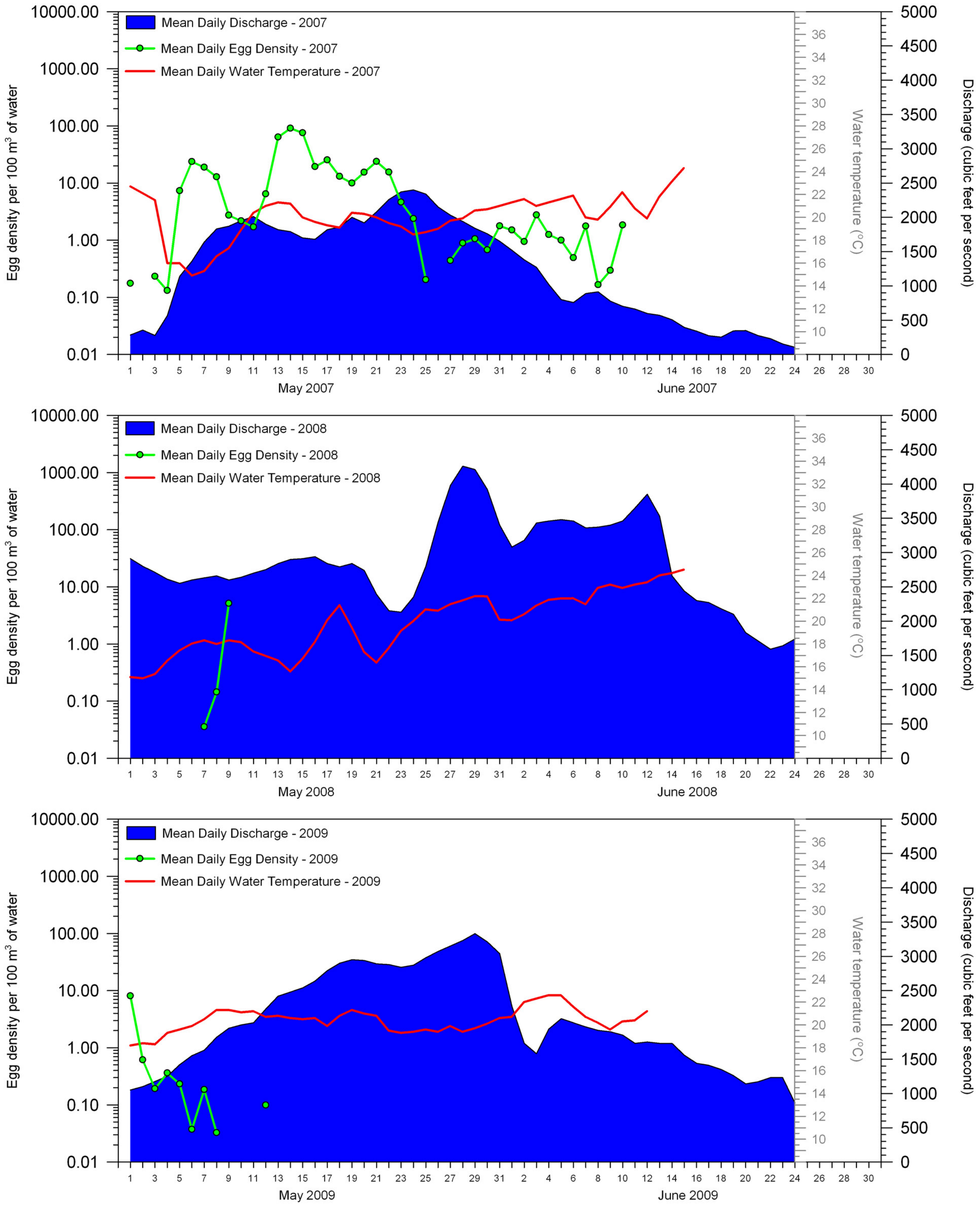

Figure 13. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2007–2009 Rio Grande Silvery Minnow spawning periodicity study periods at the San Marcial Site. Note that the Y-axis for egg density is a log-scale.

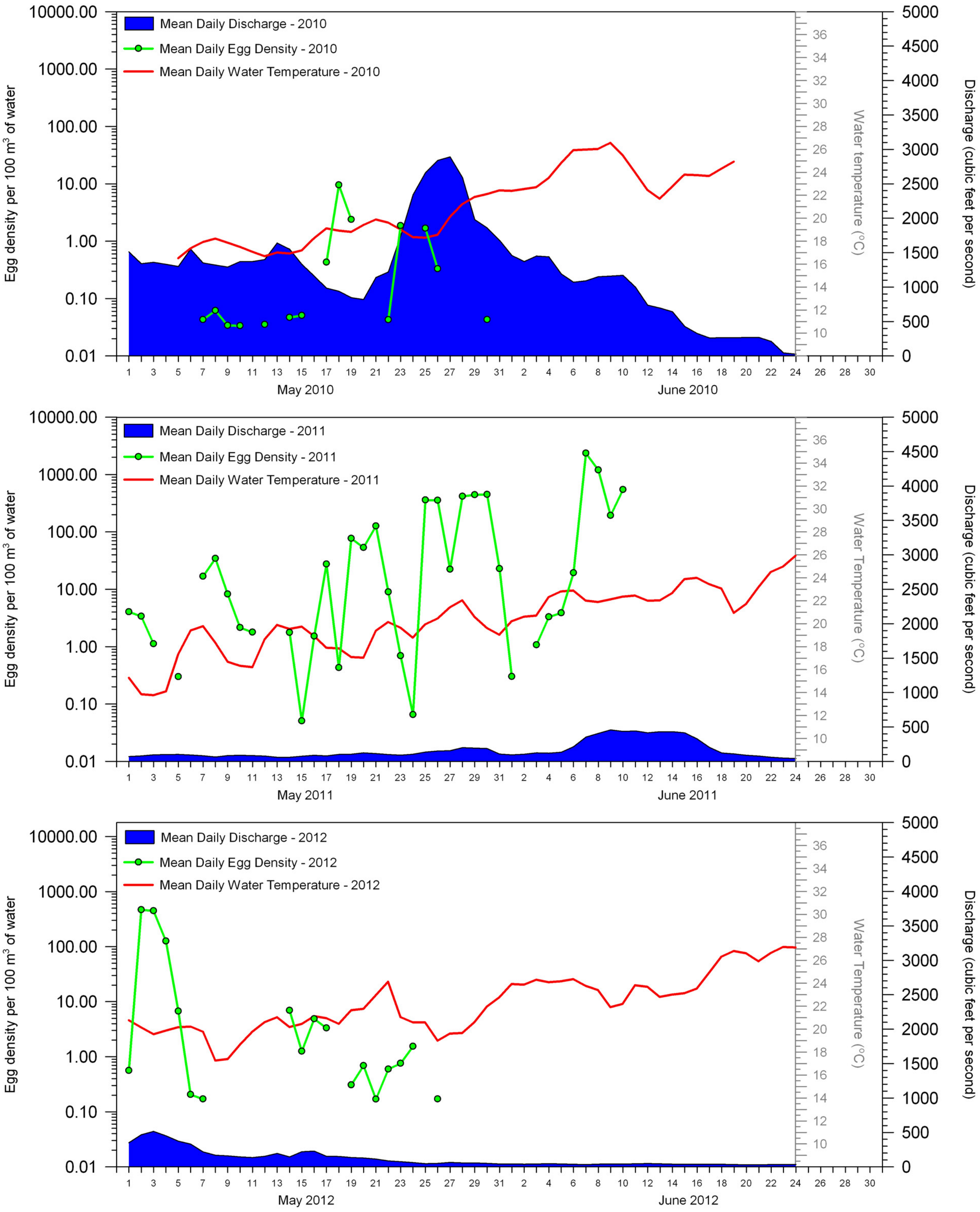

Figure 14. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2010–2012 Rio Grande Silvery Minnow spawning periodicity study periods at the San Marcial Site. Note that the Y-axis for egg density is a log-scale.

