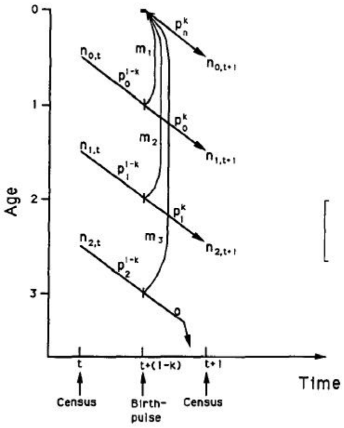

GSA GeoSystems Analysis, Inc.
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Independent Science Panel Findings Report: Rio Grande Silvery Minnow Key Scientific Uncertainties and Study Recommendations

June 2017

Prepared for:
U.S. Army Corps of Engineers
On Behalf of
The Middle Rio Grande Endangered
Species Collaborative Program

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Thomas Dunne, PhD	University of California, Santa Barbara	Panel Member
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1 PREFACE

1.1 Background

GeoSystems Analysis, Inc. (GSA) was contracted by the US Army Corps of Engineers (USACE) to support the Middle Rio Grande (MRG) Endangered Species Collaborative Program (Program) by identifying management-relevant scientific uncertainties pertaining to biology, life-history and habitat associations of the federally endangered Rio Grande silvery minnow (*Hybognathus amarus*; RGSM). Although the RGSM was listed as endangered in 1994, there continues to be substantive debate among regional scientists surrounding fundamental aspects of the fish's life-history and habitat requirements. Several of these contrasting scientific perspectives were identified and documented by GSA using formal questionnaires and follow-up interviews with RGSM "subject matter experts" (SMEs) identified by various Program signatories. After compiling survey and interview results, a subset of SMEs were asked to participate in a structured review process with an independent science panel to discuss the scientific basis for their perspectives. Independent science panel members had special expertise in fish biology, population dynamics, geomorphology, sampling theory, and assessment of endangered species. An independent science panel review meeting was held February 1-2, 2017, in Bernalillo, New Mexico. This report is a product of the panel review process, and culminates in a list of study recommendations intended to reduce scientific uncertainty on numerous topics considered relevant to water management and habitat restoration decisions for improving the RGSM population status.

1.2 Independent Science Panel

Brief biographical sketches for the four panel members are below, and these members constitute the Panel referred to in this document:

Barry R. Noon, PhD: Barry R. Noon is a professor in the Department of Fish, Wildlife, and Conservation Biology at Colorado State University. He graduated from Princeton University in 1971 with a Bachelor of Science (B.S.) degree in biology and from the State University of New York-Albany in 1977 with a PhD in ecology. In collaboration with many outstanding students and post-docs, he has conducted research on the effects of land management practices on wildlife populations for the past 40 years. His focus has primarily been on the conservation of imperiled species in forest ecosystems. During this period, he has published over 130 scientific papers and co-authored four book-length reports to the federal government on the sustainable management of public lands.

For 11 years, he directed a Forest Service Research Lab in the Pacific Northwest, and in 1995 served as Chief Scientist of the National Biological Service, Department of the Interior. During the last 15 years, he has served on federal advisory committees providing recommendations to the Secretary of Agriculture on the management of Forest Service lands to better sustain biological diversity and to the Secretary of the Interior on changes to the Endangered Species Act to encourage conservation on private lands. He has also served as chair of the global policy committee for the Society for Conservation Biology and provided testimony to the US Congress on numerous occasions on issues regarding the conservation of wildlife in the US and internationally.

Dr. Noon has received several academic awards including the Edward T. LaRoe award from the Society for Conservation Biology (1997), an Aldo Leopold Leadership Fellowship (2004), Colorado State University Distinguished Ecologist (2008-2009), and two Senior Fulbright Fellowships to India from the U.S. State Department (2003-2004 and 2010-2011). In collaboration with his students, his current research focuses on tiger (*Panthera tigris*) conservation in India, the effects of energy development on imperiled species in the US, climate change effects on wetland birds, and promoting biodiversity conservation on US Department of Defense lands.

David Hankin, PhD: David Hankin received his B.S. in Biology from Reed College in 1971, and his PhD in Fishery Science from Cornell University in 1978. From 1976-2015 he was a faculty member in the Fisheries Biology Department at Humboldt State University. His teaching emphasized Population Dynamics, Fishery Management, and Sampling Theory, and he held various administrative positions (department chair, marine lab director). His professional training and research have emphasized application of quantitative methods to development of fishery management policy, especially for Dungeness crab (*Metacarcinus magister*) and Chinook salmon (*Oncorhynchus tshawytscha*). He has been actively involved in management of Chinook salmon fisheries (including serving as a member of the Pacific Fishery Management Council's Scientific and Statistical Committee from 1987-1992) and hatcheries since 1980, with a focus on the Klamath River system and a keen interest in information generated from coded wire tag recovery data. Among other things, he was an early (circa 1980) proponent of constant fractional marking (CFM) practices that allow approximately unbiased estimation of the proportion of hatchery fish among adult salmon returns (CFM marking programs were introduced at Klamath system hatcheries in the early 1980s and in the Sacramento River system circa 2009); a consistent advocate of on-site release of hatchery fish to minimize undesirable straying of hatchery fish onto natural spawning grounds; and developed age-structured stock-recruitment models that showed that the maturation schedule of Chinook salmon stocks had an important influence on annual ocean fishery exploitation rates for multiple sustained yield and stock collapse. More recently, he developed mathematical models showing that completely random mating of Chinook salmon in hatcheries can lead to unintentional selection for earlier age at maturity. From 2010-2012 he served as a member of the California Hatchery Scientific Review Group that reviewed operation of all salmon and steelhead (*Oncorhynchus mykiss*) hatcheries in the Sacramento and Klamath-Trinity river systems. From 2001-2014 he served as one of the two US members of the Pacific Salmon Commission's Committee for Scientific Cooperation, a committee that provides objective scientific assistance regarding contentious and complex management issues. He has served on a number of expert science panels concerning endangered species of fish (delta smelt [*Hypomesus transpacificus*], winter run Chinook, Devil's Hole pupfish [*Cyprinodon diabolis*]) and mammals (southern resident killer whales [*Orcinus orca*]). He is currently working with two mathematical statisticians to complete a sampling theory text (for Oxford University Press), which will be oriented toward the natural resources and ecological sciences.

Thomas Dunne, PhD: Thomas Dunne is a Professor of Environmental Science and Management, and of Earth Science at the University of California Santa Barbara. He obtained a Bachlor of Arts in Geography from Cambridge University in 1964, and a PhD in Geography from The Johns Hopkins University in 1969. His doctoral research involved a field investigation of runoff processes under rainfall and snowmelt conditions in northern Vermont. Dr. Dunne conducts field and theoretical studies of drainage-basin, hillslope, and fluvial geomorphology, and in the application of hydrology, sediment transport, and geomorphology to landscape management and hazard analysis.

While working for the US Department of Agriculture Agricultural Research Service (1966-1969) and McGill University (1971-1973), he conducted research on the effects of topography, soil characteristics, and vegetation on runoff processes under rainfall and snowmelt in Vermont and Canada. While teaching at the University of Nairobi, Kenya (1969-1971), Dr. Dunne initiated a long-running research interest in African environments, including experimental studies of runoff and erosion processes, and statistical studies and field surveys of the effects of land use on hillslope erosion and river-basin sediment yields. While teaching in the Department of Geological Sciences at the University of Washington (1973-1995), he studied landslide and debris flows, drainage-basin sediment budgets in natural and managed forests, tephra erosion and debris-flow sedimentation on active volcanoes, and sediment transport and channel morphology in sand-bed and gravel-bed river channels. He also conducted several studies related to resource management, such as the impacts of gravel harvesting on the river-channel sedimentation and morphology, impacts of timber harvest on erosion and sedimentation, and effects of flow diversion and reservoir management on sedimentation.

Since moving to California, Dr. Dunne has studied hydrology, sediment transport, and floodplain sedimentation in the mainstem Amazon River of Brazil and in the Andes Range and adjacent floodplains of eastern Bolivia. His work, funded by the National Science Foundation and National Aeronautics and Space Administration, involved studies of runoff processes in forest and pastures, channel and bed material surveys, floodplain coring to measure rates of sediment accumulation with isotopes, measurement and interpretation of channel change and floodplain features from satellite images, and flow and sediment transport modeling in channels and floodplains. He and his students also study sediment transport, channel change, and oxbow lake sedimentation along the Sacramento River and its floodplain. With five biologist colleagues in the Bren School and the California Department of Water Resources, he is now studying how physical and biological processes interact to create and maintain habitat for fish and their food sources in the Merced River, California.

Gary D. Grossman, PhD. Gary Grossman is a Professor of Animal Ecology in the Warnell School of Forestry and Natural Resources at the University of Georgia, where he has been employed since 1981. Professor Grossman has a B.S. degree from the University of California, Berkeley (1975), and a PhD from the University of California, Davis (1979). His research interests range from community ecology, to natural resource management, to animal behavior, to innovations in biological pedagogy. Professor Grossman is the author or coauthor of 124 scientific publications that have been cited over 6,000 times. He has served on 13 review teams for both national and international governmental organizations and has evaluated 31 faculty at international and national universities for promotion/tenure. He also has served as an external evaluator for six PhD students at foreign universities ranging from Australia and New Zealand to France. He currently serves as an editorial board member or associate editor for the international journals Freshwater Biology, Ecology of Freshwater Fish, and Animal Biodiversity and Conservation.

Professor Grossman has won several international awards, including the Sullivan Award for excellence in fish conservation (American Fisheries Society), Evans Fellowship (University of Otago, New Zealand), Faculty Fellowship for the Summer Institute in Israel (Media Watch/Jewish National Fund), and was elected to the first class of Fellows of the American Fisheries Society. He was named the University Georgia Disability Services Outstanding Faculty Member of the Year in 2001 and was a Distinguished Research Professor at the University of Georgia from 2004-2009. In 2016 he provided expert testimony to the US House of Representatives Committee on Natural Resources on the effects of predation on trout and salmon populations in California. He also is a member of the Center for Independent Experts of the National Marine Fisheries Service.

1.3 Science Panel Charge

The Panel "charge" included:

- Review the available science that addresses how population characteristics (e.g., abundance, density, and occupancy) relevant to the recovery of RGSM vary over space and time and what environmental factors best explain this variation.
- Identify aspects of the species' life history that are characterized by significant uncertainty and those that are sufficiently well understood to inform management decisions.
- Provide recommendations for priority studies that address key scientific uncertainties relevant to management decisions, and thereby provide a foundation for the adaptive management of RGSM populations within the MRG.

1.4 Science Panel Meeting Topics and Presentations

Meeting topics and speaker presentation titles from the panel meeting held from February 1-2, 2017, are listed below. Copies of the speaker presentations are presented in Appendix A. A bibliography of scientific articles and reports provided by SMEs for panel review is provided in Appendix B.

1.4.1 Session 1: Scientific Perspectives on Spawn Timing

- *Scientific Perspectives on Timing of Rio Grande Silvery Minnow Reproductive Efforts.* Thomas P. Archdeacon. New Mexico Fish and Wildlife Conservation Office, US Fish and Wildlife Service (USFWS), Albuquerque, New Mexico.
- *Reproduction.* David E. Cowley. Department of Fish and Wildlife Conservation Ecology, New Mexico State University (NMSU), Las Cruces, New Mexico.

1.4.2 Session 2: Scientific Perspectives on Spawning and Larval Development

- *Scientific Perspectives on Spawning and Larval Development Locations*. David Propst. Department of Biology, University of New Mexico (UNM), Albuquerque, New Mexico.
- *Does Spawning and Larval Development of RGSM Occur in the Main Channel or on the Floodplain and in Certain Channel Features?* Richard A. Valdez. SWCA Environmental Consultants, Logan, Utah.

1.4.3 Session 3: Scientific Perspectives on Relationships between Hydro-Geomorphic Attributes and Rio Grande Silvery Minnow Population Response

- *Spring Runoff Magnitude, Timing, Duration and Channel Inundation Relationships to Estimated Densities of Rio Grande Silvery Minnow in the October Census*. Joel D. Lusk. New Mexico Ecological Services, USFWS, Albuquerque, New Mexico.
- *What is the Relationship Between Hydrology and Channel Morphology with RGSM Density, Abundance, and Spatial Distribution?* Richard A. Valdez. SWCA Environmental Consultants, Logan, Utah.

1.4.4 Session 4: Scientific Perspectives on Adult Survivorship

- *Scientific Perspectives on Longevity of Rio Grande Silvery Minnow.* Thomas P. Archdeacon. New Mexico Fish and Wildlife Conservation Office, USFWS, Albuquerque, New Mexico.
- *Life Span, Age and Growth, and Some Simulation Models.* David E. Cowley. Department of Fish and Wildlife Conservation Ecology, NMSU, Las Cruces, New Mexico.

1.4.5 Session 5: Scientific Perspectives on Intermittency of Flow for Adult Survivorship

- *Scientific Perspectives on Intermittency of Flow for Adult Survivorship.* Joel D. Lusk. New Mexico Ecological Services, USFWS, Albuquerque, New Mexico.
- *Intermittency Effects on the Viability of H. amarus Populations.* Michael D. Hatch. Department of Fish and Wildlife Conservation Ecology, NMSU, Las Cruces, New Mexico.

1.4.6 Session 6: Scientific Perspectives on Connectivity and Fish Passage

- *Scientific Perspectives on Connectivity and Fish Passage: Swimming Upstream Against the Paradigm.* Michael Porter. Albuquerque District, USACE, Albuquerque, New Mexico.
- *Scientific Perspectives on Connectivity and Fish Passage.* David Propst. Department of Biology, UNM, Albuquerque, New Mexico.

2 INTRODUCTION

2.1 How the Panel Worked

Panel members were provided with extensive background readings (peer-reviewed publications, agency reports, unpublished documents) on all topics considered by speakers at the February workshop. In addition, GSA arranged for production and internet access of pre-recorded background presentations on MRG Geomorphology (Mike Harvey, Tetra Tech), the Rio Grande Compact (Rolf Schmidt-Peterson, New Mexico Interstate Stream Commission), MRG Water Operations (Carolyn Donnelly, Bureau of Reclamation [BOR]), Climate Change and Potential Impact on MRG Water Supply and Demand (Dagmar Llewellyn, BOR), and history of the MRG Conservancy District (David Gensler). Based on our review of these reading materials and pre-corded presentations, panel members were unusually well-prepared for consideration of RGSM-related topics that were discussed at the February workshop.

Following the workshop presentations, panel members met the following morning as a group to develop a strategy for drafting a report on their findings. Discussions resulted in agreement that development of a preliminary population dynamics model should provide a vital overarching framework for further research concerning RGSM abundance and assessment of possible changes in apparent population size. The Panel Chair (Dr. Noon) agreed to take the lead on development of a population dynamics section. There was also agreement that there were many uncertainties concerning reproductive biology of RGSM; panel member Dr. Grossman agreed to take the lead on this topic. Panel member Dr. Hankin agreed to develop an evaluation of available information concerning age and growth of RGSM, and also agreed to develop a separate section addressing methodological issues with a focus on field sampling methods to provide unbiased estimates of trend. Finally, panel member Dr. Dunne agreed to develop a section concerning habitat relations in relation to fluvial dynamics. In each case, panel members attempted to match their areas of professional expertise with their report assignments. Drafts of report sections were circulated for comments among panel members, as well as scientists working for GSA (T. Caplan and G. Wilde) to assist the panel, and were revised accordingly.

2.2 How the Report is Organized

Following this chapter, we provide an Executive Summary (ES [Chapter 3]). The ES briefly summarizes the major uncertainties identified by the panel, organized according to primary thematic areas (Population Dynamics, Age and Growth, Reproductive Biology, Sampling Methodologies, and Physical Habitat of the RGSM), provides a summary of current understanding for each topic area, and provides recommendations for studies that might reduce future scientific uncertainties. Following the ES are detailed reports on each of the thematic areas.

Below we briefly comment on five specific areas highly relevant to the Panel's conclusions. These three areas include: a) the importance of population dynamics modeling as a prerequisite to the adaptive management of RGSM populations, b) our conclusion that the evidence in support of a passive "pelagic spawning" life history strategy for RGSM is unpersuasive, c) our belief that analyses of the status and temporal trend in RGSM abundance have not adequately discriminated the relative importance of the recruitment and survival processes, and d) our recommendation that the facilities at the Los Lunas Silvery Minnow Refugium (Los Lunas) and the Albuquerque BioPark be viewed in terms of their potential as experimental model systems and more fully utilized to address key RGSM life-history uncertainties.

2.3 The Importance of Population Dynamics Modeling

For managers involved in the conservation and recovery of the RGSM, the ultimate goal is to "recover" the species to the point at which it can be delisted from the Endangered Species Act (ESA). Specific demographic recovery goals include preventing extinction (Recovery Objective 1-A), and attaining self-sustaining populations (Recovery Objective 3-A; *Rio Grande Silvery Minnow Recovery Plan, First Revision* [Recovery Plan; USFWS 2010]). The Recovery Plan defines a "self-sustaining population as "… one that can sustain a specified population level without augmentation with captive-bred fish." These objectives are defined by criteria related to population size, distribution, and extinction risk.

Recovery will also require addressing and mitigating the factors that put the species at risk. The Recovery Plan identifies risk factors to include the destruction and modification of RGSM habitat due to dewatering and diversion of water, water impoundment, and modification of the river (channelization). Competition and predation by introduced non-native species, water quality degradation, and other factors may also have contributed to RGSM declines.

Studies of any fish or wildlife population begin with questions about the species' abundance, distribution and "status": is the population stable, declining or increasing? Before initiating any management actions to affect a population of interest, it is important to first have some initial estimates of the abundance of the population. This has been the approach taken in studies of RGSM where the primary emphasis has been on estimating the status and trend of the population using a catch-per-unit-effort (CPUE) -based index of abundance, with several attempts made to relate the index to more rigorous estimates of population size (Dudley et al. 2012, 2016a). Comparisons of the index values with concurrent population estimates (Dudley et al. 2012) provided insights to the reliability of the index; that is, addressing the extent to which the index reflects true changes in abundance over time.

For species like the RGSM that have been designated as threatened or endangered under the ESA, estimates of current and past abundances are used to determine if there is evidence of population recovery. However, a time series of abundance estimates (or annual indices of abundance) does not, by itself, provide any explanation for why the population may be increasing or decreasing, and does not provide information on the underlying demographic processes that drive population dynamics.

The limitations of abundance estimates alone for providing insights to inform conservation efforts for declining species are clearly discussed in Newman et al. (2014). The primary state variable for assessing the effects of environmental variation and management actions on RGSM has been count-based, CPUE metrics—proxy indices of the true, but unknown RGSM abundances (N_t) in any given year t. Because current "aggregated" (across mesohabitat type) CPUE indexes are not adjusted for differential catchability, which likely varies spatially and temporally, they do not allow reliable estimation of trend (see Chapter 7). However, even if the state of the system were known without error (all $N_1, N_2, \ldots, N_t$ values known with certainty for all t years), these data alone would tell managers nothing about the underlying birth and survival processes that gave rise to the realized abundances. To understand past dynamics of the RGSM populations, and to predict future states of the population, this requires that managers better understand the causal dynamics that generated the realized population states.

It is our perspective that the community of RGSM managers and researchers would greatly benefit from combining their count-based studies of RGSM abundance (i.e., CPUE data collected as part of the annual monitoring program), including temporal and spatial variation of the index, with a demographic model that makes explicit the birth and survival processes. Conducting short-term demographic studies to obtain estimates of vital rates can bolster information from long-term count-based time series when explored by means of integrated modeling approaches (e.g., Besbeas et al. 2003, 2005; Brooks et al. 2004; Abadi et al. 2010). In addition, inferences drawn from the estimated temporal variation in relative abundance (the CPUE indices) can be strengthened by applying integrated population modeling to the RGSM (see Newman et al. 2014). Specifically, we suggest that the population survey data be initially integrated with a demographic model in the form of an age-structured projection matrix. Eventually, we believe that formation of a state-space model, which accounts for population dynamics as well as uncertainty in knowledge of population status, should be adopted (example applications of state-space models in fisheries can be found in Newman 1998, and Meyer and Millar 1999).

In our Chapter 4, we outline some of the initial steps that we believe should to be taken to allow eventual implementation of a state-space modeling approach. The details of state-space models are well beyond the scope of our review, but we believe that eventual development of such models should be a key element of a state-of-the-art adaptive management program for RGSM populations. A useful model would take as inputs the current state of the system, N_t, (or a valid CPUE-based index of state) and the range of possible management actions available at time t, and use the model to project the future state of the system, N_{t+1}, separately for each action. The manager would then select the action with greatest possibility of attaining management objectives (Newman et al. 2014, p. 53). Effectiveness of the model could be assessed by comparing predicted and observed populations at time t+1. A lack of concordance between observation and prediction would lead to adjustment of the model or to possible changes in management practices.

