Appendix A

Final Biological and Conference Opinion for Bureau of Reclamation, Bureau of Indian Affairs, and Non-Federal Water Management and Maintenance Activities on the Middle Rio Grande, New Mexico

Consultation Number 02ENNM00-2013-F-0033

Analytical framework for evaluating the proposed water management and maintenance actions on Rio Grande silvery minnow, southwestern willow flycatcher, and yellow-billed cuckoo and their critical habitats

Appendix A

Analytical framework for evaluating the proposed water management and maintenance actions on Rio Grande silvery minnow, southwestern willow flycatcher, and yellow-billed cuckoo and their critical habitats

To achieve our goals of transparent and repeatable analyses and document, we created an analytical framework for evaluation of the proposed actions' impacts to the river environment and their effects to the listed species and their habitats (Figure A1). Analytical frameworks are non-quantitative conceptual models that can help identify the major anthropogenic drivers, impacts, and effects on species in natural systems (Ogden et al. 2005). We conducted our analysis in accordance with applicable regulations, Service policy, guidance, and the Section 7 Consultation Handbook (US Fish and Wildlife Service (Service) 1998).

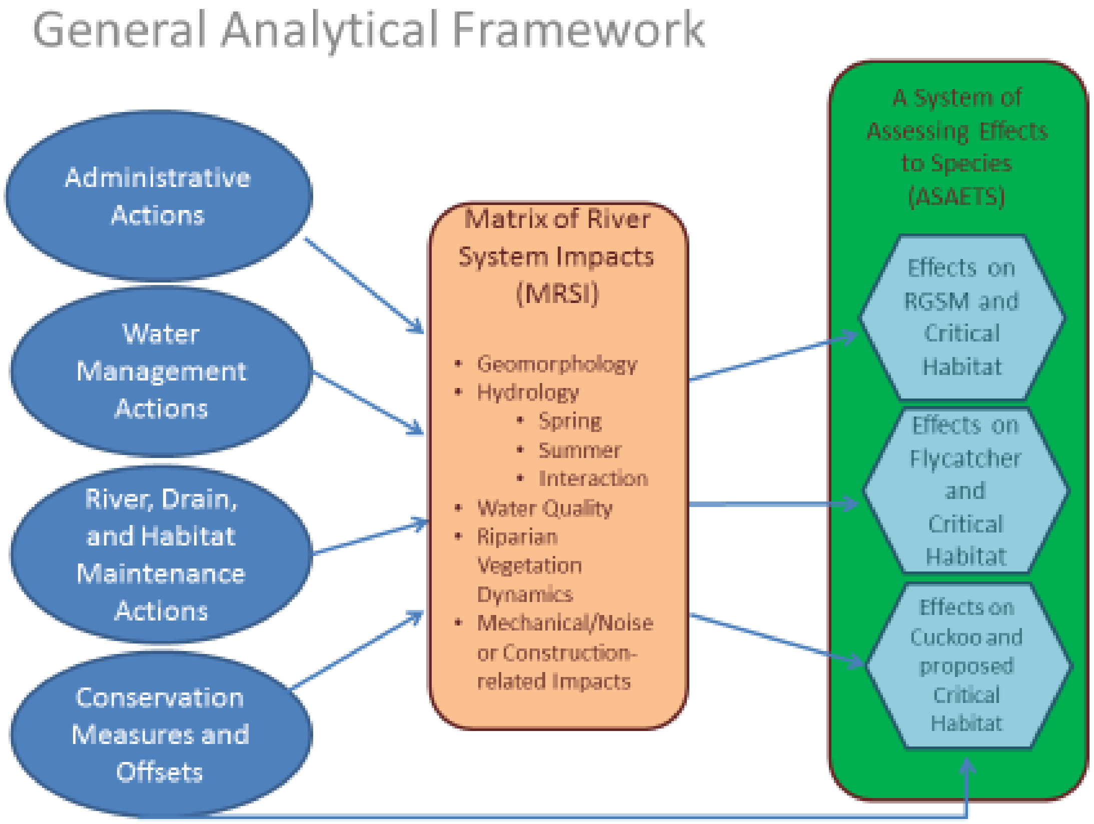

Figure A1. General analytical framework for evaluation of proposed actions on listed MRG species.

Appendix A.1. Matrix of River System Impacts and A System of Assessing Effects to Species and Critical Habitat in the MRG.

We supplemented our analysis with two conceptual spreadsheet models [Matrix of River System Impacts (MRSI) and A System of Assessing Effects to Species (ASAETS)]. MRSI and ASAETS allowed the organization and conversion of the existing scientific and technical information into the spreadsheet models. These models provide a basis for a qualitative analysis of exposure, response, and risk to silvery minnows, flycatchers, cuckoos, and their critical habitats. We based these models on a variety of environmental impact assessments, including consideration of collective professional judgment and impact significance (Leopold et al. 1971; Kane et al. 1974; Canter 1998; Rossouw 2003).

The Matrix of River System Impacts (MRSI)

The MS Excel spreadsheet file named, "20161130 MRSI - Matrix of River System Impacts.xlsx" contains the worksheet named, "Simpler MRSI with No Ranks" which is a comprehensive evaluation of most of the impacts to the MRG from: previous actions (environmental baseline); ongoing or future Federal actions (cumulative effects); and the Proposed Action (Appendix C).

River system impacts were as described in the BA and were grouped by the following categories: 1) geomorphology (of the river channel and the floodplain); 2) hydrology (focusing on spring runoff, low flows, and groundwater interactions); 3) water quality (water temperature, oxygen content, turbidity, salinity, and nutrients); 6) riparian and aquatic vegetation dynamics; and, 7) proposed construction impacts, noise, habitat restoration and associated human activities. Some of the impacts and Conservation Measures did not fit into these seven categories of impacts, and those impacts or benefits were addressed in the narratives of the BiOp.

The MRSI table is a matrix of the seven river system impacts identified above (columns), and the types of proposed agency water operations, maintenance, and conservation measures, as well as activities in the environmental baseline (rows). The cells of the MRSI matrix were filled with values using collective professional judgment of up to eight biologists, and with support from published literature, or other available facts and data provided in the BA or in other documents and literature. Uncertainties using these spreadsheet models include identification of impacts, the inability to factor time as part of the impacts, and results may vary because rating criteria and identification of impacts and effects were qualitative.

The river system impacts were described in terms of their magnitude and significance by assigning values of "LIKELY ADVERSE" to a high level of habitat impacts; "NOT ADVERSE" to a low level of impacts or marginal subsidies; "NONE" had no effects; and, "BENEFICIAL" had significant benefits to habitat. The value of "NOT ADVERSE" in any cell entry also signifies where the Service has concurred that the specific action proposed "may affect, but is not likely to adversely affect", the listed species or critical habitat for this project.

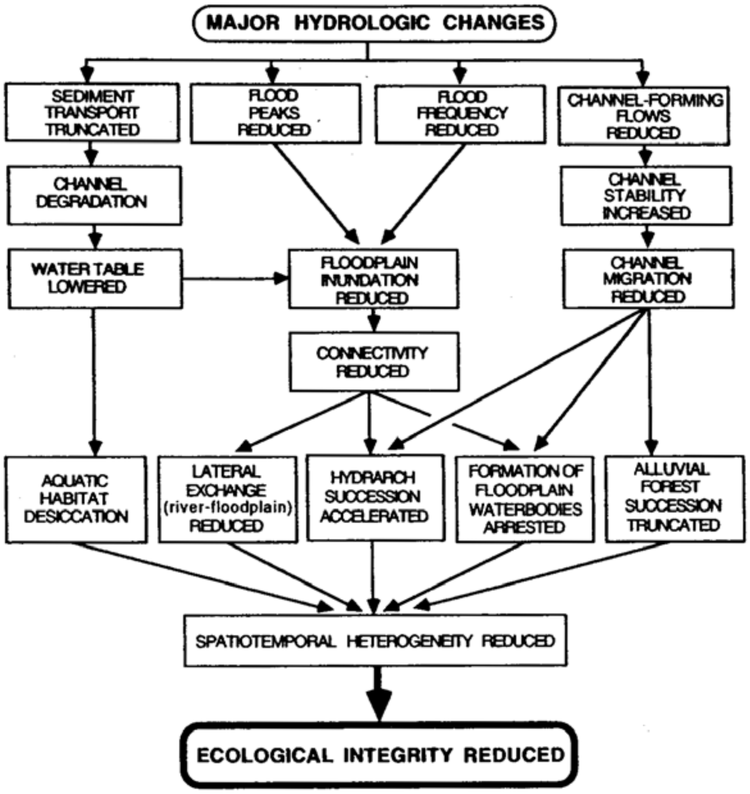

Figure A2. Ecological implications of major hydrological changes to river systems (Ward and Stanford 1995).

<u>A System of Assessing Effects to Species (ASAETS)</u>

We analyzed biological effects to listed species and critical habitat from the river system impacts (as identified in MRSI) using the ASAETS spreadsheets. Generally, the combined use of MRSI and ASAETS was used to characterize the various impacts to the fluvial system and the associated biological effects to listed species and their habitats (for example, see Ward and Stanford 1995; Figure A2).

Each species' ASAETS spreadsheet (Appendix C) contains the matrix of seven river system impacts used in MRSI (rows) and the effects to species and critical habitats (columns). Where adverse effects are likely to the listed species, either directly or indirectly, through impacts to their habitats, or by altering their biotic interactions with prey, competitors, predators, parasites, diseases, etc. we valued those effects as a 5 (medium) or 10 (high). Where the effects were minor or negligible, we valued those effects as a 0 (no effects to listed species or critical habitats) or 1 (may affect, not likely to adversely affect listed species or critical habitat).

We based our species effects analysis on silvery minnow, flycatcher, or cuckoo life history initially using the criteria described by Friggens et al. (2013) in their "System for Assessing Vulnerability of Species to Climate Change," but later modified and simplified this approach to include column variables for evaluating river system impacts with the physical and biological features of the listed species critical habitats (Service 2003, 2013a, 2014), and reduced the number and types of effects categories. This approach also aided identification and proportions of the major river system impacts, types of species effects, and categories of each. Through our analysis we identified a total of 14 major effect types for silvery minnow and cuckoo, and 17 effect types for flycatcher, as categorized by direct and indirect effects, habitat effects, and species biotic interactions (Appendix C).

Appendix A.2. Reclamation's five, 10-year Hydrologic Scenarios and the Comparison of the Proposed Action versus No Action analysis for the BiOp.

Reclamation (2015) performed the hydrologic analyses through a combination of hydrologic modeling and analytical computations using the Upper Rio Grande Water Operations Model (URGWOM). URGWOM is a computational, rule-based, water operations computer model that simulates physical processes and operations of facilities in the MRG that generate a set of daily flows using RiverWare® software. Reclamation (and others; see Roach 2009a, b; Figure A3) developed five, 10-year Hydrologic Scenarios to capture the wide range of variability in the hydrology and climate that have been experienced over the past 604 years, as captured in tree-ring records. These scenarios were developed through a statistical sorting of the hydrologic years contained in the 604-year reconstruction of the flows at Otowi Gage (using an Otowi Index Supply). The five, 10-year Hydrologic Scenarios were selected based on their being closest to having a 10, 30, 50, 70, and 90 percent chance of exceedance among the full suite of scenarios (Figure A4) that Reclamation used to analyze the impacts of their proposed water management actions and a "no action" condition through URGWOM simulations (Reclamation 2015).

Reclamation also used URGWOM to simulate the "No Action" condition with some proposed water management actions included. In the simulations of the Proposed Action, Reclamation operates Heron Dam to provide SJC Project water to its contractors. Reclamation, in coordination with the Middle Rio Grande Conservancy District (MRGCD), stores native water in El Vado Dam and releases that water as needed to meet MRGCD demand, and the MRGCD operates the MRG diversions. In the simulation of the No Action condition, these operations are turned off in URGWOM. However, not all MRGCD irrigation demand is turned off. If water is available to the irrigation network, such as from interior and riverside drains, then that water will be used to meet irrigation demand. Still, the No Action condition has never been known to exist during flow monitoring in the Period of Record (POR) and therefore, its calibration was only possible against observed conditions in which none of the Proposed Action activities were being performed.

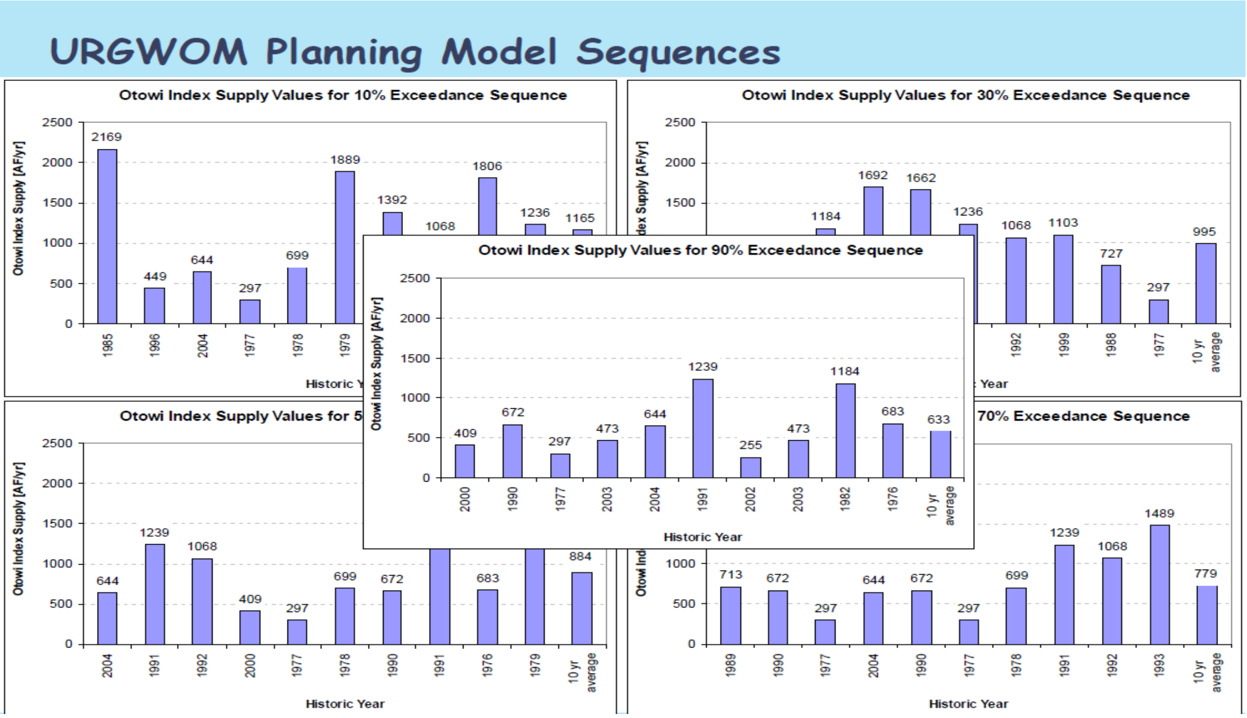

Figure A3. The five, 10-year Hydrologic Scenarios used for modeling proposed and no actions (Roach 2009a, b).

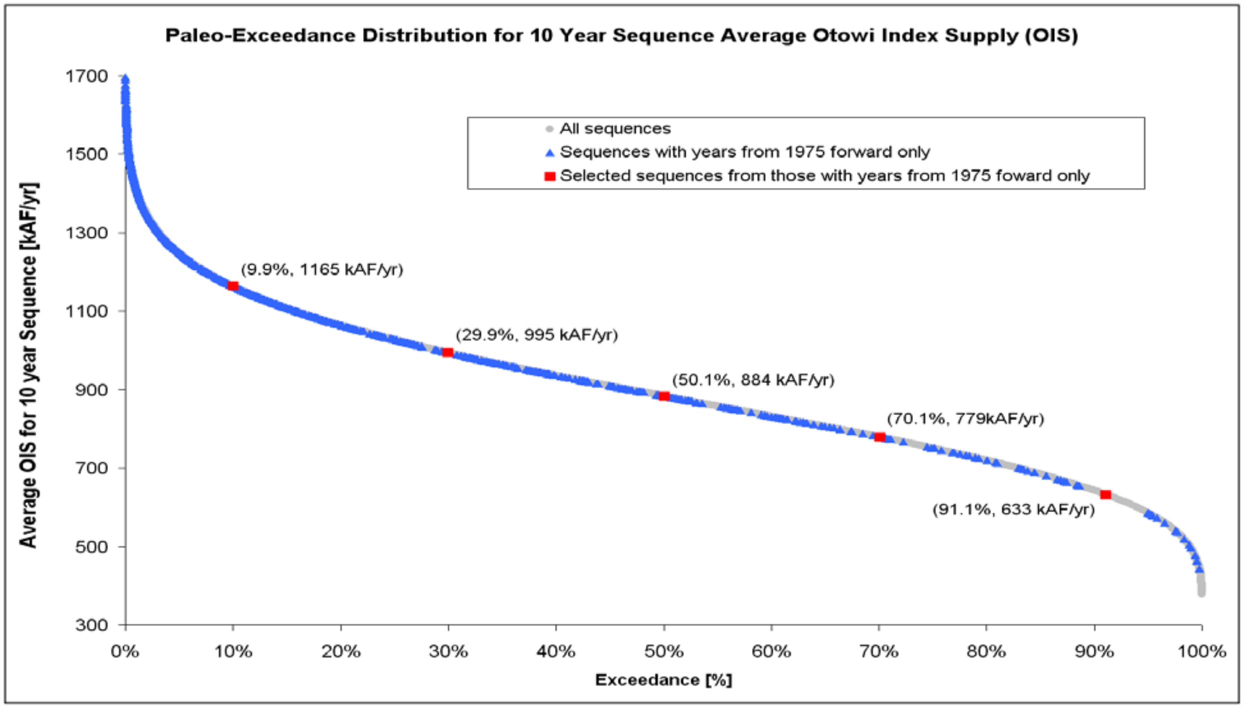

Figure A4. Distribution of post-1975 percentiles of Otowi Index Supply annual volumes (Roach 2009a, b).

We used the 605 years of tree ring data converted to flows at Otowi Gage to estimate the percentile flows derived of five, 10-year Hydrologic Scenarios. As a result of this analysis, the ranges of individual hydrologic scenarios were different than those that would be within 10 to 20 percentile range from the 5 percentiles that were selected by Reclamation (2015). We would have expected all the hydrologic scenarios in Figure A4 to be a distribution around the five, 10-year Hydrologic Scenarios selected (Table A1).

Table A1. Percentiles of the five, 10-year Hydrologic Scenarios and associated Otowi Index Supply ranges with proportional volume estimates for each 10 percentile units for the percentile ranges.

Roach(2009a, b) Percentile	Otowi Index Supply Volume (acre-feet)	Percentile	Proportional Volumes (acre-feet)
	2,723	1.0	>1,500
			1,280.0
9.9	1,165	10.0	
		20.0	1,050.0
29.9	995	30.0	
		40.0	940.0
50.1	884	50.0	
		60.0	830.0
70.1	779	70.0	
		80.0	720.0
90.0	633	90.0	
	255	99.0	<540

For the very wet scenario, 10th percentile average sequence of 1,165 Otowi Index Supply, we would have expected the 10 percentile range around that value to be from 1,050 to 1,280 Otowi Index Supply. However, the actual 10-year Hydrologic Scenarios selected ranged from 297 to 2,169 Otowi Index Supply (Figure A3). This means that the five, 10-year hydrologic scenarios are not statistical distributions, but rather individual years were "selected" (perhaps through a randomization process, see Roach 2009a, b) so that their 10-year *average* equaled one of the 5 sequence values selected. When we used each of the years in the five, 10-year hydrologic scenarios to determine average, we found that the average of the 10 years was different than if the years were derived from a statistical distribution.

We obtained the OIS for the last 76 years of the Otowi Gage POR (Spreadsheet = 20160430 Shafike 2016 Otowi Index Supply spreadsheet-Lusk 20160430 mods.xlsx). We used this to synchronize the real time data with the hydrologic scenarios then code the years into very wet, wet, average, dry, and very dry categories (Figure A5 and A6).

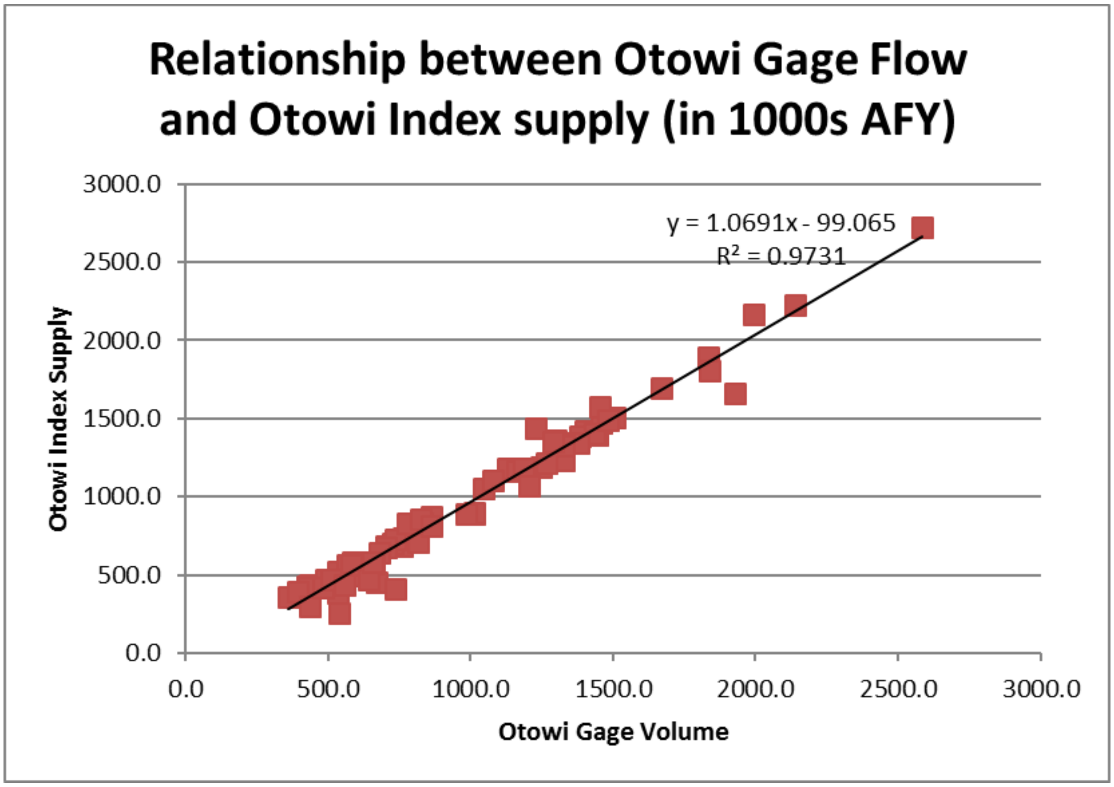

Figure A5. Relationship between Otowi Gage annual volume and the Otowi Index Supply from 1940 to 2015.