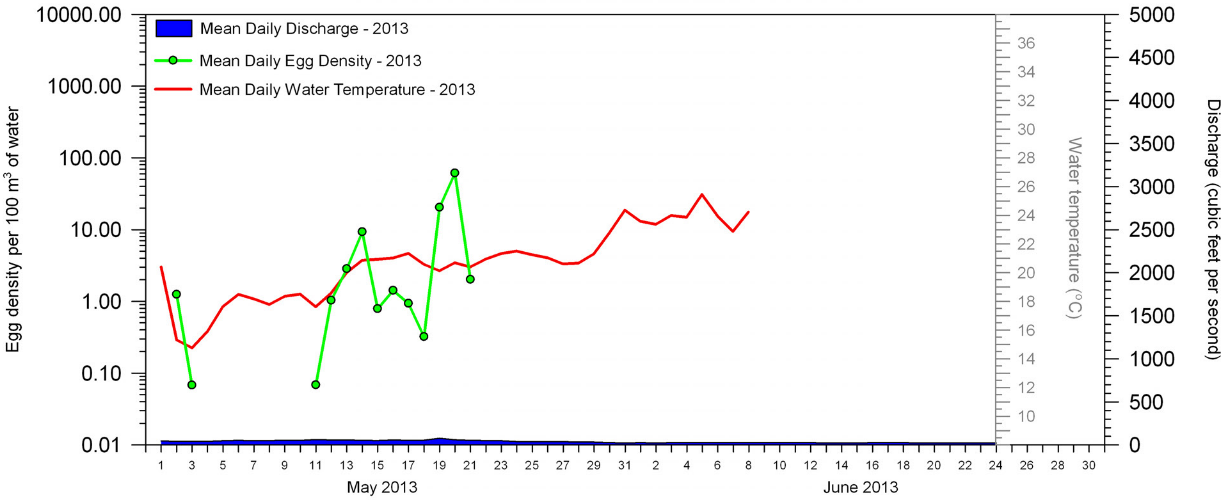

Figure 15. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2013 Rio Grande Silvery Minnow spawning periodicity study period at the San Marcial Site. Note that the Y-axis for egg density is a log-scale.

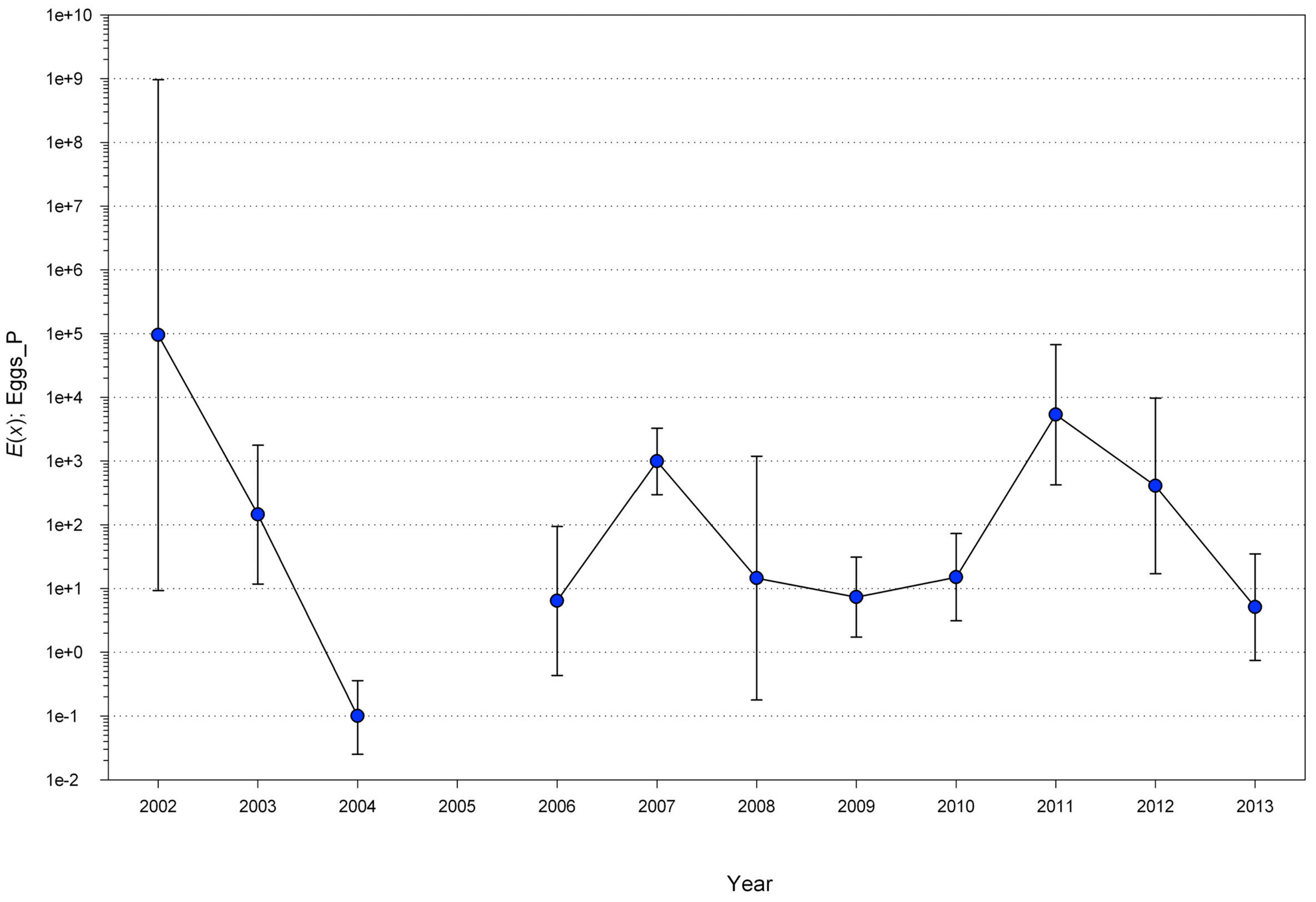

Figure 16. Rio Grande Silvery Minnow mixture-model estimates ($E(x)$), using standardized egg passage rate data (Eggs_P) at the San Marcial Site (2002–2013). Solid circles indicate modeled estimates and bars represent 95% confidence intervals. Dotted horizontal lines represent different orders of magnitude.

Table 2. General linear models of Rio Grande Silvery Minnow mixture-model estimates (Delta (δ) and Mu (μ)), using standardized egg passage rate data (Eggs_P) at the San Marcial Site from 2002–2013, and covariates (allowing for random effects). Models are ranked by Akaike's information criterion (AIC_C) and all models with an AIC_C weight (w_i) > 1% are presented.