The proposed matrix projection model described in Chapter 4 of this report is intended to be illustrative of the initial steps required to construct a dynamic model that captures the underlying processes of birth and survival that determine the realized RGSM abundances. A key advantage of this matrix projection model is that it allows identification of the life history parameters that most influence the growth rate of RGSM populations. Identification of these key life history sensitivities will provide managers with clear guidance concerning the prioritization of research studies and, in the design of those studies, helps to identify the environmental factors (e.g., acres of inundated floodplain habitat) and management actions (e.g., flow manipulation) that will most affect rates of population change.

Based on multiple perspectives, we emphasize that our example dynamic projection model, and illustrative analyses of this model, are not "definitive" treatment of RGSM population dynamics. First, available estimates of life history parameters are poorly identified and preliminary analyses do not provide definitive insights. Second, future models should explicitly incorporate at least two factors not accounted for in this preliminary model. Our recommendations are that future models: a) explicitly account for the substantial variation in lengths at age of RGSMs (this is important because fecundity [and possibly also survival] of RGSMs may be more closely related to fish length than to fish age); and b) attempt to incorporate density-dependence in recruitment of age 0 fish, and possibly also in survival of age 1 and older fish. Third, it is essential that future modeling efforts directly model the effects of augmentation of hatchery fish on overall RGSM population dynamics. Finally, it will ultimately be necessary that the population dynamics model be spatially explicit, at least with respect to availability of main channel versus floodplain-like habitat for spawning and juvenile rearing. These issues are briefly discussed in Chapter 4 of this report, but they are not explicitly addressed in the proposed example projection matrix model. We believe our modeling approach is an important preliminary step to better understand the dynamics of the RGSM, but many more steps will be needed to have a model(s) useful to the adaptive management process.

2.4 Pelagic Spawning or Floodplain Spawning?

One of the more controversial issues concerning RGSMs involves whether this species is (primarily): a) a “pelagic spawner” where eggs are spawned in the main channel, development takes place as eggs drift passively downstream, and an eventual adult upstream migration is required to maintain the population; or b) a “floodplain spawner” where eggs, larvae, and juveniles primarily develop in more protected and food-rich environments, protected from mainstem flows/velocities. The floodplain spawning strategy would not require an associated upstream migration of adults to maintain the population. Flows over the last two decades in the MRG are generally not sufficiently high, or of sufficient duration, to allow spawners access to large areas of floodplain or floodplain-like habitat. Therefore, the Panel concludes that apparently large numbers of RGSM eggs in the main channel does not constitute strong evidence in support of the pelagic spawning hypothesis. When RGSMs do not have access to floodplain-like areas for spawning, it would seem reasonable to expect eggs to be collected primarily in the main channel, regardless of spawning habitat preference. Our Panel also believes reviewed published evidence of successful floodplain spawning and larval development. In particular, we especially note the experimental work carried out the Los Lunas refugium (Tave and Hutson 2012, Project 3/4; spawning of RGSMs in the outdoor refugium by manipulating water depth and pumping rate to create a flood, and subsequent grow-out of young-of-year [YOY]) and observations made by Gonzales et al. (2014) in constructed floodplain-like habitat. Finally, if RGSMs indeed engage in substantial upstream migrations, then there should be at least “some” tangible evidence of these migrations, e.g., from predictable or consistent longitudinal variation in RGSM CPUE within each of the three reaches of the MRG. No such evidence was presented to the Panel at the workshops or encountered in the readings (see Appendix B).

2.5 Need to Separate Recruitment from Adult Survival

Throughout much of the workshop and in most of our readings of RGSM-related materials, our Panel was struck by how frequently the aggregated October CPUE metric (for age 0 and older RGSM) was used as a generic measure of "population status" and that it was also used as a generic "response variable" in numerous analyses of the possible influence of flow or flow manipulation on abundance of RGSM. The total abundance of RGSM at the October census is a reflection of two very different population processes: a) recruitment, or addition of new age 0 RGSM; and b) survival of age 1 and older individuals. October recruitment of new age 0 RGSM is a reflection of eggs spawned during the April-June period (i.e., number of adult spawners in April) and of egg/larva/juvenile survival from April-October. The number of age 1 and older adults alive in October is a function of the number of age 1 and age 2 adults in April and of adult survival from April to October. We suggest that future analyses of the possible impacts of flow (e.g., on floodplain access and spawning success) clearly separate these two distinct processes. In fish population dynamics, attaining reliable estimates of stock and recruitment (the functional relation between adult stock or egg production and recruitment) is perhaps one of the most difficult areas of analysis. Interannual variation in survival rates of adults is generally small compared to interannual variation in survival from egg to age 0 recruitment.

To reduce scientific uncertainties, the science panel proposed numerous studies, many of which will be difficult to conduct under field conditions. However, the panel believes that many hypotheses can be tested experimentally by making better use of the facilities at Los Lunas and the Albuquerque BioPark. Many environmental factors hypothesized to affect the RGSM's vital rates and behaviors can be simulated, and experimentally manipulated, at these facilities. We encourage their increased use to address key RGSM life-history uncertainties.

If adopted, the research studies and management framework we propose in our report should provide a strong foundation for the eventual adaptive management of RGSM populations. We recognize, however, that full implementation of our recommendations requires personnel with expertise in multiple areas. These include individuals with a deep knowledge of the species' biology, those with expertise in hydrology, applied statistics and modeling, and one or more quantitative ecologists to provide a bridge between these disciplines. Currently, the community of scientists and managers engaged in RGSM conservation and management may not fully span the range of required expertise.

3 EXECUTIVE SUMMARY

Our Panel's identification of major uncertainties and recommended studies is grouped thematically, and combined with summary background information that provides context and/or justification (when necessary). Many key uncertainties were identified as "significant" in two or more thematic areas and we note these occasions. Recommended studies are characterized as "Tier 1 Studies" (most critical) or "Tier 2 Studies" (important, but of a less immediate concern).

3.1 Key Uncertainties

3.1.1 A: Population Dynamics

A1. The Relationship between the Annual Catch-Per-Unit-Effort Index and True Population Size is Unknown (See Also Key Uncertainty E2 in Section 3.1.5)

The (currently calculated) CPUE index is a count-based index of population size where the fraction of the population in a sample unit actually captured (i.e., catchability) in the seine nets is unknown. In addition, catchability is likely to vary according to flow volume, mesohabitat type, and the distribution of fish sizes. As a result, the relationship between true abundance and the current CPUE index is unknown and variable over time and space. Collectively, these factors undermine the credibility of the CPUE index as a reliable measure of status and trend of the RGSM population.

A2. What Are the Key, Age-Specific, Life History Sensitivities of the Rio Grande Silvery Minnow? What Vital Rates, (Survival and/or Reproduction) Most Affect Rates of Population Change?

Sensitivity analyses of a projection matrix population dynamics model can be used to prioritize management decisions so as to implement actions that are most likely to increase rates of population growth. Initial analysis will rely on existing estimates of age-specific fecundity (for hatchery RGSMs) and survival rates available from preliminary RGSM studies or by borrowing rates from related fish species. Such preliminary analyses provide insights but not definitive inference.

A3. Age-Specific Survival Rates Are Unknown

In order to understand dynamical changes in the abundance and distribution of RGSMs (i.e., the key RGSM monitoring state variables), it is essential to have estimates of the underlying demographic parameters that together give rise to the realized values of these state variables. One critical set of such parameters is that for age-specific annual survival probabilities. Preliminary estimates of cohort survival rates, conducted by Daniel Goodman, were made available to us by Joel Lusk (USFWS). These estimates, based on regression analyses of changes in estimated abundance over time, are extremely variable across years and reaches and very imprecise. Overall, we conclude that survival rates are poorly known.

A4. Age-Specific Fecundities (Annual Egg Production) of Wild Fish Are Poorly Known

In order to understand the dynamical changes in the abundance and distribution of RGSMs (i.e., the key RGSM monitoring state variables), it is essential to have estimates of the underlying demographic parameters that give rise to the realized values of these state variables. One critical set of such parameters is that for age-specific annual egg production. There are no estimates of RGSM fecundity published in refereed scientific journals. However, preliminary estimates from hatchery fish are available (Falco et al. n.d.; Dr. C. Caldwell, New Mexico State University, pers. comm.).

A5. Relationships between Rio Grande Silvery Minnow Demographic Rates and: A) Hydrologic Factors (e.g., Flow Magnitude and Duration; Summer Drying of the Channel); B) Abiotic Environmental Factors (e.g., Temperature, Turbidity, Salinity); and C) Biotic Factors (e.g., Predation, Completion, Prey Availability) Are Poorly Known (See Also Key Uncertainties D.1 – D.4 in Section 3.1.4)

Estimating the relationships between environmental variables, particularly those that can be altered by management practices, and RGSM vital rates are an important research priority. The robustness of the insights provided by the covariate modeling of Dudley and others (e.g., Dudley et al. 2016b) is unknown because of several factors. First, the relationship of the CPUE index to actual population abundance is unknown. Therefore, it may be subject to significant measurement error and its use as a valid response variable is questionable. Second, the CPUE index combines count data across mesohabitat types that have very different RGSM abundances and catchabilities. Third, the CPUE index combines the abundance of age 0 fish (new recruits into the population) with age 1 and 1+ fish conflating recruitment with survival.

The life history sensitivities of the RGSMs emphasize the importance of age 0 survival and first year reproductive output to population growth. This suggests a high priority for studies that investigate the relationships between these response variables and multiple hydrologic factors and their importance to the creation of floodplain habitats. As note by Goodman (2011), "The strong association between spring flow and that year's reproduction indicates the primacy of spawning in temporary, low velocity, shallow habitat created by inundation of floodplain areas and bars and islands."

A6. The Existence and Strength of Any Density-Dependent Factors That May Be Limiting Population Growth Are Unknown

A preliminary analysis of age 0 annual cohort survival rates and their relation to August RGSM densities suggests a moderate to strong rate of density dependence (Goodman 2011). The apparent density dependence of first-year survival suggests a limiting resource unrelated to the availability of spawning habitat or with the extent of summer drying.

An additional possibility may relate to spawning habitat. For example, if RGSMs are primarily a demersal floodplain spawner, then reductions in flow magnitude and duration, coupled with pronounced incision of the channel and a loss of connection of the channel with its floodplain, may result in spawning habitat limitation with important demographic effects on recruitment.

A7. The Effects of Hatchery Augmentation on Population Dynamics and the Significance of Hatchery Fish to Achieving Recovery Objectives Are Poorly Understood

Specific demographic recovery goals in the Recovery Plan include preventing extinction (Recovery Objective 1-A), and attaining self-sustaining populations (Recovery Objective 3-A). The Recovery Plan defines a self-sustaining population as "… one that can sustain a specified population level without augmentation with captive-bred fish." However, the relative contributions of wild and hatchery fish to the spawning population are unknown. Understanding the dynamics of the RGSM population is complicated by frequent augmentation of age 0 fish with hatchery-reared age 0 fish released during fall (October-December).

It is likely that the overwinter survival rates of age 0 hatchery fish would be less than the overwinter survival rates for naturally-produced age 0 fish. In addition, the reproductive success of hatchery-reared fish may be different from that of wild-reared fish.

A8. Does the Collection and Translocation of Salvage Fish During Summer Drying Periods Contribute Significantly to Population Dynamics?

During summer periods of ephemeral flows, which often result in dry reaches within the river channel, RGSM are often stranded in small pools within the main channel. The current USFWS policy is to collect these fish and move them upstream to areas of the channel that are still wetted. Whether this practice contributes significantly to RGSM population dynamics and persistence is unknown.

3.1.2 B: Reproductive Biology of Rio Grande Silvery Minnow

B1. What is the Temporal Distribution of Rio Grande Silvery Minnow Spawning Activity?

Moore egg collectors (MECs) have been used to collect RGSM eggs from the main channel of the MRG from about mid-April through mid-June since 2002. Field-based egg counts are scaled by the volume of water flowing through the egg collectors and observed eggs per volume are extrapolated to total daily egg passage based on total daily flow volume. The distribution of expanded egg passage is used to infer the temporal distribution of spawning activity.

We have several concerns regarding collection of RGSM eggs in MECs and their associated use for inference of the temporal distribution of spawning activity:

- The limited temporal window for deployment of the MECs rules out any assessment of the degree to which late summer/fall monsoonal spawning may be an important component of annual spawning activities.
- Expansion from eggs per volume sampled to the entire MRG flow is based on an assumption that RGSM eggs are uniformly distributed (vertically and horizontally) throughout the water column. That assumption may be valid only at flows above those at which MECs can be safely deployed and operated. For example, at low flows, density of RGSM eggs is probably much greater near the substrate than in the upper portion of water column sampled by MECs. When the uniform distribution assumption is invalidated, expanded egg counts made at different flows are not directly comparable.

- Estimates of total egg passage, even if unbiased, provide at best an index of reproductive activity within the main channel. However, they do not provide any insights into the extent of reproductive activity that takes place in the floodplain or in floodplain-like areas when they are accessible.

B2. What are the Environmental Cues that Trigger Spawning?

Current understanding of possible environmental cues that may trigger spawning rely upon expanded egg passage counts as an indicator of the temporal distribution of spawning. Expanded egg passage counts are subsequently statistically related to a variety of flow-related covariate measures.

We have several concerns regarding methods used to develop an understanding of possible environmental cues that may trigger spawning:

- As noted in item B1 above, current expanded egg passage counts are unlikely to provide an unbiased estimate of the temporal distribution of spawning activity. Therefore, there must be some degree of both sampling variation and measurement error in the values of the response variable used in statistical analyses.
- Some of the “derived” variables linked to the expanded egg passage estimates lack a strong biological rationale. For example, Archdeacon (Workshop Presentation, Session 1) related egg passage to “percentage change in mean daily flow”. If mean daily flow changed from 100 to 200 cubic feet per second (cfs), this metric would have the same value as if mean daily flow changed from 2,000 to 4,000 cfs. Fitting some metric of egg passage against a percent change metric, for example, implies that these two situations would generate the same cues and would trigger the same biological response.

B3. What are the Size-Specific Fecundities of Naturally-Spawning Rio Grande Silvery Minnow and How Many “Batches” of Eggs May Be Released by a Female Rio Grande Silvery Minnow over the Course of a Spawning Season? (See Also Key Uncertainties A4 in Section 3.1.1)

Existing data concerning fecundity of RGSMs are based on studies of hatchery-reared fish that have been hormonally induced to release eggs. These studies demonstrate that most (about 65%), but not all, eggs are released following hormonal induction, implying that remaining eggs would normally be released at a later date, suggesting that RGSMs exhibit “fractional spawning” or “fractional release” of eggs. It is unknown whether successive “batches” of eggs may be produced in the same year, e.g., for possible release during late summer or early fall monsoonal rains. In addition, the numbers of eggs in hatchery-reared fish may exceed the numbers of eggs carried by naturally-spawning RGSMs due to improved nutritional status of hatchery-reared fish compared to naturally-spawning RGSMs.

B4. What is the Optimal Reproductive Habitat for Rio Grande Silvery Minnow?

Expanded counts of RGSM eggs collected from MECs deployed in the main channel, along with an assumption that RGSMs engage in substantial upstream migrations, implicitly invokes the assumption that the main channel provides optimal or at least suitable reproductive habitat. There is evidence, however, of successful reproduction in floodplain or floodplain-like habitat, and multiple statistical analyses have established correlations between flow-related variables linked to inundation of floodplain habitat (e.g., days with flood exceeding 3,000 cfs) and October CPUE as currently calculated. In addition, there is no clear evidence of substantial long-distance upstream migration of RGSMs.

3.1.3 C: Age and Growth

C. What is the Typical Longevity of Rio Grande Silvery Minnow?

The only peer-reviewed publication concerning age and growth or RGSM (Cowley 2006) used unknown methods to identify annuli on scales and, based on analysis of archival museum specimens collected near Sante Fe in 1874, reported ages though age 5. A subsequent study (Horwitz et al. 2011), not published in the peer-reviewed literature, reported ages of RGSMs based on scales and otoliths from contemporary samples of RGSMs, and also from the same archived museum specimens used by Cowley (2006). Maximum age reported by Horwitz et al. (2011) was age 3 and these fish were only present at low frequency during a spring sample, with none present in contemporary fall samples. Scale and otolith analysis of archived samples revealed ages 0, 1 and 2 only. Archdeacon (Workshop Presentation, Session 1) presented evidence that ages assigned by Horwitz et al. (2011) and corresponding lengths of fish are consistent with length frequencies of marked hatchery-reared fish released as age 0 in fall. Lengths at age for fish from the Cowley (2006) study seem clearly at odds with other studies.

3.1.4 D: Physical Habitat Relations of RGSMs

D1. What are the Spatial Extent and Hydraulic Quality of Habitats Used by Rio Grande Silvery Minnow for Key Life-Stages (Spawning, Larval Rearing, Juvenile, Adult)? How Are These Habitats Distributed in the River Channel and Floodplain in each Middle Rio Grande Reach Under a Range of Discharges and Seasonal Flow Regimes?

The key uncertainties concern the primary habitat(s) for RGSM spawning and larval development, and how survival rates (for all age classes) vary by habitat type. The role of shallow, low velocity habitats (floodplain, channel and bar margins) is of particular importance. If the RGSM life history plays out dominantly in the channel, why is there a positive correlation between spring flow magnitude and production if high flows make the channel a more unfavorable place for fish, egg, or larva? If the vegetated channel margins and especially the floodplain are the key productive habitats for at least the early life stages of the RGSM, how do the extent and quality of these habitats vary with river flow in each reach of the MRG?

D2. What is the Proximate Trigger for Spawning (e.g., Flow Velocity, Temperature, Rate of Increase in Flow Velocity, or Some Combination of These Factors)?

This question includes uncertainties concerning the triggers and the timing of spawning; that is, how soon after flow rises do the fish release eggs? If the trigger is water velocity (currently referred to as discharge) it might be sensed as drag on the fish's body, causing the fish to work harder to stay in place or to sense that it should move towards shelter in a lower velocity zone, perhaps the channel margin or floodplain if possible. In addition, at what threshold flow levels does the floodplain habitat become accessible to adult fish that have been holding in the main channel?

D3. What Are the Roles and Relative Contributions to Fish Production (Age 0 Recruitment and Survival of All Age-Classes) of Channel and Floodplain Habitat in a Reach of Channel and Floodplain Typical of the Middle Rio Grande?

The extent and nature of floodplain habitat that is hydraulically connected to the channel in each of the three reaches between dams is poorly known. In addition, the relationship between the area of inundated floodplain and the magnitude and duration of high flows needs to be more clearly documented. For example, at what threshold flow does the floodplain habitat become accessible to adult fish that have been holding in the main channel, and do adults move into the floodplain before spawning? The answer to this question will differ between the four reaches of the MRG and highlight the differing habitat qualities and restoration opportunities along the river.

D4. What is the Management Potential for Fish Production (Recruitment and Survival of Age 0 Fish) in Each Reach of the Middle Rio Grande if the Annual Peak Flow, and Thus the Nature and Range of Available Habitats, is Permanently Limited below Historic Levels of Availability?

This uncertainty is characterized by several specific questions. For example: How extensively do juvenile and adult fish use the main channel when flow declines below floodplain access level? As flow rises, where do adult fish move to? Are they in control of their movements or are they swept into lower velocity zones, including overbank? When the flow rises without access to the floodplain, do RGSMs get washed downstream with possible entrainment at dam locations? Of more importance, however, are factors associated with low flows. During low flows, which appear to be the most likely scenario under ongoing climatic changes, what are the threshold flow volumes and durations needed to sustain populations of RGSMs? Having evolved in this dynamic environment, the fish must have had flow refuges in times of high flow, but not necessarily in the channel itself. If the modern flow regime reduces or delays their escape from high in-channel flow velocities, the fish might be confined to habitat with lower quality and safety.

3.1.5 E: Sampling Methodologies

E1. What is the Age Composition of the Rio Grande Silvery Minnow Population?

The age structure of the RGSM is poorly identified because aging of a random subsample of RGSMs has not been carried out on a routine basis. Therefore, ages have presumably been assigned on the basis month-age-specific length "cutoffs" that are believed to separate age groups. (The Panel is not absolutely certain that cutoffs are used to separate age groups as we were unable to locate methodological details in the reports we reviewed). For a species like RGSM that exhibits extensive variation in length at age, use of cutoffs may be accompanied by high assignment uncertainty to age-class because of overlap in distributions of length at ages 0, 1, and 2. Also, there is evidence that beach seines do not catch the largest RGSMs at the same rates that they catch smaller RGSMs, thereby presumably biasing the estimated age composition to an unknown degree toward younger ages.