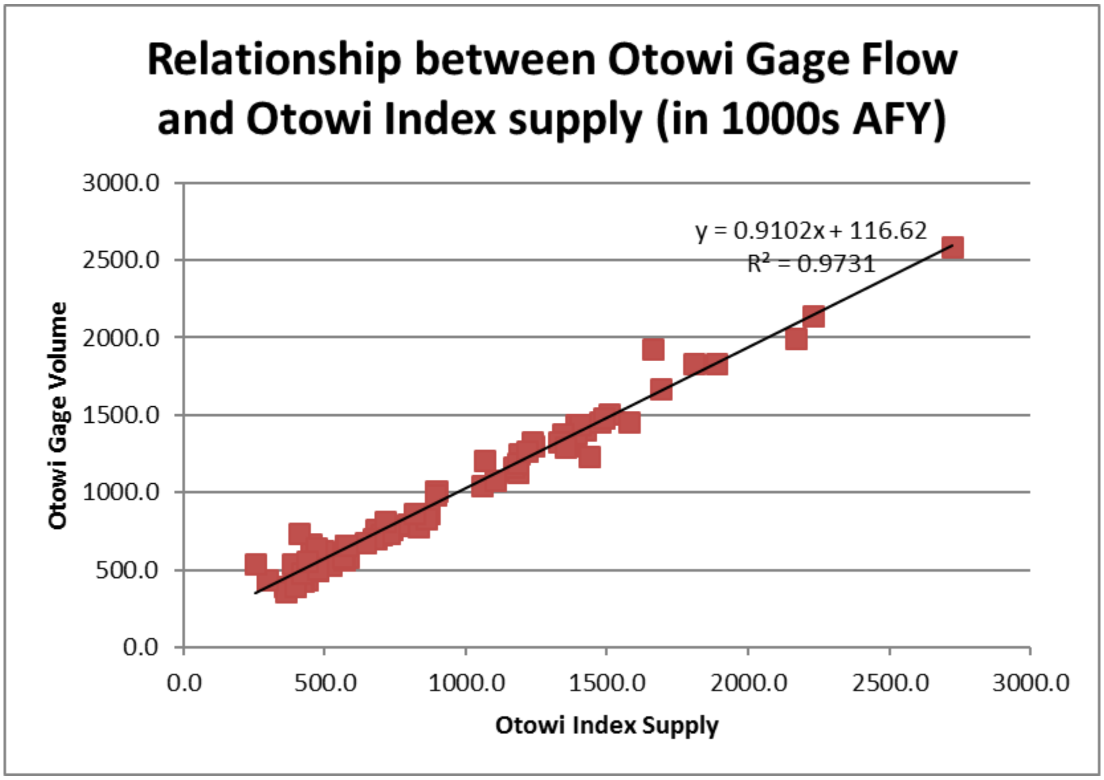

Figure A6. Relationship between Otowi Index Supply and Otowi Gage annual volume from 1940 to 2015.

We plotted the frequency of years that fell into our estimated flow range (Table A1) associated with each of the five, 10-year hydrologic scenarios. The majority of flows occurred well outside the range of these scenarios in the 1 percent range, which we termed “Snowmageddon” and the 90 to 99 percent range, which we termed “Megadrought” (Figure A7). The Otowi Gage record seems to have more years that are wetter and drier than those that make up the five, 10-year Hydrologic Scenarios used the BA. This might explain the use of “selected” years that included extremely low annual volumes and that were averaged to the five selected scenarios.

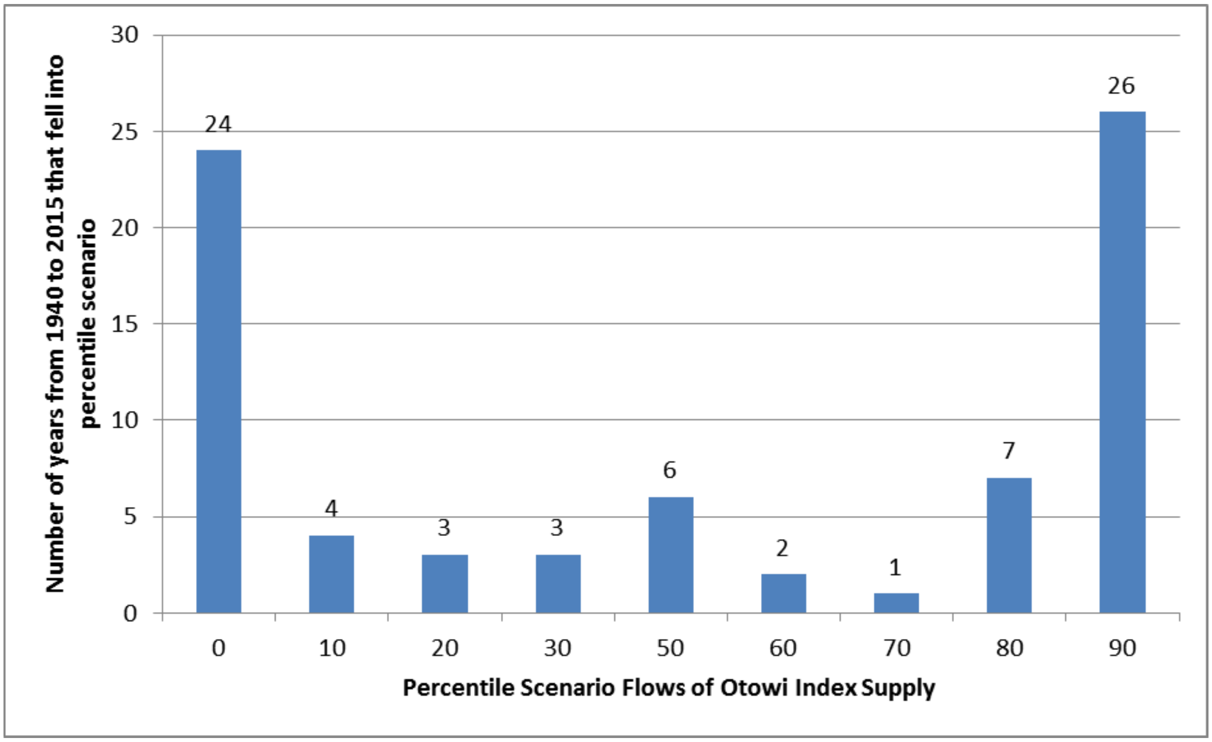

Figure A7. Frequency of 76 years of Otowi Gage annual flows from 1940 to 2015 into Hydrologic Scenario “bins.”

That told us that the pattern we saw with flows and silvery minnow densities (Service 2013b), with a cluster of very wet flow years and high silvery minnow Catch per unit effort (CPUE) and a cluster of very dry flow years and low silvery minnow CPUE in October (Figure A8) was explainable by a “boom or bust” hydrology. There were few average-type years in the data we used for silvery minnow because there are few average years that occur in the POR.

We then extended the POR for the ABQ-Central Gage (US Geological (USGS) Gage 08330000) using monthly regression relationships with the Otowi Gage (USGS Gage 08313000) POR flow, so that we could estimate the flows at the ABQ-Central Gage using the hydrological sequence identifiers to characterize them by season (May-June and July-October) over 111 years. (Spreadsheet 20160810 ABQ Gage_POR_Extended_from_Otowi_POR_and for Proposed Actions.xlsx). We also combined the 111 year record with the 100 years of the hydrologic scenarios to see where their average exceedance ranks would occur. We found that annual volumes of the average of the 10 years for each of the five, 10-year Hydrologic Scenarios represent exceedance percentiles from approximately 40 to 75 percentile flows at the ABQ-Central Gage (Table A2). In most cases the five, 10-year Hydrologic Scenarios selected appear to underestimate high flows in the 90 percentile Hydrologic Scenario and overestimate low flows in the 10 percentile Hydrologic Scenario. Several 90 percentile values were outside the POR and were used to achieve the average for the 90 percentile Hydrologic Scenario of approximately 633,000 Otowi Index Supply (in acre feet) as developed by Roach (2009a, b).

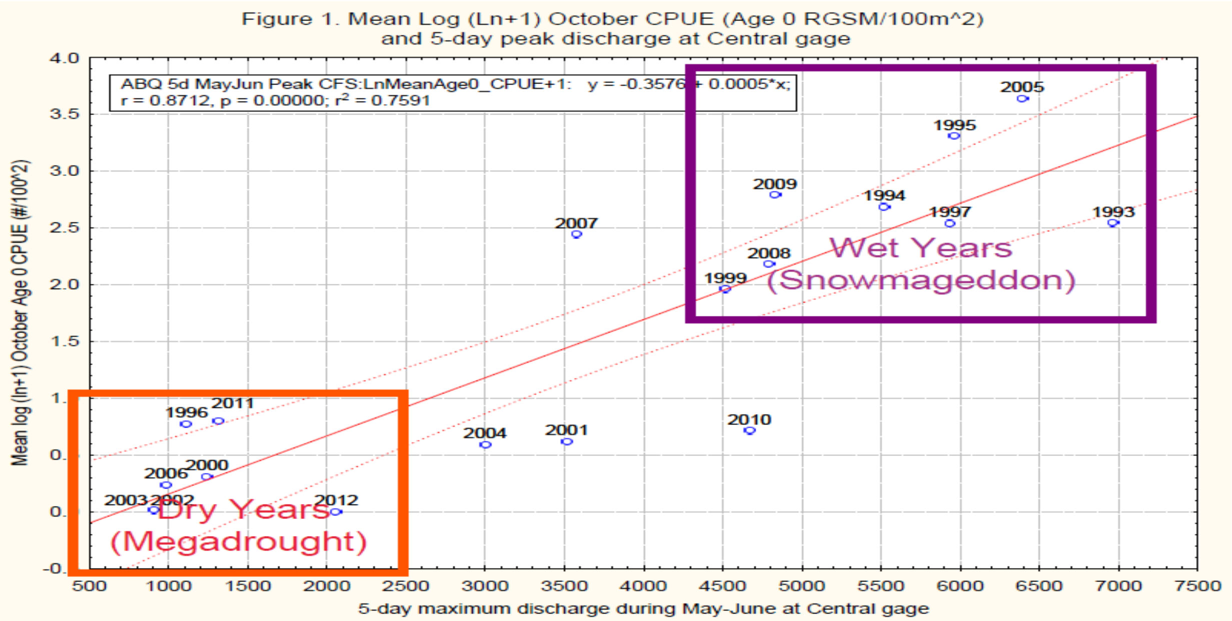

Figure A8. Relationship between the 5-day maximum discharge in May -June at the Albuquerque Gage and the base e logarithm of the average catch per unit effort of silvery minnows in the fall per 100 m^2 with depictions of the very wet (Snowmageddon) and very dry year (Megadrought) years per Hydrologic Scenarios.

We also recognized that if there was a multidecadal pattern of flow volumes at Otowi Gage, much like a sine wave that matched the frequency of high flow and low flow years, then it would tend to reflect the pattern of hydrologic year types in the POR of boom and bust. This reflects the work of SSPA (2003), Hathway and MacClune (2007), Wallace (2014); and Pascolini-Campbell et al. (2016), which related the flows at Otowi Gage to the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation and other oceanic phenomena effects to the production of salmon (Hare and Francis 1995). (See spreadsheet file name 20160731 Lusk Relationship between PDO and RGSM density.xlsx). However, we did not find any robust (p=0.45), significant relationships with these oceanic factors, perhaps, because the most recent decades have not responded similarly as these oceanic factors and Otowi flow relationships have in the past (Wallace 2016).

Table A2. Comparison of five, 10-year Hydrologic Scenarios (HS) average volumes at ABQ-Central Gage with an extended POR.

PA Hydro Scenario	average 10 yr ABQ annual volume (in acre-feet)	10 Yr avg percentile	111 yr Avg Annual Vol	How good was HS?
BOR 10	1,003,899	41	1,644,261	HS was a little low
BOR 30	860,358	49	1,119,821	HS was a little low
BOR 50	742,225	57	713,884	HS was close
BOR 70	640,977	62	498,791	HS was too high
BOR 90	499,614	75	315,444	HS was too high
PA Hydro Scenario	average 10 yr ABQ May Jun volume (in acre-feet)		111 yr Avg May Jun Vol	How good was HS?
BOR 10	399,896		805,013	HS was a very low
BOR 30	335,939		523,247	HS was a very low
BOR 50	276,527		251,128	HS was close
BOR 70	225,540		107,172	HS was too high
BOR 90	171,808		57,401	HS was very high
PA Hydro Scenario	average 10 yr ABQ Jul Oct volume (in acre-feet)		111 yr Avg Jul Oct Vol	How good was HS?
BOR 10	197,813		310,002	HS was very low
BOR 30	189,658		181,819	HS was close
BOR 50	158,280		96,137	HS was too high
BOR 70	103,848		119,150	HS was close
BOR 90	91,561		55,056	HS was too high

Appendix A.3. Estimation of Climate Change Impacts on MRG Hydrology

The hydrologic scenarios do not explicitly consider the potential impacts of climate change on water operations in the MRG. Since 2011, Reclamation (2013, 2016) used emission scenarios and along with climate projections containing temperature and precipitation data to develop and downscale a set of hydrologic projections that capture the variability of the Rio Grande Basin (Llewellyn and Hastings 2015; Reclamation 2016). (Spreadsheet file name 20160801 modified USBR 2016 Appendix C_URGWOM HDe Flow Output.xlsx). These data include 48 years of simulations of flows at various MRG gages under a variety of emission-based, climate change scenarios (termed Warm and Dry (WD), Warm and Wet (WW), Hot and Dry (HD), Hot and Wet (HW), and a Central Tendency (CT) among these various scenarios) and compared to the observed condition for the timeframes including the 2020s, 2050s, and 2080s.

We used Reclamation (2016) data to evaluate spring runoff (May and June) and low flows conditions (July through October) at the ABQ-Central Gage for a 15-year action. We evaluated the rate of change in flow volumes for the 48-year simulations and scaled that rate of change to 15 years to establish the anticipated effects of climate change in the Cumulative Effects section for the next 15 years to spring runoff, silvery minnow abundances (in the fall), low flow conditions, and silvery minnow distribution (in the fall) in the BiOp analyses.

Without foreknowledge of the type of climatic scenarios that were likely to occur, we used the Central Tendency scenario to estimate the reduction in median spring runoff volume at ABQ-Central Gage as 6,580 acre-feet in 15 years for the average hydrologic scenario. We used the WW climate scenario to estimate the volumes for the Very Wet (10) Hydrologic Scenario and the HD climate scenario to estimate the volumes for the Very Dry (90) Hydrologic Scenario. Using flow assessments (below) we anticipated that the frequency of estimated silvery minnow densities (in the fall) less than 1.0 fish per 100 m^2 (a self-sustaining population) would increase from two times (observed during the last 48 years using these models) to four times during the next 15 years (although it could range from two to six times based on a standard error of our estimates). Using similar analyses, we expect the May - June volume at the ABQ-Central Gage to be reduced by approximately 43,000 acre-feet in the 2050s, and by approximately 130,000 acre-feet in the 2080s, suggesting dire conditions and potentially reduced abundances of silvery minnow in the mid-to-late 21st century (Figure A9). In addition, some of the high flow years are also detrimental to silvery minnow distribution as the likely channel velocities will be so fast as to adversely affect silvery minnow directly, or indirectly through reduced habitat quality and reduced prey (Figure A10).

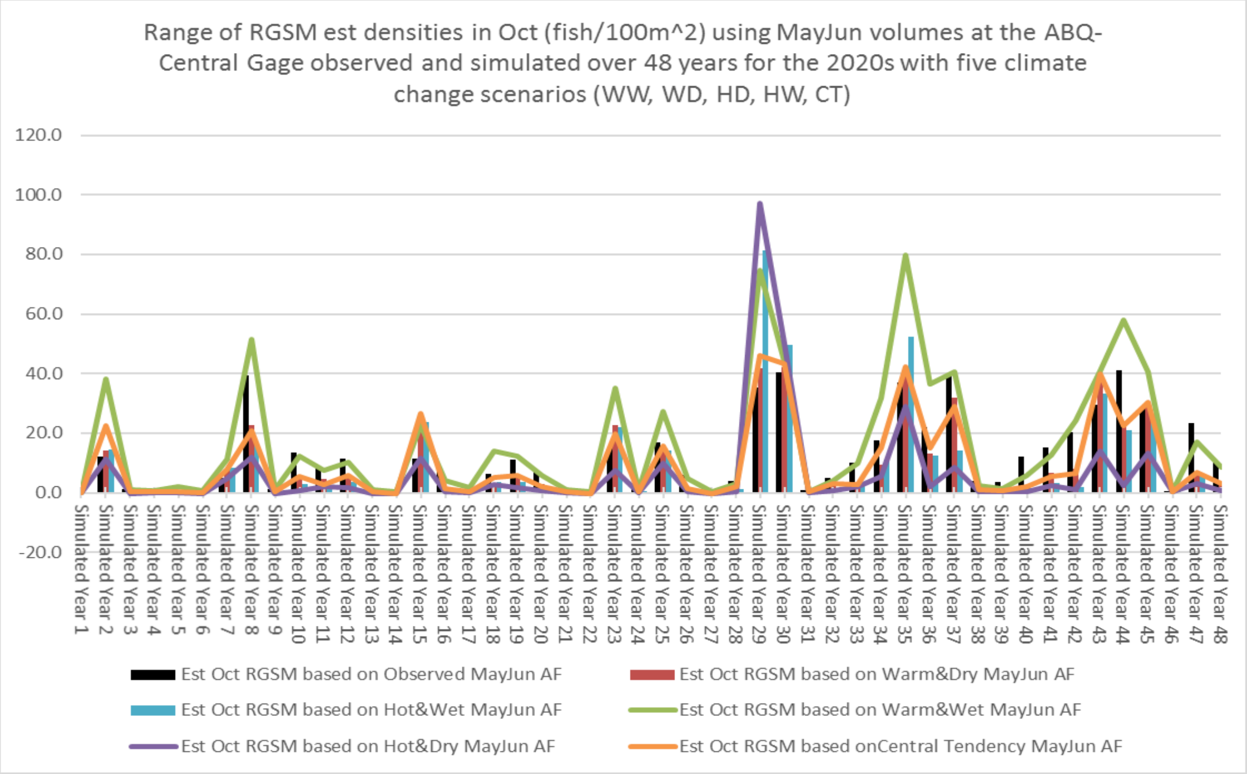

Figure A9. Estimated densities of silvery minnows in the fall based on a relationship (Equation 1, below) with May and June volumes at the ABQ-Central Gage for the 48 simulated years under a variety of climate scenarios.

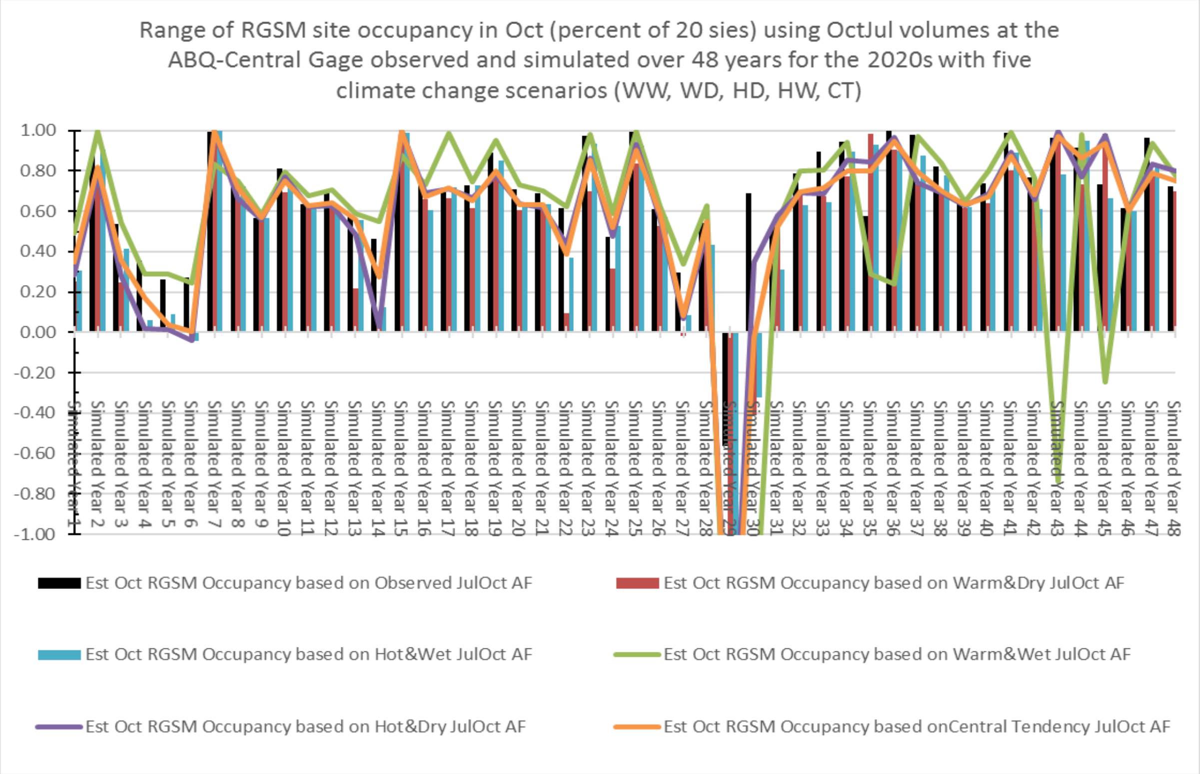

Figure A10. Estimated occupancy of silvery minnows at PMP sites in fall based on a relationship (Equation x, below) with July through October volumes at the ABQ-Central Gage for the 48 simulated years under a variety of climate scenarios.