Model[1]	**logLike**[2]	**K**[3]	**AIC_C**	**w_i**
δ(Year) μ(ABQ>2,000+random)	929.04	25	982.12	0.18
δ(Year) μ(ABQmax+random)	929.49	25	982.57	0.14
δ(ABQ>2,000+random) μ(ABQ>2,000+random)	964.40	9	982.81	0.12
δ(ABQ>1,000+random) μ(ABQ>2,000+random)	964.67	9	983.08	0.11
δ(ABQmax+random) μ(ABQ>2,000+random)	964.68	9	983.09	0.11
δ(Year) μ(ABQ>1,000+random)	930.21	25	983.29	0.10
δ(ABQmax+random) μ(ABQmax+random)	964.96	9	983.37	0.09
δ(Year) μ(ABQ>3,000+random)	931.75	25	984.83	0.05
δ(ABQ>3,000+random) μ(ABQ>3,000+random)	966.43	9	984.84	0.04

[1] = Model variables included year (2002–2013), various hydraulic variables at USGS Gages (#08330000 [ABQ; Rio Grande at Albuquerque, NM] and #08358400 [SAN; Rio Grande Floodway at San Marcial, NM]), and the estimated density of juvenile and adult Rio Grande Silvery Minnow *E*(*x*) from the previous October of each sampling year

[2] = -2[log-likelihood] of the model

[3] = Number of parameters in the model

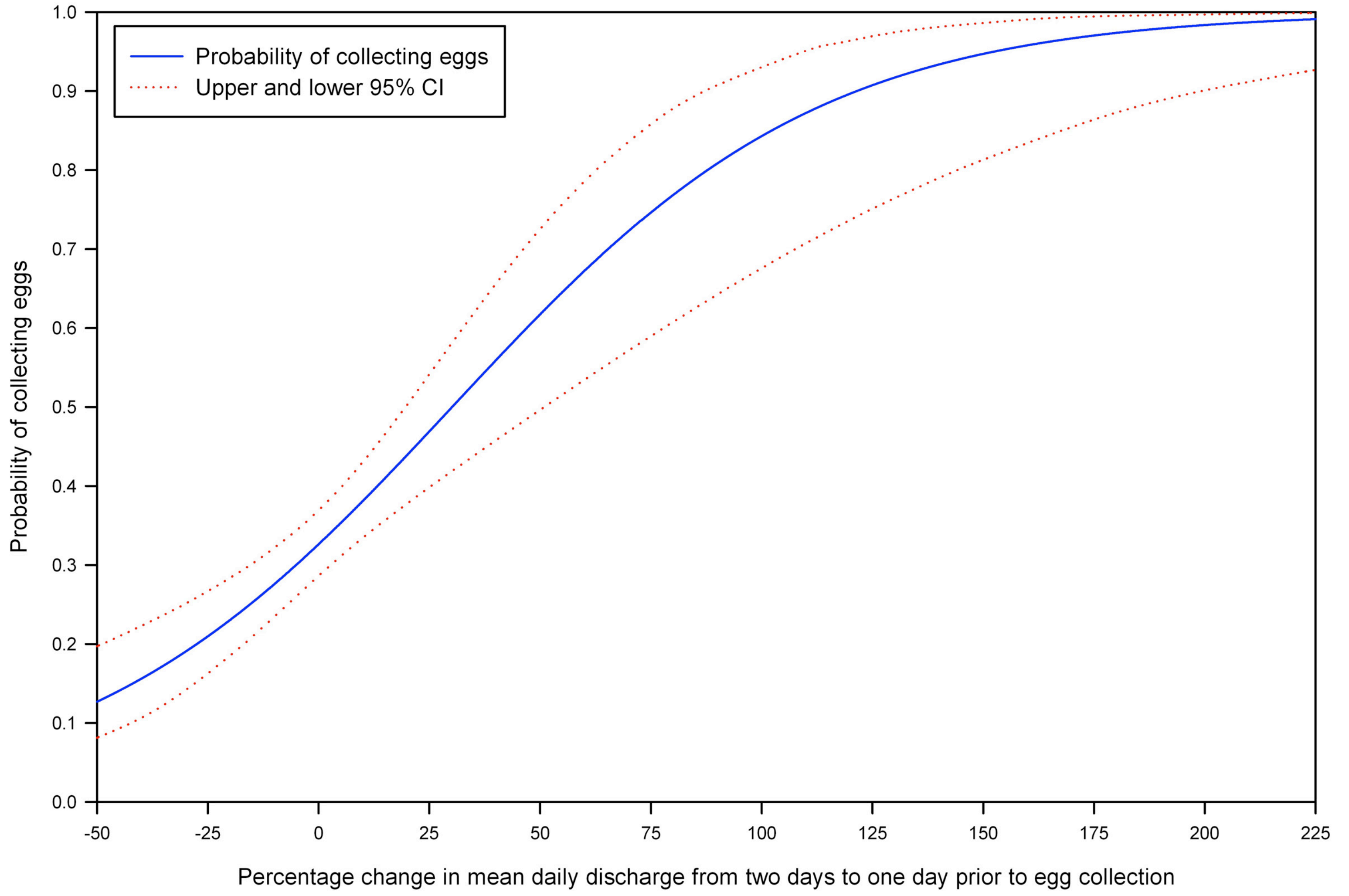

Figure 17. Logistic regression plot, using San Marcial Site data (2002–2013), illustrating the probability of collecting eggs as a function of the percentage change in mean daily discharge prior to egg collection. Graph shows logistic regression line (solid) and 95% confidence intervals (dotted).

Table 3. Number of Rio Grande Silvery Minnow eggs collected per day at each of the six sampling localities (canal sites are highlighted in gray). Table does not include dates that eggs were not collected at any of the sampling localities (NS = Not Sampled; only San Marcial Site sampled on weekends/holidays).

Sampling Date	**Belen High Line**	**Peralta**	**Socorro Main**	**Isleta**	**San Acacia**	**San Marcial**
2-May-13	0	0	0	0	2	19
3-May-13	0	0	0	0	2	1
11-May-13	NS	NS	NS	NS	NS	1
12-May-13	NS	NS	NS	NS	NS	16
13-May-13	0	0	0	0	0	50
14-May-13	0	0	0	1	1	164
15-May-13	0	0	0	0	2	13
16-May-13	0	0	0	0	0	23
17-May-13	0	0	0	0	10	17
18-May-13	NS	NS	NS	NS	NS	3
19-May-13	NS	NS	NS	NS	NS	355
20-May-13	0	0	0	0	4	1,049
21-May-13	0	0	0	0	1	34
23-May-13	0	0	0	0	1	0
24-May-13	0	1	0	0	2	0
28-May-13	0	0	0	0	1	0
Total (All Days)	***0***	***1***	***0***	***1***	***26***	***1,745***