E2. How does the Vertical and Horizontal Distribution of Rio Grande Silvery Minnow Eggs in the Middle Rio Grande Mainstem Channel Vary as a Function of Flow and Location?

Key Uncertainties A1 also addresses this issue because both uncertainties are premised on potentially biased assumptions about the temporal distribution of spawning activity that emerges from the current expansions of egg counts from MECs to the entire flow past a given location. See Key Uncertainties A1 in Section 3.1.1 for further details.

E3. Currently Calculated Catch-Per-Unit-Effort Values Cannot Provide a Valid Index of Rio Grande Silvery Minnow Population Abundance

We show that the currently calculated CPUE metric can provide a valid index of abundance only under the untenable assumption that catchability (proportion of fish captured compared to fish subjected to sampling gear) is identical across all mesohabitat types. Also, the fraction of mesohabitat area within primary sampling units (reaches) that are sampled is not constant across sampling units, further complicating aggregation of CPUE (see Hubert et al. 2016). Mesohabitat-specific CPUE values, however, appear to have similar temporal trends across mesohabitat types (at least on a log scale: see Figure 11 in Dudley et al. 2016b), implying that CPUE for a specific mesohabitat type (e.g., one with generally high density) should provide a reasonably valid index of total population size.

3.2 Recommended Studies

3.2.1 A: Population Dynamics

A1. Clarify the Relationship between the Annual Catch-Per-Unit-Effort Index and True Population Size by Estimating Catchability. (See Also Recommended Studies E3 in Section 3.2.5; Tier 1 Study)

Several methods are proposed to acquire estimates of catchability by mesohabitat type in this chapter and in Chapter 7. These include:

- Combining traditional seine-based survey methods with more intensive capture and removal methods (as in Dudley et al. 2012). The latter estimates are more accurate (if extensive numbers of removals are made in each unit) and can be used to calibrate the CPUE index methods using ratio estimates. Two variables must be estimated: CPUE based on traditional survey methods and 'true' abundance (N_{True}) based on removal methods.
- Conducting gear selectivity studies (see also Recommended Studies E1b in Section 3.2.5) where traditional seining methods and mesh sizes are augmented by finer mesh seines that presumably sample all fish exposed to the seine (i.e., they are non-selective sampling devices). The latter estimates are more accurate and can be used to calibrate the CPUE index methods. Two variables must be estimated: CPUE based on traditional survey

methods and $\hat{N}_{True}$ based on the fine-mesh seine assumed to be non-selective with respect to fish size. Counter to the usual situation where the count of smaller fish is biased low, it appears that larger RGSMs are captured at lower rates than smaller RGSMs. Comparing catches in two seines types varying in size selectivity would allow assessment of the degree to which smaller age 0 RGSMs are missed in mid-summer surveys. An example application of these methods for delta smelt is described in Newman (2008).

- These studies would be conducted in the field as an extension to ongoing surveys.

A2. Determine the Key, Age-Specific, Life History Sensitivities of the Rio Grande Silvery Minnow (That is, Use Eigenanalysis Methods to Determine Which Vital Rates [Survival and/or Reproduction] Most Affect Rates of Population Change; Tier 1 Study)

Estimates of life history sensitivities (that is, what vital rates most affect rates of population growth) could be calculated based on preliminary estimates of the age-specific birth and survival rates.

- Initial estimates of life-history sensitivities should focus on estimating the elasticity value of each age-specific rate. This can be done in straightforward fashion as part of an eigenanalysis of the projection matrix (see Recommended Studies A in Section 3.2.1).
- Because the sensitivity of population growth rate to a given vital rate is also a function of that rate's process variance, a life stage simulation analysis should also be conducted.
- To conduct these analyses, preliminary estimates of the vital rates, and their process variances, are needed.

A3. Estimate Age-Specific Survival Rates. (Tier 1 Study)

Even for RGSMs in the same age-class, survival rates may vary according to many different factors. Methods proposed to estimate mesohabitat type specific estimates of survival include:

- If CPUE data could be partitioned by age-class (age 0, age 1, age 2), then ratio estimators of annual October CPUE indices, by meoshabitat type, from successive survey years (e.g., $CPUE_1(t+1)/CPUE_0(t)$), could provide an estimate of annual survival rate in mesohabotat type *j*, assuming catchability is constant within a mesohabitat type.
- A proxy for first year survival would be a "correctly" calculated CPUE of age 0 fish in October, scaled by the age 1 and older CPUE metric for April.
- Regression estimators where the survival of an initial cohort of RGSMs is followed over a yearly time-step (see Skalski et al. 2005, page 210; Goodman 2011). This study requires estimates of the initial abundance of a cohort at time *t* and its abundance at time *t+1*. Cohorts could be age-specific if the CPUE data were partitioned by age-class to derive age-specific survival estimates. Note: if these analyses are used to estimate monthly survival rates, for example, they depend on the critical assumption of constant catchability over the year. This assumption is unlikely to be true because of varying flow conditions. Estimates of annual survival probability based on CPUE estimates collected at the same time and at similar flows (e.g., October) in subsequent years also require an assumption of constant *q*, but this assumption may be more likely to be met.

- Precise estimates of survival may be very difficult to make from wild populations, but RGSM hatchery facilities (Los Lunas and Albuquerque BioPark) could possibly be employed to conduct controlled experiments focused on key aspects of the RGSM's life-history uncertainties.

A4. Estimate Age-Specific Fecundities of Wild Fish. (See Also Recommended Studies B3 in Section 3.2.2; Tier 1 Study)

Even for RGSMs in the same age-class, fecundity rates may vary according to many different factors, including fish size and physiological state. To address this uncertainty, we suggest several possible studies:

- Collect a sample of gravid fish, spanning a range of body lengths, to be taken just before initiation of peak flows in the spring. These fish would be sacrificed, aged via otilith examination, and the number of eggs in various stage of development counted. The goal of these studies would be to derive fecundity size (age) relationships for wild fish. Collection of fish for this study would involve field sampling.
- An alternative would be to capture wild fish, move them to a hatchery facility, hold them for a short period, induce spawning, and release them back into the wild. If it could be demonstrated that the majority of eggs are released following induced spawning, then it is possible the fish would not have to be sacrificed. These data would then be used to estimate size (age) fecundity relationships based on wild fish.
- Laboratory studies would require a captive population of RGSM of sufficient size to estimate the size-fecundity relationship precisely (see Recommended Studies B in Section 3.2.2] and Recommended Studies C in Section 3.2.3).
- Variables to be included in these studies would be number of eggs produced per individual female and fish size (age) as dependent variables.

A5. Using Statistical Modeling, Estimate the Relationships between Rio Grande Silvery Minnow Demographic Rates and A) Hydrologic Factors (Flow Magnitude and Duration, Summer Drying of the Channel); B) Abiotic Environmental Factors (Temperature, Turbidity, Salinity); and C) Biotic Factors (Predation, Completion, Prey Availability; Tier 1 Study)

We recommend that demographic rates, in addition to CPUE data, be modeled as a function of broad-scale hydrologic variables, mesohabitat type, and abiotic factors that may vary across mesohabitat types (e.g., salinity, turbidity, water depth, local flow rates, etc.).

- Field-based, observational studies taking advantage of natural temporal and spatial variation in candidate response variables, including survival, reproduction, and abundance (response variables) evaluated as function of a suite of environmental covariates (predictor variables). These studies, primarily based on inferences drawn from regression type models, are appropriately viewed as correlational studies.
- Targeted studies, focusing on the above mentioned response variables, conducted under controlled conditions at the Los Lunas or Albuquerque BioPark hatchery facilities. Inference would be limited to those environmental factors that can be simulated under

experimental conditions. Inferences from experimental studies may have greater certainty than those from observational studies.

A6. Evaluate the Existence and Strength of Any Density-Dependent Factors That May Be Limiting Population Growth. (Tier 2 Study)

Recommended studies to explore the possibility of density-dependent limitations at some point in the RGSM annual cycle are similar to those discussed above (Recommended Study A4). In this case, demographic rates, in addition to CPUE data, could be modeled as a function of current $(\hat{N}_t)$ and past $(\hat{N}_{t-1})$ population densities, for example:

- Explore the monthly, or bi-monthly, CPUE data collected annually as a function of current and past CPUE estimates (similar to approaches used by Goodman 2011). In general, the relationships to be explored are of the form: $N_{t+1} \sim f\left(N_t, N_{t-1}, \ldots\right)$. Inferences from these regression analyses would be considerably strengthened if the CPUE catch data were adjusted for differential catchability (Key Uncertainties: A1) prior to analysis. To the extent possible, analyses should be partitioned by age-class.
- Of equal or greater value would be studies to investigate the relationship between survival and reproduction rates (response variables) and current and past estimates of population size (or density) as predictor variables. These relationships would be difficult to study under field conditions and may require experiments conducted under controlled conditions at the Los Lunas or Albuquerque BioPark hatchery facilities.

A7. Model the Potential Effects of Hatchery Augmentation on Population Dynamics and the Significance of Hatchery Fish to Achieving Recovery Objectives

The magnitude of annual augmentation is governed by a policy based on October CPUE data (USFWS 2013) and should be treated as an "external addition" that increases abundance of adult spawners present the following spring. In our discussion of population dynamics we did not include augmentation in our proposed matrix population model, but recognize that it may be critical to do so in the future. Our focus was on the wild population of RGSMs because a key recovery objective in the RGSM Recovery Plan is to achieve "Three populations of Rio Grande silvery minnow, in the historical range of the species, each of which demonstrate (using quantitative analysis) a probability of extinction in the wild of less than 10% within 100 years."

- Because hatchery fish carry marks, RGSM survey data can be partitioned into wild and hatchery fish. This allows separate CPUE index estimates of wild and hatchery fish and provides an opportunity to model their dynamics separately. However, independent estimates of, or critical assumptions about, birth and survival rates of hatchery fish relative to wild fish are required to model the joint dynamics of the mixed hatchery and wild population.

A8. Determine if the Collection and Translocation of Salvage Fish during Summer Drying Periods Contributes Significantly to Population Dynamics

To include fish salvage data into estimates of the RGSM abundance (from late summer/early fall surveys) would require assignment of each rescued individual to an age-class. Age classified counts could be added to the CPUE counts (assuming adjustment for catchability) to arrive at a late fall estimate of the age-distribution and the potential number of spawners in the subsequent spring. In addition, it would be necessary to assume that rescued fish survive at their age-specific survival rate. We believe that it is highly unlikely that these fish contribute significantly to population growth.

3.2.2 B: Reproductive Biology of Rio Grande Silvery Minnow

B1. Development and Deployment of "Vertically-Integrating" Moore Egg Collectors (Tier 1 Study)

If feasible, "vertically-integrating" (see Recommended Studies E in Section 3.2.5) MECs should be developed and deployed in the MRG from April through September for at least two seasons. Comparison of number of eggs collected (per filtered volume) in such "vertically-integrating" modified MECs with numbers of eggs collected in MECs as currently deployed should allow development of flow-dependent "adjustment factors" that might allow bias-adjustment of current and past expansions of egg collections to nearly unbiased estimates of total egg passage. Deployment of these modified MECs from March through September should allow improved assessment of the temporal distribution of spawning activity in the main channel. (Intervals between sampling days should be shorter during the April-June period of intense spawning than for the June-September period when relatively little spawning is expected to take place.)

Additional quantitative collection of eggs and larvae needs to be carried out in floodplain or flooplain-like habitat when flows make such habitat available for spawning activity and egg/larval rearing, so that egg deposition on the floodplain can be compared to egg passage in the mainstem channel. The logistics of carrying out such sampling will no doubt be complicated.

B2. Improved Assessments of Relations between Possible Environmental Cues That Trigger Spawning Activity (Tier 1 Study)

Although it is no doubt true that RGSM spawning activity is related to both flows and temperatures, we believe that it would be useful for a geomorphologist/hydrologist to team with a fisheries biologist with expertise in reproductive biology to develop plausible theoretical relations between spawning activity and possible environmental cues. (For example, what is it that an adult RGSM "senses", and how does the fish sense it, as flows increase and, at some point, perhaps in combination with water temperature, triggers spawning?) Based on these theoretical relations, and using improved and approximately unbiased estimates of temporal main channel spawning activity, this team should develop a suite of alternative statistical models that could be used to establish proximate cues for spawning. Ideally, this work should be carried out during years for which flows never or rarely exceed levels that would allow off-channel or floodplain spawning so that (improved) main channel estimates of egg passage probably provide a reliable notion of the distribution of spawning activity through time.

B3. Establish Size-Specific Fecundities of Natural-Spawning Rio Grande Silvery Minnow (Tier 2 Study).

There are two groups of naturally-spawning RGSMs: those that are traceable to natural spawning of RGSMs in the MRG, and those that are hatchery-reared fish that have been released in the

MRG in the fall as age 0 fish. Size-specific fecundities of these two naturally-spawning types may differ. Therefore, collections of gravid RGSM females should be made during the spawning season. A sample size of 25 fish each of unmarked (naturally-spawned) and elastomer-marked (hatchery-reared and released) RGSMs should be collected during the mid-April to mid-June period. These relatively small sample sizes should prove adequate if there is a concerted effort made to select females so that they represent the full size range of adult RGSMs, say by selecting five fish per each of five 10-millimeter (mm) length intervals (ranging from 35-85 mm standard length, SL). These fish could be subjected to hormonal induction to determine if fractional release is similar to that observed in hatchery fish. Fish will need to be sacrificed so that eggs released and eggs retained can be separately recorded. Total fecundity would be the sum of the two values.

3.2.3 C: Age and Growth

C. Clarify the Details of Annular Mark Formation on Otoliths and Firmly Establish the Longevity of Rio Grande Silvery Minnow (Tier 2 Study)

Lang (workshop poster) reported on preliminary work carried out at the Albuquerque BioPark, under semi-natural conditions, that was designed to determine: a) when annuli form on otoliths of RGSMs, and b) verify that annuli formation takes place on an annual basis. This kind of work needs to be continued, modified if necessary (e.g., rearing fish in a more natural setting, if possible), and published. Such a study would allow: a) validation of annular mark identification that has been used in other studies, and b) resolution of the apparent controversy concerning longevity of RGSMs. Instead of relying on opportunist mortalities of RGSMs, an improved study would deliberately sacrifice, say, five hatchery-reared RGSMs from each of three cohorts (age 1, 2, and 3) on a monthly basis throughout an entire year.

3.2.4 D: Physical Habitat Relations of RGSMs

D1. Estimate the Spatial Extent and Hydraulic Quality of Habitats Used by Rio Grande Silvery Minnow for Key Life-Stages (Spawning, Larval Rearing, Juvenile and Adult Survival). Estimate How These Habitats Are Distributed in the River Channel And Floodplain in Each Middle Rio Grande Reach Under a Range of Discharges and Seasonal Flow Regimes

Field-based data sources would take advantage of natural, or management-enhanced, variation in flow magnitude and duration. Statistical analysis would couple current and past monitoring data (response variables) with various attributes of the hydrograph (predictor variables). The first step would be to identify years in the US Geological Survey (USGS) flow records when the annual peak flow indicated that habitat access was: a) confined to the sandy channel and unvegetated bars; b) included (a) and also vegetated islands and sloping riparian zones described informally in various reports; and c) included (a) and (b), and also extensive floodplain areas. During years of low flows (less than about 1,250 cfs), fish would be confined to the sand-bed channel and (mainly unvegetated) bars. Egg and fish production data for these and similar years would allow estimates of an upper limit for the productive capacity of the channel alone. Segregation of years with flows in the range between (say) 1,500 cfs and the threshold discharge for more extensive floodplain inundation, estimated to be 2,500 cfs for the Albuquerque reach in 2002, could be used to estimate the additional level of egg and fish production gained when the vegetated in-channel and riparian zone is inundated. Finally, a suite of years with extensive floodplain inundation with discharges exceeding (say) 3,000 cfs in the Albuquerque reach and lower threshold values in downstream reaches could be used to define a lower bound on the productive value of floodplain inundation. A spatially registered analysis of where critical life stages occur coupled with population metrics (e.g., CPUE data) would reveal population-level changes to habitat availability and provide the critical link between fish populations and water management operations in a changing climate.

To avoid some of the obvious complicating factors and uncertainties associated within field data, experiments could be designed to isolate some of the same environmental drivers in the Los Lunas or Albuquerque BioPark facilities. For example, in one set of experiments, fish could be confined to the channel and their condition and spawning responses to rapid flow increases could be monitored continually throughout a spawning season. The success of egg maturation, and larval and juvenile development could be monitored, along with food availability, growth rates, site selection within the flow field, and the energetics of growth. This would establish a limit on channel-bound fish production. A parallel set of experiments with higher discharges could allow fish access to an experimental floodplain of sufficient extent. Egg release, larvae and fish growth rates, stomach contents, and life history processes could again be tracked continuously to measure whether the incremental production under floodplain conditions. Environmental conditions of both channel and floodplain, along with such factors as food availability and water temperature, could be characterized in detail.

D2. Establish the Proximate Trigger(s) for Spawning by Evaluating the Effects of Flow Velocity, Temperature, Rate of Increase in Flow Velocity, or Some Combination of These Factors

Studies to address factors triggering spawning behavior are best conducted under experimental conditions using the Los Lunas or Albuquerque BioPark facilities. For example, a study might begin under low-flow conditions with fish in the channel, suddenly exposed to a rapid increase in discharge that would give them access to low-flow channel margins or floodplain. This would allow an assessment of whether the eggs are released while the fish are in the channel and then carried into riparian zones by the overbank flow, or whether the fish prefer to access the floodplain before releasing eggs. Varying the rate of flow increase to mimic representative rising hydrographs in the MRG would allow the examination how of spawning success is affected by this management-related variable. Other experiments could quantify the effects of duration of floodplain access and whether stranding is a quantitatively significant factor at the population level.

D3. Determine the Roles and Relative Contributions to Fish Production (Age 0 Recruitment and Survival of All Age-Classes) of Channel and Floodplain Habitat in a Reach of Channel and Floodplain Typical of the Middle Rio Grande

We suggest building on the initial work conducted by Tetra Tech (2014) that modeled the extent, threshold discharge, and the duration of floodplain inundation and in-channel hydraulic conditions. Further study would focus on a finer-resolution characterization of topography, vegetation, and substrate together with 2-dimensional (2D) flow modeling to facilitate a clearer, quantitative assessment of the amount and quality of the habitat at various streamflows. A finer resolution model would provide a more reliable mechanistic perspective on: floodplain accessibility, the area and quality of habitat for egg and larva retention and maturation, food resources, juvenile rearing, and prospects of fish stranding during falling water. The characterization and modeling of channel and floodplain habitat could be a flexible tool for habitat assessment, and would allow the assessment of competing hypotheses concerning the necessary conditions for each life stage of the RGSM.

D4. What is the Management Potential for Fish Production (Recruitment and Survival of Age 0 Fish) in Each Reach of the Middle Rio Grande if the Annual Peak Flow, and thus the Nature and Range of Available Habitats, is Permanently Limited below Historic Levels of Availability?

A spatial model of habitat distribution and extent, by river reach, is needed to establish a concrete basis for analysis of the fish's life cycle and its reaction to habitat change. Characterization and modeling of channel and floodplain habitat would provide a flexible tool for habitat assessment, and would allow the evaluation of competing hypotheses concerning necessary conditions for each life stage of the RGSM. The model could serve as a template for many characterizations of biological response such as location of fish, fate of eggs, pool salvaging, evidence for upstream migration, etc. It could be used, for example, when designing spatially representative surveys aligned with predicted habitat preferences and growth responses.

Some of the biological response studies may be more feasible, and the results less ambiguous, if they were conducted under experimental conditions at the Los Lunas or Albuquerque BioPark experimental facilities. Whether the biological characterizations of habitat preference and quality were conducted experimentally or based on field surveys, the spatial model would provide the integrating template and allow issues of scalability and representativeness to be evaluated.

The spatial model recommended here could be a logical extension of the state-space, demographic model as outlined in Section 3.2.1 of this report. Birth and survival rates in that model, for example, can be directly linked to habitat type and dynamic components of the environment by regression models and directed studies. These models are also sufficiently flexible to include density-dependent process that may arise as shallow, low-flow environments become limiting under drought or climate change scenarios. Finally, development of a spatially explicit, population dynamics model will eventually be required to manage RGSM populations in an adaptive fashion.

3.2.5 E: Sampling Methodologies

E1. Establish the Age Composition of the Rio Grande Silvery Minnow Population (Tier 1 Study)

Two distinct studies are needed to address this issue.