Appendix A.4. MRG Gage Flow and Hydraulic Assessments in Relation to Silvery Minnow Abundance and Occupancy in the Fall (Hydrobiological Objectives for Management of Rio Grande Silvery Minnow Abundance and Distribution in the Middle Rio Grande)

Purpose of these Hydrobiological Objectives

River systems are physically and biologically complex. Understanding the relationships between hydrology and stream fish can be a daunting task because both are highly variable, and it is difficult to measure relationships between flow and fish abundance (Stanford and Ward 1983; Poff and Ward 1989; Hatfield et al. 2000; Rogers et al. 2005). Flows and the level of water in a river can strongly influence stream fish populations (Rogers et al. 2005). High water levels create inundated areas that fish may utilize (Welcomme 1979; Dudley and Platania 1997; Pease et al. 2006; Porter and Massong 2006; Dudley and Platania 2015a, b; Dudley et al. 2016), whereas low water surface levels may limit fish movements, available habitat, or degrade water quality (Heggenes et al. 1996; Rogers et al. 2005; Dudley et al. 2008; Hatch et al. 2008; Durham and Wilde 2009; Archdeacon 2016).

Variable river flows influence the structure of lotic communities and indirectly affect stream fishes by changing habitat availability, nutrient cycling, food availability or create suboptimal conditions that decrease survival (Stalnaker 1981; Fisher et al. 1982; Balcombe et al. 2005; Rogers et al. 2005; Dudley et al. 2008; Dutterer et al. 2013). In low-gradient river floodplain systems, wet season high flows usually provide annual connectivity and inundation of the floodplain (Welcomme 1979; Dutterer et al. 2013). Commonly, fish in river floodplain systems respond to rising water levels and floodplain inundation as cues for spawning (Agostinho et al., 2004; Dudley and Platania 2015a). As spawning and nursery habitat for river fish assemblages, inundated floodplain habitats provide food and complex cover for refuge from predation (Dudley and Platania 1997; Pease et al. 2006; Porter and Massong 2006; Arthington and Balcombe 2011; Dudley and Platania 2015a, b; Dudley et al. 2016). Consequently, annual variation in fish recruitment is often influenced by river flows and floodplain inundation levels (DiCenzo and Duval, 2002; Janac et al. 2010; Dutterer et al. 2013; Dudley et al. 2016).

Our goals for this analysis were to determine (or affirm) relationships between indices of Rio Grande silvery minnow (*Hybognathus amarus*; silvery minnow) population abundance estimates and occupancy distribution indices (Dudley et al. 2016) with measures river discharge (at selected U.S. Geological Survey stream gages) and levels or areas of water inundation of the channel and associated floodplain (USACE 2010; Bui 2016) in the Middle Rio Grande (MRG). Dudley et al. (2016) found that prolonged high flows during spring were most predictive of increased density and prolonged low flows during summer were most predictive of decreased occurrence of Rio Grande Silvery Minnow in the Middle Rio Grande between 1993 and 2015. We wanted to affirm these and develop simpler models that could be used rapidly to describe relationships between stream flow, channel hydraulics, and indices of silvery minnow abundance and distribution and build evidence to test water management options in an adaptive management context as part of the U.S. Bureau of Reclamation’s River Integrated Operations (RIO; Reclamation 2015). This analysis also helps support the needs of fishery biologists, managers, and the public to have simple electronically-available tools to provide a consistent, repeatable, and transparent basis for recommendations for management, hypotheses testing, effect analyses, and forecasting.

Hydrobiology is the analysis and assessment of life in water and their interconnection with the cycling of natural resources in a body of water. Our hydrobiological analyses were based on linear and polynomial relationships (using scatterplots) between silvery minnow abundance and distribution indices (and other endpoints) and historical river flows, channel inundation areas, and other hydrological attributes and measurements that were collected contemporaneously annually. These Hydrobiological Objectives are our recommendations for potential water management flow regimes according to the historical information about the duration, magnitude, and timing of spring runoff and areas of channel inundation that appear necessary to support the survival and conservation of the silvery minnow population in the MRG.

The Hydrobiological Objectives are comprised potential water management strategies to foster the production of young (Age 0) silvery minnows during spring and a survival strategy to manage adult (Age 1+) silvery minnows when spring and summer flows are low. These Hydrobiological Objectives and relationships provide a basis for supporting management decisions because they are based upon over 20 years of observations from several sites along the MRG under a variety of environmental conditions. We recognize that simple plots do not imply a cause-and-effect relationship, but they can provide a testable and repeatable method of analysis. We expect that the Hydrobiological Objectives can be considered for testing through adaptive management.

Methods

Data on silvery minnow estimated abundance densities (E(x)) and rates of site occupancy during the October surveys of the Rio Grande Silvery Minnow Population Monitoring Program (silvery minnow PMP) were collected from Dudley et al. (2016) and verified with the authors. Results from the October surveys were used because fall is when silvery minnows reach adult size and the discharge during October has been consistent and suitable for sampling by beach seines making it the time of year for evaluating long-term trends in their occurrence and abundance (Dudley et al. 2016). Historical patterns of silvery minnow estimated densities (estimated densities (E(x)) are an index of silvery minnow abundance) and frequency of site occupancy (which are an index of distribution or presence at silvery minnow PMP sites) were used as part of the data collected from the long-term, consistent silvery minnow population monitoring study (1993 to 2015) for these hydrobiological analyses.

Silvery minnow mesohabitat-specific density data collected during October (2002–2015) were used to calculate silvery minnow density estimates (E(x)) for different mesohabitats by year (Dudley et al. 2016; p. 20). Occupancy surveys were also conducted as part of the silvery minnow PMP as a method to assess the likelihood of detecting the presence or absence of a species (Dudley et al. 2016). Additional information was collected from previous silvery minnow PMP reports for the density and occupancy of silvery minnows during the July and October surveys for comparison. All the estimated silvery minnow abundance density data was added to one and were logarithm (base 10) transformed to assure a normal distribution for these analyses. The silvery minnow PMP, with its current sampling protocols, results in a reliable level of sampling precision and silvery minnow population trend consistency across years

(Dudley et al. 2016, p. 34).

River discharge data in cubic feet per second (cfs) was reported as the mean daily flow on each day and was collected from the U.S. Geological Survey (USGS) streamflow web site (http://waterdata.usgs.gov/nwis/) for gage stations (Rio Grande at Otowi 08313000 (Otowi Gage), Rio Grande at Albuquerque 08330000 (ABQ-Central or Central Gage); Rio Grande at Bernardo 08332010 (Bernardo Gage); Rio Grande at San Acacia 08354900 (San Acacia Gage); and Rio Grande at San Marcial 08358400 (San Marcial Gage). There were no USGS stream gages in the Isleta Reach that had consistently measured flow during the 20-year study period. While the Bernardo Gage data were used, there were several large data gaps that affected the analysis and were thereafter removed. All river data were compiled on worksheets by "minnow year." A minnow year starts in November with the fall of precipitation in the mountains and highlands of the Rio Grande watershed and concludes when silvery minnows become adult-sized in fall. Summary discharge data by minnow year are similar to water year used by the U.S. Geological Survey and to calendar year used by the Rio Grande Compact Commission with the exception of summaries of total annual volume per year.

Our flow data included, minimum, average, and maximum mean daily flow discharges in cubic feet per second (cfs) at each gage during the minnow year. Total, seasonal, and monthly flows at gages were used to determine volume in acre-feet. Water volumes were characterized by season according to Bui (2014). That is, winter flows occurred from 1 November through end of February; pre-runoff flows occurred from 1 March through 30 April; spring runoff from 1 May through 30 June; and post runoff or low flows occurred from 1 July through 31 October. Additional characterizations of minimum, average, and maximum flows were conducted for the spring runoff and post-runoff low flow seasons. The dates of the start of spring runoff were determined by the increase in mean daily flow compared to the average mean daily flow at the ABQ-Central Gage. The dates of the end of spring runoff were determined by the decrease in mean daily flow compared to the average mean daily flow at the San Acacia Gage. In some cases, spring runoff events occurred into the summer months, but it is referred to as spring runoff. Additional flow metrics included the number of days the mean daily flow at the ABQ-Central, Bernardo, or San Acacia Gages were above or below certain criteria flows. Additional flow metrics were used to indicate the flows associated with various hydrological scenarios (of very wet, wet, average, dry and very dry categories of flows see Roach 2009a, b; Reclamation 2015) or the likelihood and duration that river intermittency or river drying would occur (Reclamation 2015, Appendix H).

Our hydraulic channel data included the area of channel inundation and the area of floodplain flooded by overbanking runoff as determined using a modified historic inundation model (USACE 2010) for only the three reaches in the MRG. The modification of the USACE (2010) model included a trend analysis to ascertain likely channel inundation areas below 500 cfs at the ABQ-Central Gage. Additionally, Bui (2016) used HEC-RAS analysis on the current (2012) channel figuration to generate reach-averaged widths and depths using various ABQ-Central Gage flows. We used those reach-averaged width and depth relationships for spring runoff and post runoff seasons for flows that occurred during years that corresponded to the hydrologic scenarios of very wet (10th percentile), wet (30th percentile), average (50th percentile), dry (70th percentile), and very dry (90th percentile) (see Reclamation 2015 for description of hydrologic scenarios). Values for the hydraulic channel data were described by individual reaches (Angostura, Isleta, and San Acacia) and summed or averaged for all three reaches (MRG3) in the MRG. For the case of missing flows in the Isleta Reach, corresponding width and depth were omitted from analysis and an average was determined for only two of the river reaches; Angostura and San Acacia (or MRG2).

All data were evaluated by minnow year using the spreadsheet file named, “20160801 Hydrobiologic data from 1993 to 2015 with RGSM Habitat Model.xlsx” and can be made electronically available and are incorporated here by reference.

Analyses

We developed quantitative flow relationships with historical silvery minnow abundance and distribution using (1) historical flow regime, (2) channel hydraulics, and (3) habitat characteristics according to Jowett (1997). Although all these methods evaluate the river system, they focus on different aspects of the stream, such as flow, wetted perimeter, or physical habitat. The goal of the flow methods is to characterize the abundance and distribution of silvery minnows that are associated with the historical flow range. Factors such as, food, habitat, water quality and temperature were not considered explicitly, but were assumed satisfactory because silvery minnows have survived with variation in these factors in the past (after Jowett 1997).

Similarly, Dudley et al. (2016) found that mixture-model estimates of silvery minnow abundance were more reliably predicted by changes in flow variables over the period of study (1993 to 2015; their Table A3). For example, the top model of using spring flow variation, including when average flow exceeded 3,000 cfs (plus a random factor), received a higher percentage of explanatory weight compared to the null model. Their three top parsimonious models, which accounted for most of the cumulative explanatory weight, were related to the interaction among silvery minnow abundance and distribution with elevated spring flows in the Angostura Reach.

We also developed quantitative hydraulic relationships with historical silvery minnow abundance and distribution. Hydraulic methods relate various parameters of the hydraulic geometry of stream channels to discharge and these parameters can be related to historical silvery minnow abundance and distribution. The hydraulic geometry was based on surveyed cross-sections, from which parameters such as width, depth, velocity and wetted perimeter were determined through hydraulic modeling (USACE 2010, Bui 2016). The effect on silvery minnow abundance and distribution can be related to the average morphological parameters of wetted acreage, river width, depth, and width-to-depth ratios. Width and depth are particularly relevant because several researchers have indicated that areas of the channel, when deep, and the floodplain, when flow is wide, provide areas for spawning fish, cover, food, and nursery areas for recruitment (Welcomme 1979; Dudley and Platania 1997; Pease et al. 2006; Porter and Massong 2006; Dudley and Platania 2015a, b; Dudley et al. 2016). While the supporting hydraulic analyses are dated, overall patterns from these types of models remain valid according to Tetra Tech (2014).

Habitat methods are a natural extension of hydraulic methods as some habitat features are directly related to flow (Bovee et al. 2008). However, we were unable to develop habitat methods at this time as consistent habitat models have not been developed for the MRG over time (Bovee et al. 2008; Tetra Tech 2014). Flow and hydraulic methods are useful in cases where there is a poor understanding of the habitat relationships to a river system or where a high level of protection is required (Jowett 1997).

Derivation of Criteria

The Service's (2010) silvery minnow recovery plan defines recovery criteria that if met, provide a basis for determining whether a species can be considered for downlisting (reclassification to threatened status) or delisting (removal from the list of threatened and endangered species). In the downlisting and delisting criteria there are demographic criteria and criteria that address the alleviation of threats. We only used and described the demographic criteria below:

Recovery Criterion 1-A-1. Using the standard sampling protocol (Service 2010; Appendix E), and sampling at a minimum of 20 sites distributed throughout the middle Rio Grande in New Mexico, document the presence of Rio Grande silvery minnow (all unmarked fish) at ¾ of all sites, per reach, sampled during October. (We assumed this criterion equated to an occupancy during October silvery minnow PMP surveys of 0.75 (or when rounded and used on a graph axis = 0.8).

Recovery Criterion 2-A-1. Using the standard sampling protocol (Service 2010; Appendix E), and sampling at a minimum of 20 sites distributed throughout the middle Rio Grande in New Mexico, document for at least 5 consecutive years, an October catch per unit effort (CPUE) from all monitoring sites within each reach of > 5 fish/100 m2. (We assumed this criterion equated to an estimated density during October silvery minnow PMP surveys of 5.0 fish per 100 m^2 (or added to one and base 10 log-transformed and used it on the graph axes = 0.8) (We termed this value "conservation goal or conservation status").

Recovery Criterion 2-A-2. Annual reproduction in the middle Rio Grande below Cochiti Reservoir, as indicated by the presence of young-of-year from ¾ of the monitoring sites, per reach, for at least five consecutive years. (We assumed this criterion equated to an occupancy during July silvery minnow PMP surveys of 0.75 (or when rounded and used on graph axes = ~0.8).

Recovery Objective 3-A. Three self-sustaining populations within the Rio Grande silvery minnow's historical range, as defined by criteria related to population size, distribution and extinction risk. (We assumed this criterion equated to an estimated density during October surveys of 5.0 fish per 100 m^2 per basin for 3 basins, or approximately 15 fish per 100 m^2 (we did not further evaluate this potential criterion associated with delisting and species recovery and therefore do not refer to "Recovery Goals" in these Hydrobiological Objectives).

We identified the need for a criterion that describes a level of annual species survival associated with genetic viability. The minimum viable population (MVP) is defined as a population that is sufficiently abundant and well adapted to its environment for long-term persistence without significant artificial demographic or genetic manipulations. Use of MVP does not mean that populations should be allowed to drop to these levels, but is used to assess their genetic and demographic viability. It must be recognized that some populations of any wild animal species may be below an MVP, as dictated by carrying capacity. It cannot be expected that every population will exceed an MVP; linkages to other populations help to keep smaller populations viable.

One way to judge genetic viability is through the use of a "genetic effective population size" (Ne), which is the number of individuals contributing genes to the next generation (Gilpin and Soulé 1986; Soulé 1987; Alo and Turner 2005). Alo and Turner (2005) found that if life history and river fragmentation interact to affect measures of genetic diversity to low values in contemporary silvery minnow populations. If fragmentation remains unabated then large numbers of adult fishes must be maintained (e.g., through hatchery supplementation) in the wild to meet generally prescribed levels of genetic diversity (Alo and Turner 2005). Alo and Turner (2005) suggested that more than 5 million adult fishes must be maintained in the wild to approach Ne = 5,000, a theoretical value for which sufficient levels of quantitative genetic variation are maintained over evolutionary time. Therefore, we used Ne = 5,000 in the derivation of the silvery minnow MVP as follows:

Computation of a MVP for silvery minnow in the MRG:

Ng = Ne/(Ne/Ng) Equation 1

Where: Ne = genetic effective population size, 5,000

Ne/Ng = proportion of adults contributing genes to next generation; ~0.30 for most fish (Service 2002, their Table 2)

Therefore: Ng = 5000/0.30 (~assuming 30 percent successfully spawn)

Ng = 16,667, the minimum number of spawners in May

Given our assumptions, we estimated that the MVP was 16,667 individual spawners and that it was necessary to achieve this number by each May to protect against genetic inbreeding or other injuries. We used a modified analysis provided by Bui (2016) to estimate the average top width of MRG [Angostura Dam until about River Mile (RM) (RM 60) or 253 kilometer (km) (157 miles (mi)] during low flow conditions (July through October) for the three hydrologic scenarios (Very Wet, Average, Very Dry). When you divide this number of spawners by the average area of approximately 49,202,405 m^2 area, the result is the estimated density of (16,667 fish divided by 49,202.4x100m^2) = 0.3 fish per 100 m^2. To protect against genetic inbreeding and other genetic diversity issues, this should be the lowest density silvery minnows (0.3 fish per 100 m^2) should drop prior to their spawning. The monthly rates of silvery minnow mortality from May to October varies substantially (Miller 2012), and we estimated that the estimated density in October with the average of the range of monthly mortality rates would be approximately 1.6 fish per 100 m^2.

However, the MVP calculation does not reflect a density dependent population factor appropriate for the type of hydrologic scenario year type that silvery minnow experiences across types of years. We added a mortality factor to estimate a genetically viable population because of stochastic events or the failure to spawn (Ralls et al. 1996). We used a modified annual mortality factor (after Goodman (2012)) and runoff rates (Very Dry =1.33; when the year is Average = 1.46, and if the years is Very Wet = 1.92), to develop a buffered MVP. We used the following density dependent population factors compensate for annual adult mortality from previous May-June.

Very Dry Year buffered MVP = 16,667 x 1.33 = 22,167 adults

Average Year buffered MVP = 16,667 x 1.46 = 24,334 adults

Very Wet Year buffered MVP = 16,667 x 1.92 = 32,001 adults

The buffered MVP population sizes ranged from 22,167 to 32,001 spawning adults that are estimated for May and June. We assumed there was 33 to 92 percent loss from the previous May and June to October. We used a modified analysis provided by Bui (2016) to estimate the channel width of three river reaches during low flow conditions for the three hydrologic scenarios (Very Wet, Average, Very Dry). For Very Wet years there are approximately 63,095,135 m^2 at maximum top width by its length from Angostura Dam until about RM 60 or 253 km (157 mi) and with an estimated density of (32,001 fish divided by 63,095.1x100m^2) = 0.8 fish per 100 m^2. Similarly, for Average type years, there are approximately 25,561.1 m^2 at maximum top width in the MRG with 24,404 silvery minnows, resulting in estimated density of (24,404 fish/25,561.1x100 m^2) of approximately 1.0 fish per 100 m^2. For Very Dry years, there are approximately 20,635.7 m^2 at maximum top width in the MRG with 20,635 silvery minnows, resulting in estimated density of (20,635 fish/20,635.7x100 m^2) of approximately 1.1 fish per 100 m^2. The overall average of 32,001 fish in an average river width of 49,202,205 m^2, was 0.7 fish per 100 m^2. That is, we used a buffered MVP or an overall density (rounding up) of approximately 1.0 fish per 100 m^2 to evaluate whether a self-sustaining population was achieved. The distribution (or occupancy) that is related to this buffered MVP density is approximately 50 percent (~0.53 frequency of site occupancy). That is, managing at or above the silvery minnow buffered MVP density of approximately 1.0 fish per 100 m^2, and so that it is distributed within at least 50 percent (10 to 11) of the 20 silvery minnow PMP sites in fall, will help maintain a minimum self-sustaining silvery minnow population in the MRG.

By establishing these silvery minnow estimated abundance goals for conservation (5 fish per 100 m^2 with a distribution of at least 75 percent) and for self-sustaining survival (~1 fish per 100 m^2 with a distribution of at least 50 percent), it is possible to consider these flow assessments and decide on the type of water management goals for any particular hydrologic scenario to achieve these Hydrobiological Objectives. These Hydrobiological Objectives can be then translated into operating guidelines using these flow assessment methods and results.

Graphical Interpretation Methods

We used scatterplots with linear regression and first-order polynomial fitting to assess the relationship between silvery minnow abundance and distribution as a response to various flow variables and hydraulic conditions quantified for a year (from November to October), during spring runoff (May and June), or during low flow conditions (July through October). Those plots showed distinct patterns in fish density and distribution and were useful for quantitatively comparing years, reaches, seasons, and various flow regimes associated with meeting silvery minnow survival (~1 fish per 100 m^2) and conservation (~5 fish per 100 m^2) goals. One goal of reviewing these relationships was to explain as much variation observed as possible in the response (y) variables (that is, the indices of silvery minnow abundance and distribution in the fall) using r- and p-values.

While we often used the polynomial relationships between hydrologic variables and estimated fish abundance and distribution, we also carried along the linear relationships for comparison in our figures and tables below. Where applicable, we censored our plots and tables to the range of data that were used in our analyses. For these analyses we used an alpha value equal to 0.05, a p-value of less than or equal to alpha (0.05), an absolute value for r-value greater than 0.54, and pairwise (versus case wise) data omission to state that any relationships between hydrologic variables and fish abundance or distribution were significant. Other biological responses (e.g., egg density, genetic metrics, silvery minnow abundance in July) and surrogate measures (e.g., length of river drying, maximum air temperatures, various hydrological indices) were also reviewed and used in our flow assessment methods but they did not necessarily vary significantly and linearly with flow variables and therefore, were not all presented and discussed below. Various plots and spreadsheets of these relationships were reviewed and are available by request.