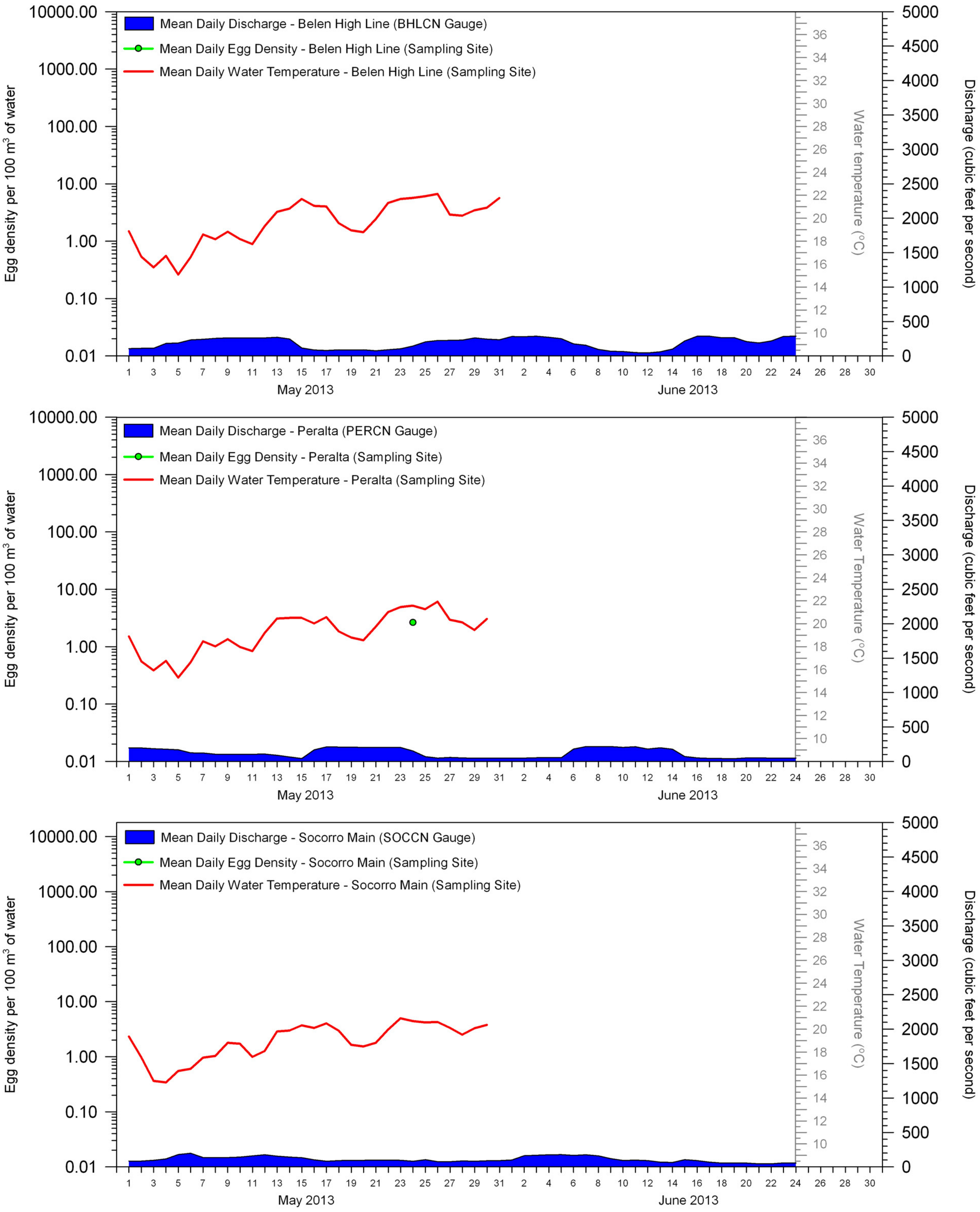

Figure 18. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2013 Rio Grande Silvery Minnow spawning periodicity study period at the canal-monitoring sites. Note that the Y-axis for egg density is a log-scale.

system over the duration of the study, from all canal-monitoring sites combined, was 9,676. The highest number of eggs estimated to be entrained in a single day was also 9,676 (24 May 2013).

River-monitoring sites

Sampling at the Isleta and San Acacia river-monitoring sites was conducted during weekdays from 1 May through 31 May (22 days). Sampling at the San Marcial Site was conducted daily from 22 April through 10 June (50 days). The cumulative volume of water sampled at the Isleta and San Acacia sites was similar (3,859.0 m^3 and 3,046.3 m^3, respectively) but notably higher at the San Marcial site (62,214.4 m^3). Two MECs were used at the San Marcial Site and sampling occurred over a longer duration (i.e., more days and hours/day) there as compared with the other two river-monitoring sites. Rio Grande Silvery Minnow spawning was documented at all three river-monitoring sites (see Table 3). A total of 1,772 eggs was collected from the three sites with the vast majority collected at the San Marcial Site (n = 1,745). Daily egg densities (number per 100 m^3 of water sampled) only included a single non-zero value at Isleta (0.50), ranged between 0.54 and 8.30 at San Acacia, and ranged between 0.07 and 61.00 at San Marcial (Figure 19).

The egg passage rate could not be estimated for the Isleta Site, using the mixture-model, since only a single value was recorded. The mixture-model was used to estimate the egg passage rate at the San Acacia ($E(x) = 5.04$) and San Marcial ($E(x) = 5.11$) sites. However, these estimates were not significantly different ($p > 0.05$).

The volume of water sampled at the river-monitoring sites constituted only a small fraction of the total volume available (ca. 0.5–1.0%) at the Isleta and San Acacia sites. However, the increased sampling efforts, combined with reduced flows, resulted in a relatively higher fraction sampled (ca. 5–10%) at the San Marcial Site. The number of eggs estimated to be transported downstream over the duration of the study was 2,383 at Isleta, 106,110 at San Acacia, and 151,947 at San Marcial. The highest number of eggs estimated to be transported downstream in a single day was 88,059 (20 May 2013) at the San Marcial Site.

Comparisons among canal and river monitoring sites

Sampling at the Belen and Peralta canal-monitoring sites was longitudinally comparable to sampling at the Isleta river-monitoring site. Water temperatures were very similar among these three sampling sites with the difference in mean daily temperatures rarely exceeding 1°C. Differences in temperatures were typically < 0.5°C with the Belen and Isleta sites showing the most congruence. The largest temperature differences were observed when flows were very low at the Peralta site (i.e., resulting in low overnight temperatures). There was only a single egg collected at the Peralta and Isleta sampling sites and no eggs were collected at the Belen Site. The lack of egg density data from the canal and river monitoring sites in the Isleta Reach during 2013 precluded further statistical comparison among those sites. Flows at the Belen Site ranged from 75 to 270 cfs (mean = 174.4 cfs). Flows at the Peralta Site were slightly lower and ranged from 41 to 209 cfs (mean = 129.1 cfs). The operating schedule of the two canal-monitoring sites resulted in elevated flows at one site for an extended period with reduced flows at the other site. Elevated flows occurred approximately during the second and forth weeks in May at the Belen Site whereas they occurred during the first and third weeks in May at the Peralta Site. In contrast, flows at the Isleta Site were higher and more stable (range = 196 to 267 cfs; mean = 216.8 cfs) as compared with either of the two canal-monitoring sites.

Sampling at the Socorro canal-monitoring site was longitudinally comparable to sampling at the San Acacia river-monitoring site. Water temperatures were similar among these two sites; the difference in mean daily temperatures was generally < 0.5°C and only exceeded 1°C on three occasions. While there were no eggs collected at the Socorro Site, there were 26 eggs collected at the San Acacia Site. The estimated egg passage rate at the San Acacia Site ($E(x) = 5.04$) was significantly higher ($p > 0.05$) than at the Socorro Site ($E(x) = 0.00$). Flows at the Socorro Site ranged from 81 to 196 cfs (mean = 109.7 cfs). However, only a small fraction (often < 10%) of the water at the Socorro Site originated from the San Acacia Diversion Dam during the period of spawning (as documented at the San Acacia Site). The operating schedule of the Socorro Site resulted in elevated flows approximately during the second and third weeks in May. In contrast, flows at the San Acacia Site were higher and more stable (range = 164 to 243 cfs; mean = 188.8 cfs) as compared with the Socorro Site.