E1a. Application of Distribution Separation Methods to Estimate Age Composition

Ideally, small samples of RGSMs should be aged each year (October and spring) to provide estimates of mean length and variance in length at age. Annual estimate allow for time-dependent assignments to age-class and provide insights into how size is varying over time. These estimates would be used as input for R package "*mixdist*" (MacDonald 2015) that is designed to separate overlapping distributions into component distributions and thereby allow estimation of age composition. Three age groups should be assumed (ages 0, 1, and 2 in October; ages 1, 2, and

3 in spring). If no aged samples can be collected, then current "best guesses" of means and variances at ages 0, 1, 2, and 3 should be used, based on historic age samples.

E1b. Gear Selection Study

The analyses proposed in C1 could be applied to length frequency data that are either free of gear selection biases or that have been adjusted for gear selection bias. The apparent negative bias of beach seines (larger RGSMs not caught at same rate as smaller RGSMs, and probably also smallest age 0 fish that pass through the larger mesh seines) implies that some adjustment of collected length frequency data (collected from beach seines) is required. We recommend that quantitative comparisons of RGSMs catches in fyke nets and in beach seines should be carried out in flooded floodplain habitat where both gear types can be effectively deployed (see Gonzales et al. 2014). Comparison of length frequencies of fish collected in the two gears should allow generation of a size selection curve for the beach seine gear under the (reasonable, but difficult to test) assumption that the (passive) fyke net gear is non-selective with respect to size of fish. A fitted selection curve can in turn be used to adjust length frequency data (collected using beach seines in the main channel) for gear selection bias prior to distribution separation for estimation of age composition.

E2. Determine How the Vertical and Horizontal Distribution of Rio Grande Silvery Minnow Eggs in the Middle Rio Grande Mainstem Channel varies as a Function of Flow and Location? (Tier 1 Study)

Recommended Studies: A1 also addresses this issue because both are premised on potentially biased assumptions about the temporal distribution of spawning activity that emerges from the current expansions of egg counts from MECs to the entire flow past a given location. See Key Uncertainties A1 in Section 3.1.1 for further details.

E3. Calculate Revised Catch-Per-Unit-Effort Values at Mesohabitat-Specific Levels and Do Not Combine Across Mesohabitat Types. The Mesohabitat-Specific Catch-Per-Unit-Effort Calculated for the Most Abundant High Density Mesohabitat Type Should Be Used for Assessment of Trend in Abundance of the Rio Grande Silvery Minnow Population at the October Sampling Date (Tier 2 Study)

We propose that the current aggregated (across mesohabitat types) CPUE metric be replaced with a mesohabitat-specific metric calculated for a “high density” mesohabitat type that has substantial availability in all primary sampling reaches. The time-series of this metric should provide a more reliable indicator of trends in October abundance of RGSMs because it assumes only that catchability within this mesohabitat type are constant across years at the time of October sampling. As flows during October are probably low and have relatively little variation across years (relative to other months), we believe that this assumption is a reasonable one.

4 A FRAMEWORK FOR ANALYSIS OF RIO GRANDE SILVERY MINNOW POPULATION DYNAMICS

4.1 Overview

The fundamental challenge to all natural resources managers is to determine what actions they need to take today to meet their future management goals. Projecting future outcomes that may result from management actions we implement today requires development of a model of how a managed system “works”. Verbal or conceptual models can be initially useful for guiding our thinking about how a system may work, but they do not allow managers to make quantitative predictions of the effects of management actions. Instead, models must eventually be developed and expressed in clear and unambiguous mathematical terms. Rigorous statistical methods must be used to estimate key model parameters and to establish the uncertainty associated with model predictions.

Although the absolute abundance of the RGSM population is not well identified, CPUE index data collected from long-term annual monitoring programs have provided strong evidence that there has been a generally decreasing trend in population abundance, that population abundance is currently low compared to its historic size, and that in some years the population has been largely composed of hatchery-reared fish. The endangered status of the RGSM under the ESA makes it obvious that it is critical to identify management actions that will help move the population from its current unacceptably low abundance level to an improved (increased) abundance level that would one day allow recovery and delisting of the species. Natural populations of fish, however, even under pristine conditions, often fluctuate dramatically in abundance across years due to substantial variation in environmental conditions, such as rainfall, temperature, abundance of food organisms, abundance of predators, etc. Therefore, it is more realistic to think that management actions are needed to move the distribution of RGSM abundance levels from the current distribution (an unacceptably low mean) to a future distribution that will have a mean that is judged adequate to reflect recovery of the species. It may also be desirable to reduce the future degree of variation in abundance, if that proves possible.

Figure 1 (adapted from Hobbs et al. 2015 and Raiho et al. 2015), visually illustrates the concepts described in the previous paragraph. The first panel (“current distribution”) illustrates the current distribution of RGSM abundance (*N*) as indexed, for example, by the distribution of the annual CPUE indices. The second panel (desired distribution) illustrates the desired long-term distribution of RGSM abundance (or of an abundance index) with a mean that is well above the current level and which would reflect a value consistent with attainment of recovery objectives. The third panel illustrates a successful shift of the RGSM abundance distribution, through management actions, so as to maintain RGSM abundance above the target mean population size in most years.

Successful attainment of recovery goals (as illustrated by the third panel in Figure 1) requires that the life history and dynamics of RGSMs are well understood, and that management actions can be taken which will increase the magnitude of critical life history parameters (e.g., egg and larval survival rates) that make key contributions to dynamics and abundance of RGSMs. Identification of appropriate management actions in turn requires understanding of how physical variables that can be changed by management actions, such as timing and duration of flows that allow floodplain access during the spawning season, affect the magnitude of specific critical life history parameters (e.g., larval survival rate) or some aggregated population level response (e.g., total abundance).

In this chapter, we propose a mathematical modeling framework to address key aspects of the population dynamics of the RGSM. Analysis of the population dynamics expressed in this modeling framework can be used to identify studies and statistical analyses to improve understanding of how RGSM dynamics may be affected by specific management actions.

The dynamics of natural populations are affected by all aspects of a species' biology, including its life-history, behavior, and habitat requirements. As a consequence, the mathematical modeling framework developed in this chapter makes reference to many life history, behavior and habitat topics that are considered in detail in other main sections of our report (see sections 3.2.2 [Reproductive Biology], 3.2.3 [Age and Growth], and 3.2.4 [Physical Habitat Relations -specifically focusing on hydrology and fluvial geomorphology). Our understanding of many of these topics is imperfect and fraught with uncertainties, some of which are due in part to issues involving sampling methodologies (Chapter 7) used to collect and summarize field data. In development of our modeling framework, we reference other sections of our report as appropriate and we indicate whether or not certain key life history attributes (e.g., longevity, spawning locations) are well identified, but we do not focus on the uncertainties associated with these attributes. Key uncertainties associated with these topics are identified and discussed in detail in the above-noted main sections of our report.

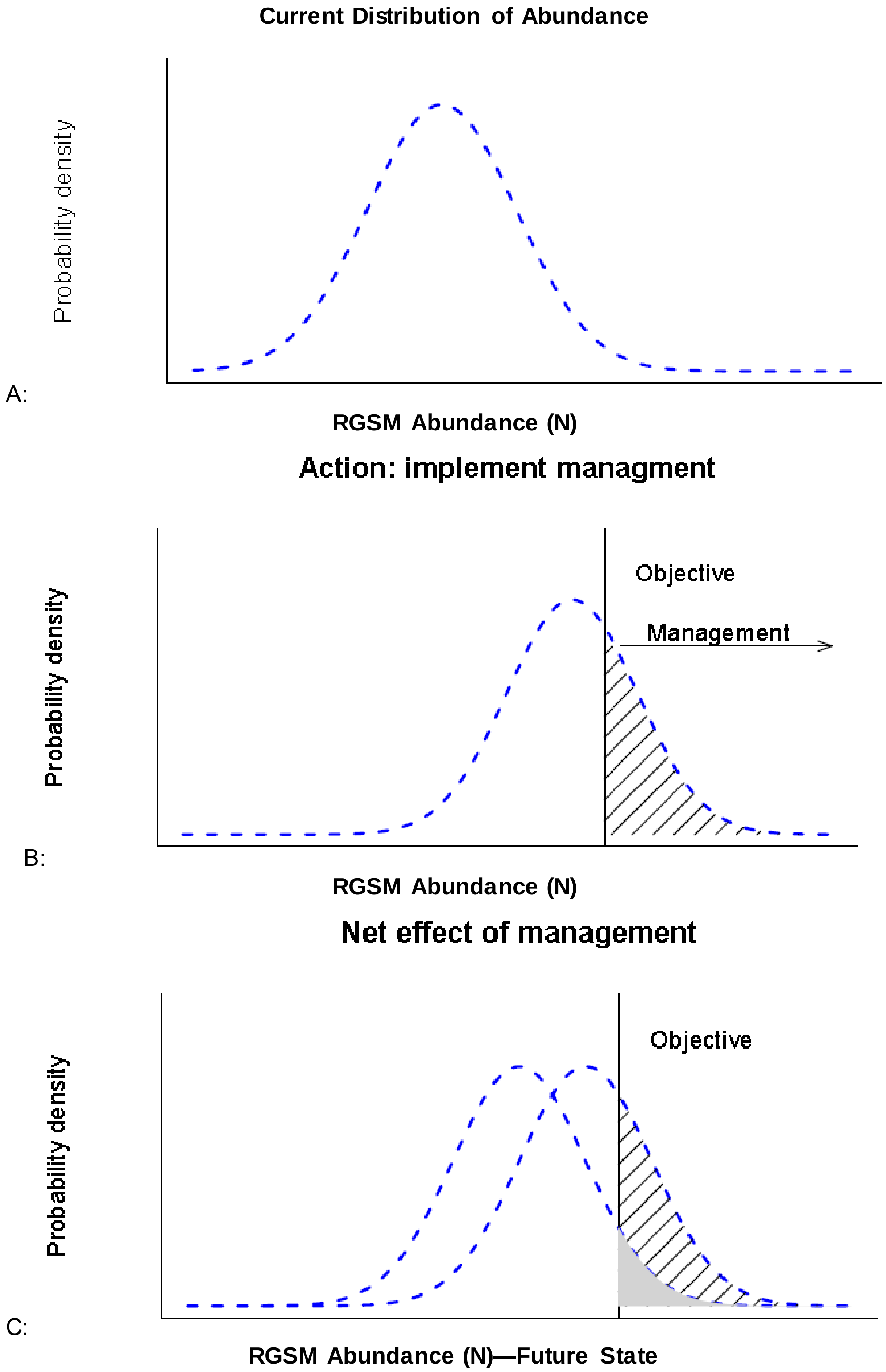

Figure 1. The vertical line indicates the manager's objective for the population. (A) the current distribution of abundances ; (B) the long-term desired distribution of abundances conditional on management action; (C) a successful shift in the abundances distribution with a goal of obtaining high abundance levelsin most years. Figure adapted from Hobbs et al. (2015) and Raiho et al. (2015).

Finally, we wish to acknowledge and stress that the dynamics of the RGSM population is complicated by frequent augmentation of age 0 fish with hatchery-reared age 0 fish released during fall (October-December). First, it would be unreasonable to assume that overwinter survival rates of these fish would be the same as overwinter survival rates for naturally-produced age 0 fish. Instead, it would be reasonable to postulate that overwinter survival rates for age 0 fish released in fall are considerably less than for naturally-produced fish. Second, the "dynamics" of augmentation are entirely different from the population dynamics of the naturally reproducing, mixed population of hatchery and wild adults. The magnitude of annual augmentation is governed by a policy based on October CPUE data (USFWS 2013) and should be treated as an "external addition" that increases abundance of adults present the following spring. In this chapter, we do not include augmentation on our proposed matrix population model, but recognize that it is critical to do so in the future.

4.2 A State-Space Modeling Framework

Newman et al. (2014) provides an excellent presentation of modern state-space modeling approaches used in natural resources population modeling contexts similar to the setting of RGSMs. The state-space modeling framework generally consists of two linked parts: a) a mathematical model of the population dynamics of a species (often a matrix projection model) which generates a predicted future state of the system (e.g., actual abundance of RGSM); and b) a time-series of estimates of the "state" of the system (i.e., estimated abundance of RGSM). The advantage of the state-space modeling approach is that it explicitly identifies and incorporates two distinct sources of variation that critically affect model performance and interpretation. First, there is "natural process variance" , or the variability in a demographic rate due to environmental factors such as variability in peak flows, rainfall, water temperatures, etc. These environmental drivers give rise to variations in the birth and survival processes that are ultimately expressed as variations in RGSM abundance in space and time. Second, there is statistical uncertainty (sampling variation and measurement error) in estimates of the state of the system (RGSM abundance, age composition). Statistical uncertainty in estimates of the state is due to factors completely unrelated to those that cause process variation and is due instead to issues such as sample selection, sample sizes, gear selection, and other factors that are considered, in part, in Section 3.2.5 of our report.

Although the state-space approach typically requires unbiased estimates of state variables such as RGSM abundance,_Davis et al. (2014) recently developed a novel method that links two data sources, with no direct parameters in common, that should be applicable to the RGSM monitoring program. The data sources, count-based and model-based, can be linked through a common derived parameter, the population growth rate, *λ*. In the case of the count data, a year-specific *λ* can be unbiasedly estimated (assuming catchability, *q*, is constant over time or estimated) as:

$$\hat{\lambda}_t = \frac{CPUE_{t+1}}{CPUE_t}, \text{ where the count } C_t = qE_tN_t$$
$$\text{and } CPUE_t = C_t / E_t = qN_t$$

The parameter N_t is the true, but unknown, population size at time t.

The growth rate, λ, for the demographic model is estimated as the dominant eigenvalue of the projection matrix (see below). As noted by Davis et al. (2014), the λ parameters based on the demographic model and on the CPUE data are not necessarily identical, but they are closely related because they measure the same population metric.[1]

Due to limitations on time allocated for our RGSM review, we do not present a fully developed state-space model for RGSMs. However, we believe that development of such a model, which links annual CPUE index data to a matrix projection model, is the direction that should be taken in the future for assessing and predicting the dynamics of RGSMs. Below we provide a detailed description of what we believe would be an appropriate matrix projection model for RGSMs. This projection model could be used within the context of a state-space model.

4.3 A Female Age-Based Matrix Projection Model for the Rio Grande Silvery Minnow

The intent of the following model outline is provide an example of how to: 1) develop a life history based matrix projection model that could be linked to the October RGSM CPUE survey data; 2) identify specific model parameters for which estimates would be needed; and 3) outline how this modeling framework could be integrated with the count-based data to provide estimates of model parameters and to more directly link the CPUE data and management actions, such as water management to projected demographic outcomes.

For the RGSM, the cycle of regeneration can be visualized as Figure 2:

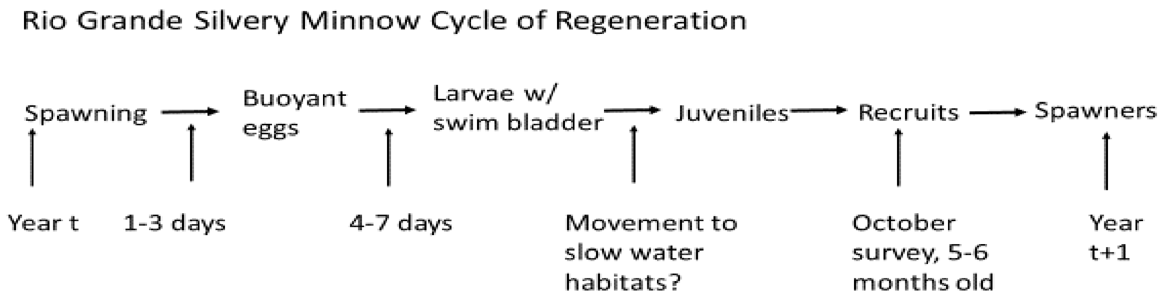

Figure 2. Key life-history transitions of the Rio Grande silvery minnow.

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[1] Though the demographic λ rests on asymptotic properties of the projection matrix, λ can be made time-dependent if the vital rates are updated over time. The CPUE index values can also be linked to model projections by conditioning current year projections on the previous year's CPUE index values. This is accomplished by using the CPUE data to estimate the RGSM age distribution in year t-1. These conditional projections assume that catchability issues have been addressed as discussed above.

In our model, we initially assume the RGSM to be an iteroparus, birth-pulse (complete spawning) species with a maximum reproductive life span of three years; that is, females die during their fourth year of life at age 3. However, the “birth-pulse” may extend over several weeks, in which case at least some females act more like fractional spawners (Lusk et al. 2012). There is some evidence that some portion of the adult population may breed, or breed again (serial spawner), during the summer period after the peak spring flows (see additional discussion of Key Uncertainties B in Section 3.1.2 and Recommended Studies B in Section 3.2.2). However, if the vast majority of spawning occurs in a relatively short time interval following the spring peak flows, then the birth-pulse assumption of the projection model should still be approximately valid. The RGSM monitoring program generates size-frequency data on a nearly monthly basis. Analysis of these data, over the many years of monitoring, would provide insights into magnitude of late summer (July-September) spawning and contributions to age 0 fish alive at time of the October monitoring surveys. Further, the size-frequency data from the December surveys could be used to assess the likelihood that any fish spawned in mid-summer will survive to enter the over-wintering age 0 population. If late summer spawning is rare, or few late spawned age 0 fish survive to the next spring, the birth-pulse assumption remains valid.

Size in fish is often a better predictor of their reproductive potential or survival rate than age. However, the advantages of a size-based model are often outweighed by their additional complexity and conversion of size to age independently and then using age-structured models is often the best choice (Quinn and Deriso 1999). For RGSMs, age classes are generally defined by specifying body length intervals that are closely associated with age (see length-age discussion, below). This is the method used to assigned fish caught in the October surveys, for example, to age-classes (Dudley et al. 2016b). To be consistent with this classification, and to minimize model complexity, we develop an age-based model and assume that RGSMs are assigned to age-classes based on their standard length.

The RGSM is short-lived species, with maximum age in the wild typically less than four years of age (USFWS 2010). The short life span of this species means that it has limited ability to recover from a small population size and years of low recruitment.

In the following example, we describe an age-based model assuming that individual fish are assigned to an age class based on an assignment algorithm informed by an estimated length-age relationship (see below).

Model Development

Definitions:

m	total number of female eggs produced at the spawning birth pulse
m_i	expected number of female eggs for each female of age *i* at the birth pulse
p_i	probability of survival from *t* to *t+1* of females in age class i
$n_{i,t}$	number of individual females in age class *i* at time *t*
w	maximum attainable age or age of reproductive senescence

i age class index, *$i = 0, 1, \ldots, w-1$*

k the proportion of time (in years) between the birth-pulse and the census; *$0 \leq k \leq 1$*

p_0^k probability of survival of 'newborn' fish from the birth pulse to the time of the next census;

Usually, age-based models are considered to be either a pre-birth-pulse (*$k = 1$*) or post-birth-pulse (*$k = 0$*) model with the 'census' occurring immediate before, or immediately after the birth-pulse, respectively. We have generalized the model to allow the birth-pulse to occur anywhere between census periods assumed to be one year apart. In this model, individuals in age class *i* survive from the time of census in year *t* to the birth-pulse with probability p_i^{1-k}. Surviving females then produce young at rate m_{i+1} Newborns females (age class 0) then survive from the birth-pulse to the next census time with probability p_0^k.

In general, age-specific fecundities are then, $F_i = p_i^{1-k} m_{i+1} p_0^k$.

In this model, individual females have their final reproductive pulse at age 3, and then die during the fourth year of their life, after the birth-pulse.

We made this change to the model to reflect the timing of the October population survey, the primary data source used to estimate population trend (e.g., Dudley et al. 2016a). Assuming that the birth pulse occurs in May, then *$k = 5/12$*---that is, five months pass between the May birth pulse and the subsequent October census. In the model, we define p_i as having two parts, p_i^{1-k} and p_i^k. Adults (*$i \geq 1$*) must survive from the time of the census in year *t* to the time of the birth pulse with probability p_i^{1-k}, and survive after the birth pulse to the time of the next census in year *t+1* with probability p_i^k (see Figure 3; adapted from Noon and Sauer 1992).