Results

There were many collinear (or autocorrelative) relationships found with a number of the hydrologic variables. For example, the total and spring runoff volume of water measured at consecutive stream gages (that is, at Otowi Gage, ABQ-Central Gage, San Acacia Gage, and San Marcial Gage) were strongly correlated ($r^2 > 0.97$) with each other. It was assumed that this was because these consecutive stream gauges shared discharges originating from upstream. For example, water flowing across the Rio Grande at Otowi, San Acacia and at San Marcial Gages, will share discharges that pass the ABQ-Central Gage. Therefore, for the remainder of this analysis, we focused on relationships with runoff variables measured at the ABQ-Central Gage, as those were most strongly correlated with silvery minnow abundance estimated in October ($r^2 > 0.83$). The ABQ-Central Gage may also represent the most likely flows going into occupied silvery minnow habitat in the MRG and was the most consistently measured discharge at a MRG gage from 1993 to 2015.

Silvery Minnow Abundance Related to Duration, Magnitude, and Timing of Runoff

The October silvery minnow abundance estimates ((E(x); see Dudley et al. 2016) were significantly related with several hydraulic variables at the ABQ-Central Gage. Silvery minnow estimated abundances in October (and July) increased significantly with spring runoff volume, total volume, and combinations of number of days with discharge exceeding a threshold value or the timing of spring runoff (Tables 2-8, Figures 1-6). Silvery minnow abundance estimates were also similarly strongly related to the area of channel inundated and its depth and width during spring runoff and throughout the year (Tables 2, 9-11, Figures 7-9). The relationship that explained the most variation (91 percent) in estimated silvery minnow abundance in October was number of days in May and June with discharge greater than or equal to 3,000 cfs measured as mean daily flow at the ABQ-Central Gage (Tables 2, 5, Figure 3).

The magnitude of spring runoff was strongly correlated with number of Age 0 fish surveyed in fall (that is, estimated densities (E(x) in October; see Dudley et al. 2016), which are a source of wild fish that may spawn the following spring. Magnitude of spring runoff flow (both volume in units of acre-feet and average rates of discharge in cfs as mean daily flow) can be used to estimate the number of offspring (Age 0 fish) produced and that survive into the fall. There will be fewer numbers of (Age 0) silvery minnows produced with low magnitude or low duration spring runoff events, and higher numbers of (Age 0) silvery minnows produced and surviving with increased magnitude and duration of spring runoff events from 1993 to 2015 (Figures 1-6).

1. Higher magnitude spring runoff volume during May and June resulted in greater numbers of silvery minnows in fall.

- Approximately 318,000 acre-feet (that is, an average discharge during May and June of 2,550 cfs) crossing the ABQ-Central Gage during May and June produced an estimated abundance of 5.0 silvery minnow per 100 m^2 in fall.

- Approximately 251,500 acre-feet (that is, an average discharge during May and June of 2,020 cfs) crossing the ABQ-Central Gage during May and June produced an estimated abundance of 3.0 silvery minnow per 100m^2 in fall.

- Approximately 145,000 acre-feet (that is, an average discharge during May and June of 1,200 cfs) crossing the ABQ-Central Gage during May and June produced an estimated abundance of 1.0 silvery minnow per 100m^2 in fall.

Polynomial Regression Equation 1: Estimated silvery minnow abundance in fall = (10^((-0.1477) + (0.0000032265* May and June Volume (in acre-feet) at ABQ Gage) - ((May and June Volume (in acre-feet) at ABQ Gage ^2)*0.00000000000097574))) - 1. (Figure A11, Table A3).

Linear Regression Equation 2: Estimated silvery minnow abundance in fall = (10^((-0.0781) + (0.0000025692* May and June Volume (in acre-feet) at ABQ Gage)) - 1. (Number of cases = 21, r = 0.9090, t=9.5089, p = 0.00000) (Figure A11, Table A3).

Similarly, as spring runoff volume was determined using mean daily flow (that is, the average discharge in cfs per day), the estimated silvery minnow abundance in the fall = (10^((-0.1477) + (0.0004*average discharge during May and June (in cfs) at ABQ Central Gage) - ((average discharge during May and June (in cfs) at ABQ Central Gage ^2) * 0.000000014284))) - 1. (Figure A12, Table A4)

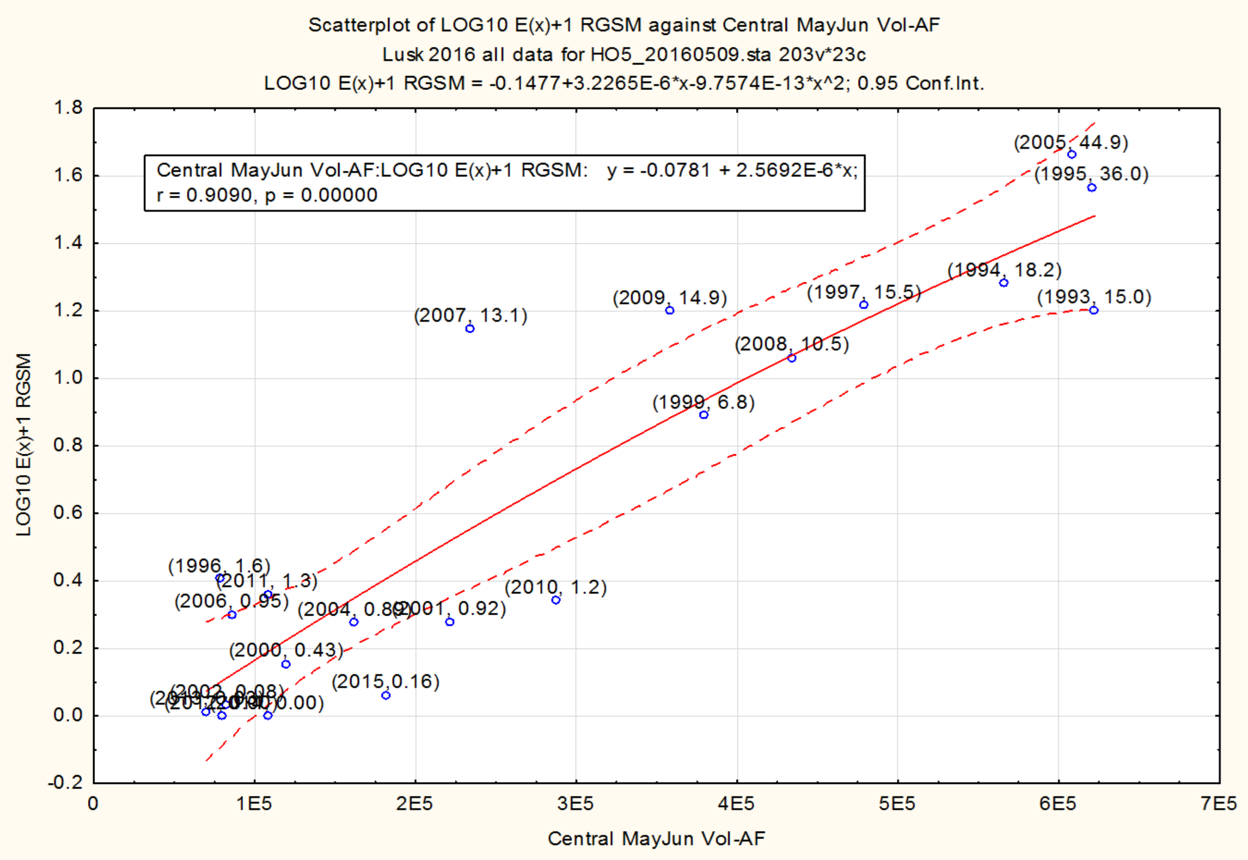

Figure A10. Relationship between the volume (in acre-feet) crossing the ABQ-Central Gage during May and June and the estimated abundance of silvery minnows in fall (transformed base 10 logarithms of estimated silvery minnow abundance mixture densities (fish per 100 m^2) + 1) from 1993 to 2015 (see Dudley et al. 2016).

Table A3. Relationship between the volume (in acre-feet) crossing the ABQ-Central Gage during May and June and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated October silvery minnow abundance densities ((E(x)) ~fish per 100 m^2 + 1)(Dudley et al. 2016).

May and June Runoff Volume (in acre-feet) at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model in Figure 1	Estimated silvery minnow abundance in fall using a polynomial model (Estimated October abundance E(x) = fish per 100 m^2+1)	Estimated silvery minnow abundance in fall using a LINEAR model (Estimated October abundance E(x) = fish per 100 m^2+1)
20,000	-0.08	-0.2	-0.1
40,000	-0.02	0.0	0.1
60,000	0.04	0.1	0.2
80,000	0.10	0.3	0.3
100,000	0.17	0.5	0.5
120,000	0.23	0.7	0.7
145,000	0.30	1.0	1.0
165,000	0.36	1.3	1.2
180,000	0.40	1.5	1.4
200,000	0.46	1.9	1.7
220,000	0.51	2.3	2.1
251,500	0.60	3.0	2.7
260,000	0.63	3.2	2.9
280,000	0.68	3.8	3.4
295,000	0.72	4.2	3.8
318,000	0.78	5.0	4.5
332,000	0.82	5.5	5.0
360,000	0.89	6.7	6.0
380,000	0.94	7.7	6.9
400,000	0.99	8.7	7.9
420,000	1.04	9.8	9.0
440,000	1.08	11.1	10.3
460,000	1.13	12.5	11.7
480,000	1.18	14.0	13.3
500,000	1.22	15.7	15.1

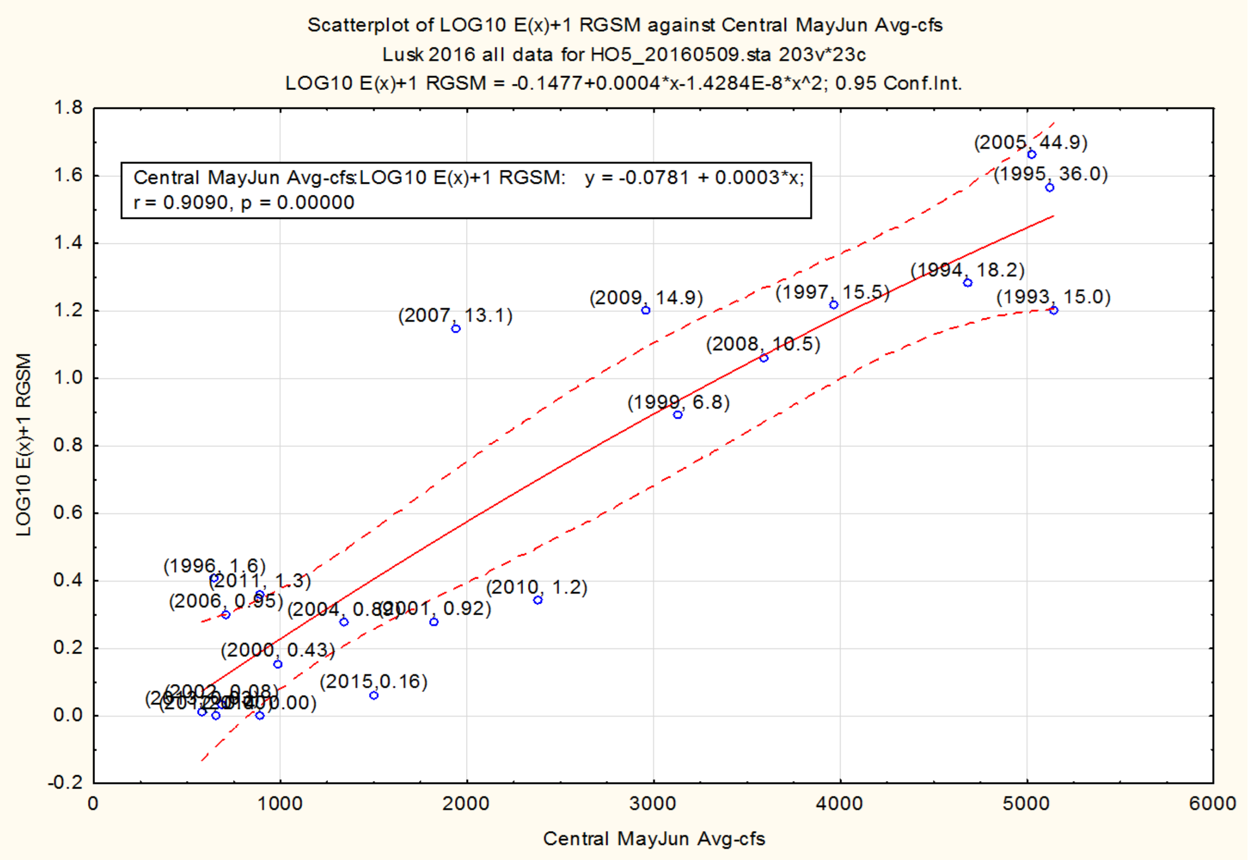

Figure A11. Relationship between average discharge (mean daily flow as average cfs per day) crossing the ABQ-Central Gage during May and June and estimated density of silvery minnows in fall (transformed base 10 logarithms of estimated silvery minnow abundance densities (fish per 100 m^2) + 1) from 1993 to 2015.

Table A4. Relationship between the average discharge (in cfs mean daily flow) crossing the ABQ-Central Gage during May and June and the estimated density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October silvery minnow abundance densities (fish per 100 m^2) + 1).

Average Mean Daily Discharge (average cfs per day) at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model in Figure 2	Estimated silvery minnow abundance in fall using a polynomial model (Estimated October E(x) =fish per 100 m^2+1)	Estimated silvery minnow abundance in fall using a LINEAR model (Estimated October E(x) = fish per 100 m^2+1)
200	-0.07	-0.1	0.0
400	0.01	0.0	0.1
600	0.09	0.2	0.3
800	0.16	0.5	0.5
1,000	0.24	0.7	0.7
1,200	0.31	1.05	0.9
1,400	0.38	1.4	1.2
1,600	0.46	1.9	1.5
1,800	0.53	2.4	1.9
2,020	0.60	3.0	2.4
2,200	0.66	3.6	2.8
2,400	0.73	4.4	3.4
2,550	0.78	5.0	3.9
2,850	0.88	6.5	5.0
3,000	0.92	7.4	5.6
3,200	0.99	8.7	6.6
3,400	1.05	10.1	7.7
3,600	1.11	11.8	9.0
3,800	1.17	13.7	10.5
4,000	1.22	15.7	12.2

2. Increased duration of spring runoff events (that is, days of average discharge greater than or equal to various discharge rates (such as 3,000 cfs, 2,500 cfs, 2,000 cfs, or 1,500 cfs per day as mean daily flow) during May and June as measured at the ABQ-Central Gage) resulted in greater numbers of silvery minnows in fall. For example, at ABQ-Central Gage the average discharge (cfs/day) for a duration of:

- 22 days at 3,000 cfs produced an estimated density of 5.0 fish per 100 m^2 in the fall
- 15 days at 3,000 cfs produced an estimated density of 3.1 fish per 100 m^2 in the fall
- 4 days at 3,000 cfs produced an estimated density of 1.0 fish per 100 m^2 in the fall

2a. Polynomial Regression Equation 3: Estimated silvery minnow abundance density in the fall = (10^((0.1794) + (0.0317*Days average discharge during May and June at ABQ Gage was greater than or equal to 3,000 cfs) - ((Days average discharge during May and June at ABQ Gage was greater than or equal to 3,000 cfs ^2)*0.0002))) - 1. (Figure A13, Table A5).

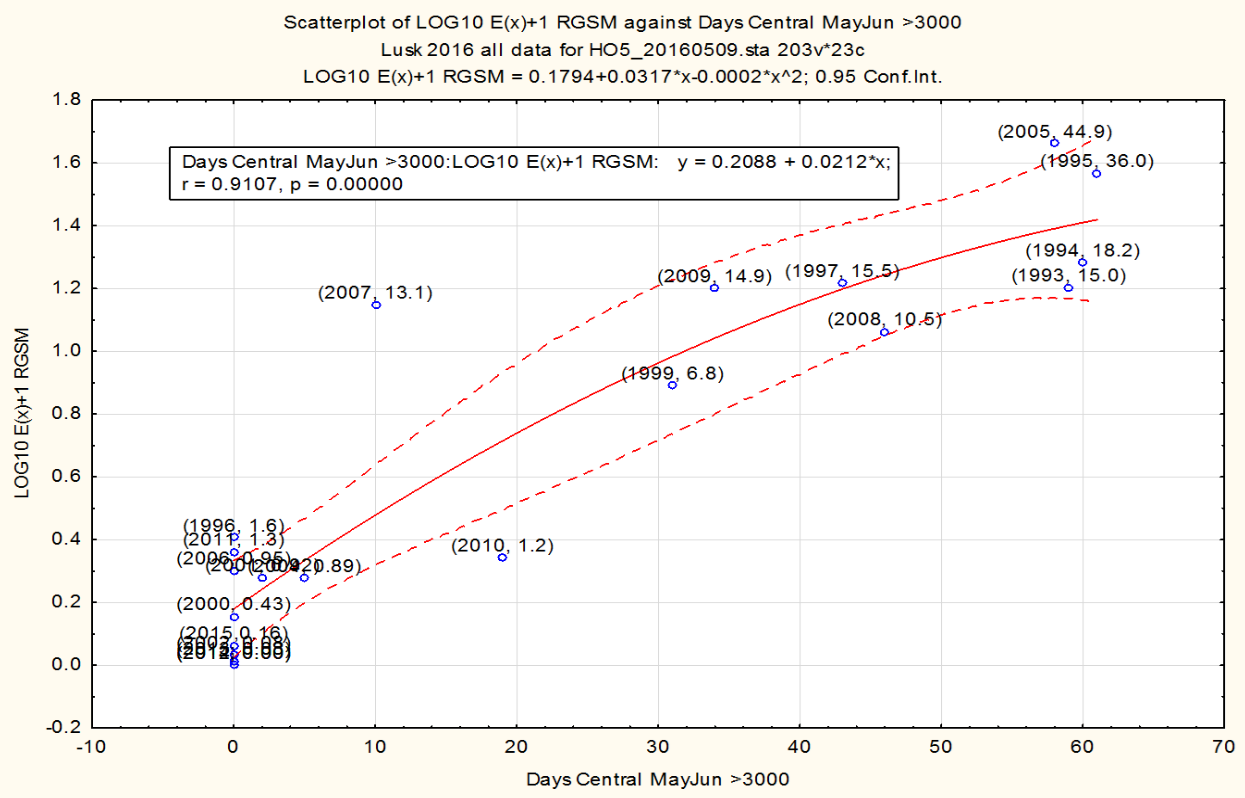

Figure A12. Relationship between the number of days average discharge (in cfs, mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 3,000 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2)+ 1) from 1993 to 2015.

Table A5. Relationship between the number of days average discharge (in cfs mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 3,000 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and their expected frequency of occupancy (distribution) at PMP sites in October.

Days mean daily flow exceeded 3,000 cfs in May and June at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model in Figure 3.	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (proportion of PMP sites, N=20)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
1	0.21	0.6	0.37	0.5
2	0.24	0.7	0.40	0.5
3	0.27	0.9	0.42	0.6
4	0.30	1.0	0.45	0.7
5	0.33	1.2	0.47	0.8
6	0.36	1.3	0.50	0.9
7	0.39	1.5	0.52	1.0
8	0.42	1.6	0.54	1.0
9	0.45	1.8	0.56	1.1
10	0.48	2.0	0.58	1.2
11	0.50	2.2	0.60	1.4
12	0.53	2.4	0.62	1.5
13	0.56	2.6	0.64	1.6
14	0.58	2.8	0.66	1.7
15	0.61	3.1	0.68	1.8
16	0.64	3.3	0.70	2.0
17	0.66	3.6	0.71	2.1
18	0.69	3.8	0.73	2.3
19	0.71	4.1	0.74	2.4
20	0.73	4.4	0.76	2.6
21	0.76	4.7	0.77	2.7
22	0.78	5.0	0.79	2.9
25	0.85	6.0	0.83	3.5
30	0.95	7.9	0.88	4.7
31	0.97	8.3	0.88	5.0
32	0.99	8.7	0.89	5.3
33	1.01	9.2	0.90	5.6
34	1.03	9.6	0.91	5.9
35	1.04	10.1	0.91	6.2
36	1.06	10.5	0.92	6.5

Table A5. Relationship between the number of days average discharge (in cfs mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 3,000 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and their expected frequency of occupancy (distribution) at PMP sites in October.

Days mean daily flow exceeded 3,000 cfs in May and June at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model in Figure 3.	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (proportion of PMP sites, N=20)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
37	1.08	11.0	0.92	6.9
38	1.10	11.5	0.93	7.3
39	1.11	11.9	0.93	7.7
40	1.13	12.4	0.93	8.1
41	1.14	12.9	0.93	8.5
42	1.16	13.4	0.94	9.0
43	1.17	13.9	0.94	9.4
44	1.19	14.4	0.94	9.9
45	1.20	14.9	0.94	10.4

2b. Polynomial Regression Equation 4: Estimated silvery minnow abundance density in the fall = (10^((0.1485) + (0.0205*Days average discharge during May and June at ABQ Gage was greater than or equal to 2,500 cfs) - ((Days average discharge during May and June at ABQ Gage was greater than or equal to 2,500 cfs ^2)*0.0000064967))) - 1. (Figure A14, Table A6).