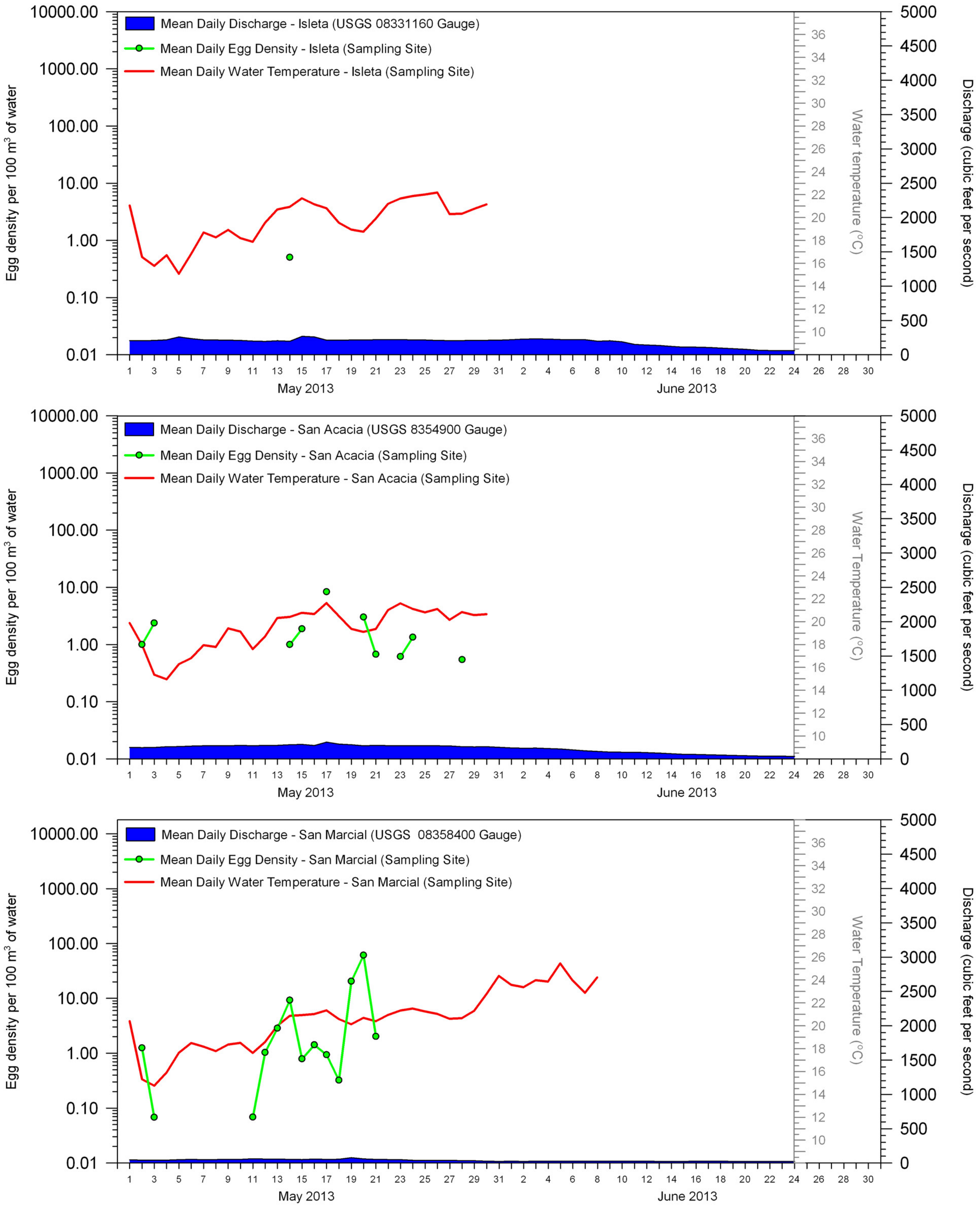

Figure 19. Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2013 Rio Grande Silvery Minnow spawning periodicity study period at the river-monitoring sites. Note that the Y-axis for egg density is a log-scale.

DISCUSSION

As rivers have become increasingly fragmented, one factor limiting the recolonization of upstream reaches and imperiling pelagic spawning cyprinids is the downstream transport of reproductive products below barriers or displacement into highly degraded downstream riverine habitats and reservoirs (Dudley and Platania, 2007). The negative impacts of dam-related modifications of flow and habitat on Great Plains stream cyprinids that employ drifting eggs and larvae as an early life history strategy have been well documented (Stanford and Ward, 1979; Cross et al., 1983; Cross et al. 1985, Cross and Moss, 1987; Winston et al., 1991; Luttrell et al., 1999). In the Middle Rio Grande, large numbers of eggs of the federally endangered Rio Grande Silvery Minnow are annually transported past downstream collecting sites (Dudley and Platania, 2012). The downstream transport of this reproductive effort from upstream sources is potentially one factor that led to the apparent loss of Rio Grande Silvery Minnow from the Cochiti Reach and to its decline in the Angostura Reach in the Middle Rio Grande (Platania and Altenbach, 1998).

In addition to the problems created by river fragmentation, habitat simplification (caused by flow regulation, bank armoring, etc.) also appears to contribute to the downstream displacement of the Rio Grande Silvery Minnow reproductive effort. The closure of Cochiti Dam resulted in a greatly reduced passage of fine sediments through the Middle Rio Grande that has, in turn, contributed to channel degradation, armoring, and narrowing (Lagasse, 1985). Arroyos, backwaters, and other “nursery habitats” may result in increased upstream retention of eggs and larvae because their off-channel location often results in negligible water velocities (Porter and Massong, 2004a; Porter and Massong, 2004b; Pease et al., 2006). The reduction in the number and size of low velocity mesohabitats has likely reduced egg retention in upper reaches of the Middle Rio Grande.

Since Rio Grande Silvery Minnow is the only extant species of the reproductive guild of pelagic spawers in the Middle Rio Grande, the species-specific identification of any semibuoyant egg collected during this study was unambiguous. The only other fish eggs that we have captured in the Middle Rio Grande during this and previous investigations were those of the Common Carp, *Cyprinus carpio*. Fortunately, there are numerous differences between eggs of these species that aid in identification. As the eggs of common carp are adhesive, there are usually small pieces of particulate matter attached to the chorion. Additionally, common carp eggs are smaller and more opaque than Rio Grande Silvery Minnow eggs, and the eyes of carp embryos become pigmented very early in development. Conversely, the eggs of Rio Grande Silvery Minnow are clear, non-adhesive, smooth, large, and the embryos lack discernible pigment.

Prior to spawning, the gonadosomatic index (GSI) values of Rio Grande Silvery Minnow increase during early spring (Platania and Altenbach, 1996). The GSI value is the ratio of gonad weight to body weight and higher GSI values indicate an increased readiness to spawn. Field collections (1993 to 1995) indicated that the increase in GSI values generally corresponded with the gradually increasing flows of spring runoff along with the gradually increasing water temperatures of the river (Platania and Altenbach, 1996). It is possible that some combination of factors (e.g., extended photoperiod and increasing water temperatures) could be the initial trigger for GSI values to increase in the early spring and that the steadily increasing flows of spring runoff contribute to this effect, especially during higher flow years.

Spawning of Rio Grande Silvery Minnow and other members in its reproductive guild is triggered by specific environmental cues (Platania and Altenbach, 1998). These fishes often spawned shortly after increases in flow during spring and summer months. Egg densities in the Pecos River and Rio Grande may be more related to flow increases than to absolute water volume. This relationship has been observed throughout the Middle Pecos River from early-May until late-September. Spawning was closely correlated to sharp increases in flow from local rainstorms and egg densities would drop as soon as flows began to drop. This sequential pattern (increased flow, increased spawning, decreased flow, decreased spawning) occurred throughout the summer in the Pecos River, NM. By late-September, the association between spawning and flow was minimal, indicating the end of the reproductive season for the five members of the reproductive guild that occupy the Pecos River.