The number of recruits (age class 0 fish) at the time of the October census is

$$n_{0,t+1} = \sum_{i=0}^{w-1} n_{i,t} p_i^{1-k} m_i p_0^k ,$$

and the number of fish in the other age classes is

$$n_{i+1,t+1} = n_{i,t} p_i \quad i = 0, 1, \ldots, w-1$$

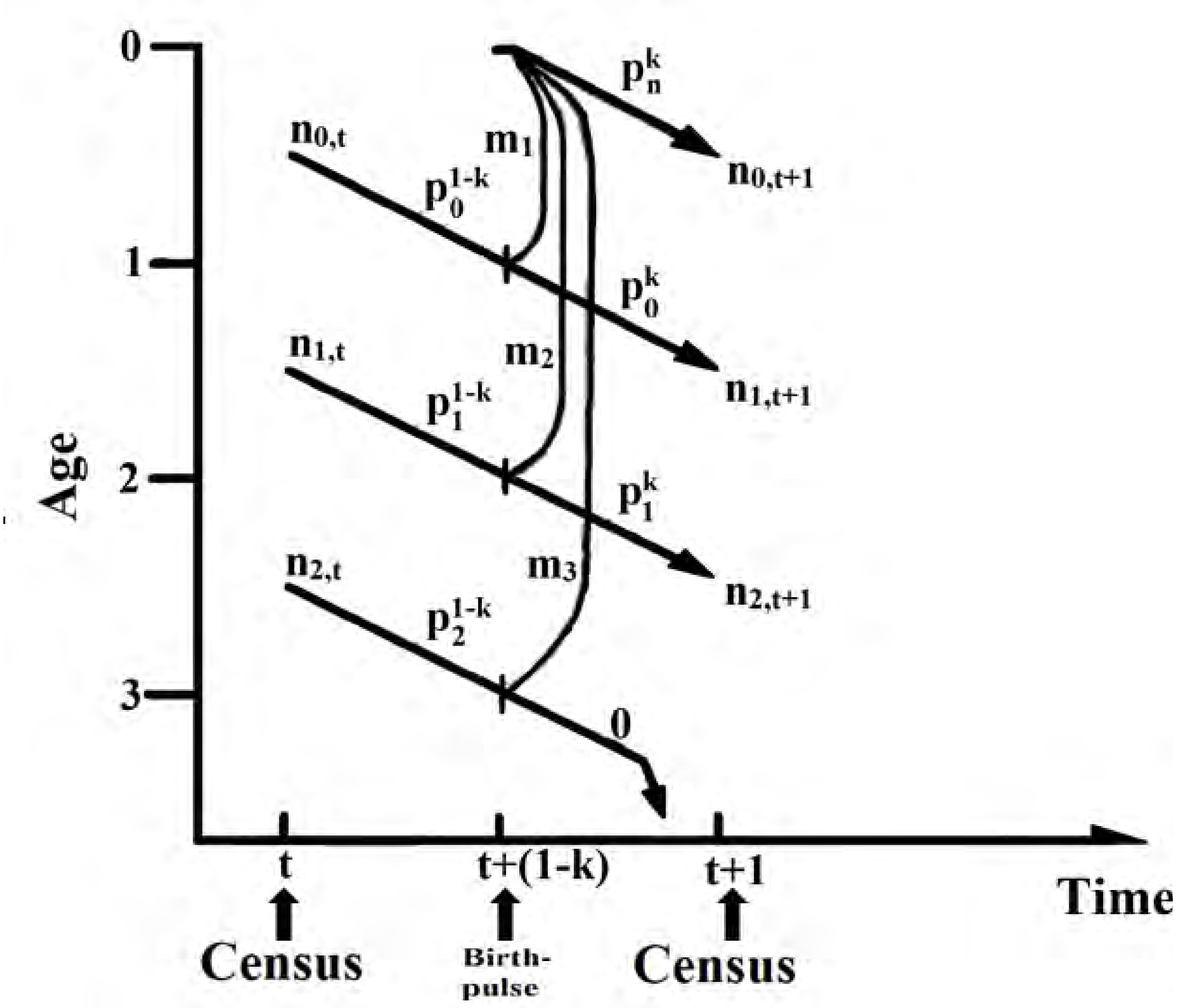

Figure 3. A general time-by-age biplot showing cohort transitions between census periods. Redrawn from Noon and Sauer (1992).

We recast Figure 3 into a matrix form that is suitable for the RGSM (Figure 4). The left-side of the equal sign is the age abundance vector at the October census data at time *t+1*. The transpose of the age abundance vector at time *t+1* ($N_{t+1} = \left[n_o, n_1, n_2\right]_{t+1}$) is the product of the projection matrix (L) times the age abundance vector (N_t) at time *t*.

$$N_{t+1} = \begin{pmatrix} n_o \\ n_1 \\ n_2 \end{pmatrix}_{t+1} = \begin{pmatrix} p_0^{1-k} m_1 p_0^k & p_1^{1-k} m_2 p_0^k & p_2^{1-k} m_3 p_0^k \\ p_0^{1-k} p_0^k & 0 & 0 \\ 0 & p_1^{1-k} p_1^k & 0 \end{pmatrix} \begin{pmatrix} n_0 \\ n_1 \\ n_2 \end{pmatrix}_t = LN_t$$

Figure 4. Example projection matrix for Rio Grande silvery minnow, assuming the "census" to occur some fraction *k* of the year following the spawning birth-pulse.

Based on known age-size relationships (see below), we have structured the model to reflect death during the fourth year of life, but the model is easily extended to include older-age fish. For example, uncertainty over RGSM longevity could be evaluated by changing matrix element $L_{3,3}$ from 0 and setting matrix element $L_{3,3} = p_1^{1-k} p_1^k$. In the simplest case, each element of L would be a numeric estimate; however, the model can be modified so that each element is a function of one or more environmental covariates, including population size at time *t-1*.

In order to better understand what RGSM life-history stages most affect the rate of population change, λ, it is useful to break down the survival intervals by life-history stage. For example, we define the survival probability of newborn fish prior to the October survey and beginning at the birth-pulse as:

$$p_0^k = p_e \times p_l \times p_j$$

where survival over the five months between the May birth-pulse and the October survey is the joint probability of:

p_e = probability of survival of eggs to the larval stage,

p_l = probability of survival from the larval to the juvenile stage, and

p_j = probability of juvenile survival to the time of the October census.

In addition, we can define the probability of survival from the October survey in year *t* to the May birth-pulse in year *t+1* as an age-specific, over-winter survival rate ($p_{ow,i}$):

$$p_{ow,i} = p_i^{1-k}$$

4.3.1 Using Catch-Per-Unit-Effort Data to Inform Model Development

There is a long history of sampling RGSM populations and these samples are usually taken multiple times per year (e.g., Dudley et al. 2016a). In order to estimate the current status and temporal trend in RGSM populations in the MRG, a CPUE index from the October survey is estimated from the total catch pooled across all sizes and ages of RGSMs. The assumption is that the October CPUE data provides an acceptable estimate of the cohort available for spawning in year *t+1*.

The CPUE is generically defined as:

$$C_t = qE_tN_t$$

$$\frac{C_t}{E_t} = qN_t = CPUE_t$$

Where C_t = the number of fish caught during sampling occasion t:

$N_t =$ true unknown population abundance at time *t*,

$E_t =$ effort at time *t*, and

$q =$ catchability (probability that a fish in the sample unit is caught).

Because catch is the product of abundance and catchability, trends in CPUE over time can reflect changes in abundance, catchability, or both. Unfortunately, the relationship of the $CPUE_t$ index to the true population size N_t is unknown because catchability (*q*) is not estimated in the RGSM monitoring program (e.g., Dudley et al. 2016b). Of importance is the fact that *q* is expected to be highly variable because it is affected by a multiple factors, including hydrology, fish size (e.g., by fish length), mesohabitat type, and mesh size of the sampling gear, and across time and space (e.g., habitat types; see Recommended Studies E in Section 3.2.5). Failure to estimate catchability is a significant data limitation of the current monitoring program. If this limitation was addressed, it would lead to more reliable inference to the true status and trend of RGSM populations, and allow RGSM researchers to make better use the CPUE data to address scientific uncertainties. For example, knowledge of catchability would allow one to derive independent estimates of *λ* and estimates of unknown survival and reproduction parameters for the proposed population model (see Recommended Studies E in Section 3.2.5).

One problem with the current CPUE index is that it is aggregated across mesohabitat types within which density of fish, and presumably catchability, vary. If, as recommended in the Sampling Methodologies Recommended Studies, the CPUE metric is calculated separately by mesohabitat type, then, at time of the October census, it is may be safe to assume catchability is a fixed mesohabitat-dependent constant. If that assumption is defensible, the CPUE index would be directly proportional to abundance, and growth rate can be estimated as, $\frac{CPUE_{j,t+1}}{CPUE_{j,t}} = \hat{\lambda}_{j,t}$ for mesohabitat type j. In addition, the ratio $\frac{CPUE_{i.j,t+1}}{CPUE_{i,j,t}} = p_{i,j}$ could provide an estimate of survival probability for age class *i* and mesohabitat type *j* even if *q* is not known.

4.3.2 Length-Age Relationships-Theoretical Background

Substantial difference of opinion exists concerning how size varies with age and the longevity of RGSMs. Longevity, for example, may be an important element of the population dynamics of the species. For example, there may be greater resilience to periods of drought if there are more older-age fish participating in spawning. Size (length) at age affects fecundity and in turn affects total annual egg deposition of the RGSM population. There may also be important, but unknown, relationships between RGSM size and survival probability. An extended discussion of uncertainties and recommended studies relevant to this topic can be found in Age and Growth Recommended Studies.

Estimated length-age relationships allow the assignment of individual fish to an age class. The RGSMs caught during CPUE surveys are regularly assigned to age classes based on reach-specific standard length and age-length relationships (Dudley et al. 2009, Horwitz et al. 2011). Such assignments are common in fishery management because fish growth, measured either as an increase in length or weight, accompanies increasing age (Quinn and Dersio 1999). However, size-based assignments to age class are imperfect because of overlapping size-age distributions (see below).

Several functions or models have been used to model the mean length (*L*) or weight of fish as a function of age. One model, the von Bertalanffy growth model (VBGM, von Bertalanffy 1938), is the most popular:

$$E\left[L \mid t\right] = L_{asy}\left[1 - \exp(-K(t - t_0))\right]$$

where:

$E\left[L \mid t\right] =$ the expected or average length at time (or age) *t*;

$L_{asy} =$ the asymptotic average length;

$K =$ the so-called Brody growth rate coefficient (units are yr^{-1}), *K* measures the exponential rate of approach to the asymptotic size; and

$t_0 =$ theoretical age when the average length was zero.

Data from Appendix E of Horwitz et al. (2011), augmented by three additional, larger fish to account for possible size-selection bias in the survey data (see Recommended Studies C in Section 3.2.3) are plotted in Figure 5A. Fitting these data to the VBGM function (Figure 5B) suggests a maximum size of approximately 94 mm.

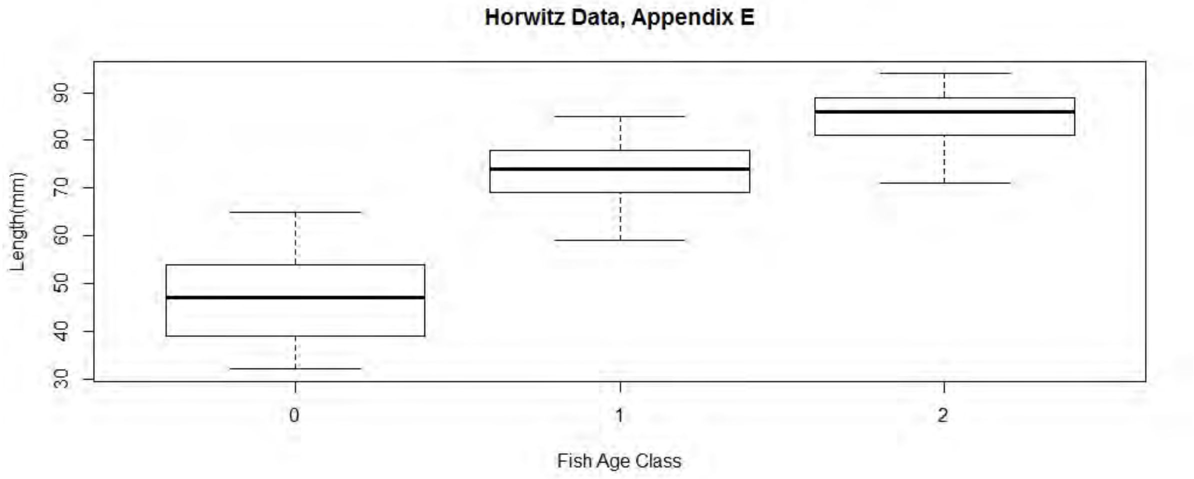

Figure 5A. Plot of (augmented) age-length data (Horwitz et al. 2011).

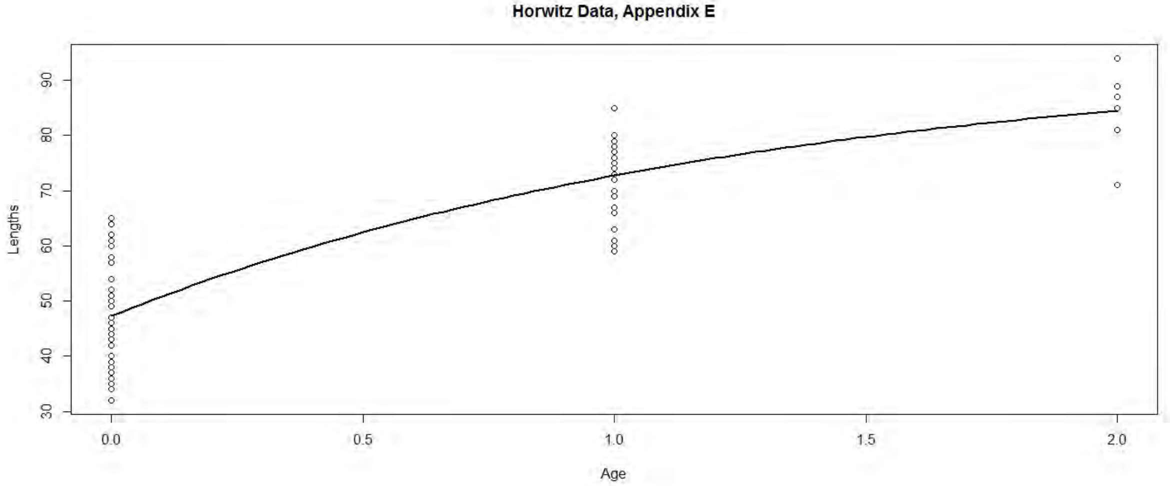

Figure 5B. Age-length relationships (Horwitz et al. 2011) derived from fitting the von Bertalanffy (1938) function to Rio Grande silvery minnow standard length data.

The apparent consistency of measurements of lengths of known aged hatchery-stocked fish (primarily ages 0 and age 1), and lengths of wild fish (with ages based on examination of their otiliths), suggests a maximum age of three years in the wild (Archdeacon [Workshop Presentation, Session 4], reproduced as Figure 6 below). Large variability in the length of age 0 fish may reflect variability in time of spawning among adults and staggered recruitment into the age 0 cohort.

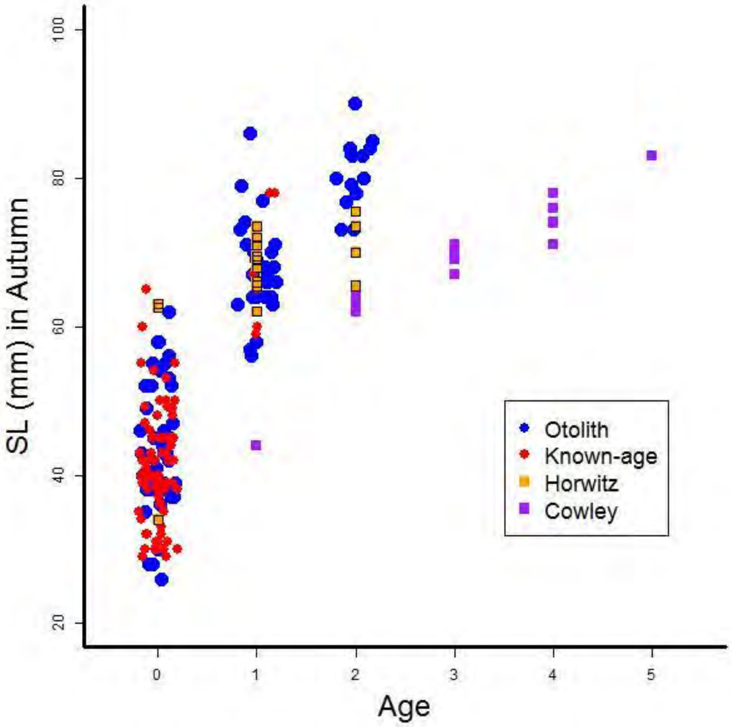

Figure 6. Age-length relationships in Rio Grande silvery minnow (Archdeacon [Workshop Presentation, Session 4]).

4.3.3 Length-Fecundity Relationships

There are no estimates of RGSM fecundity published in peer-reviewed scientific journals, although some information exists in unpublished form (Falco et al., n.d.; Dr. Caldwell, pers. comm.). Fecundity for cultured RGSMs, based on a sample size of five for each age class, ranges from just over 3,017 for age 1 fish to 15,522 for age 5 fish (Dr. Caldwell, pers. comm.). An extended discussion of uncertainties and recommended studies relevant to this topic can be found in Section 3.2.2 of our report.

Fecundity-size relationships in most fishes are described by the power function relating fecundity to fish standard length (Bagenal 1978):

$$f = aL^b$$

where, $f =$ fecundity (number of eggs from a female RGSM of length L and $L =$ fish length [mm]).

Assuming a multiplicative error structure, the parameters *a* and *b* are estimated from a log-log, linear regression model:

$$\log(f) = \log(a) + b\log(L) + \varepsilon .$$

Preliminary estimates of these parameters (on a log10 scale) are available from an analysis of Dr. Caldwell's unpublished data (pers. Comm.). The fitted function $(R^2 = 0.91)$ is:

$$\log_{10}[\#\text{eggs}] = -2.30 + 3.275 * \left(\log_{10}[\text{length}]\right)$$

$$\#\text{eggs} = 10^{(-2.3+3.3\log_{10}[\mathit{length}]}$$

Importantly, it is possible to combine the results from fitting the VBGM function to the RGSM length-age data with the fitted RGSM length-fecundity relationship to derive estimates of age-related fecundities (Table 1; see Recommended Studies C in Section 3.2.3). These preliminary fecundity estimates could be used for an initial parameterization of a deterministic version of the projection matrix. If the model were female-only (the usual method), then the number of eggs would by multiplied by 0.5 before computing fecundity values (see additional discussion of the Key Uncertainties B in Section 3.1.2 and Recommended Studies B in Section 3.2.2).

Table 1. Example of expected age-specific fecundity estimates (number of eggs) based on estimated length-age relationships combined with estimated fecundity-length relationships.

Age	Predicted Length (mm)	Number of Eggs
1	47.28	1,520
2	72.76	6,239
3	84.50	10,184
4	89.91	12,480

4.3.4 Assigning Rio Grande Silvery Minnow to Age-Classes Based on Body Length

The standard lengths of all RGSMs caught during population seine surveys are recorded (e.g., Dudley et al. 2016b). Histograms of frequencies of body length in many fish species, including RGSMs, often show distinct modes that hypothetically represent different age classes. Samples from a multi-aged fish population represents a mixture distribution because body sizes vary considerably within a given age class (Quinn and Dersio 1999). Statistical methods exist to extract a specified number of groups from, for example, length-frequency data, and these methods are commonly used to assign ages to fish based on their body lengths (MacDonald and Pitcher 1979, Quinn and Dersio 1999). Because the length of fish sampled in the monthly monitoring surveys is routinely measured, a post-hoc age assignments to age-class using the mixture distribution algorithm in R package *mixdist*, is recommended.

Mathematically, the heterogeneous histogram is fit by a mixed probability density function g that is a weighted sum of component density functions:

$$g(X \mid \mu, \sigma) = \pi_1 f(x \mid \mu_1, \sigma_1) + \ldots + \pi_k f(x \mid \mu_k, \sigma_k)$$

The component distributions $f(x)$, can be normal, lognormal, exponential, etc., and the weights, π_i represent the estimated proportion of the sample in each of the *k* distinct age-class probability density functions. Fitting the mixture distribution to RGSM length-frequency data is easily done using R package *mixdist*. To use these methods requires an *a priori* specification of the number of groups and initial starting values for group means and variances. Starting values for these parameters could be based on length-age relationships derived from otolith-aged fish. Application of these methods to the length frequency data collected in the October/November CPUE surveys would allow assignment of sampled RGSM to age groups based on the their length. Assignments could be informed by the results of modeled length-age relationships discussed previously.