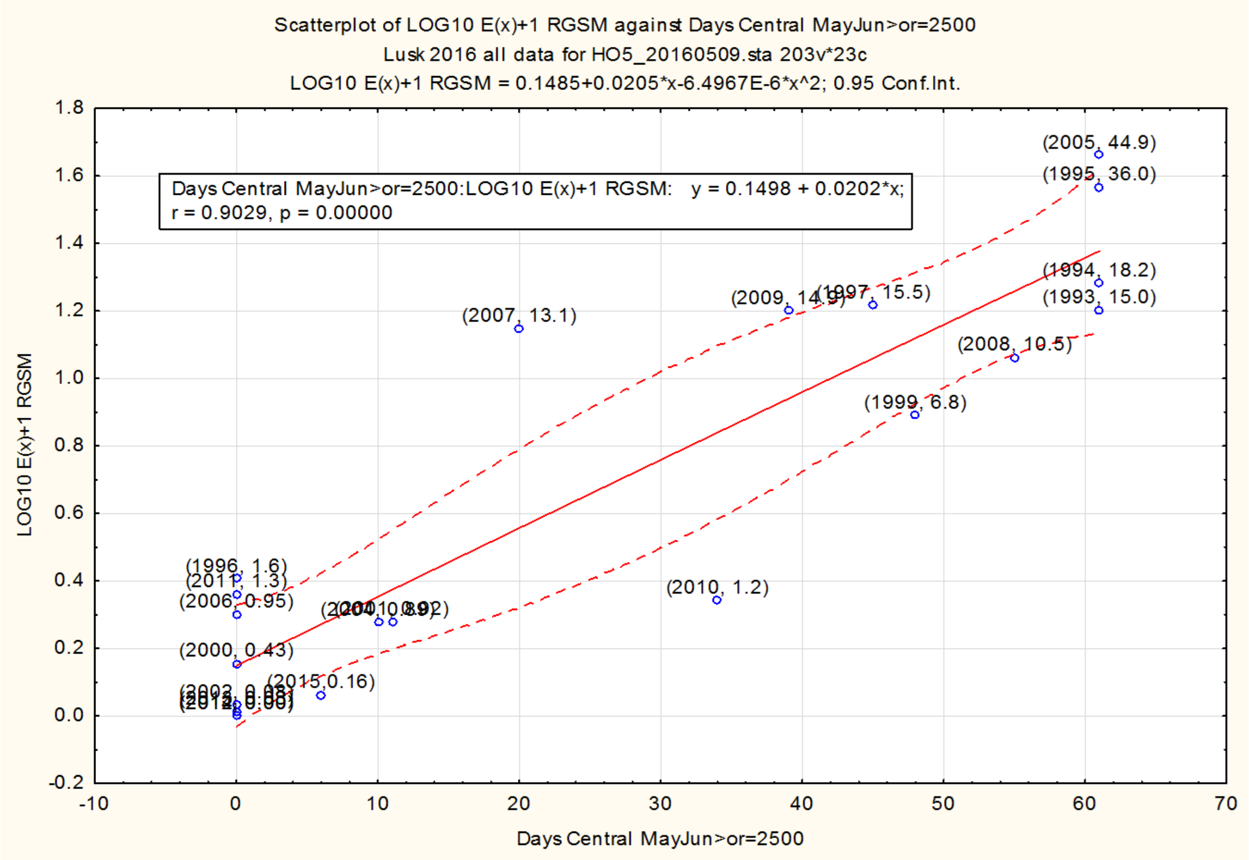

Figure A13. Relationship between the number of days average discharge (in cfs, mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 2,500 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) from 1993 to 2015.

Table A6. Relationship between the number of days average discharge (in cfs mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 2,500 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and their expected frequency of occupancy (distribution) at silvery minnow PMP sites in October.

Days mean daily flow exceeded 2,500 cfs in May and June at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model in Figure 4	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
1	0.17	0.5	0.33	0.5
5	0.25	0.8	0.42	0.8
6	0.27	0.9	0.44	0.9
7	0.29	1.0	0.46	1.0
8	0.31	1.1	0.48	1.0
9	0.33	1.2	0.50	1.1
10	0.35	1.3	0.52	1.2
11	0.37	1.4	0.54	1.4
12	0.39	1.5	0.56	1.5
13	0.41	1.6	0.58	1.6
14	0.43	1.7	0.60	1.7
15	0.45	1.8	0.61	1.8
16	0.47	2.0	0.63	2.0
17	0.50	2.1	0.65	2.1
18	0.52	2.3	0.66	2.3
19	0.54	2.4	0.68	2.4
20	0.56	2.6	0.70	2.6
21	0.58	2.8	0.71	2.7
22	0.60	2.9	0.73	2.9
23	0.62	3.1	0.74	3.1
24	0.64	3.3	0.75	3.3
25	0.66	3.5	0.77	3.5
26	0.68	3.8	0.78	3.7
27	0.70	4.0	0.79	4.0
28	0.72	4.2	0.80	4.2
29	0.74	4.5	0.82	4.4
30	0.76	4.7	0.83	4.7
31	0.78	5.0	0.84	5.0

2c. Polynomial Regression Equation 5: Estimated silvery minnow abundance density in the fall = (10^((0.1453) + (0.0073*Days average discharge during May and June at ABQ Gage was greater than or equal to 2,000 cfs) - ((Days average discharge during May and June at ABQ Gage was greater than or equal to 2,000 cfs ^2)*0.0002))) - 1. (Figure A15, Table A7).

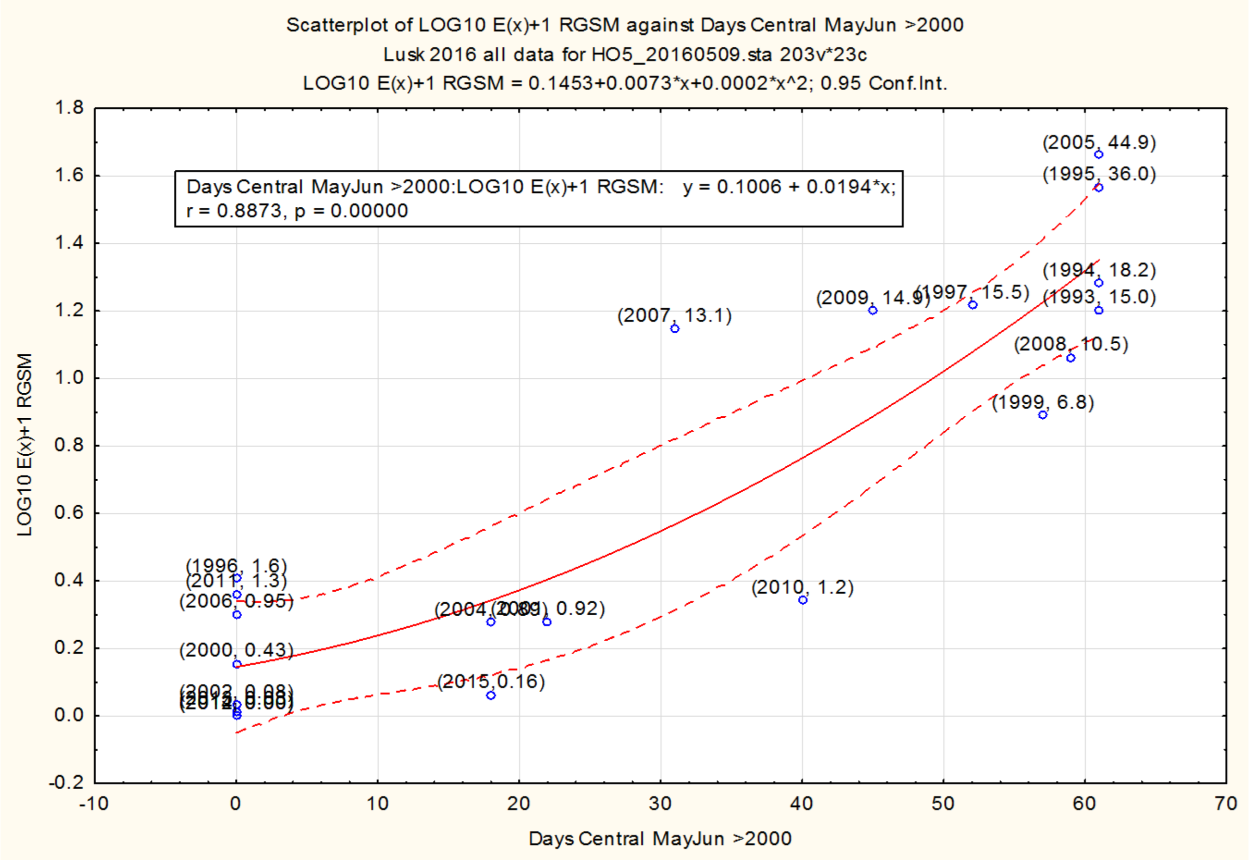

Figure A14. Relationship between the number of days average discharge (in cfs, mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 2,000 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per $100m^2$) + 1) from 1993 to 2015.

Table A7. Relationship between the number of days average discharge (in cfs mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 2,000 cfs and the estimated abundance of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and their expected frequency of occupancy (distribution) at silvery minnow PMP sites in October.

Days mean daily flow exceeded 2,000 cfs in May and June at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model in Figure 5	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
1	0.15	0.4	0.31	0.3
5	0.19	0.5	0.37	0.6
10	0.24	0.7	0.45	1.0
15	0.30	1.0	0.52	1.5
16	0.31	1.1	0.53	1.6
17	0.33	1.1	0.54	1.7
18	0.34	1.2	0.55	1.8
19	0.36	1.3	0.57	1.9
20	0.37	1.4	0.58	2.1
21	0.39	1.4	0.59	2.2
22	0.40	1.5	0.60	2.4
23	0.42	1.6	0.61	2.5
24	0.44	1.7	0.63	2.7
25	0.45	1.8	0.64	2.9
26	0.47	2.0	0.65	3.0
27	0.49	2.1	0.66	3.2
28	0.51	2.2	0.67	3.4
29	0.53	2.4	0.68	3.6
30	0.54	2.5	0.69	3.8
31	0.56	2.7	0.70	4.0
32	0.58	2.8	0.71	4.3
33	0.60	3.0	0.72	4.5
34	0.62	3.2	0.73	4.8
35	0.65	3.4	0.74	5.0
36	0.67	3.6	0.75	5.3
37	0.69	3.9	0.76	5.6
38	0.71	4.1	0.77	5.9
39	0.73	4.4	0.78	6.2
40	0.76	4.7	0.79	6.5
41	0.78	5.0	0.80	6.9

2d. Polynomial Regression Equation 6: Estimated silvery minnow abundance density in the fall = (10^((0.1533) - (0.002*Days average discharge during May and June at ABQ Gage was greater than or equal to 1,500 cfs) - ((Days average discharge during May and June at ABQ Gage was greater than or equal to 1,500 cfs ^2)*0.0003))) - 1. (Figure A16, Table A8).

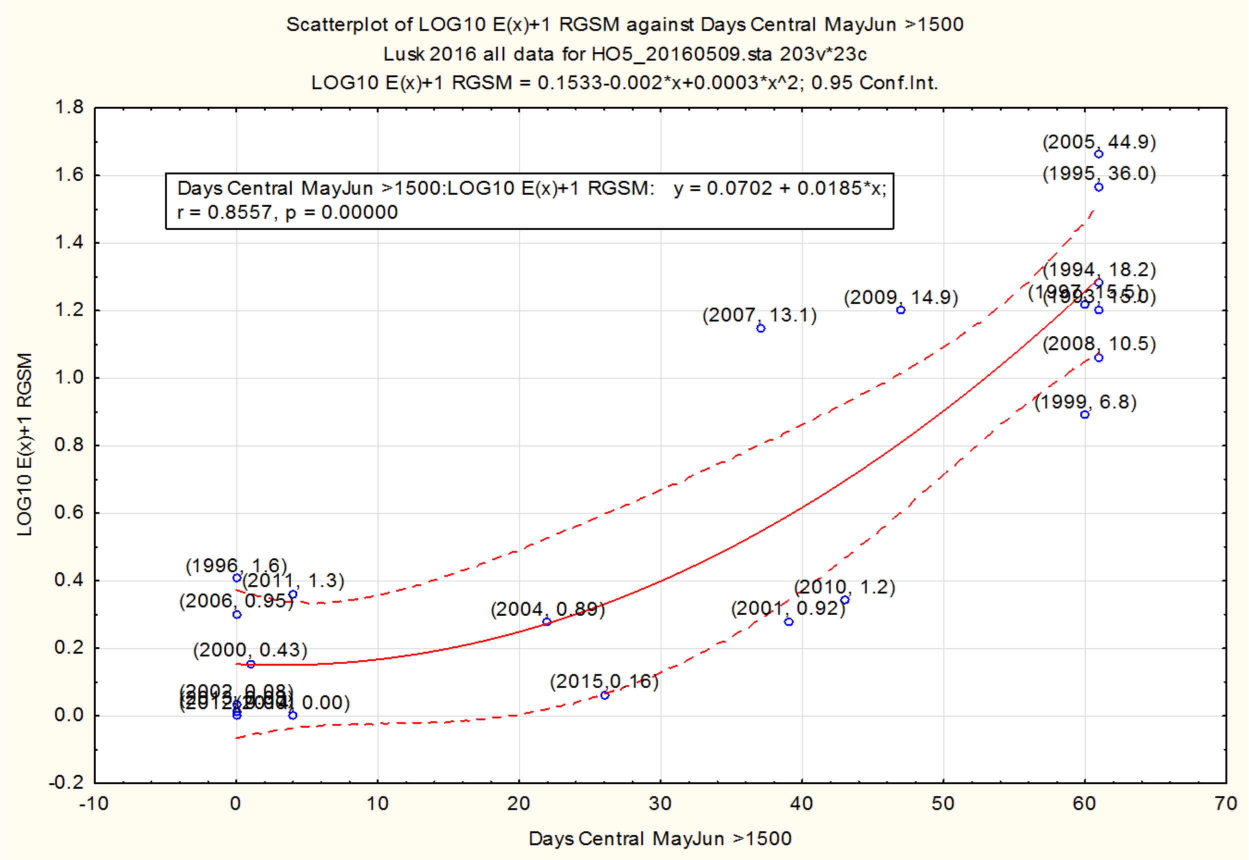

Figure A15. Relationship between the number of days average discharge (in cfs, mean daily flow) crossing the ABQ-Central Gage during May and June equaled or exceeded 1,500 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100m^2) + 1) from 1993 to 2015.

Table A8. Relationship between number of days average discharge (in cfs mean daily flow) crossing ABQ-Central Gage during May and June equaled or exceeded 1,500 cfs and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and their expected frequency of occupancy (distribution) at silvery minnow PMP sites in October.

Days mean daily flow exceeded 1,500 cfs in May and June at ABQ-Central Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
1	0.15	0.4	0.31	0.2
5	0.15	0.4	0.34	0.5
10	0.16	0.5	0.39	0.8
15	0.19	0.6	0.43	1.2
20	0.23	0.7	0.48	1.8
25	0.29	1.0	0.53	2.4
26	0.30	1.0	0.54	2.6
27	0.32	1.1	0.55	2.7
28	0.33	1.2	0.56	2.9
29	0.35	1.2	0.57	3.0
30	0.36	1.3	0.58	3.2
31	0.38	1.4	0.59	3.4
32	0.40	1.5	0.60	3.6
33	0.41	1.6	0.61	3.8
34	0.43	1.7	0.63	4.0
35	0.45	1.8	0.64	4.2
36	0.47	2.0	0.65	4.4
37	0.49	2.1	0.66	4.7
38	0.51	2.2	0.67	4.9
39	0.53	2.4	0.68	5.2
40	0.55	2.6	0.69	5.5
41	0.58	2.8	0.70	5.7
42	0.60	3.0	0.71	6.0
43	0.62	3.2	0.72	6.3
44	0.65	3.4	0.73	6.7
45	0.67	3.7	0.74	7.0
46	0.70	4.0	0.76	7.3
47	0.72	4.3	0.77	7.7
48	0.75	4.6	0.78	8.1
49	0.78	5.0	0.79	8.5

3. We found no significant relationships between silvery minnow abundance and the date of the onset or peak of the spring runoff event. However, the timings of spring runoff events (such as the number of days spring runoff increased, the number of days spring runoff decreased, and the Julian Date of the conclusion of spring runoff) were significantly related to estimated silvery minnow abundance observed in the fall. The greater the number of days that spring runoff increased or decreased likely resulted in the later Julian Date of the conclusion of spring runoff. We found that the Julian Date of spring runoff conclusion was significantly related to the estimated abundances of silvery minnows in the fall. It is likely that longer duration spring runoff events may favor higher rates of hatch, development, and early life stage survival, and recruitment of silvery minnow eggs, embryos, larvae, and fry into later life stages (juveniles and adults) that are later observed in the fall. Median water temperatures were also greater in May and June below Cochiti Dam (USGS Gage 08317400) compared with water temperatures in the earlier months of March and April. Percent hatch and rates of silvery minnow larval development occur at higher rates at higher water temperatures (Platania 2000; Mapula et al. 2007). There may also be circadian rhythms, timing of diatom blooms and other food availability (phenology), or genetic relationships that affect silvery minnow reproductive timing (Turner et al. 2010; Krabbenhoft 2012; Krabbenhoft et al. 2014; Cadadi-Fueloep et al. 2014). That is, those runoff conditions that favor increased hatch, larval development, and survival likely produce increased recruitment of silvery minnow in the fall.

3a. Polynomial Regression Equation 7: Estimated silvery minnow abundance density in the fall = (10^((-0.7211) - (0.0026*Julian Date that spring runoff discharge at San Acacia Gage during May and June dropped below the annual average discharge at San Acacia Gage) - ((Julian Date that spring runoff discharge at San Acacia Gage during May and June dropped below the annual average discharge at San Acacia Gage ^2)*0.000062856))) - 1. (Figure A17, Tables A9).

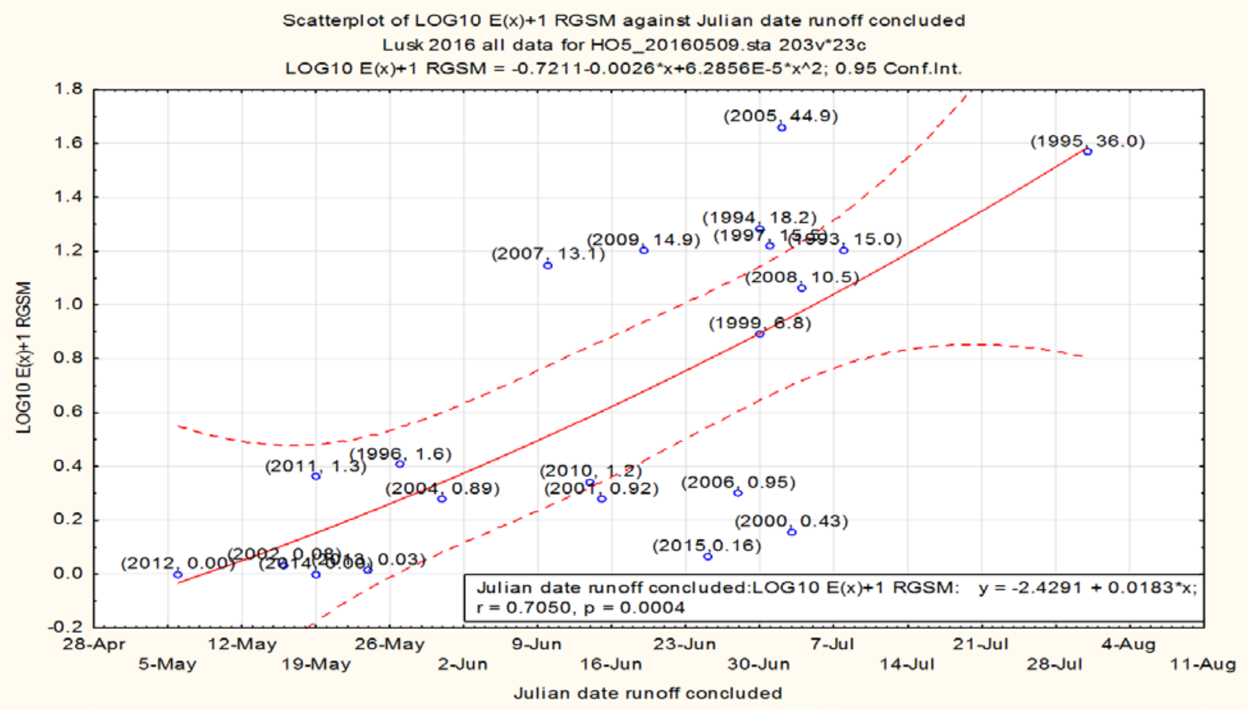

Figure A16. Relationship between the Julian Date of the conclusion of spring runoff events and the estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per $100m^2$) + 1) in October from 1993 to 2015.

Table A9. Relationship between the Julian Date of the conclusion of spring runoff events and estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100m^2) + 1) and their expected frequency of occupancy at silvery minnow PMP sites in October.

Julian Date Spring Runoff Concluded at San Acacia Gage	Y-axis value (log10 E(x) + 1) for silvery minnow abundance model	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
30-Apr	-0.12	-0.2	-0.15	-0.4
7-May	-0.02	-0.1	0.00	-0.2
11-May	0.03	0.1	0.08	0.0
16-May	0.10	0.3	0.18	0.2
17-May	0.12	0.3	0.20	0.2
18-May	0.13	0.4	0.21	0.3
20-May	0.16	0.5	0.25	0.4
21-May	0.18	0.5	0.27	0.5
22-May	0.19	0.6	0.28	0.5
23-May	0.21	0.6	0.30	0.6
24-May	0.22	0.7	0.32	0.7
25-May	0.24	0.7	0.34	0.7
26-May	0.25	0.8	0.35	0.8
27-May	0.27	0.9	0.37	0.9
28-May	0.29	0.9	0.39	1.0
29-May	0.30	1.0	0.40	1.1
30-May	0.32	1.1	0.42	1.2
31-May	0.34	1.2	0.43	1.3
1-Jun	0.35	1.3	0.45	1.3
2-Jun	0.37	1.3	0.46	1.4
3-Jun	0.39	1.4	0.48	1.6
4-Jun	0.40	1.5	0.49	1.7
5-Jun	0.42	1.6	0.51	1.8
6-Jun	0.44	1.7	0.52	1.9
7-Jun	0.45	1.8	0.54	2.0
8-Jun	0.47	2.0	0.55	2.2
9-Jun	0.49	2.1	0.57	2.3
10-Jun	0.51	2.2	0.58	2.4
11-Jun	0.53	2.4	0.59	2.6
12-Jun	0.54	2.5	0.61	2.7
13-Jun	0.56	2.6	0.62	2.9
14-Jun	0.58	2.8	0.63	3.1

Table A9. Relationship between the Julian Date of the conclusion of spring runoff events and estimated abundance density of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100m^2) + 1) and their expected frequency of occupancy at silvery minnow PMP sites in October.