The results of this study suggest that the number of eggs produced in the Middle Rio Grande may be related to some combination of discharge and water temperature conditions. Large increases in flow over a relatively short period just prior to egg collection seemed particularly related to increased spawning activity of Rio Grande Silvery Minnow. This relationship was especially robust during years when flows in

May and June were relatively low (i.e., 2002, 2003, 2006, 2001, and 2013), which led to more dramatic increases in spawning following relatively brief increases in flow. However, the propensity of Rio Grande Silvery Minnow to spawn shortly after these flow increases could have negative consequences on recruitment success in low flow years if appropriate nursery habitats do not persist over an extended period. In contrast, there is a more protracted spawning period during higher flow years (i.e., 2004 and 2007 to 2010), primarily occurring during periods of elevated flow in May. While peak spawning by Rio Grande Silvery Minnow generally occurred soon after the initiation of spring runoff (often during the first two weeks of May), extended spawning while nursery habitats persist could lead to increased recruitment success.

Elevated flows lead to a series of changes to the physical dynamics of the river (e.g., increased water velocities/depths in some areas and augmented or new “flooded” low velocity habitats in other areas) that could be important spawning cues associated with rising flows. Additionally, there are frequently changes in water chemistry that accompany flow increases, particularly when large amounts of sediment are carried into the river from formerly dry shoreline areas, eroding banks, or flowing arroyos. The increased sediment load results in increased turbidity levels (decreased water clarity), slightly decreased water temperatures, and can lead to substantial increases in salinity levels. For example, three-fold increases/decreases in salinity levels (at the same sampling site) are regularly documented as a result of different flow conditions during spring/summer population monitoring surveys. It is possible the Rio Grande Silvery Minnow are spawning as a result of some combination of changing habitat and water chemistry conditions that result from these increased flow events.

While increases in discharge appear to be the primary cue for spawning, water temperature seems to be an important factor as well. Spawning appears to occur over a wide range of mean daily water temperatures (ca. 13 to 26°C) but with the majority occurring over a narrower range of temperatures (ca. 17 to 23°C). However, this interaction is complex and varies among years and reaches. Also, sampling has focused on May through mid-June as part of this project but spawning has been documented from late March into late June (Platania and Dudley, 2000). The mean daily water temperatures during these extended periods were at the limits of the range at which spawning has been documented (i.e., 13 to 26°C).

It is possible that this range of spawning temperatures is even broader, particularly at warmer water temperatures, but there have been no longer-duration systematic studies conducted to document this possibility. Despite the lack of field spawning studies earlier or later in the year, experimental water temperature treatments on eggs and larvae of Rio Grande Silvery Minnow revealed that mortality was notably higher at 15°C or 30°C as compared with 20°C or 25°C (Platania, 2000). It is likely that individuals spawned earlier in the year (e.g., April) or later in the year (e.g., July), when water temperatures are at the presumed limits of their spawning range, have an increased rate of mortality. However, those individuals that are spawned slightly earlier in the year might have an increased chance of early survival as compared to those spawned later in the year since there would presumably be reduced competitive pressure from other early stage larval fishes, which are generally less abundant in May as compared with June or July (Pease et al., 2006).

There are, however, multiple factors that affect survival of Rio Grande Silvery Minnow throughout the spring and summer, including numerous abiotic (e.g., flow, temperature, water quality) and biotic (e.g., temporal/spatial resource availability, competitive interactions, predation pressure) factors. Genetic analyses of wild Rio Grande Silvery Minnow eggs and adults suggested that survival was highly variable, leading to large differences in reproductive success among individuals (Osborne et al., 2005). In fact, the broad range of conditions that result in Rio Grande Silvery Minnow reproduction could indicate that there is no “perfect” spawning cue (i.e., combination of abiotic/biotic conditions) that would result in a consistently higher chance of early survival and recruitment into the population. The closest combination of favorable conditions, based on the last decade of spawning studies, appears to be increased flows that occur with appropriately warm water temperatures. While increased flows can, and often do, lead to the creation of new or the expansion of existing larval fish nursery habitats and presumably higher recruitment success, there is no guarantee that flows will continue to rise or remain stable after spawning. Sometimes flow in the river will briefly increase and then return to low levels either as a result of changes in ambient temperature (affecting the rate of snowmelt) or as a result of short-term precipitation events. The young that are produced as a result of these flow events are often subjected to biotic and physical conditions that may preclude their successful growth and survivorship, particularly during summer months. Excessively elevated water temperatures (>30°C) in the Rio Grande, caused by warm ambient conditions and low flows, may reduce the hatching success of newly spawned eggs and survival of larvae. In addition to high water temperatures and possibly poor water quality, the likelihood of intra- and inter-specific interactions (e.g., predator-prey or competition) would be expected to increase during low flows as available aquatic habitat decreases. The complex interactions among abiotic and biotic variables in the early survival, growth, and recruitment of Rio Grande Silvery Minnow continue to give new insight to the patterns of their spatial spawning periodicity over time.

A general linear model of October densities of juvenile and adult Rio Grande Silvery Minnow (1993–1997, 1999–2011) revealed significant associations with hydraulic variables (Dudley and Platania, 2013). The relationships that explained the most variation in estimated density were number of days with discharge >2,000 cfs or >3,000 cfs (as measured at the Albuquerque gage). Similarly, the top general linear models obtained when using the long-term spawning data (2002–2013) indicated that spawning intensity increased with increasing spring discharge. The physical conditions produced by prolonged and elevated flows result in overbank flooding of vegetated areas, formation of inundated habitats within the river channel, and creation of shoreline and island backwaters. Shallow low-velocity habitats (e.g., shoreline pools, backwaters, overbank floodplains etc.) are well known to be essential for the successful recruitment of early life history stages of many freshwater fish species throughout the world (for review see Welcomme, 1979). Similar processes are likely important for the successful survival and recruitment of the Middle Rio Grande ichthyofaunal community, including early life stages of Rio Grande Silvery Minnow (Pease et al., 2006; Turner et al., 2010).

Efforts were made to estimate the number of eggs transported downstream of each sampling site based on the total number of eggs collected, volume of water sampled, volume of water available to be sampled, and duration of sampling. This approach required several simplifying assumptions including: 1) eggs were approximately evenly distributed within the volume of water passing the sampling site, 2) eggs collected during a four hour period of sampling in a given day approximately represented the rate at which eggs were transported downstream of the site during that day, and 3) the volume of water at the nearest upstream USGS station approximately represented the volume of water passing the sampling site. While these assumptions seem reasonable, it is likely that some non-quantified error is introduced into the calculations through these extrapolations. Even with modest violations of these assumptions, the number of eggs estimated to be transported downstream would likely still be quite high. These results indicate a substantial downstream transport of drifting eggs at San Marcial Site in the Middle Rio Grande despite the seemingly modest numbers collected in individual MECs. However, it is unknown what proportion of these eggs was viable since that was not an objective of this study.