The R package *mixdist* provides functions that allow estimation of age-specific mean lengths, corresponding variances, and proportions of age groups from an unknown mixture of age groups given different assumed distributional forms of length frequencies at age (see MacDonald 1979, 1987). An example application of R package *mixdist* to simulated RGSM length-frequency data is shown below (Figure 7) based on a simulated data set. In this application, we specified as starting values: 1) three age classes; 2) mean age-specific lengths estimated from fitting the VBGM to the RGSM age-length data; and 3) age-specific variances estimated from Archdeacon (Workshop Presentation, Session 4). Estimated age distribution values were: age 0 = 0.58, age 1 = 0.27, and age 2^+ = 0.15.

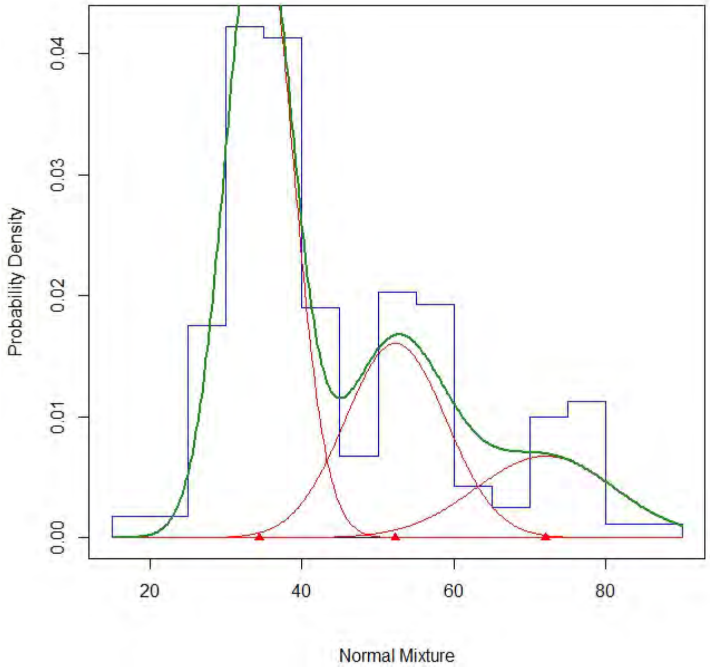

Figure 7. Example of fitting a mixture distribution to the frequency distribution of Rio Grande silvery minnow standard lengths using R package *mixdist*.

Length frequency data of RGSM collected with non-selective sampling gear, or adjusted for gear selection (see Recommended Studies E in Section 3.2.5), fit to a mixture distribution would allow estimation of the age-specific proportions in the RGSM population. Multiplication of this vector by the projection matrix would provide a projection of the expected abundance vector at survey time *t+1*. Lack of concordance between the observed age abundance vector based on the October survey in year *t+1* and the model-projected distribution would suggest some environmentally driven change in recruitment or survival. Associating these temporal changes with environmental covariates (e.g., flow regime in year *t+1*) could provide insights into causal relationships between population abundance outcomes and environmental factors.

It is important to recognize that the size frequency distribution of a sample may not accurately represent population size structure because of biases arising from size-dependent catchability. Standardization of gear and sampling effort and other factors that affect catchability do not address biases associated with environmental variation of variation among mesohabitat types (see discussion in Breton et al. 2013). Reliably drawing inference from the analyses described in this chapter may again be dependent on estimates of catchability (*q*) or, alternatively, restricted to specific mesohabitat types if one can assume that catchabilities are relatively constant, even if unknown, with a given mesohabitat type (for addressing issues of catchability, see Key Uncertainties E in Section 3.1.5 and Recommended Studies E in Section 3.2.5).

4.3.5 Spawning Behavior

<u>Fractional Versus Complete Spawning</u>

Recent research by Dr. Caldwell (unpublished data, pers. comm.) based on captive RGSMs in a laboratory setting, found that a considerable number of eggs remains in the ovaries relative to what is initially released after the first ovulation and spawn (Figure 8). The first spawn released the majority of the eggs for the year (an average of 65%). Further, the relationship between numbers of eggs released during the first spawning and total fecundity (eggs released + remaining) was generally consistent across age classes. These results suggest that RGSMs across all age classes are potentially fractional spawners. A key uncertainty, however, is whether egg number, and the temporal pattern of release, in hatchery fish reflects the spawning potential and behavior of wild fish. If hatchery fish are valid proxies for wild fish, then it is important to take into consideration the eggs that remain in the ovaries after the first spawn to get a clearer picture of total fecundity potential for the year.

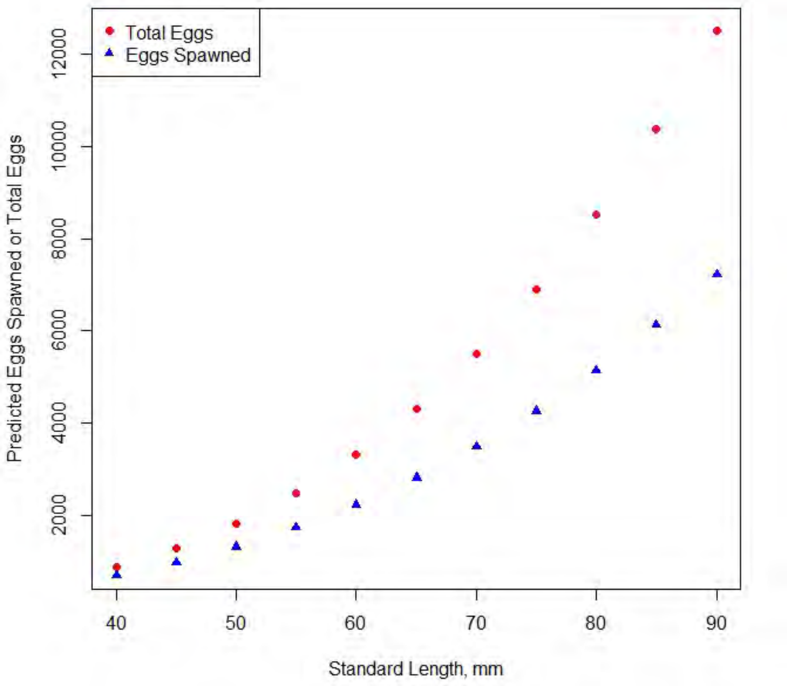

Figure 8. Relationships between the total number of eggs spawned, or retained, after hormonally induced spawning in Rio Grande silvery minnows (Dr. Caldwell, unpublished data, pers. comm.).

In additional to experiment studies, histological classification of ovarian follicles are the most precise method for determining reproductive condition and also can determine whether RGSMs are complete or fractional spawners (Erickson et al. 1985a). Uncertainties associated with spawning behavior (that is, is the RGSM primarily a complete, fractional or serial spawner) are important to resolve and would need to be addressed in the structure of the projection model. An extended discussion relevant to this topic can be found in the Key Uncertainties and Recommended Studies: Reproductive Biology.

Spawning Time(s)

The distribution of spawning times could, in principle, be estimated from collections of eggs made using Moore Egg collectors during egg sampling conducted monthly from May through August. If the design of these collectors could be improved to allow samplers to collect eggs from throughout the water column, then approximately unbiased estimation of egg passage through time would allow to determination of the duration, intensity and range of spawning activities, including late summer monsoonal events (see Chapter 7).

Careful examination of size-frequency data for presumed age 0 fish collected in the October monitoring survey (e.g., Dudley et al. 2012), should allow determination of the extent to which spawning occurs after the spring high-flow period. Presumably, age 0 fish originating from late summer spawning would be noticeably smaller, at time of the October census, than age 0 fish originating from the April-June spawning. Analysis of these size frequency data, over the long number of years of monitoring, should provide insights into whether or not late summer (July-September) spawning produces age 0 fish that are alive at time of the late fall monitoring surveys. Finally, these data should also allow an estimate of the extent to which late summer/fall spawning contributes potential recruits to the age 1 cohort at the next spawning period (length frequency data from April sampling).

4.3.6 Estimates of Total Eggs Production (Fecundity)

One component of the RGSM monitoring program is egg counts surveys (conducted since 2001) occurring shortly after the spawning period (e.g., Dudley et al. 2016a). These studies have demonstrated that the primary period of spawning is mid-April to mid-June. Based on general linear mixture models (a mixture of occurrence [binomial] and count-based [log normal] distributions), relatively strong relationships have been found between egg passage rates (eggs per second) and various hydraulic variables (see Recommended Studies D in Section 3.2.4).

Total egg deposition at the time of spawning is a reflection of the sum of size-specific fecundities over all adults alive in the population at time of spawning. Estimates of the number of eggs produced by spawners in year *t+1* can be projected from the size distribution of RGSMs in the October survey discounted by the age specific over-winter (October to May) survival rates.

Population projections can be made by implementing the following steps: 1) partition the size frequency data from the October survey data into three age classes using the algorithms in R package *mixdist* (the distribution mixture of the overlapping sizes at age); 2) from the identified age class distribution, compute the mean and variance (and distributional form) of length for each of the three age groups; 3) given these distributions, generate n_i random values of length for each of the *i* ages (note; the n_i values are the age-specific abundance estimates based on the October survey data adjusted for catchability and using the population expansion factors in Dudley et al. 2016a population estimation study); and 4) apply the fecundity-length relationship to estimates the total number of eggs produced in year *t+1.*

Given a frequency distribution of body lengths for each age class (0, 1, 2), compute:

Total number of spawners, $\hat{N}_T = \sum_{i=0}^{2} \hat{n}_i$; and

Total number of eggs, $\hat{E}_T = \sum_{i=1}^{\hat{N}_T} \hat{a} L_i^{\hat{b}}$, where L_i = length of spawner *i*, and $\hat{b}$ is the power function exponent estimated from a regression of number of eggs produced by a fish of length *i* (see below).

A key assumption of this estimate is that there is no sampling bias arising from size-dependent or gear-dependent catchability. That is, that the size-frequency distribution from the sample is an unbiased estimate of the true distribution (see Chapter 7). It will be challenging to estimate catchability for each mesohabitat type, scale up by the estimated areas of each mesohabitat type, and derive unbiased estimates of total number of eggs across age classes.

This is an ambitious goal if a global estimate across all mesohabitats is the objective. A more realistic, but still important, goal would be to focus on a high density mesohabitat type where catchability can be assumed constant across years and reaches. A defensible "index" of adult abundance would allow an estimate of age composition via application of R package *mixdist*, accompanied by informative priors (number of age groups, mean/median length per age group). Finally, application of the fecundity-length relationship would allow calculation of a useful index of egg deposition in that mesohabitat type.

4.4 Model Parameterization

Parameterizing the RGSM projection model is admittedly very difficult, requiring targeted studies to estimate the vital rates and their relationships to key environmental covariates. One method to acquire preliminary estimates of survival rates, for example, is to include observations on key intermediate life stages, i.e., use estimates of larva, juvenile, and adult abundances from the ongoing RGSM surveys in the model-fitting step. Some preliminary estimates are available for survival rates (Goodman 2010, 2011a, 2011b; Cowley [Workshop Presentation, Session 4]) and fecundities (Dr. Caldwell, pers. comm.) which allow for preliminary sensitivity analyses to prioritize demographic studies (see discussion below). Importantly, the CPUE data collected throughout the year as part of ongoing surveys provide significant opportunities for survival and growth rate estimates if the data are first corrected for temporal and spatial differences in catchability.

4.4.1 Abundance Estimates: Catchability

The population state vector of the projection model is initialized with an estimate of the age distribution vector $N_0^{'} = [n_0, n_1, n_{2+}]_{t=0}$ at time 0. Estimates of the initial age vector can be based on late fall CPUE survey data after adjustment for imperfect catchability. Dynamic changes in the state vector are projected forward in time as function of the age-specific birth and survival rates (matrix *L*, Figure 4. To initialize the model, and to determine if projected abundances from the model match the survey estimates, requires unbiased estimates of N_t. The importance of estimating catchability to adjust the CPUE index to achieve unbiased estimates of N_t has been mentioned numerous times in this chapter (see detailed discussion in Chapter 7). Catchability is also relevant to acquiring a more complete understanding of the life history of RGSMs. Biases introduced by spatial and temporal variation in catchability affect estimates of survival rates and estimates of reproductive potential based on size-fecundity relationships as well as population age structure. For example, using length-frequency data that have not been adjusted for imperfect detection can result in erroneous conclusions regarding population structure and dynamics with implications for management (Breton et al. 2013).

We propose that the challenge of estimating mesohabitat-specific catchabilities can be partially addressed by comparing mesohabitat-specific CPUE (an index of mesohabitat-specific fish density) based on October monitoring surveys to mesohabitat-specific estimates of density based on October closed population removal method estimation as carried out previously by Dudley et al. (2012). Our recommended approach rests on two critical assumptions. First, we assume that beach seine catchability, though unknown, is relatively constant within a given mesohabitat type if annual sampling in this habitat type is conducted under similar flow conditions. Second, we assume that the numbers of fish present within enclosures used for removal method estimation (see Dudley et al. 2012) are equal to the numbers originally present within the areas of the enclosures so that the removal method estimates of abundance allow approximately unbiased estimation of mesohabitat-specific density. (The second assumption should be rigorously "tested" in a realistic field setting.)

In October population monitoring surveys (Dudley et al. 2016a), multiple random beach seine hauls (20 hauls) are taken within each primary sample unit with sampling effort in each primary unit stratified by mesohabitat type. Mesohabitat-specific CPUE values can be calculated by summing all seine catches within a mesohabitat type and dividing by the total area swept by all seine hauls (see Chapter 7; Figure 11 in Dudley et al. 2016a). This calculated CPUE value should be directly proportional to the density of fish in a given mesohabitat type, with the proportionality factor equal to habitat-specific catchability.

In the population estimation surveys (see Dudley et al. 2012), *n* random locations within a given mesohabitat type (within a primary sampling units) are selected and enclosures are deployed over these selected locations. The abundance of fish within these enclosures is estimated using removal method estimation based on multiple-pass electrofishing (Zippin 1958, Otis et al. 1978). If estimates of abundance within enclosures are of high accuracy, they can be combined across enclosures within mesohabitat types and then divided by the total area of all sampled enclosures, thereby generating an estimate of fish density (fish per unit area) in a given mesohabitat type. This estimate of fish density will be approximately unbiased if capture electrofishing probability is high and at least three removals are taken.

Thus, the expected value of the CPUE index in mesohabitat type *j* would be the product of q_j (catchability) and density, whereas the removal method sampling would generate a nearly unbiased estimate of actual density. Computing the ratio of mesohabitat-specific CPUE to the estimated mesohabitat-specific density would provide a good estimate of mesohabitat-specific catchability.

The approximate variance of the estimated *q* can be estimated via Taylor series approximation. Based on the variance of the ratio of two independent random variables, the approximate variance is:

$$v\hat{a}r(\hat{q}) = \left(\frac{(CP\hat{\hat{U}}E)^2}{\hat{\hat{N}}^2} \right) \left(\frac{s^2_{CPUE}}{(CP\hat{\hat{U}}E)^2} + \frac{s^2_N}{\hat{\hat{N}}^2} \right)$$

where, s^2_{CPUE} is the variance in the CPUE index computed across sample units, and s^2_N is the variance associated with the removal estimate of *N*

Given mesohabitat-specific estimates of catchability, and maps of areas of mesohabitat types within each primary sample unit (as in Dudley et al. 2012), this allows mesohabitat-specific abundance estimates in the 20 primary sample units. To expand beyond these sampled reaches would require maps and estimates of total area of mesohabitat type for the entire MRG channel. This method of extrapolation to the entire RGSM population in the MGR was used in the Dudley et al. (2012) population estimation study.

4.4.2 Survival Rates

Very rough "back-of-the-envelope" estimates of annual survival rates have been made from analyses of the CPUE data collected over multiple time periods that approximately span the interval from one birth pulse to the next. For example, Goodman (2011) estimated annual survival rate across all age classes combined based on regression estimators assuming that monthly survival rates can be calculated as:

Survival, $\hat{s}_t = CPUE_{t+1} / CPUE_t$, where *t* is a particular month.

If monthly survival were constant over a period of multiple monthly surveys, then a common monthly survival rate could be estimated by linear regression (Skalski et al. 2005),

$E[N_t] = N_0 e^{-rt}$, expected cohort abundance at time *t* is a function of the initial cohort abundance N_0;

$\ln\left(\frac{N_t}{N_0}\right) = -rt$, log-linear model of the form $y_t = \beta t$, where the slope $\hat{\beta} = -\hat{r}$;

$\hat{S}_t = e^{\hat{\beta}}$, survival from one month to another; and

$S_{annual} = S_t^{12}$, annual survival rate.

Survival estimates could be age-specific if the CPUE data were first partitioned by age-class to define age-specific cohorts; to define cohort *i* as members of age-class *i* at time *t* as $N_{i,t}$. However, it is important to recognize that an assumption of constant catchability across all surveys is required for unbiased estimates of survival. In addition, the size-frequency distribution likely changes over time as smaller fish, which are expected to have lower survival rates, are lost from the population.

Initial estimates of over-winter survival rates could be made based on age ratios, $(n_{i,t+1} / n_{i,t})$, comparing October CPUE survey data (*t*) to early spring (*t+1*) CPUE survey data. Based on life-history sensitivities of *r*-selected species, early life-history survival rates, including p_e, p_l, p_j, are expected to greatly affect rates of population change (see Section 4.5). Given the monthly sampling that occurs from April to October (Dudley et al. 2016a), monthly or multi-month survival rates estimates are possible if the CPUE data are adjusted for time and habitat-dependent differences in catchability. Such analyses may be particularly important if mortality rates are highly variable across this interval, for example, during summer low-flow periods. Within-year, temporal variation in survival rates could be related to temporally varying environmental factors via statistical modeling to identify causal relationships.

Precise estimates of survival may be very difficult to make from wild populations, but RGSM hatchery facilities (Los Lunas and Albuquerque BioPark) could be employed to conduct controlled experiments focused on key aspects of the RGSM's life-history uncertainties.

4.4.3 Age-Specific Fecundities

As discussed above, there are no estimates of RGSM fecundity published in refereed scientific journals. However, preliminary estimates from hatchery fish are available (Falco et al., n.d.; Dr. Caldwell, pers. comm.). The relationship between fecundity estimates from cultured fish under laboratory conditions and that realized by wild fish is unknown. It may be that fecundity estimates from hatchery fish, reared under optimal conditions, are not representative of the fecundities of wild fish. To address this uncertainty, we suggest that a sample of gravid fish, spanning a range of body lengths, be taken just before initiation of peak flows in the spring. These fish would be sacrificed, aged via otilith examination, and the number of eggs in various stage of development counted. (An alternative would be to capture wild fish, move them to a hatchery facility, hold them for a short period, induce spawning, and release them back into the wild, requiring no sacrifice). These data would then be used to estimate size (age) fecundity relationships based on wild fish.

As discussed previously, age-specific fecundity estimates are possible by combining estimates from length-age models (via fitting the VBGM function to RGSM length-age data) with estimates of RGSM size-fecundity relationships. The estimated fecundities could be used to parameterize a deterministic version of the projection matrix.

The advantage of even preliminary, "back-of-the-envelope" estimates of vital rate parameters, as discussed in this chapter, would allow a formal life-history sensitivity analyses to be conducted.

4.5 Sensitivity Analyses

When a population's fecundity and survival rates are constant, a dynamic population will quickly reach a stable age distribution where the relative abundances of the age classes remains constant over time. Under these conditions, the dominant eigenvalue of the projection matrix, λ, can be interpreted as a measure of the finite rate of change of the RGSM population. Values of $\lambda < 1$ indicate the population is in decline, whereas $\lambda \geq 1$ indicates the population is stable ($\lambda = 1$) or increasing. Intuitively, λ can be understood as $\lambda = \frac{N_{t+1}}{N_t}$ where N_t is total population size at time t. Estimates of λ_t over time provides an independent estimate of population trend not directly based on regression modeling of the October CPUE data (Dudley et al. 2016a).

How λ changes as a function of an infinitesimal change in a matrix element in row *i* and column *j* (a_{ij}) of the projection matrix, or how λ changes based on a small change in a given vital rate (e.g., p_0) can be easily estimated. These estimates of λ sensitivities, coupled with estimates of the natural variance of a vital rate (discussed below), are very important analyses to conduct. Insights from these analyses can inform management decisions and identify key life-history uncertainties relevant to sustaining populations of the RGSM.

Analytical sensitivity is the tiny absolute change in λ caused by a tiny absolute change in a vital rate (or matrix element) holding all other rates constant. Sensitivity (s_{ij}) of λ to matrix element a_{ij} is:

$$s_{ij} = \frac{\partial \lambda}{\partial a_{ij}}$$ (the partial derivative of λ with respect to a_{ij}.