15-Jun	0.60	3.0	0.64	3.2
16-Jun	0.62	3.1	0.66	3.4
17-Jun	0.63	3.3	0.67	3.6
18-Jun	0.65	3.5	0.68	3.8
19-Jun	0.67	3.7	0.69	4.0
20-Jun	0.69	3.9	0.71	4.2
21-Jun	0.71	4.1	0.72	4.5
22-Jun	0.73	4.4	0.73	4.7
23-Jun	0.75	4.6	0.74	4.9
24-Jun	0.77	4.9	0.75	5.2
25-Jun	0.79	5.1	0.76	5.5

4. Hydraulic Analyses: We found significant relationships between silvery minnow abundance and area of the MRG channel that was inundated during the year, during spring runoff in May and June, and during the low flow period from July through October. These areas of channel inundation help characterize the magnitude, duration, and frequency of inundation of designated critical habitat (Service 2003). Channel inundation during May and June of 2005 (over 155,800 ha (385,000 acres) of channel with more acres inundated in the overbank) probably represents the apex of inundated critical habitat that has occurred since its designation. We found significant relationships between silvery minnow abundance and the average width and average maximum depth of spring runoff in each of the river reaches (Angostura, Isleta, and San Acacia Reaches). However, these reach-specific average widths and depths were not further evaluated here.

4a. Polynomial Regression Equation 8: Estimated silvery minnow abundance densities in the fall = (10^((0.6712) - (0.000007638*acres of MRG channel inundated (using a modified USACE 2010 model) during May and June) - ((acres of MRG channel inundated (using a modified USACE 2010 model) during May and June ^2)* 0.000000000024863))) - 1. (Figure A18, Tables A10).

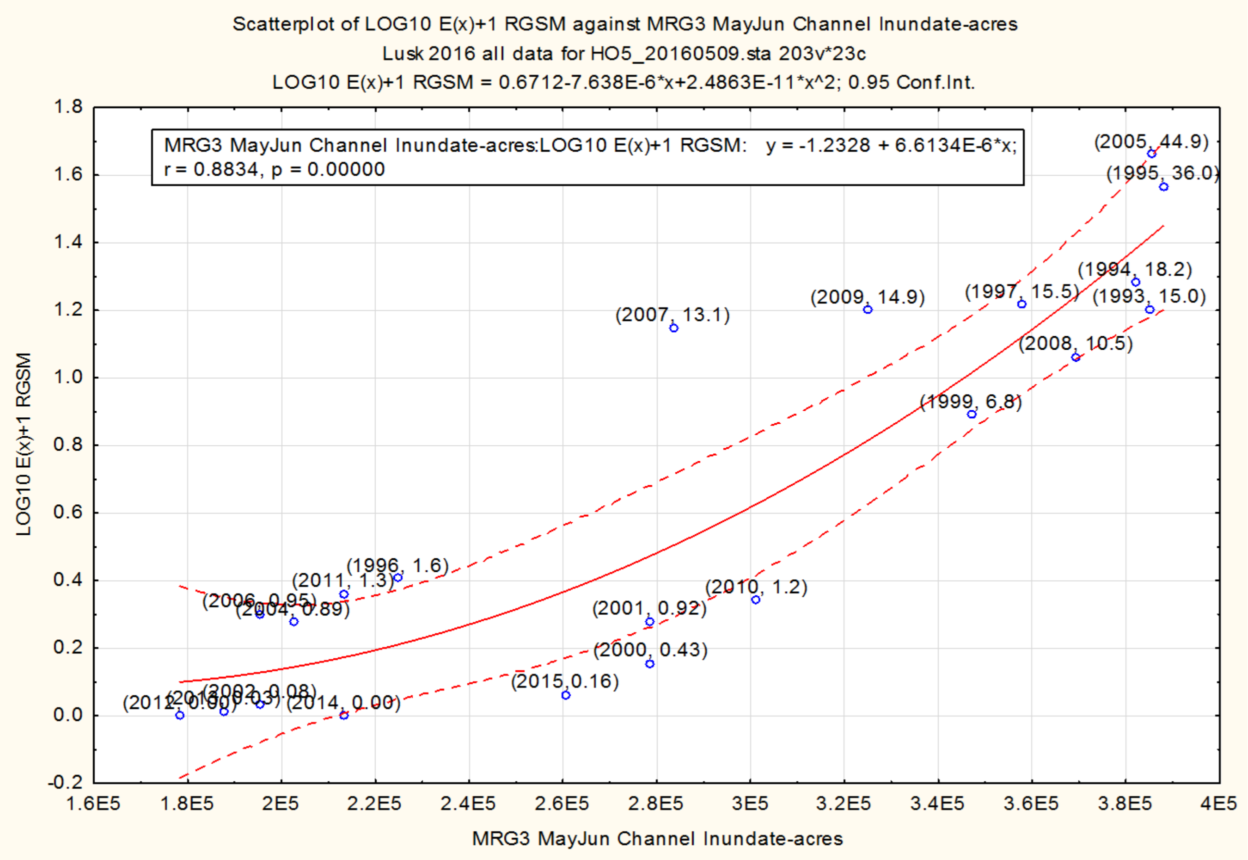

Figure A17. Relationship between the area of channel inundated in three river reaches of the MRG during May and June and the estimated abundance densities of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1).

Table A10. Relationship between the area of channel inundated in three river reaches of the MRG during May and June and the estimated abundance densities of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and expected frequency of occupancy at silvery minnow PMP sites in October from 1993 to 2015.

Acres of Channel (only) Inundation during May and June (using a modified USACE 2010 model)	Y-axis value (log10 E(x) + 1) for RGSM abundance model in Figure 8	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
150,000	0.08	0.2	0.03	-0.4
160,000	0.09	0.2	0.09	-0.3
170,000	0.09	0.2	0.14	-0.2
180,000	0.10	0.3	0.20	-0.1
190,000	0.12	0.3	0.25	0.1
200,000	0.14	0.4	0.30	0.2
210,000	0.16	0.5	0.35	0.4
220,000	0.19	0.6	0.40	0.7
230,000	0.23	0.7	0.44	0.9
235,000	0.25	0.8	0.46	1.1
240,000	0.27	0.9	0.49	1.3
245,000	0.29	1.0	0.51	1.4
250,000	0.32	1.1	0.53	1.6
255,000	0.34	1.2	0.55	1.8
260,000	0.37	1.3	0.57	2.1
265,000	0.39	1.5	0.59	2.3
270,000	0.42	1.6	0.61	2.6
275,000	0.45	1.8	0.63	2.9
280,000	0.48	2.0	0.65	3.2
285,000	0.51	2.3	0.66	3.5
290,000	0.55	2.5	0.68	3.8
295,000	0.58	2.8	0.70	4.2
300,000	0.62	3.1	0.72	4.6
305,000	0.65	3.5	0.73	5.1
310,000	0.69	3.9	0.75	5.6
315,000	0.73	4.4	0.77	6.1
321,000	0.78	5.0	0.78	6.8
325,000	0.82	5.5	0.80	7.3
330,000	0.86	6.2	0.81	7.9
335,000	0.90	7.0	0.82	8.6
340,000	0.95	7.9	0.84	9.4

Table A10. Relationship between the area of channel inundated in three river reaches of the MRG during May and June and the estimated abundance densities of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and expected frequency of occupancy at silvery minnow PMP sites in October from 1993 to 2015.

Acres of Channel (only) Inundation during May and June (using a modified USACE 2010 model)	Y-axis value (log10 E(x) + 1) for RGSM abundance model in Figure 8	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
345,000	1.00	8.9	0.85	10.2
350,000	1.04	10.1	0.87	11.1
360,000	1.14	12.9	0.89	13.1
370,000	1.25	16.7	0.91	15.4
380,000	1.36	21.9	0.94	18.1
390,000	1.47	28.8	0.96	21.2
400,000	1.59	38.3	0.97	24.9

4b. Polynomial Regression Equation 9: Estimated silvery minnow abundance densities in the fall = (10^((0.6712) - (0.000007638*acres of MRG channel inundated (using a modified USACE 2010 model) during a year) - ((acres of MRG channel inundated (using a modified USACE 2010 model) during a year ^2)* 0.000000000024863))) - 1. (Figure A19; Table A11).

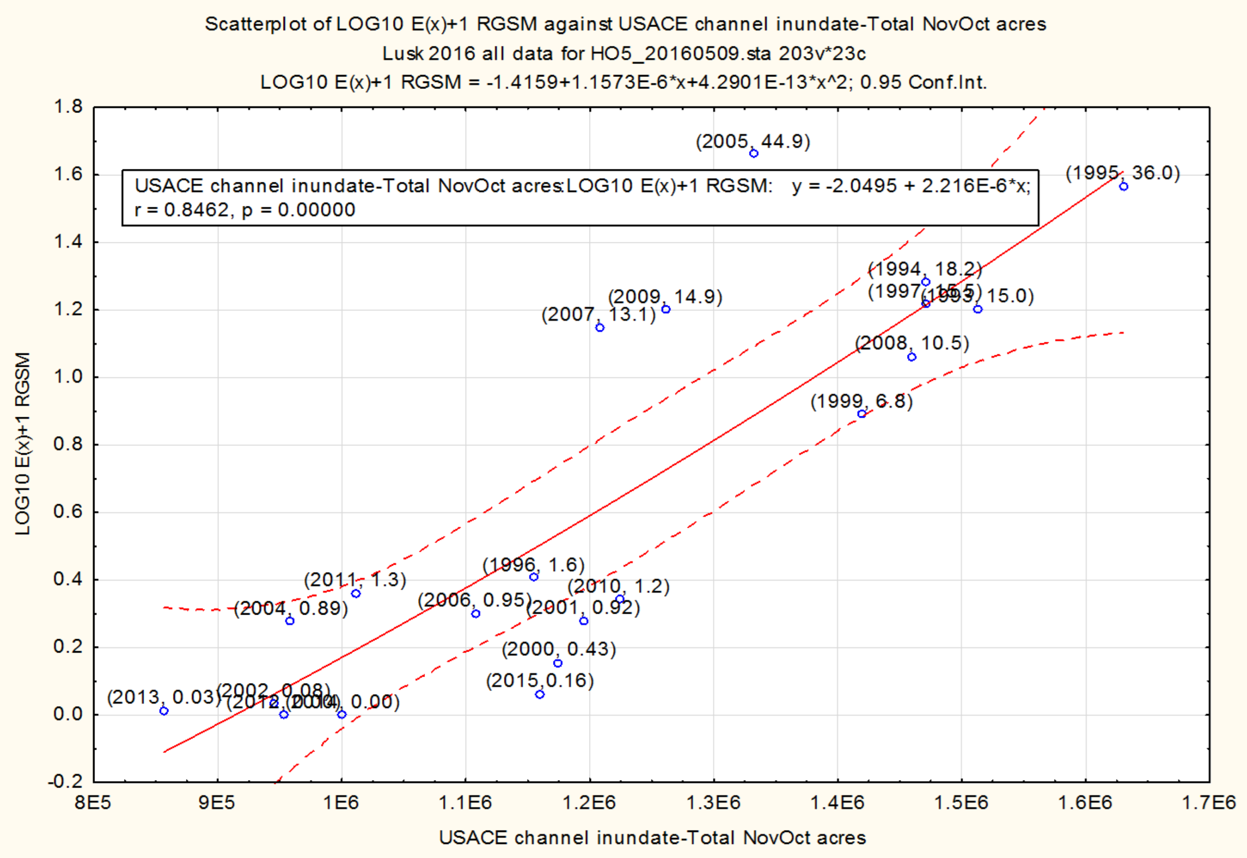

Figure A18. Relationship between the area of channel inundated in three river reaches of the MRG during the year (a "minnow" year from November through October) and the estimated abundance densities of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1).

Table A11. Relationship between the area of channel inundated in three river reaches of the MRG during the year (a “minnow” year from November through October) and the estimated abundance densities of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and expected frequency of occupancy (distribution) at silvery minnow PMP sites in October from 1993 to 2015.

Acres of Channel (only) Inundation during a year (using a modified USACE 2010 model)	Y-axis value (log10 E(x) + 1) for RGSM abundance model in Figure 9	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
700,000	-0.40	-0.6	-0.27	-0.7
800,000	-0.22	-0.4	-0.04	-0.5
900,000	-0.03	-0.1	0.17	-0.1
920,000	0.01	0.0	0.21	0.0
940,000	0.05	0.1	0.25	0.1
960,000	0.09	0.2	0.29	0.2
980,000	0.13	0.3	0.32	0.3
1,000,000	0.17	0.5	0.36	0.5
1,020,000	0.21	0.6	0.39	0.6
1,040,000	0.25	0.8	0.43	0.8
1,060,000	0.29	1.0	0.46	1.0
1,080,000	0.33	1.2	0.49	1.2
1,100,000	0.38	1.4	0.52	1.4
1,120,000	0.42	1.6	0.55	1.7
1,140,000	0.46	1.9	0.58	2.0
1,160,000	0.50	2.2	0.61	2.3
1,180,000	0.55	2.5	0.64	2.7
1,200,000	0.59	2.9	0.66	3.1
1,220,000	0.63	3.3	0.69	3.5
1,240,000	0.68	3.8	0.71	4.0
1,260,000	0.72	4.3	0.73	4.5
1,285,000	0.78	5.0	0.76	5.3
1,300,000	0.81	5.5	0.78	5.8
1,320,000	0.86	6.2	0.80	6.5
1,340,000	0.91	7.0	0.82	7.3
1,360,000	0.95	7.9	0.84	8.2
1,380,000	1.00	9.0	0.85	9.2
1,400,000	1.05	10.1	0.87	10.3
1,420,000	1.09	11.4	0.89	11.5
1,440,000	1.14	12.8	0.90	12.9
1,460,000	1.19	14.4	0.92	14.3

4c. Polynomial Regression Equation 10: Estimated silvery minnow abundance in the fall = (10^((-0.2668) + (0.0000018593*acres of MRG channel inundated (using a modified USACE 2010 model) during July through October) - ((acres of MRG channel inundated (using a modified USACE 2010 model) during July through October ^2)* 0.000000000002716))) - 1. (Figure A20, Table A12).

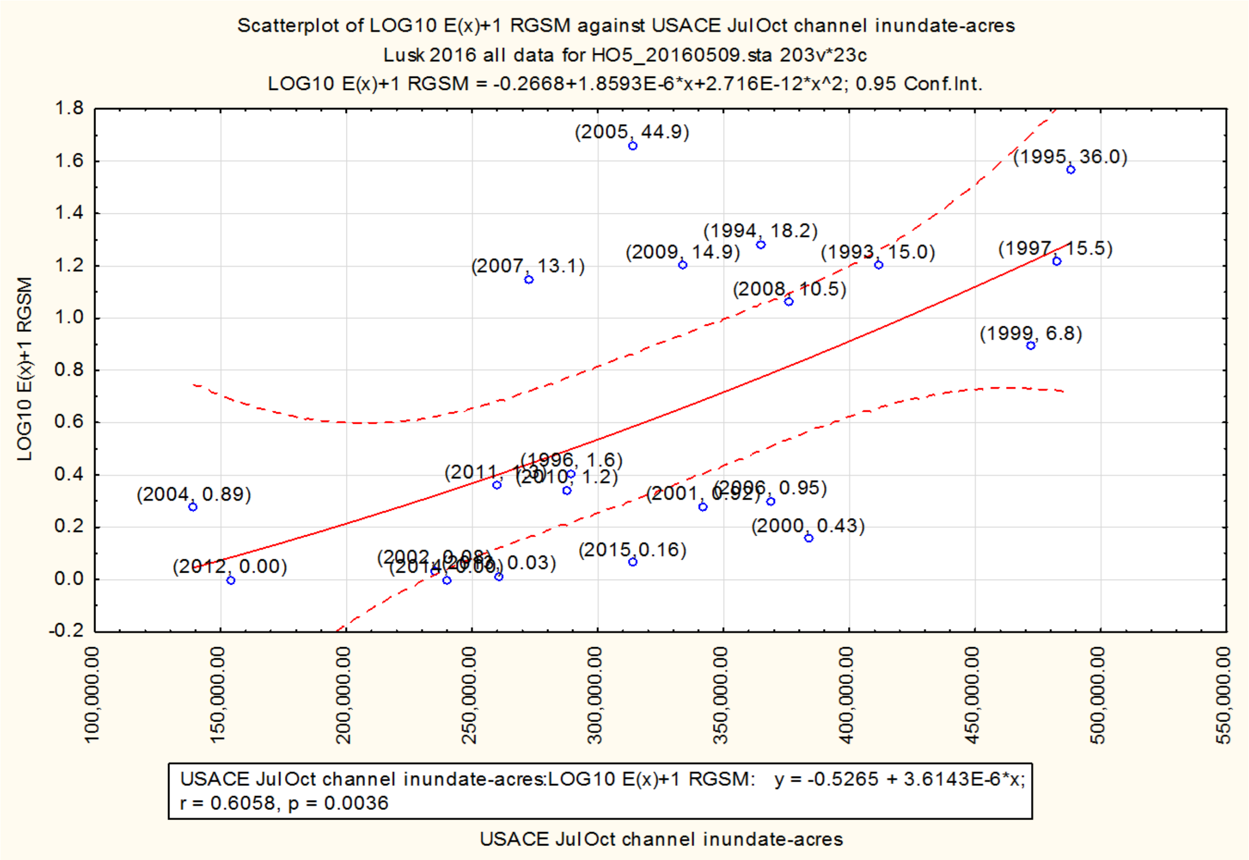

Figure A19. Relationship between the area of channel inundated in three river reaches of the MRG during July through October (the low flow, post runoff period) and the estimated abundance of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1).

Table A12. Relationship between the area of channel inundated in three river reaches of the MRG during July through October (during the low flow, post runoff period) and the estimated abundance of silvery minnows in fall (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) and expected frequency of occupancy (distribution) at silvery minnow PMP sites in October from 1993 to 2015.

Acres of Channel (only) Inundation during July through October (using a modified USACE 2010 model)	Y-axis value (log10 E(x) + 1) for RGSM abundance model in Figure 10	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites)	RGSM abundance ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
75,000	-0.11	-0.2	-0.22	-0.4
100,000	-0.05	-0.1	-0.11	-0.3
125,000	0.01	0.0	-0.01	-0.2
140,000	0.05	0.1	0.05	0.0
175,000	0.14	0.4	0.19	0.3
200,000	0.21	0.6	0.28	0.6
230,000	0.30	1.0	0.38	1.0
250,000	0.37	1.3	0.44	1.4
275,000	0.45	1.8	0.52	1.9
300,000	0.54	2.4	0.59	2.6
325,000	0.62	3.2	0.65	3.4
350,000	0.72	4.2	0.71	4.5
366,000	0.78	5.0	0.75	5.3
400,000	0.91	7.2	0.82	7.3
425,000	1.01	9.3	0.86	9.2
450,000	1.12	12.2	0.90	11.6
475,000	1.23	15.9	0.94	14.5

Low Flow Condition (post Runoff Season from July through October)

5. We found significant relationships between silvery minnow distribution and abundance and minimum flows at the ABQ-Central Gage during the year as well as the number of days at a low flow at the Bernardo Gage during the low flow period from July through October. These flows help characterize the magnitude, duration, and frequency of low flows during July through October necessary for silvery minnows to survive. The frequency of occupancy (or distribution) of silvery minnows at the silvery minnow PMP sites in the MRG was significantly related to the probability of extirpation of Age 0 (r = -0.6768) and Age 1 (r = -0.666) fish. As the distribution of silvery minnows in the MRG is reduced, the probability that stochastic events or extreme low flows and river drying can extirpate these fish increases their risk of extinction (Norris et al.

2008; Miller 2012; Dudley et al. 2016). Therefore, we assumed that a distribution (or occupancy) of less than 50 percent of sites surveyed in the fall or of occupied critical habitat was related to high risk of extirpation and a low likelihood of survival of a buffered MVP of silvery minnows.

5a. Polynomial Regression Equation 11: Estimated silvery minnow distribution (occupancy of silvery minnow PMP sites) in the fall = ((-0.2945) + (0.0063*minimum mean daily flow in cfs at ABQ-Central Gage in a year) - ((minimum mean daily flow in cfs at ABQ-Central Gage in a year ^2) * 0.0000082543)) (Figure A21, Table A13).