The total number of Rio Grande Silvery Minnow eggs collected was generally obtained through direct counting of individual propagules in the field. This direct counting method was used for nearly all sampling days during the spawning season across years. However, there was an occasional need to preserve egg samples when the total number of eggs collected exceeded our ability to accurately count them while also effectively operating the MECs. This threshold was exceeded when more than about 1,000 eggs were collected every hour. While these elevated spawning events occurred only a few times since 2002, the need to accurately quantify the number of eggs was particularly crucial since these events compose the vast majority of the total spawning effort within a given year. While we did not use estimates of the number of eggs collected during this study (i.e., only actual counts), we had employed a volumetric estimation of the number of eggs in 2001. Since 2002, we have only used actual counts because we found that volumetric determination of the number of Rio Grande Silvery Minnow eggs collected lacked the rigor necessary for effective evaluation of the relative level of spawning by this species. Based on several trials conducted in 2011, we also determined that time-based estimates of the number of eggs collected were even more problematic than volumetric estimates and consistently resulted in overestimated total egg counts (Dudley and Platania, 2011). On 5 June 2011, eggs were enumerated following multiple five-minute sampling periods and data were extrapolated to determine time-based estimates of egg density over longer durations. All eggs collected during that sample date were retained and individually enumerated in the laboratory. Comparison of the multiple time-based estimates of the eggs with the actual number of eggs retained revealed that the time-based estimates were sometimes an order of magnitude higher than actual counts. These problems were most exacerbated when the number of eggs was higher than could be counted accurately and perhaps led to an excited tendency to overestimate (or round up) the number of eggs collected. While these issues could be partially addressed through training or replication to essentially “calibrate” the time-based (or volumetric) estimates to actual numbers, it is clear that for this study there is a need to count individual eggs to accurately evaluate the level of spawning by Rio Grande Silvery Minnow.

The total number of eggs collected at a site, from multiple MECs and over an extended daily sampling period, has been combined for the purposes of this report. The variation in egg densities among MECs and different sequential periods in a single day was minimal compared to the variation among days. The primary purpose in sampling with two MECs over an extended time period was to filter an adequate volume of water to both detect the presence of eggs and to obtain an accurate estimate of the level of spawning over time. The volume of water currently sampled daily at each of the sampling sites is very high, primarily because of the use of the modified and more efficient sampling screens.

Population trends lend support to the observation that substantial numbers of eggs (and presumably larvae) are being transported downstream every year. The highest densities of Rio Grande Silvery Minnow eggs likely occur in the lower Isleta Reach and throughout the San Acacia Reach. In support of these observations, the highest densities of juvenile Rio Grande Silvery Minnow are most frequently found in the southern reaches of the Middle Rio Grande (Dudley and Platania, 2013). This trend was first noted over two decades ago (Bestgen and Platania, 1991), before Rio Grande Silvery Minnow was listed as a federally endangered species, and it persists to the present time. The few exceptions to this trend (i.e., higher densities of juveniles found in upstream reaches) have almost always occurred following years when flows were very low in the San Acacia Reach, resulting in substantial river drying and loss of fish in that area.

Despite the seemingly large number of Rio Grande Silvery Minnow propagules transported downstream every year, some portion does remain upstream (Dudley and Platania, 2007; Widmer et al., 2013). It is likely that the proportion of individuals retained and successfully recruited upstream is related to the complexity of instream habitat conditions and the long-term availability of nursery habitat. Since successful growth and survival of Rio Grande Silvery Minnow from the egg to the juvenile stage requires about six weeks (Platania, 1995), the persistence of these nursery habitats throughout this critical phase of development could lead to improved recruitment success.

Increased flows in May apparently resulted in an elevated spawning effort during the 2013 study period. Summer monsoonal rainstorms (during July) that sometimes help maintain flow throughout the study area occurred periodically in 2013, resulting in somewhat elevated but unpredictable flows during the post-spawning period. Rio Grande Silvery Minnow appear to have had a modest year for spawning but it is possible that poor recruitment in 2013 (apparently as a result of a truncated spring runoff followed by erratic summer flows) could translate into decreased numbers of reproductively capable females available to spawn in the spring of 2014.

The potential association between Rio Grande Silvery Minnow October densities, from the Population Monitoring Program (see Dudley and Platania, 2013), and spring spawning frequency and magnitude was examined over the period of record (2002–2013). However, the density of Rio Grande Silvery Minnow during October was poorly related to spawning intensity at the San Marcial Site. These preliminary findings suggest that the number of eggs produced in the river during spring does not appear to be strongly related to the abundance of Rio Grande Silvery Minnow from the previous October. Rather, the intensity of spawning appears more related to the magnitude and duration of the spring runoff. Additionally, eggs collected at the San Marcial Site represented individuals that were going to be transported farther downstream, possibly into Elephant Butte Reservoir, and therefore might not contribute substantially to the San Acacia Reach population. The number of Rio Grande Silvery Minnow eggs collected at a particular sampling site is likely a result of the complex interrelationships among the spatial distribution of upstream population concentrations, egg development time (i.e., faster at higher water temperatures), and local egg transport efficiencies (e.g., decreased habitat complexity will likely result in increased egg transport (Dudley and Platania, 2007; Widmer et al., 2013)). Additional years of data will hopefully further elucidate these subtle relationships and lend insight to the causal mechanisms resulting in the successful recruitment of Rio Grande Silvery Minnow.

Sampling from multiple canal and river locations in the Isleta and San Acacia reaches provided additional insight to Rio Grande Silvery Minnow spatial spawning patterns during 2013. The egg passage rate at the San Marcial Site in 2013 indicated a marked decline in spawning intensity as compared with 2011. While the low numbers of eggs collected in 2013 precluded statistical analyses for all but the San Acacia and San Marcial sites, it was apparent that egg passage rates were greatly reduced in the Isleta

Reach as compared with the San Acacia Reach. The large discrepancy in estimated egg passage rates between the Socorro (canal) and San Acacia (river) sites appears to be driven by the source of the canal water. The vast majority of the water at the Socorro Site originated from the upper Isleta Reach during days when spawning was detected at the San Acacia Site. The relative lack of water being diverted at San Acacia Diversion Dam during river spawning events appears to have minimized entrainment of eggs into the San Acacia Reach irrigation network during 2013.

Populations of Rio Grande Silvery Minnow have declined since 2009 and the lack of an adequately high spring runoff (high magnitude over an extended duration) combined with late summer drying in 2013 could result in persistently low population levels in all three reaches of the Middle Rio Grande. The loss of individuals from downstream reaches during river drying events is particularly problematic as these are the areas that most frequently and consistently support the highest densities of Rio Grande Silvery Minnow. The future conservation status of Rio Grande Silvery Minnow appears strongly dependent on ensuring appropriate flow and habitat conditions that are timed with the typical spawning and early recruitment phases of this species.

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LITERATURE CITED

Akaike, H. 1973. Information theory as an extension of the maximum likelihood principle. In: B. N. Petrov and F. Csaki (eds.). Second International Symposium on Information Theory. Akademiai, Budapest.

Altenbach, C. S., R. K. Dudley, and S. P. Platania. 2000. A new device for collecting drifting semibuoyant fish eggs. Transactions of the American Fisheries Society 129:296–300.

Bestgen, K. R., and S. P. Platania. 1990. Extirpation and notes on the life history of Notropis simus simus and Notropis orca (Cypriniformes: Cyprinidae) from the Rio Grande, New Mexico. Occasional Papers of the Museum of Southwestern Biology 6:1–8.

Bestgen, K. R., and S. P. Platania. 1991. Status and conservation of the Rio Grande Silvery Minnow, Hybognathus amarus. Southwestern Naturalist 36:225–232.

Cross, F. B., and R. E. Moss. 1987. Historic changes in fish communities and aquatic habitats in plains streams of Kansas, p. 155–165. In: Community and evolutionary ecology of North American stream fishes. W. J. Matthews and D. C. Heins (eds.). University of Oklahoma Press, Norman, Oklahoma.