When sensitivities are rescaled to account for the magnitude of a vital rate (note the very different scales and measurement units for *m* and p_0, for example), they are called proportional sensitivities or elasticities to matrix element a_{ij}:

$$s^*_{ij} = \frac{\partial \lambda}{\partial a_{ij}} \times \frac{a_{ij}}{\lambda}.$$

However, we are most often interested in how λ is affected by tiny changes in individual vital rates, the so-called lower-level sensitivities and elasticities. Because an individual vital rate may occur in more than one matrix element, sensitivities and elasticities must include information on all matrix element containing a given vital rate (r_k):

$$s_{r_k} = \sum_i \sum_j \frac{\partial \lambda}{\partial a_{ij}} \times \frac{\partial a_{ij}}{\partial r_k}$$ (sensitivity of λ to vital rate r_k)

and,

$$s^*_{r_k} = \frac{r_k}{\lambda} \sum_i \sum_j \frac{\partial \lambda}{\partial a_{ij}} \times \frac{\partial a_{ij}}{\partial r_k}$$ (elasticity of λ to vital rate r_k).

Estimates of vital rate sensitivities (particularly elasticities), provide powerful management insights: they point out which aspects of a species life-history are most likely to affect rates of population change. There remains one important caveat: evolution and natural selection usually select for minimal variation in those vital rates that most affect a species’ rate of population change, a process called canalization (Gaillard et al. 1998). Such rates are often resistant to change by management actions. Therefore, a second piece of information is needed: what is the natural, background temporal variation in a given vital rate (i.e., its process variance)? A vital rate with a small elasticity but high process variance may affect population growth rate more than a rate with high elasticity but small process variance (Mills et al. 1999, Mills 2013). Therefore, vital rates with both high elasticities and high process variance are those life-history attributes that should be intensely studied and the target of management actions.

Estimates of population growth rate (λ) sensitivities to variation in a given vital rate, including information on the rate's process variance, are referred to as "life stage simulation analyses" (Wisdom et al. 2000, Morris and Doak 2002). Given initial estimates of these process variances, sensitivities can be easily estimated using R package *popbio* (Stubben et al. 2007).

4.5.1 Preliminary Analysis

We used preliminary estimates of RGSM vital rates as summarizing in Miller (2012) to construct both a pre-birth pulse and post-birth-pulse projection matrix. Miller (2012) summarized the results of a population viability analysis (PVA) workshop sponsored by the PVA Workgroup of the MRG Endangered Species Collaborative Program. Since Miller (2012) assumed a pre-birth pulse matrix with four age classes, and eigenvalues and elasticities are identical across pre and post matrix representations, we also analyzed a pre-birth-pulse model. Vital rate estimates to parameterize the matrix used by Miller (2012) were derived from various sources, including Goodman (2011), Remshardt (2007), and estimates provided at the PVA workshop (Valdez [Workshop Presentation, Session3]). Parameter estimates from the workshop were, $p_0 =$ 0.0016, $p_1 = 0.039,\ \ p = 0.05,\ \ m_1 = 658,\ m = 1480$ (fecundities expressed as the number of female eggs/adult female). Leading to the following matrix structure:

$$\begin{pmatrix} p_0 m_1 & p_0 m & p_0 m \\ p_1 & 0 & 0 \\ 0 & p & p \end{pmatrix}$$

Note that this matrix is different than in Miller (2102) for two reasons: 1) the matrix in Miller (2012) was structured incorrectly, and; 2) we allowed fish to live beyond three years of age.

We conducted a preliminary life-history sensitivity analysis of the above matrix to compute life-history elasticities (Figure 9).

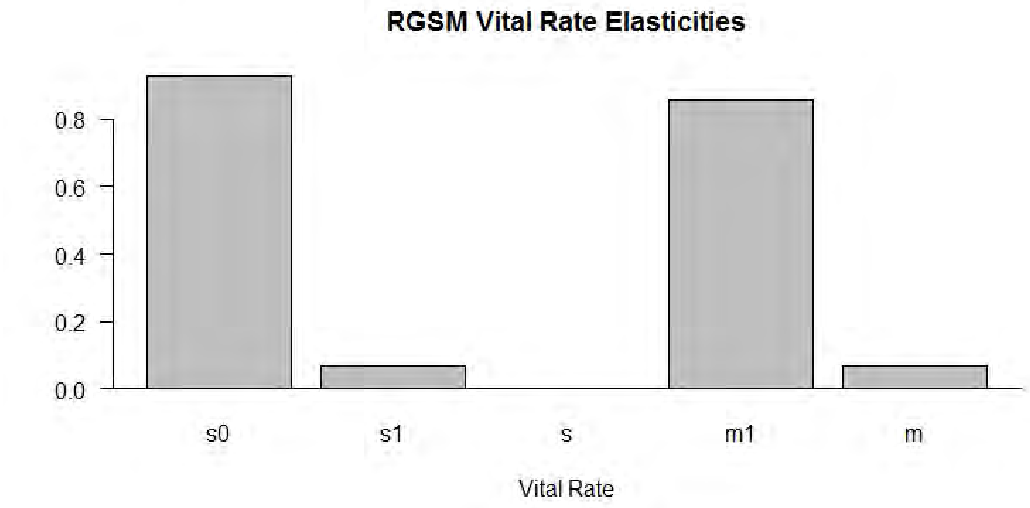

Figure 9. Preliminary estimates of vital rate elasticities for the Rio Grande silvery minnow.

In terms of the ordinal ranging of elasticities, the results of this analysis are not surprising; age 0 survival rate and age 1 fecundity rate most strongly affect rates of population change, λ (cf. Wilde and Durham 2008). The growth rate estimate from this matrix was $\lambda = 1.138$ suggesting the potential for an approximate annual rate of increase of about 14%. The stable stage distribution from a post birth-pulse matrix using the same parameter estimates indicated that about 98% of the population is in age class 0.

Note that in the above matrix we set matrix element {3, 3} (third row, third column) equal to the adult survival rate (p), effectively allowing adult RGSMs to live forever. Alternatively, if we set matrix element {3, 3} = 0, we force death during the fourth year of life. Importantly, the estimates of growth rate (λ) in these two matrix representations are effectively equal. Therefore, resolution of the apparent dispute concerning longevity of RGSMs (see Recommended Studies C in Section 3.2.3) may have little relevance with respect to RGSM population growth rates. On the other hand, this result depends on an assumption that the survival rates are well-identified and emphasizes the importance of generating improved estimates of survival rates.

It is important to note that results from eigenanalyses of projection matrices are asymptotic properties of the matrix and reflect deterministic assumptions. The estimate of λ from Miller (2012) assumed constant vital rates, exponential growth, and a stable age distribution—three conditions that are unlikely to be true for RGSM populations. Dynamic models, with time-varying parameters, can show quite different dynamics. Even populations with a deterministic λ >1 are unlike to show population increases if one or more of the vital rates are characterized by even moderate degrees of process variance (Lande et al. 2003).

Finally, the specific value of λ depends directly on the specific values of parameters incorporated in the projection matrix. As noted previously, estimates of age-specific fecundities are not available for wild fish and estimates of early life survival rates have high levels of uncertainty. Therefore, it should not be assumed that our calculated λ (1.138) is a well-identified value. Nevertheless, we believe that the essential relationships among parameter elasticities should be quite robust to uncertainty in parameter estimates. It is very likely that the key parameters controlling growth rate of the RGSM population are age 0 survival rate and age 1 fecundity rate.

4.6 Including Management Covariates

Estimating the relationships between environmental variables, particularly those that can be altered by management practices, and RGSM vital rates is an important research priority. The covariate modeling conducted by Dudley and others (e.g., Dudley et al. 2016b) provides an excellent foundation. Their statistical models relate temporal and spatial variation in the CPUE index to multiple environmental and hydrologic factors, including several within the purview of managers. Their major findings were that the CPUE index of RGSM abundance "… was reliably predicted by changes in hydraulic variables over time". Specifically, temporal trends in CPUE were closely related to the timing, duration, and magnitude of spring and early summer flows. Flow magnitude and duration are clearly related to the creation and availability of in-channel habitats (low-velocity shoreline and island backwater habitats, as well as to inundation of the floodplain (see detailed discussion of the relationship between flow characteristics and creation of mesohabitats relevant to the life-history requirements of the RGSM in Chapter 8).

Chapter 8 report identifies the key habitat types that could be further explored in statistical models evaluating the relationships between key RGSM vital rates (i.e., survival and birth rates as response variables), as well as habitat types and hydrodynamic variables as candidate predictor variables. These models could be used to estimate the extent of the temporal and spatial variation in a given vital rate that can be explained by each habitat type and any significant interactions between hydrodynamic variables and habitat types.

In Chapter 8, we classify the MRG into spatial components with potentially different degrees of significance for various life stages:

i) main channel;
ii) channel margins;
iii) in-channel bars (mid-channel or bank-attached);
iv) in-channel pools;
v) floodplain surfaces, including channels and pools; and
vi) irrigation drain outlets.

The extent of each of these habitat components varies among the four major reaches between diversion dams, as do their connectivity and their responses to gauged flow magnitude and duration. The ecological role of each mesohabitat component is acknowledged to at least some degree by most of the literature and briefings that the panel received, although there is no agreement on the relative importance of all components for production rates, growth rates, or survival rates at various life-history stages.

The most recent population monitoring report we reviewed (Dudley et al. 2016a) reports significant relationships between the October CPUE index and several broad-scale hydrologic variables. For example, RGSM density estimates showed strong relationships with the number of days with flows greater than 3,000 cfs, mean daily flows (March-October), days with flows less than 200 cfs (March-October), and estimated acres of floodplain inundation (May). However, to fully understand, and effectively manage, the dynamics of RGSM populations requires further study into how broad-scale hydrologic factors, as well as fine-scale environmental conditions, affect the underlying processes of birth and survival that give rise to observed RGSM abundance.

We recommend that demographic rates be modeled as a function of broad-scale hydrologic variables, mesohabitat type, and abiotic factors that may vary across mesohabitat types (e.g., salinity, turbidity, water depth, local flow rates, etc.). Some of these studies may be possible to implement in the field, as observational studies taking advantage of natural temporal and spatial variation in the covariates. Others may require experiments conducted under controlled conditions in the Los Lunas or Albuquerque BioPark hatchery facilities.

4.6.1 Example: Covariate Modeling of Survival Rates

The projection model assumes that all fish within age class *i* have the same survival rate. However, this unlikely to be true; even individuals in the same age class are likely to vary in their survival probabilities as a result of experiencing different environmental conditions. Suppose we wish to model first-year survival, p_0 as a function of broad-scale flow (*F*), mesohabitat type (*H*), and local environmental conditions (*E*). Our model must reflect the constraint that $0 \leq p_0 \leq 1$, so we will use a logistic model with a logit link:

$$p_{0,t} = \frac{1}{1 + \exp(\beta_0 + \beta_1 F_t + \beta_2 H_i + \beta_3 E_{j,t})}$$

By including covariates that vary by time (*F* and *E*) and by space (*H*), the above model allows p_0 to be temporally and spatially dynamic. After estimating the regression function, it could be inserted into the matrix model in place of p_0. Updating estimates of the covariates *F* and *E* would make the matrix time-specific so as to reflect current (or past) environmental conditions. In general, replacing fixed vital rate values with functions relating them to environmental covariates links the projection model directly to environmental variation.

Other vital rates, such as fecundity, could be modeled in a similar fashion using an appropriate link function and an informed selection of covariates. For example, Goodman (2009) makes an initial attempt to account for the influence of adult population on recruitment using an estimate of "per capita recruitment" (recruits per adult) as a dependent variable and examined its relationship to various flow covariates. In addition, it would be useful to model egg production as a function of the number of acres of inundated floodplain using a normal or Poisson regression model (see Recommended Studies B in Section 3.2.2).

4.7 Density-Dependent Effects

Studies of most imperiled species generally do not consider density-dependent effects because most at-risk species are characterized by small populations. However, if the primary driver of a severe population decline is habitat loss or declines in habitat quality, density dependence can be operative even at small population sizes. For example, if RGSMs are primarily a demersal floodplain spawner, then reductions in flow magnitude and duration, coupled with pronounced incision of the channel and a loss of connection of the channel with its floodplain, may result in spawning habitat limitation with important demographic effects on recruitment. (See further discussion of this topic in Chapter 8 and Section 3.2.4 to better understand the significance of floodplain habitats to early life-history stages of the RGSM.)

Preliminary analyses by Goodman (2011) suggest an absence of a strong relationship between the estimated number of potential future spawners (age 0 and age 1+ fish) near the end of year *t* and reproduction in year *t+1*. This pattern suggests that even when the RGSM populations are small near the end of year t (e.g., few age 0 and 1+ fish in the October survey), there are enough spawners in year *t+1* to essentially saturate the reproductive potential of the available spawning habitat. This suggests the possible presence of density-dependent constraints on reproduction that are driven by limitations in the area and availability of spawning habitat.

Goodman (2011) explored the relationship between annual age 0 cohort survival rates and August CPUE estimates. These preliminary regression-based analyses suggested an apparent density-dependence in first-year survival. Goodman (2011) went further to hypothesize the possibility of some limiting resource that does not vary in concert with the availability of spawning habitat or with the extent of summer drying.

In the following, we provide an example of how density-dependence in recruitment could be incorporated into the projection matrix. To do this, we make use of the Ricker function (Ricker 1954), commonly used in fishery applications:

$$N_{t+1} = N_t \exp\left[r \left[1 - \left(\frac{N_t}{K} \right) \right] + \varepsilon_t \right],$$

where r = the intrinsic growth rate, K = the environmental carrying capacity, and ε represents environmental stochasticity.

In the Ricker function, as K goes to infinity, $N_{t+1} = \lambda_t N_t$, equivalent to projection matrix dynamics without density dependence.

If we define E_t to be initial egg density at time *t*, and s_0 as the survival rate of eggs when egg numbers are small, then we can enter egg survival into the model as (Morris and Doak 2002, page 317):

$$s_0\left[E_t\right] = s_0 \exp(-\beta E_t)$$

where s_0 is age 0 survival rate in the absence of any density limitation and β describes the decline in survival rate as spawning habitat becomes limiting. The $\beta-$coefficient in the above equation is estimated from a regression of log egg survival versus number of eggs, with data derived from experiments that may be feasible under hatchery conditions.

5 RIO GRANDE SILVERY MINNOW AGE AND GROWTH RELATIONSHIPS

5.1 Key Uncertainties

What is the longevity of RGSMs in the wild?

What is the relationship between length and age?

5.2 Management Relevance

Substantial difference of opinion exists concerning longevity and size at age of RGSMs. Longevity is an important element of the population dynamics of the species. For example, there is greater resilience to periods of drought if there are more age classes participating in spawning. Size (length) at age affects fecundity and in turn affects total annual egg deposition of the RGSM population.

5.3 Summary of Available Information

1. **Cowley et al. (2006)**
   a. Cowley et al. (2006) reasonably argue that the best evidence of historic age structure might come from historic preserved specimens of RGSM, under an (unstated) assumption that historic collections were representative of the size and age structure of the species. They worked up scale and ray counts of specimens collected in the MRG in 1874 near Santa Fe (USNM # 15801) and originally identified/curated as *Hybognathus nuchalis* (Mississippi minnow). The authors provided unconvincing quantitative evidence that the museum specimens are instead *H. amarus* (RGSM), but the maximum size of Mississippi minnow (180 mm), commonly seen to 125 mm and lengths at age 1 and age 2 of 75 mm and 100 mm, respectively (Fishes of Texas Project 2013) makes it unlikely that the specimens were *H. nuchalis*, even though the historic native distribution of this other species may have included the Rio Grande in New Mexico.

   b. Cowley et al. (2006) aged 13 of the 20 fish in the museum collection. Criteria used to identify annual marks were not described and no photographs of scales were included, so it is not possible to determine how the presence of annuli was determined.

   c. On the basis of identified annuli, Cowley et al. (2006) found the following numbers of fish at age in the historic sample: age 1 (one specimen), age 2 (three), age 3 (four), age 4 (four), and age 5 (one). Based on a regression of standard lengths against the logarithm of age (which has no theoretical basis of which we are aware), Cowley et al. (2006) predicted the following lengths based on annuli: age 1: 46.3 mm; age 2: 61.1 mm; age 3: 69.8 mm; age 4: 75.9 mm; and age 5: 80.7 mm.

2. **Horwitz et al. 2011**
    a. Using otoliths and scales, and measures of standard lengths (SL), Horwitz et al. (2011) reexamined the 1874 museum collection and also aged contemporary otoliths and scales deliberately collected to represent the full wide range of lengths of collected RGSMs: 83 fish collected in autumn 2009 (28-90 mm SL), and 75 fish collected in spring 2010 (32-87 mm SL).
    b. The Horwitz et al. (2011) lengths of museum specimens do not appear to match up with those lengths reported by Cowley et al. (2006), presumably due to curvature of preserved museum specimens (see Archdeacon [Workshop Presentation, Session 4 (slide 13)]; and item 3 below).
    c. Horwitz et al. (2011) found that scale ages were a bit greater than otolith ages, which is unusual. However, otoliths are usually a more reliable hard part for aging.
    d. The Horwitz et al. (2011) otolith ages are “surface” ages, which may possibly underage long-lived fish due to the physical shape of otoliths and difficulty to separate annuli at the otolith margins.
    e. Horwitz et al. (2011) did provide photos of scales, including clear illustrations of criteria used to establish annuli on scales and otoliths.
    f. Between-reader agreement was near 90% for both otoliths and scales, but age agreement between scales and otoliths was relatively poor.
    g. The Horwitz et al. (2011) ages suggest that contemporary ages of RGSMs range from age 0 to age 3. No age 3 fish were identified in autumn 2009, but a few were detected in spring 2010 collections, presumably age 2 fish that survived over the winter and then became age 3.
    h. The Horwitz et al. (2011) age assignments for museum specimens, based on both otolith and scale ages, provide evidence of only three age groups: age 0, age 1, and age 2. These ages seem entirely consistent with contemporary collections that are dominated by the same age groups.
    i. Age assignments are bit “odd/unusual” in that annuli are “inferred” (i.e., have not yet formed, or is not yet “visible”) in spring collections. Thus, a fish with two prominent annuli, and substantial evident “plus growth” beyond the annulus, if collected in spring, is given an assignment of age 3. This practice seems consistent with the convention of aging fish according to a January birthday, but it also implies that annulus formation takes place during spring. This is odd as monthly water temperatures (Alameda gauge, Bernallilo County) clearly show that coldest mean monthly water temperatures are achieved during January (USGS 2017).
    j. Horwitz et al. also present extensive length frequency histograms of RGSMs by collection date at Rio Rancho and Socorro (from USFWS 1999) from 1993-1995. These data are broadly consistent with recruitment of age 0 fish beginning in June/July at sizes of about 20-40 mm, and with growth through October at sizes of about 30-50 mm. Sizes in June/July are no doubt larger than “average” due to

gear selection (difficulty in catching smallest age 0 fish in seines). Older ages cannot be resolved via length frequency inspection.

   k. Horwitz et al. (2011) fitted a von Bertlanffy growth equation (VBGE; "form #2 – not the usual form") and found an ultimate length of about 82 mm.

   l. Data suggest very substantial variability in length at age, but deliberate collection of equal numbers of fish from different size intervals distort the actual (real) variation in length at age: extreme values (unusually small, unusually large) are overrepresented and average values (near the mean) are underrepresented. Based on Figure 15 in Horwitz et al. (2011), RGSMs range from about 32-65 mm at age 1, to about 57-83 mm at age 2, and from perhaps 70-85 mm at age 3 (few data). Large variability in length at age is no doubt due to large variability in time of spawning among adults and in recruitment to the age 0 cohort.

3. **Archdeacon Workshop Presentation (Session 4):** *Scientific Perspectives on Longevity of RGSM*
   a. Archeadcon summarized work of Cowley et al. (2006) and Horwitz et al. (2011).

   b. He compared lengths of known-age hatchery-reared, Visible Implant Elastomer (VIE)-marked fish, released as age 0 in fall, with lengths at age in Horwitz et al. (2011) and Cowley et al. (2006): 163 VIE-marked fish were collected in March-May, and 133 were collected in August-September by the USFWS (2007-2016).

   c. Archdeacon's slide 11 displays lengths of known age fish with lengths of Horwitz et al. (2011) otolith-aged fish from the spring collections. Agreement seems quite good: ages 1, 2, and 3 are represented, with very few age 3.

   d. Archdeacon's slide 14 displays Horwitz et al. (2011) and Cowley et al. (2006) age assignments for 1874 collections as well as Horwitz et al. (2011) contemporary age assignments and known age fish from autumn collections. Ages 0, 1, and 2 are represented in contemporary and 1874 museum collections (Horwitz et al. 2011), and lengths at assigned ages compare well with those of known-age fish. Cowley et al. (2006) age assignments are again clearly at odds with other evidence of age.

   e. Archdeacon concluded that there was no empirical evidence that RGSMs live past age 3 in the wild.