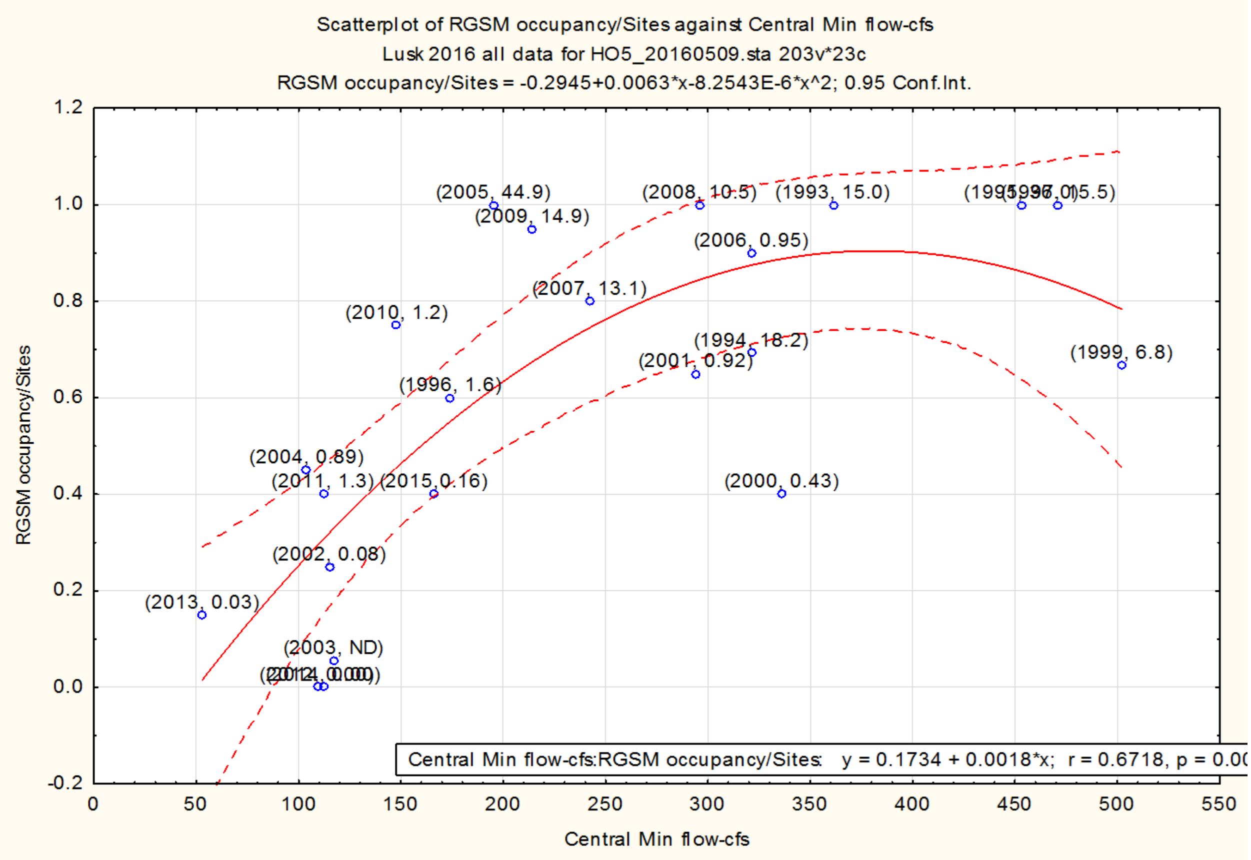

Figure A20. Relationship between the minimum mean daily flow (in cfs) at the ABQ-Central Gage in a year (that is, a “minnow” year from November through October) and the estimated distribution or occupancy of silvery minnows at survey sites in fall.

Table A13. Relationship between the minimum mean daily flow at the ABQ-Central Gage (during a "minnow" year from November through October) and the estimated distribution or occupancy of silvery minnows at survey sites in fall as well as the expected abundance in October (transformed base 10 logarithms of estimated (E(x)) October fish densities (fish per 100 m^2) + 1) from 1993 to 2015.

Minimum Mean Daily Flow at the ABQ-Central Gage (in cfs for a year)	Y-axis value (log10 E(x) + 1) for RGSM abundance model	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites) in Figure 11	RGSM occupancy ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
0	-0.38	-0.6	-0.29	0.17
50	-0.08	-0.2	0.00	0.26
60	-0.03	-0.1	0.05	0.28
70	0.03	0.1	0.11	0.30
80	0.08	0.2	0.16	0.32
90	0.13	0.4	0.21	0.34
100	0.18	0.5	0.25	0.35
110	0.23	0.7	0.30	0.37
120	0.28	0.9	0.34	0.39
125	0.30	1.0	0.36	0.40
140	0.37	1.3	0.43	0.43
150	0.41	1.6	0.46	0.44
160	0.46	1.9	0.50	0.46
170	0.50	2.1	0.54	0.48
180	0.54	2.4	0.57	0.50
190	0.57	2.7	0.60	0.52
200	0.61	3.1	0.64	0.53
210	0.65	3.4	0.66	0.55
220	0.68	3.8	0.69	0.57
230	0.71	4.2	0.72	0.59
245	0.76	4.7	0.75	0.61
251	0.78	5.0	0.77	0.63
260	0.80	5.4	0.79	0.64
270	0.83	5.8	0.80	0.66

5b. Polynomial Regression Equation 12: Estimated silvery minnow distribution (occupancy of survey sites) in the fall = ((-0.2945) + (0.0063*number of days that the discharge measures at the Bernardo Gage was less than 85 cfs during a year) - ((number of days that the discharge measures at the Bernardo Gage was less than 85 cfs during a year ^2) * 0.0000082543)). (Figure A22, Table A14).

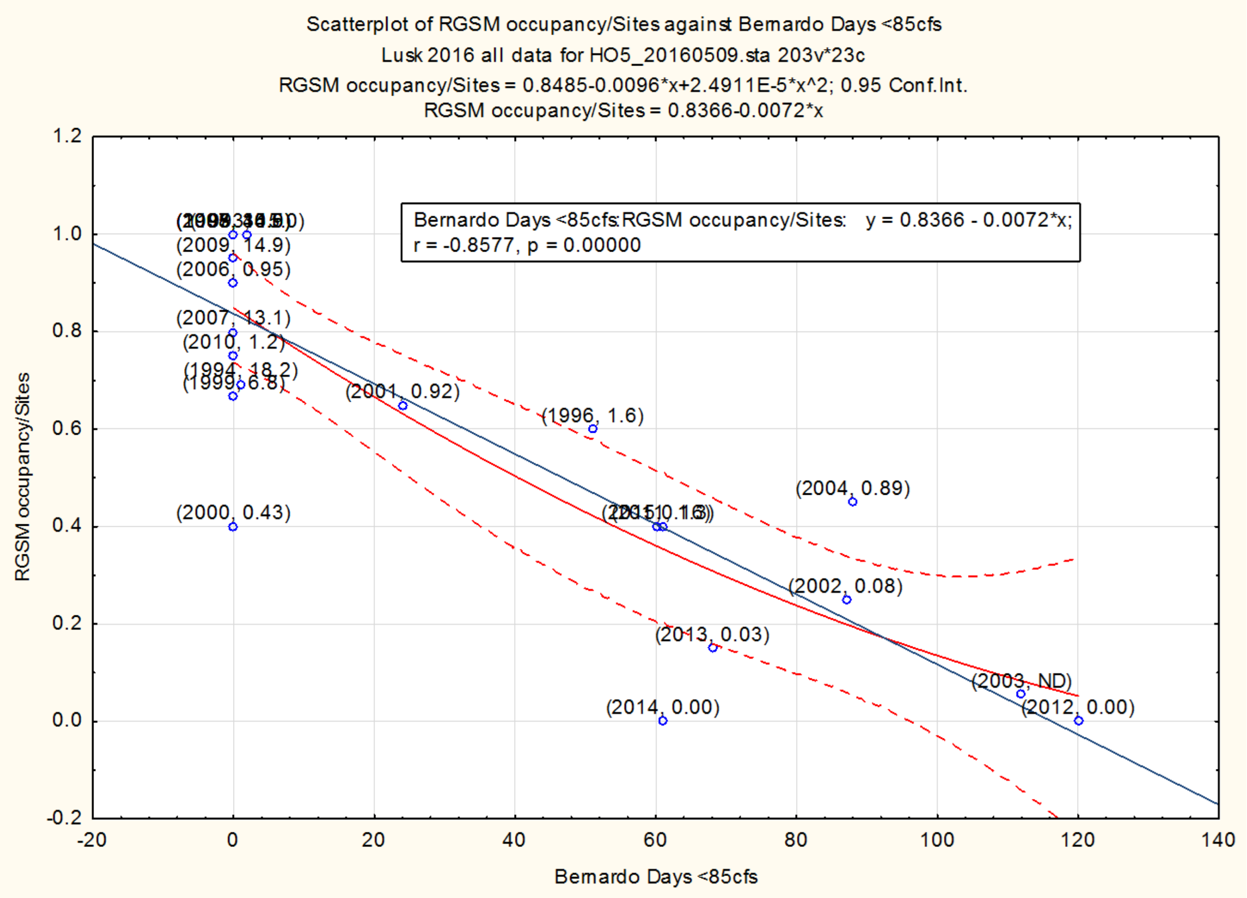

Figure A21. Relationship between the number of days' discharge at the Bernardo Gage was less than 85 cfs mean daily flow) during a year (a "minnow" year from November through October) and the estimated distribution or occupancy of silvery minnows at survey sites in the fall.

Table A14. Relationship between the number of days' discharge at the Bernardo Gage was less than 85 cfs mean daily flow) during a year (that is, a "minnow" year from November through October) and the estimated distribution or occupancy of silvery minnows at survey sites in the fall and the expected abundance (transformed base 10 logarithms of estimated (E(x)) October densities (fish per 100 m^2) + 1) in 1993 to 2015.

Days discharge at the Bernardo Gage is less than 85 cfs mean daily flow	Y-axis value (log10 E(x) + 1) for RGSM abundance model	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites) in Figure 12	RGSM occupancy ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
0	0.99	8.9	0.85	0.84
2	0.95	8.0	0.83	0.82
4	0.92	7.2	0.81	0.81
6	0.88	6.6	0.79	0.79
8	0.84	5.9	0.77	0.78
11	0.79	5.1	0.74	0.76
12	0.77	4.9	0.73	0.75
14	0.73	4.4	0.71	0.74
16	0.70	4.0	0.69	0.72
18	0.67	3.7	0.67	0.71
20	0.64	3.3	0.65	0.69
22	0.60	3.0	0.63	0.68
24	0.57	2.7	0.60	0.66
26	0.54	2.5	0.58	0.65
28	0.52	2.3	0.56	0.64
30	0.49	2.1	0.54	0.62
32	0.46	1.9	0.52	0.61
34	0.43	1.7	0.49	0.59
36	0.41	1.6	0.47	0.58
38	0.38	1.4	0.45	0.56
40	0.36	1.3	0.42	0.55
42	0.33	1.2	0.40	0.53
44	0.31	1.1	0.38	0.52
46	0.29	1.0	0.35	0.51
48	0.27	0.9	0.33	0.49
50	0.25	0.8	0.31	0.48
52	0.23	0.7	0.28	0.46
54	0.21	0.6	0.26	0.45
56	0.19	0.6	0.23	0.43
58	0.18	0.5	0.21	0.42
60	0.16	0.4	0.18	0.40

Table A14. Relationship between the number of days' discharge at the Bernardo Gage was less than 85 cfs mean daily flow) during a year (that is, a "minnow" year from November through October) and the estimated distribution or occupancy of silvery minnows at survey sites in the fall and the expected abundance (transformed base 10 logarithms of estimated (E(x)) October densities (fish per 100 m^2) + 1) in 1993 to 2015.

Days discharge at the Bernardo Gage is less than 85 cfs mean daily flow	Y-axis value (log10 E(x) + 1) for RGSM abundance model	RGSM abundance ~ polynomial model (Estimated October E(x) =fish per 100 m^2)	RGSM October occupancy polynomial model (percent of Sites) in Figure 12	RGSM occupancy ~ LINEAR model (Estimated October E(x) = fish per 100 m^2)
62	0.14	0.4	0.16	0.39
64	0.13	0.3	0.13	0.38
66	0.12	0.3	0.11	0.36
68	0.10	0.3	0.08	0.35
70	0.09	0.2	0.05	0.33
72	0.08	0.2	0.03	0.32
74	0.07	0.2	0.00	0.30
76	0.06	0.1	-0.02	0.29
78	0.05	0.1	-0.05	0.28
80	0.04	0.1	-0.08	0.26
82	0.03	0.1	-0.11	0.25
84	0.03	0.1	-0.13	0.23
86	0.02	0.1	-0.16	0.22
88	0.02	0.0	-0.19	0.20
90	0.01	0.0	-0.22	0.19
92	0.01	0.0	-0.25	0.17
94	0.01	0.0	-0.27	0.16
96	0.01	0.0	-0.30	0.15
98	0.00	0.0	-0.33	0.13
100	0.00	0.0	-0.36	0.12
102	0.00	0.0	-0.39	0.10
104	0.01	0.0	-0.42	0.09
106	0.01	0.0	-0.45	0.07
108	0.01	0.0	-0.48	0.06
110	0.01	0.0	-0.51	0.04
112	0.02	0.0	-0.54	0.03
114	0.02	0.1	-0.57	0.02
116	0.03	0.1	-0.60	0.00
118	0.04	0.1	-0.63	-0.01
120	0.05	0.1	-0.66	-0.03

5c. Polynomial Regression Equation 13: Estimated silvery minnow distribution (occupancy of survey sites) in the fall = ((-0.2945) + (0.0063*number of days that the discharge measures at the Bernardo Gage was less than 85 cfs during a year) - ((number of days that the discharge measures at the Bernardo Gage was less than 85 cfs during a year ^2) * 0.0000082543)). (Figure A23, Table A15).

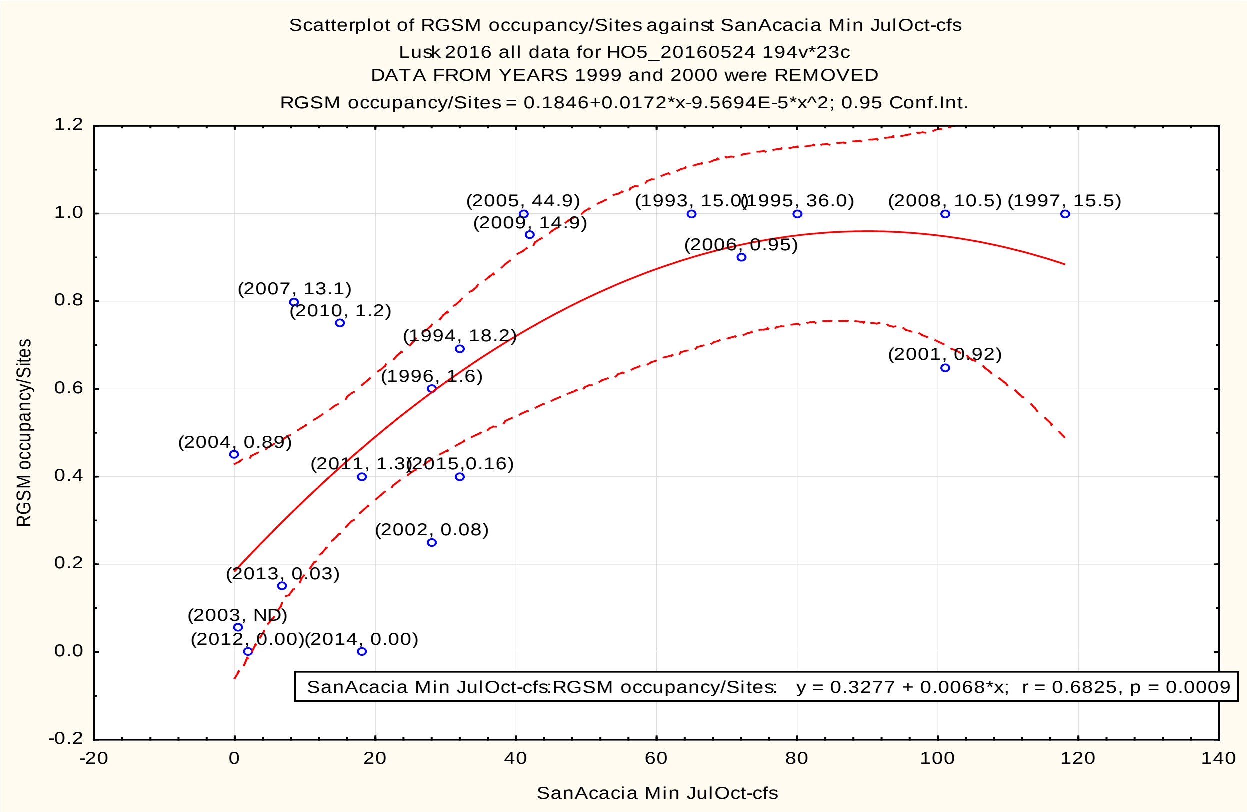

Figure A22. Relationship between the minimum flow (mean daily flow in cfs) at the San Acacia Gage omitting data from 1999 and 2000) during the low flow period from July through October and the estimated distribution (or occupancy) of silvery minnows at survey sites in the fall.

Table A15. Relationship between the minimum flow (minimum mean daily flow in cfs) at the San Acacia Gage during the low flow period from July through October (omitting data from 1999 and 2000) and the estimated distribution (or occupancy) of silvery minnows at survey sites in the fall and the expected abundance (transformed base 10 logarithms of estimated (E(x)) October densities (fish per 100 m^2) + 1) from 1993 to 2015.

San Acacia Gage minimum mean daily flow (in cfs) during July through October (without 1999 and 2000 data)	Silvery minnow October occupancy polynomial model (percent of Sites) used in Figure 13.	Silvery minnow occupancy ~ LINEAR model (percent of silvery minnow PMP sites occupied)
0	0.18	0.33
4	0.25	0.35
8	0.32	0.38
10	0.35	0.40
14	0.41	0.42
18	0.46	0.45
21	0.50	0.47
22	0.52	0.48
24	0.54	0.49
26	0.57	0.50
28	0.59	0.52
30	0.61	0.53
32	0.64	0.55
34	0.66	0.56
36	0.68	0.57
38	0.70	0.59
40	0.72	0.60
43	0.75	0.62
44	0.76	0.63
46	0.77	0.64
48	0.79	0.65
50	0.81	0.67
52	0.82	0.68
54	0.83	0.69
56	0.85	0.71
58	0.86	0.72
61	0.88	0.74
62	0.88	0.75
64	0.89	0.76
66	0.90	0.78
68	0.91	0.79
70	0.92	0.80

Table A15. Relationship between the minimum flow (minimum mean daily flow in cfs) at the San Acacia Gage during the low flow period from July through October (omitting data from 1999 and 2000) and the estimated distribution (or occupancy) of silvery minnows at survey sites in the fall and the expected abundance (transformed base 10 logarithms of estimated (E(x)) October densities (fish per 100 m^2) + 1) from 1993 to 2015.

San Acacia Gage minimum mean daily flow (in cfs) during July through October (without 1999 and 2000 data)	Silvery minnow October occupancy polynomial model (percent of Sites) used in Figure 13.	Silvery minnow occupancy ~ LINEAR model (percent of silvery minnow PMP sites occupied)
72	0.93	0.82
74	0.93	0.83
76	0.94	0.84
78	0.94	0.86
80	0.95	0.87
82	0.95	0.89
84	0.95	0.90
86	0.96	0.91
88	0.96	0.93
90	0.96	0.94

Discussion

Hydrobiological Objectives for Production Events during Spring Runoff in the MRG

Together, the duration, magnitude, and timing of spring runoff events, and the duration and magnitude of low flow events accounted for the majority of the variance in silvery minnow abundance and distribution estimates in the MRG from 1993 to 2015. The silvery minnow thrives when the spring runoff volume measured at ABQ-Central Gage is over 318,000 acre-feet during May and June. The silvery minnow survives when the spring runoff measured at ABQ-Central Gage is over 145,000 acre-feet during May and June.

Based on our flow assessments, over ninety percent of the silvery minnow population variance appears to be significantly related to the duration, magnitude, and timing of spring runoff events. The statistical significance of these findings seems to indicate biological significance provided our other knowledge about eggs, larval fish habitat, flows and channel elevations, and silvery minnow life history. The physical conditions produced by prolonged and elevated spring runoff events result in the inundation of newly flooded floodplain, shelves, braids, shoreline, inlets, island edges, pools, backwaters, and vegetated areas forming shallow, low-velocity habitats with increased nutrients, food, cover, and warm temperatures known to be essential for the successful recruitment of early life history stages of many freshwater fish species throughout the world (Welcomme 1979; Junk et al. 1989; Copp 1992; Dutterer et al. 2013) including silvery minnow in the MRG (Dudley and Platania 1997; Valett et al. 2005; Pease et al. 2006; Porter and Massong 2006; Dudley and Platania 2007; Turner et al. 2010, Hoagstrom and Turner 2013; Dudley and Platania 2015a, b; Dudley et al. 2016).

The silvery minnow appears to thrive when the mean daily flow at the ABQ-Central Gage is over 3,500 cfs for 16 days, or over 3,000 cfs for 22 days, or over 2,500 cfs for 31 days, or over 2,000 cfs for 41 days, or over 1,500 cfs for 49 days, and over 1,000 cfs for 54 days during May and June. The silvery minnow population appears to be self-sustaining and survive when the mean daily flow at ABQ-Central Gage is over 3,500 cfs for 2 days, or over 3,000 cfs for 4 days, or over 2,500 cfs for 7 days, or over 2,000 cfs for 15 days, or over 1,500 cfs for 25 days, and over 1,000 cfs for 38 days during May and June. When spring runoff increases for 37 days and decreases 30 days and concludes on June 25th, the silvery minnow is likely to thrive. When spring runoff increases for 13 days and decreases 10 days and concludes on May 29th, the silvery minnow is likely to survive. It appears that well-timed, sustained, and increased spring runoff events that inundate the MRG channel, its shorelines, and floodplains for a duration over three weeks may maximize the benefit of these newly flooded nursery habitats for successful growth and survival of silvery minnows from the egg through the early larval stages to recruitment in the fall (Dudley et al. 2016). “Other studies have reported similar relationships between strong year-classes of fish and elevated water levels or stream flows for multiple riverine or river influenced habitats, including estuaries , reservoirs, rivers (and river floodplain systems” (Dutterer et al. 2013).