Cross, F. B., O. T. Gorman, and S. G. Haslouer. 1983. The Red River shiner, Notropis bairdi, in Kansas with notes on depletion of its Arkansas River cognate, Notropis girardi. Transactions of the Kansas Academy of Science 86:93–98.

Cross, F. B., R. E. Moss, and J. T. Collins. 1985. Assessment of dewatering impacts on stream fisheries in the Arkansas and Cimarron rivers. University of Kansas Natural History Museum, Lawrence, Kansas.

Dudley, R. K., and S. P. Platania. 2007. Flow regulation and fragmentation imperil pelagic-spawning riverine fishes. Ecological Applications 17: 2074–2086.

Dudley, R. K. and S. P. Platania. 2011. Spatial spawning periodicity of Rio Grande Silvery Minnow during 2011. Report to the Middle Rio Grande Endangered Species Collaborative Program and the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Dudley, R. K. and S. P. Platania. 2012. Spatial spawning periodicity of Rio Grande Silvery Minnow during 2012. Report to the Middle Rio Grande Endangered Species Collaborative Program and the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Dudley, R. K. and S. P. Platania. 2013. Rio Grande Silvery Minnow population monitoring program results from December 2011 to October 2012. Report to the Middle Rio Grande Endangered Species Collaborative Program and the U.S. Bureau of Reclamation, Albuquerque, New Mexico. 158 pp.

Fletcher, D., D. Mackenzie, and E. Villouta. 2005. Modelling skewed data with many zeros: A simple approach combining ordinary and logistic regression. Environmental and Ecological Statistics 12: 45–54.

Gold, R. L., and L. P. Denis. 1985. National water summary: New Mexico surface-water resources. U.S. Geological Survey Water-Supply Paper 2300:341–346.

Lagasse, P. F. 1985. An assessment of the response of the Rio Grande to dam construction–Cochiti to Isleta reach. A technical report for the U.S. Army Engineer District, Albuquerque, Corps of Engineers, Albuquerque, New Mexico.

Luttrell, G. A., A. A. Echelle, W. L. Fisher, and D. J. Eisenhour. 1999. Declining status of two species of the Macrhybopsis aestivalis complex (Teleostei: Cyprinidae) in the Arkansas River Basin and related effects of reservoirs as barriers to dispersal. Copeia 1999:981–989.

Martin, T. G., B. A. Wintle, J. R. Rhodes, P. M. Kuhnert, S. A. Field, S. J. Low-Choy, A. J. Tyre, and H. P. Possingham. 2005. Zero tolerance ecology: improving ecological inference by modelling the source of zero observations. Ecology Letters 8: 1235–1246.

Nagelkerke, N. J. D. 1991. A note on a general definition of the coefficient of determination. Biometrika 78: 691–692

Osborne, M. J., M. A. Benavides, and T. F. Turner. 2005. Genetic heterogeneity among pelagic egg samples and variance in reproductive success in an endangered freshwater fish, Hybognathus amarus (Cyprinidae). Environmental Biology of Fishes 73:463–472.

Pease, A. A. 2006. Habitat and resource use by larval and juvenile fishes in an arid-land river (Rio Grande, New Mexico). Freshwater Biology 51:475–486.

Platania, S. P. 1991. Fishes of the Rio Chama and Upper Rio Grande, New Mexico, with preliminary comments on their longitudinal distribution. Southwestern Naturalist 36:186–193.

Platania, S. P. 1995. Reproductive biology and early life-history of Rio Grande Silvery Minnow, Hybognathus amarus. Submitted to the U.S. Army Corps of Engineers, Albuquerque, New Mexico.

Platania, S. P. 2000. Effects of four water temperature treatments on survival, growth, and developmental rates of Rio Grande Silvery Minnow, Hybognathus amarus, eggs and larvae. Submitted to the U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

Platania, S. P., and C. S. Altenbach. 1996. Reproductive ecology of Rio Grande Silvery Minnow Hybognathus amarus: Clutch and batch production and fecundity estimates. Submitted to the U.S. Army Corps of Engineers, Albuquerque, New Mexico.

Platania, S. P., and C. S. Altenbach. 1998. Reproductive strategies and egg types of seven Rio Grande Basin cyprinids. Copeia 1998:559–569.

Platania, S. P., and R. K. Dudley. 2000. Spatial spawning periodicity of Rio Grande Silvery Minnow, during 1999. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2002. Spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2001. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2003. Spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2002. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2004. Spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2003. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2005. Spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2004. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2006. Spatial spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2006. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2007. Spatial spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2007. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2008. Spatial spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2008. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P., and R. K. Dudley. 2009. Spatial spawning periodicity of Rio Grande Silvery Minnow, Hybognathus amarus, during 2009. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Platania, S. P. and C. W. Hoagstrom. 1996. Response of Rio Grande fish community to an artificial flow spike. Museum of Southwestern Biology, University of New Mexico, Albuquerque, New Mexico.

Porter, M. D., and T. M. Massong. 2004a. Contributions to delisting Rio Grande Silvery Minnow: egg habitat identification. Submitted to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Porter, M. D., and T. M. Massong. 2004b. Analyzing changes in river channel morphology using GIS for Rio Grande Silvery Minnow habitat assessment. GIS/Spatial Analyses in Fishery and Aquatic Sciences: 433–446.

SAS Institute Inc. 2007. JMP Statistics and Graphics Guide. Cary, NC: SAS Institute Inc. 1035 pp.

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Scurlock, D. 1998. From the rio to the sierra: An environmental history of the Middle Rio Grande Basin. General Technical Report RMRS-GTR-5. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Smith, J. R. 1998. Summary of Low Flow Conveyance Channel fish investigations for fiscal year 1997. Report to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Smith, J. R. 1999. A summary of easy egg catching in the Low Flow Conveyance Channel in the 9 mile study reach during spring 1998 operations. Report to the U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Speirs, D. C., and W. S. C. Gurney. 2001. Population persistence in rivers and estuaries. Ecology 82:1219–1237.

Stanford, J. A., and J. V. Ward. 1979. Stream regulation in North America, p. 215–236. In: The ecology of regulated streams. J. V. Ward and J. A. Stanford (eds.). Plenum Press, New York, New York.

Turner, T.F., T.J. Krabbenhoft, and A.S. Burdett. 2010. Reproductive phenology and fish community structure in an arid-land river system. Pages 427–446 in K.B. Gido and D.A. Jackson, editors. Community ecology of stream fishes: concepts, approaches, and techniques. American Fisheries Society, Symposium Series 73, Bethesda, MD. 664 pp.

U.S. Fish and Wildlife Service. 2010. Rio Grande Silvery Minnow (Hybognathus amarus) recovery plan. 1st revision. Albuquerque, New Mexico, USA.

Welcomme, R. L. 1979. The fisheries ecology of floodplain rivers. Longman, London. 317 pp.

Welsh, A. H., R. B. Cunningham, C. F. Donnelly, and D. B. Lindenmayer. 1996. Modelling the abundance of rare species: statistical models for counts with extra zeros. Ecological Modelling 88: 297–308.

White, G. C. 1978. Estimation of plant biomass from quadrat data using the lognormal distribution. Journal of Range Management 31:118–120.

Widmer, A. M., J. J. Fluder, J. W. Kehmeier, C. N. Medley and R. A. Valdez. 2013. Drift and retention of pelagic spawning minnow eggs in a regulated river. River Research and Applications 28:192–203.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society 120:98–105.

Zar, J. H. 2010. Biostatistical Analysis. Fifth edition. Prentice Hall Inc., Upper Saddle River, New Jersey. 944 pp.