Age 0 silvery minnows are known to comprise over 95 percent of the MRG silvery minnow population surveyed in October (Dudley et al., 2003, 2004, 2007, 2012; Dudley and Platania 2008, 2009, 2010, 2011, Mapula et al 2009; Horwitz et al 2011). Therefore, we developed six Age 0 Hydrobiological Objectives to optimize production of silvery minnows to meet survival and conservation goals in the MRG. The six Age 0 Hydrobiological Objectives for Production Events address the three primary components of spring runoff critical for silvery minnow production and recruitment including timing of flow, flow duration, and flow magnitude. We had originally developed additional Hydrobiological Objectives for Production at higher magnitude spring runoff events with greater than 240,000 acre-feet crossing the ABQ-Central Gage during May and June. However, our modeled results were less than those that were naturally attained and therefore, we restricted these recommendations to between 120,000 and 220,000 acre-feet in magnitude. Spring runoff events over 240,000 acre-feet should require little additional management than what occurs naturally. Spring runoff events were optimized by allocating the majority (~64 percent) of the volume into May and the remainder (~36 percent) into June. Thereafter, the number of days of flows equal to or greater than 1,000, 1,500, 2,000, 2,500, and 3,000 cfs were maximized with the available spring runoff volume. Lastly, the dates of runoff conclusion were considered in the timing of spring runoff start, peak, and conclusion during May or June. This resulted in a series of step-like plateaus that might be seen as unnatural. However, we suspect that in practice the variation in natural runoff and human abilities and managed release timings will result in additional variation and smoothing of these proposed hydrographs. Nonetheless, a formal process of mathematical optimization should be conducted prior to implementation. The Hydrological Objectives for Production of silvery minnows are in Figures A24 to A29, below.

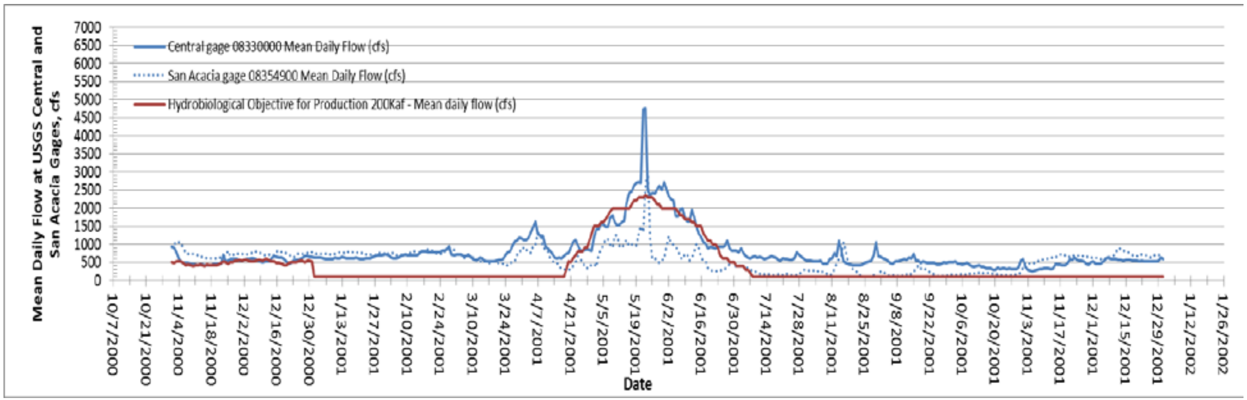

Figure 23. Hydrobiological Objective for production using 200,000 acre-feet versus 2001 hydrograph.

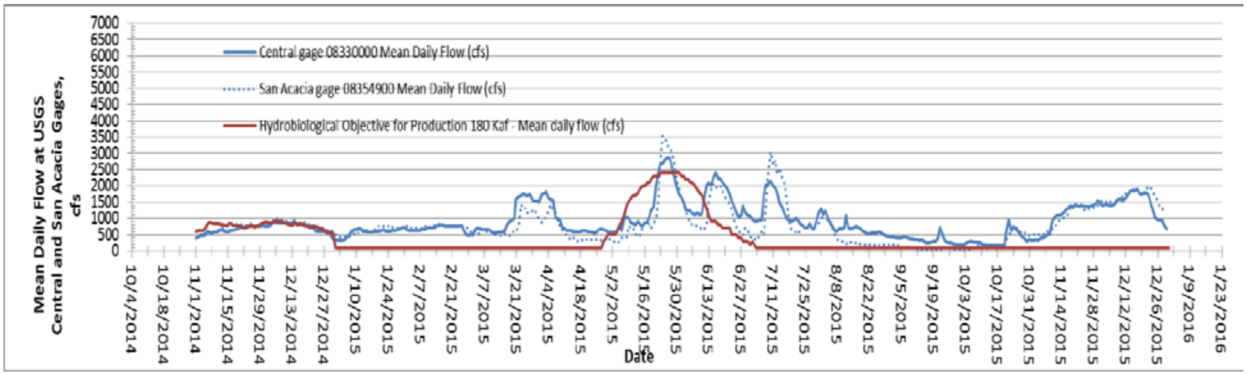

Figure A25. Hydrobiological Objective for production using 180,000 acre-feet versus 2015 hydrograph.

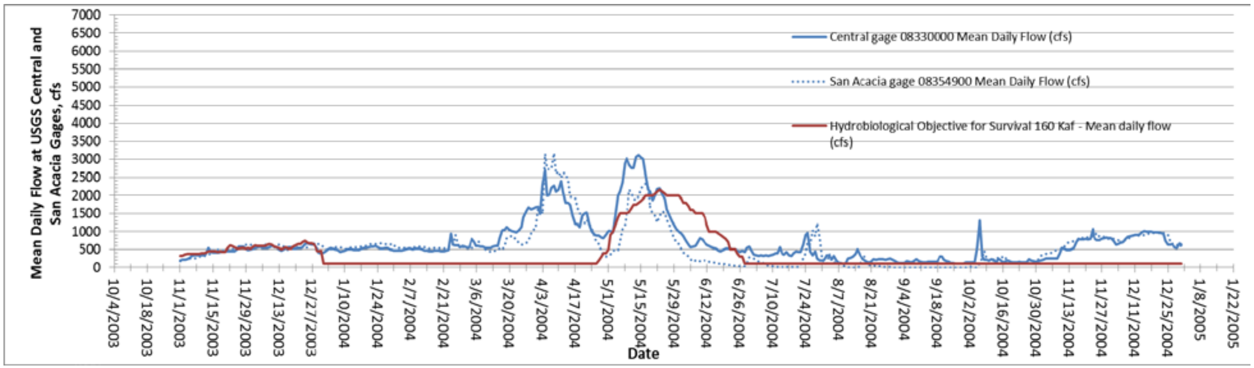

Figure A26. Hydrobiological Objective for production using 160,000 acre-feet versus 2004 hydrograph.

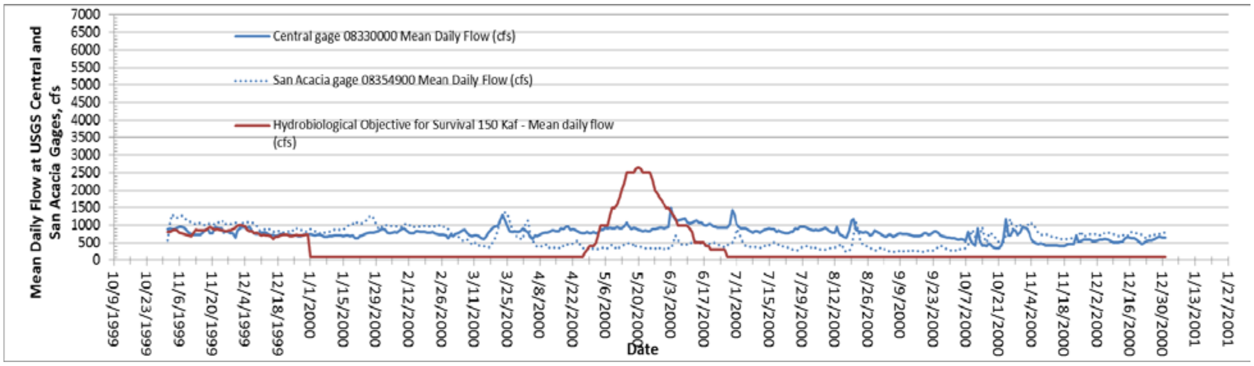

Figure A27. Hydrobiological Objective for production using 150,000 acre-feet versus 2000 hydrograph.

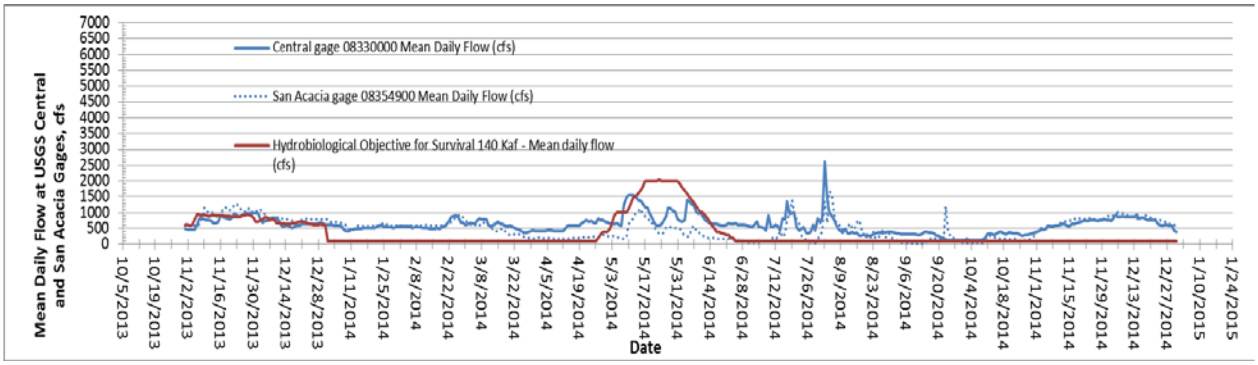

Figure A28. Hydrobiological Objective for production using 140,000 acre-feet versus 2014 hydrograph.

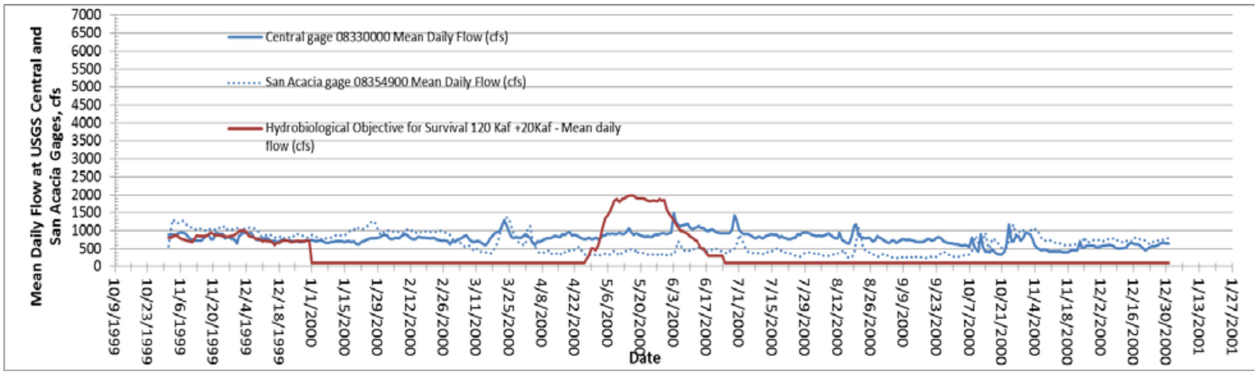

Figure A29. Hydrobiological Objective for production using 120,000+20,000 acre-feet versus 2000 hydrograph.

Hydrobiological Objectives for Survival Events During Low Flows in the MRG

When the water forecast during May and June is less than 120,000 acre-feet, or there are inadequate resources, authorities, or agency discretion available that would be necessary to manage spring runoff for silvery minnow production, then water must be made available for silvery minnow survival in the MRG until the following spring. The goal of the Hydrobiological Objectives for Survival is in promoting the survival of Age 1+ silvery minnows in the MRG.

One option is to use flow targets (Service 2003). For example, there were significant relationships between survival of silvery minnows and 1) a minimum flow of 125 cfs at the ABQ-Central Gage; 2) a minimum 358 days with flows at Bernardo Gage less than 85 cfs; and, 3) a minimum flow of 43 cfs at the San Acacia Gage during July through October. Similarly, the minimum mean daily flow at the ABQ-Central Gage was 1,200 cfs and the minimum mean daily flow at the San Acacia Gage was 600 cfs that were associated with silvery minnow survival on an annual basis. The relationships between low flow hydrological variables and silvery minnow abundance and occupancy were less robust and less significant than they were for spring runoff. Also, water managers in the MRG have expressed that they find minimum flow targets to be burdensome and wasteful (Minnow Action Team (MAT) 2013a).

Another option to be considered is Refugia Planning (Hatch et al. 2008; MRGCD 2012; MAT 2013a, b). Refugia are perennial water bodies that are anticipated to provide adequate conditions for silvery minnow survival during drying events in the MRG (MAT 2013a, b). However, the sources of water to maintain Refugia of adequate size, water quality, as well as the depth, width, length, and properties of the refugia have yet to be identified. It is unlikely that the state of knowledge of silvery minnow survival under extreme conditions (such as extended duration in isolated pools or Refugia) will ever reach a degree where the effect on survival can be predicted with certainty.

Recall that we derived a MVP estimate considering the genetic diversity of the silvery minnow, the average annual rate of mortality, and a buffer to against stochastic events and poor spring runoff in the following year. Note that when the surveyed silvery minnow population abundance was at or below an estimated density of 0.1 fish per 100 m^2 (that is, below the MVP) there were substantial losses in the number of haplotypes in silvery minnows and issues with genetic bottlenecks (Alo and Turner 2005; Osborne and Turner 2007; Osborne et al. 2012, 2015).

We used the hydraulic relationships between flows at the ABQ-Central Gage and the areas of channel inundated during post runoff (from July through October) to quantify the areas of channel inundation necessary for survival of a MVP and Buffered MVP of silvery minnow during these low flow periods. Because of diversity of water depths in a sandbed river, the flexibility of most aquatic organisms, and the paucity of empirical information about silvery minnow survival during extended droughts, we were not able to produce one ‘minimum flow’ that is guaranteed to sustain silvery minnow survival for an extended duration. Recall that the average maximum depth and area of water necessary to support a minimum viable population (MVP) of silvery minnows for an extended duration and maintain their genetic diversity has not been formally tested necessary to refine this analysis.

If we assume that the average maximum depth of 1.5 feet of inundation is optimal (Tetra Tech 2014), then survival of a buffered MVP of ~80,000 silvery minnows over an area of inundated channel of 230,000 acres would be approximately 345,000 acre-feet during July through the next May. If we assumed an average maximum depth of one-foot-deep of inundation, then approximately 230,000 acre-feet of water would be necessary to support a buffered MVP of 80,000 silvery minnows between July through the next May. If we assumed an average maximum depth of one half-foot-deep, then approximately 115,000 acre-feet of water would be necessary to support 80,000 silvery minnows between July through the next May. Dividing these amounts of water by 304 days results in an average daily rate of water for channel inundation ranged from 378 to 757 to 1,135 acre-feet of water per day.

Recall that a Buffered MVP of 32,001 silvery minnows in October was a conservative estimate that was buffered assuming an annual mortality rate in the case that the following spring runoff was low and recruitment fails during the year. Should the following spring runoff be high, then approximately 32,000 adults (approximately a density of 0.3 fish per 100 m^2) would be the minimum necessary to conserve genetic diversity (assuming no stochastic events or excess mortality rates) from July through October. The area of channel inundation necessary to support a MVP of approximately 32,000 adult silvery minnows in October would be 135,000 acres during July through October. Archdeacon (2016) reported that the average maximum depth of water in isolated pools observed containing silvery minnows was 2.23 feet during periods of river intermittency. If we assumed an average maximum depth of 2.23 feet deep inundation was necessary, then approximately (140,000 acre-feet * 2.23 feet) 312,200 acre feet of water would be necessary to support a MVP of 33,000 silvery minnows during July through October. If we assumed an average maximum depth of one half foot deep, then 70,000 acre-feet of water (approximately 575 acre-feet per day) would be necessary to maintain 32,000 silvery minnows during low flow conditions from July through October.

We reviewed the historical period of record for the ABQ-Central Gage and found that observations of less than 70,000 acre-feet of water occurred during July through October almost 30 percent of the time (of 73 years of record from 1942 to 2015). We then reviewed the period of record for the Otowi Gage and found that observations of less than 70,000 acre-feet of water occurred during July through October only 1.8 percent of the time (over 111 years of record from 1986 to 2015) during the droughts of 1956 and 1963. We did not further review if other tributaries (such as the Rio Chama or downstream below the San Marcial Gage) provided sufficient water during July through October to support a MVP of silvery minnows, but these data suggest that if fish move during low flow periods, then adequate volumes of water were largely available to support their survival upstream. This highlights the role that fish passages at dams play in allowing silvery minnow access to perennial water during droughts and other periods of low flows.

Conclusions

We demonstrated how simple plots can be used to support water management by identifying key resources necessary for silvery minnow production and survival. We used the past 21 years of observations of the relationships between hydrological factors and the variation in the indices of silvery minnow abundance to derive Hydrobiological Objectives for spring runoff events forecast to occur between 120,000 acre-feet and 220,000 acre-feet to optimize the production performance (recruitment) and survival of silvery minnows (and other wildlife adapted to spring runoff) in the MRG to provide recommendations for water management to states, Tribes, stakeholders, and the public.

Low flows in the MRG occur naturally and fish populations can generally persist through unfavorable conditions (Goodman 2011) though at some genetic cost (Alo and Turner 2005; Osborne et al. 2012). There appears to be a general downward trend in spring runoff volume and alteration in its timing in the MRG basin (Reclamation 2014; Krabbenhoft et al. 2014). These findings highlight the need for Hydrobiological Objectives for survival of silvery minnow that are resilient against the effects of reduced flow likely to occur in the future. Our results identified the minimum viable population necessary for survival and identified the water management options of flows, refugia, or fish passage that are necessary to maintain the silvery minnow in the MRG. We believe that a combination of fish passage so that fish can access perennial water upstream (or downstream) and Refugia Planning to maintain a Buffered MVP in the available wetted channel are the most expedient solutions to increasing survival in the MRG during droughts. Alternatively, maintaining flow targets in the MRG has proven successful in the past but comes at great cost. Additional planning will then be necessary for addressing uncertainty and any increased rates of back-to-back droughts as the silvery minnow population in the MRG is composed primarily of fish less than age two.

Uncertainty and Assumptions

There were a number of assumptions and uncertainties that were not addressed above. The use of Hydrobiological Objectives does not necessarily ensure a consistent outcome in the production of silvery minnows as natural fluctuations and stochastic events can alter their impact. We did not include a random factor in our models. We assumed simple, nonlinear relationships between the rates and amounts of flow and the abundance or occupancy of silvery minnow in the MRG were valid. We assumed that there was some cut-off level or ‘minimum’ flow below which silvery minnows would not survive or would experience a loss of haplotype diversity. With our plots we depicted some of the dominant relationships between silvery minnow abundance and distribution and rates of flow by averaging many measured values across time and space. Our results do not depict the amount of variation in conditions and fish densities that occurs within a variety of sites and temporal data collection events or sampling gear artifacts. Though multivariate modeling approaches would certainly have explained more variation in silvery minnow abundance and distribution, we limited our analysis to two dimensional plots to make them more user-friendly. These simple, data-driven, decision support tools are useful for silvery minnow management and for hypothesis testing.

We assumed that other factors did not necessarily affect silvery minnow abundance or distribution. We did not consider habitat studies in our flow assessments. We assumed that silvery minnow abundance may have been solely due to variations in spring runoff amounts and rates of flow; however, we do not know how variability in channel inundation influenced habitat availability. Multiple studies have shown variation in silvery minnow abundance and distribution by mesohabitats (Dudley et al. 2016). We also did not consider food availability, predation, competition, or other ecological factors (Orth 1987). The relationships between habitat availability, fluctuating river levels, and biotic interactions should be further examined. Jowett (1997) reviewed flow assessments by different methods and found that habitat methods usually gave higher minimum flow estimates for small streams and lower estimates for large streams.

Errors or biases associated with data collection or model prediction could limit the accuracy of the relationships we described. There could be mathematical errors or failed assumptions using statistical methods or inadequate review of the rates and type of errors in these initial analyses. We noted several errors during our analysis, some due to the fluctuating proposed actions and the impacts in the environmental baseline that affected our estimates of the MVP, buffered MVP, and the estimated densities in October. There were mathematical errors in the estimates of the 2011 year data that were noted, and corrected, but additional analyses were not conducted.

We found that the relationship between spring runoff amounts and silvery minnow abundances was strong and significant that it is likely that a wide variety of statistical distributions and mathematical modeling available will find similar results (for example, Goodman 2011; Miller 2012; Dudley et al. 2016). However, mistakes do occur and we did not further review the residuals or examine the underlying variability between seine hauls and fish caught by the silvery minnow PMP were likely overabundant at one sampling site versus another, within the portions of the sampled open channel habitat, or according to sampling date. No mark-recapture or depletion data were collected to affirm the abundance of silvery minnow densities across sample events. The sampling conducted for the silvery minnow PMP was highly standardized (Atkins 2016) although improvements into the methods of analysis could be made to reduce the uncontrolled variation among samples and improve both the accuracy and precision.

Appendix A.5. RGSM habitat in the Cochiti Reach

Velocities reported by Torrez et al. (2008) and Buntjer and Remshardt (2005) demonstrated that habitat with velocities less than 1.6 feet per second existed at most sites. The presence and capture of mosquitofish was an indicator of slackwater availability in the reach. At low flows, the average channel velocities were sometimes (often) less than 1.6 feet per second at nearby, but downstream gages, as analyzed by Bui (2016). In 1984, approximately 5 percent of the silvery minnows were collected in Cochiti Reach (Bestgen and Platania 1991). There are issues of high velocities and colder temperatures that affect silvery minnow habitat in the Cochiti Reach. Silvery minnows are not likely to use this reach for spawning based on these degraded conditions; however, we assume these conditions will allow for silvery minnow survival.

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