4. **Lang (2016) poster:** *Validating the use of otoliths and scales……*
   a. Lang's intent was to "validate" otolith and scale annuli using known age captive-reared fish held under "near-natural temperatures" at the Albuquerque BioPark.

   b. Scales and otoliths (lapillus) were collected from fish that died in outdoor culture tanks between September-November 2016: 23 of the 2016 year class, two of the 2015 year class, one of the 2014 year class, and three of the 2013 year class.

c. Lang reported that: "Preliminary results indicate that annuli on scales are not as recognizable as annuli on otoliths… However, annuli on both structures do appear to be laid down once per year." Lang also reported that otoliths would be retained as reference collections for other researchers.

5.4 What is Known?

1. Age assignments of Cowley et al. (2006) are clearly at odds with ages assigned by Horwitz et al. (2011) for the same historic museum collections, with Horwitz et al. (2011) age assignments for contemporary collections, and with lengths of known age VIE-marked hatchery-reared fish released as age zero in fall (Archdeacon [Workshop Presentation, Session 4] nicely summarizes these findings). The adult population seems clearly dominated by age 1 and age 2 individuals, with age 3 individuals present in low numbers and rarely collected. There is no available evidence of fish reaching age 4 in the wild, though this certainly seems "possible" based on longevity of hatchery-held RGSMs and in consideration of beach seine gear selection that seems less effective for larger adult RGSMs.
2. Lang's recent work holds promise for "validating" age assignments made by Howitz et al. (2011), but the poster we had access to does not provide adequate information for proper validation.

5.5 Key Uncertainties

1. What are the (typical) distributions of length at age? (Tier 2 Study Issue)

Although the above assessment of ages of RGSMs in the wild provides strong evidence that these fish essentially never live past age three in the wild, the distributions of length at age, critical for population dynamics modeling, remain poorly characterized. As noted previously, the distributions of lengths at age from Horwitz et al. (2011) are seriously distorted by the intentional selection of similar numbers of fish from all length intervals. Also, very few lengths at age are available for age 3 fish for which beach seine gear used for most collections is probably less effective in catching the largest (and presumably oldest) RGSMs (see Gonzales et al. 2012). This kind of gear selection may also result in "truncation" of the age 2 size distribution.

2. When are annuli formed on scales and otoliths of RGSM? (Tier 1 Issue)

Although the age assignments made by Horwitz et al. (2011) appear consistent with lengths of known age hatchery-reared fish growing naturally in the MRG, the practice of "adding a year" to observed annuli for fish collected in April is baffling and raises an important question of when annuli are formed and when they become visible in this species. Proper "validation" of age assignments requires this knowledge and current age assignments lack such validation. Based on the very cool January mean water temperatures at the Alamdea gauge (3-5 degrees Celsius [C]; USGS 2017), annulus formation should occur during January or February. Thus, a fish with two annuli in October (which would be given age 2+) should theoretically have three annuli visible in April. (April mean water temperatures at the Alameda gauge range from 12-14 degrees C; USGS 2017.)

3. **Are current fitted growth curves appropriate for RGSM? (Tier 2 issue)**

   The ultimate length of RGSM was estimated by Horwitz et al. (2011) as 82 mm. This estimate may be negatively biased due to beach seine gear selection and other model parameter estimates may also be biased due to non-representative sampling of age-specific length frequency distributions (see Uncertainty 1, above). As noted above, beach seines may not effectively capture the largest (and presumably oldest) RGSMs.

5.6 Recommended Studies:

1. Tier 1: Examine the archived otoliths and scales of known age fish reared at the Albuquerque BioPark under “near natural water temperatures” (see Lang 2016 workshop poster) to firmly establish that one annular mark is deposited on otoliths each year and to firmly establish the time of annulus formation. Use this information to reevaluate the age assignments of Horwitz et al. (2011).
2. Tier 1: Develop quantitative field studies that can establish the size-selective properties of the beach seine gear that appears to be the primary gear used to collect RGSMs and monitor the status and trend of RGSM populations (e.g., Dudley et al. 2016a).
3. Tier 2: Quantitatively explore the possible consequences of gear selection bias on fitted parameters of the VBGE and on associated life-history parameters such as fecundity at age. An example of such calculations follows:

5.7 Example Calculations: Recommended Studies 3

Based on the Gonzales et al. (2012) gear comparison study, it seems fair to conclude that the "beach seine" gear typically used for catching RGSMs is less effective at catching the very largest RGSMs. If so, the age-length data used by Horwitz et al. (2011) for spring collected fish may not fully represent the sizes at age 3, and possibly also at age 2. The sensitivity of the VBGE parameter estimates to such gear selection bias can be explored by augmentation of the age 3 lengths, so that they are believed to “better represent” the full length distribution of age 3 fish, and re-fitting of the VBGE.

For example, suppose that three “imagined” observations are added to the spring 2010 age 3 group reported in Horwitz et al. (2011). Suppose that these new lengths at age 3 are 85, 89, and 94 mm (94 mm is the largest SL of a RGSM that we have heard reported). Calculations displayed below show that the estimate of ultimate length and corresponding size at age are, in fact, quite sensitive to the distribution of lengths at age 3, thereby implying that is important to develop a better understanding of the selection properties of the beach seine gear and/or to find a gear type that is less size selective.

Fitted VBGE for the lengths and ages reported in Horwitz et al. (2011), augmented by these three “imagined” data points are (Tables 2-3):

Table 2. Parameter estimates from fitting the VBGM to RGSM length and age data.

Formula: Lengths ~ Linf * (1 - exp(-k * (Age - tzero))) Parameter	Estimate	Std. Error	t value	Pr(>|t|)
Linf	94.53	12.51	7.56	<0.001
k	0.77	0.35	2.24	0.03
tzero	0.11	0.24	0.43	0.67

Table 3. Predicted lengths at ages 1-4 (Pred.Lengths) and predicted fecundities (Pred.AllEggs = spawned + counted, from Dr. Caldwell's regression formulas, unpublished, pers. comm.) at these lengths.

Ages	Pred.Lengths	Pred.AllEggs
1	47.275	1519.920
2	72.759	6239.218
3	84.500	10184.361
4	89.910	12479.677

We suggest that these parameter estimates and associated predicted lengths at age and corresponding length-specific fecundities be compared to results obtained using only the actual collected data.

6 RIO GRANDE SILVERY MINNOW REPRODUCTIVE BIOLOGY

Knowledge of the reproductive biology of the RGSM is essential for persistence of the MRG population and adaptive management of the species. Specifically, knowing when, where, and how frequently RGSMs spawn, as well as their fecundity, is essential for any science-based adaptive management plan for the species. Data on the reproductive biology of RGSMs must be included in population models, and also as input into science-based flow and habitat manipulation and management actions, as well as population augmentation strategies.

Most of the data on the reproductive physiology of the RGSM is not published in scientific journals, and consequently, has not undergone peer review. Consequently, data interpretations are widely scattered and mostly available in technical reports rather than in peer-reviewed publications. Much data has come from cultured populations and the applicability of these findings to wild fish is a matter of current debate. These uncertainties have limited our ability to synthesize extant patterns in reproductive biology for this species, although it does facilitate identification of knowledge gaps that should be pursued in the adaptive management plan. In addition, it appears that scientific research for this species has been negatively affected by the restrictions imposed by its status as endangered and the resulting need for complex permitting.

6.1 Quantifying the Reproductive Cycle of Female Rio Grande Silvery Minnow

6.1.1 Summary of Available Information

Reproductive Physiology

RGSM eggs are semiboyant, non-adhesive, and hatch within 48 hours (Platania and Altenbach 1998, Cowley et al. 2005). Larvae are non-motile and take four to seven days to become motile (Platania 1995). Mortality of eggs and larvae is “notably higher” at 15 or 30 degrees C compared to 20 or 25 degrees C (Platania 2000) but even at 15 and 30 degrees C, survival was relatively high (68% and 66%, respectively) versus survival at 20 and 25 degrees C (80% and 86%, respectively). Based on egg and larval surveys, RGSMs may begin spawning as early as April and typically finish by June, although apparently there has been no egg or larval sampling pre-April or post-June. There is no information published in refereed scientific journals on the annual reproductive cycle of the RGSM, although there is some information in unpublished data and reports and presentations (Dr. Caldwell, pers. comm). The spatial distribution of males and females appears to vary with an overabundance (i.e., more than 50%) of females in downstream samples (Appendix 4 in Lusk et al. 2012) although the difference may not be statistically significant. The exact distribution and sample sizes are unknown because the table containing the study site descriptions is missing from the appendix. However, if these are the same sites listed in Lusk et al. (2012, Appendix 5) then we assume that downstream refers to San Antonio, La Joya, and perhaps Los Lunas. Nonetheless, if sex-based differences in spatial distribution are possible, this should be included in any sampling scheme. Lusk et al. (2012, Appendix 4) conclude that histological evidence suggests that RGSMs are synchronous, fractional spawners that reproduce between April and July. However, this inference is based on very small sample sizes (less than 10 in all cases) and data were only collected quarterly, which is too coarse of a temporal resolution.

6.1.2 Key Uncertainties

The following questions focus on wild populations of RGSMs. When do females reproduce? Is reproductive effort constant across RGSM size classes? Are RGSMs fractional or complete spawners? This information is essential for scientific management of this endangered species. Knowledge of when females reproduce is needed for flow and habitat management and potential prediction of how environmental factors may affect annual reproduction.

6.1.3 Study Questions

What is the annual female reproductive cycle? Is reproductive effort constant across RGSM size classes? What is the contribution of young spawned at different times to the population?

6.1.4 Management Relevance

Water availability is a crucial issue in the MRG and knowledge of the reproductive biology of RGSMs will aid management agencies in ensuring that sufficient water and variation in flows is available for spawning.

6.1.5 Measurement Variables and Key Considerations for Study Design

Key variables for measurement include: egg abundance and female reproductive condition (i.e., ripeness) including gonadosomatic index (GSI) values, ultrasound assessment, and histological assessment of ripeness, and their variation over time.

Future egg sampling to assess the spawning period should be conducted from March through August (when flow levels allow sampling) to sample the range of potential spawning events, including monsoonal events. Sampling should be discontinued once two semimonthly or monthly samples indicate a lack of eggs. The one exception would be for low-flow years where spawning may occur following monsoonal rains and sharp increases in discharge. Sampling should occur in representative reaches under conditions of homogenous velocities to facilitate construction of flow and egg abundance/density relationships. Egg sampling should include spatial coverage of different reaches to gain insights into spatial variation in spawning (i.e., possible source-sink dynamics).

For quantification of the reproductive period, we suggest field sampling of wild fish from January to October. If possible, non-destructive sampling should be used to quantify reproductive condition, such as visual examinations of females, or adaptations of length – weight relationships. Recently, ultrasound machines have shown promise as a means of assessing female reproductive condition in the field (Novelo and Tiersch 2012, Bangs and Nagler 2014): although it is unknown if this method is practical for RGSM. Nonetheless, Bryan et al. (2005) used ultrasound to quantify reproductive condition in Neosho madtom (*Noturus placidus*), which is of similar size to RGSMs. Given the logistical difficulties in obtaining specimens for dissection, every effort should be made to develop new, nondestructive methodologies for quantification of reproductive condition of wild RGSMs.

There is strong evidence for a peak in spawning in late-March to early-June, so the more pertinent question may be whether spawning occurs during monsoonal events in mid-summer to autumn. If it is impossible to assess reproductive condition in a non-destructive manner, a small number of wild females should be collected and an index of female reproductive condition calculated (i.e., the GSI). Collections may need to be conducted on a biweekly basis if RGSMs are fractional spawners, and if that is the case then females may not display readily identifiable morphological characteristics of reproduction. Because reproductively active females show little size variation, more complicated indices such as the relative gonadal index are not necessary (Erickson et al. 1985a). These data could be compared to the same data collected from hatchery or other refugia fish, which would yield an indication of how well-nourished, wild fish are, as well as spawn "quality". Furthermore, controlled experiments altering food rations (treatment combinations could include full rations, half rations, and quarter rations) for hatchery/refugia fish could be conducted to determine how food rations affect reproductive output. These experiments would provide insights into whether wild fish had sufficient rations and how current rations could affect spawning and year-class success. Many reproductive studies have used one ovarian lobe for GSI calculations and the other for histological classification, although this is not always possible.

Histological classification of ovarian follicles is the most precise method for determining reproductive condition and may allow determination of spawning pattern (i.e., complete or fractional; Erickson et al. 1985b). The combination of monthly, or more frequent, calculation of a reproductive index and histological analyses are the most efficient methods for quantifying variation in reproductive condition (Erickson et al. 1985b), but those methods require sacrificing fish. It may be necessary to sample biweekly for assessment of reproductive condition given the quickness with which female RGSMs are able to ripen eggs. Although the data are unpublished, several previous investigators were able to classify RGSM oocytes using histological criteria (e.g., Lusk et al. 2012).

Monthly or semi-monthly GSI or histologically classified (e.g., % ripe oocytes) could be compared across seasonal collections and size-classes to address the questions posed above. Comparisons of reproductive indices and length composition of population samples could be compared to assess whether monsoonal spawning events contributed to year class size.

At present, the unpublished histological and fecundity estimates support the hypothesis that RGSMs are fractional spawners. This can be confirmed by obtaining future data on histological condition and classification of oocytes in RGSM ovaries. Monthly or biweekly histological samples could be used to determine if RGSMs are fractional or complete spawners using the methodology of Erickson et al. (1985a, 1986). Once again, the use of fish kept under semi-natural conditions in Los Lunas or Albuquerque BioPark facilities would likely provide sufficiently "natural" condition to minimize or avoid sampling wild fish.

6.2 Identifying Relationships between Environmental Variables and the Female Rio Grande Silvery Minnow Reproductive Cycle

6.2.1 Summary of Available Information

Environmental Factors Potentially Affecting Reproduction

Extant information on spawning periods and the relationship between environmental factors and RGSM spawning are based primarily on egg sampling and sampling of YOY in the Rio Grande (Archdeacon [Workshop Presentation, Session 1]), Cowley [Workshop Presentation, Session 1], and Lusk [Workshop Presentation, Session 3; Archdeacon 2016). Egg sampling started in 2001 and continued in 2002 and 2004 in the San Acacia reach of the river (Dudley and Platania 2014, Dudley et al. 2016b). Sampling was expanded upstream in 2006-2008 and included the Isleta and Angostura reaches, and continued annually until 2014. Rapid increases in discharge seem to be the main environmental cue for spawning, although there is an interaction with water temperature (Dudley et al. 2016, Krabbenhoft et al. 2014). Spawning has been observed over a range of daily water temperatures (~13 - 26°C), but the majority appears to occurs at temperatures between 17 - 23 degrees C (Dudley and Platania 2014, Dudley et al. 2016). A variety of correlational studies have been performed comparing egg abundance with temperature, discharge, and the change in discharge, but these comparisons have yielded few insights because the relationships are weak (correlation statistics below 0.15, see summary in Dudley et al. 2016). It appears that photoperiod has been rejected as a causal mechanism because reproduction occurs both before and after the solstice. (Note, this contradicts the conclusions of other authors who claim there is no late reproduction [Archdeacon, pers. comm.].) According to Archdeacon (Workshop Presentation, Session 1), a doubling of flow creates an 80% chance of collecting eggs, but it is unclear if this is corrected for water volume sampled (i.e., if it is uncorrected then the samples are sampling a much higher volume of water at higher flows and thus have a higher probability of collecting eggs even though the egg abundance/volume relationship is constant).

The interaction between spawning, discharge and temperature is complex and varies both annually and spatially (Krabbenhoft et al. 2014). However, in low-flow years (2002, 2003) spawning is much more closely associated with peaks in the hydrograph (Dudley and Platania 2014). Egg sampling studies only appear to have been funded from mid-April to mid-June (Archdeacon [Workshop Presentation, Session 1]) in San Acacia, but only occurred during May at Isleta. Nonetheless, the presence of small YOY in August and later suggests some monsoonal spawning in July and August (Archdeacon [Workshop Presentation, Session 1], Cowley [Workshop Presentation, Session 1], and Lusk [Workshop Presentation, Session 3). Opinions are mixed regarding the importance of monsoonal spawning to subsequent population size and structure (Archdeacon [Workshop Presentation, Session 1]), Cowley [Workshop Presentation, Session 1], and Lusk [Workshop Presentation, Session 3) both argued against monsoonal spawning because the size of small YOY in late summer is not significantly smaller than the variance in individual RGSM growth from May/June spawning. Nonetheless, it does not appear there are sufficient data to reach a firm conclusion regarding the presence, and population-level importance, of monsoonal spawning, especially in low-flow years.

6.2.2 Key Uncertainties

What is the relationship between environmental variables and reproduction? This information is essential for scientific management of this endangered species, especially for management of flow regimes and habitat quality.

6.2.3 Study Questions

What are the relationships between potential environmental drivers of reproduction, such as average flow and temperature, changes in flow and temperature, and seasonal changes in photoperiod and the annual female reproductive cycle? How do these relationships vary across years given that the environment is highly variable?

6.2.4 Management Relevance

Given the endangered status of this species and the strong anthropogenic demands for water, a greater understanding of the environment triggers of reproduction will aid in water management and in maintaining a healthy population of RGSMs.

6.2.5 Measurement Variables and Key Considerations for Study Design

Measurement variables include: egg abundance and female reproductive condition (i.e., ripeness) including (GSI values, ultrasound assessment, and histological assessment of ripeness) versus time series of environmental variables (water temperature, discharge, rate of change of temperature, rate of change of discharge, etc.). We recommended a series of reproductive studies to quantify the female reproductive cycle and to provide insights into the conditions of wild fish via comparisons between wild and hatchery fish. Estimates of these variables can be regressed on water temperatures or discharge values (changes in discharge, for example, to identify potential relationships with environmental variables (discharge, change in discharge, temperature, change in temperature, etc.). Clearly these studies should be conducted over multiple years that span a range of environmental conditions (e.g., both low-flow and high-flow years, years with no monsoonal rains, and years with extensive monsoonal rains).

Estimates of the percentage of fish containing ripe oocytes (histologically classified) would be the best data to regress on environmental covariates, but GSI could also be used as a response variable. Any statistical analysis should use univariate and multivariate methods and linear and non-linear statistical models. These data should be examined with non-linear methods in order to identify any threshold relationships.

6.3 What is the Spawning and Larval Rearing Habitat for Rio Grande Silvery Minnow?

6.3.1 Summary of Available Information

<u>Spawning and Larval Habitat</u>

There has been a substantial loss of potential breeding and larval habitat as the river has become channelized and floodplains cut off from the main channel even in high flows (Porter and Massong 2004a, 2004b; Dudley and Platania 2007). Islands may become spawning/larval habitat at high flows, although there are scant data to support this conclusion. Egg retention is a function of flow and channel complexity (Widmer et al. 2010), which has decreased significantly in the last 70 years (Dudley and Platania 2007). Eggs are regularly detected in the main channel of the river, which led Dudley and Platania (2014) to conclude that RGSMs are pelagic broadcast spawners that utilize the main channel for spawning: a pattern similar to other *Hybognathus* species. Nonetheless, there is evidence of spawning in floodplain habitat (movement of ripe females and the presence of eggs and larvae) from multiple investigators in multiple years (Tave and Hutson 2012, Medley and Shirey 2013, Gonzales et al. 2014; Cowley [Workshop Presentation, Session 3], Valdez [Workshop Presentation, Session 3]). Floodplain habitat has decreased substantially over time, which likely has affected RGSM abundance because larvae depend on slow-water habitat (Pease et al. 2006, Widmer et al. 2010). Gonzales et al. (2014) found that RGSM abundance was much higher on a natural floodplain habitat than on two artificially constructed floodplain habitats. Valdez ([Workshop Presentation, Session 3]) suggested that during low-flow years there may be portions of the main channel that resemble floodplain habitat and would provide good spawning habitat.

In the last 40 years, researchers have recognized the need to conduct demographic analyses on a habitat-specific basis. This was succinctly elucidated by Pulliam (1988), who argued that habitats could be classified as sources (habitats that produce a surplus of young that emigrate to other habitats) and sinks (habitats that do not produce sufficient young that survive and are therefore dependent on immigration of young from other habitats). For RGSMs, little is known about habitat-specific reproductive parameters, although it is clear that habitat fragmentation is occurring (Dudley and Platania 2007). These circumstances demonstrate the need for habitat-specific estimates of reproductive parameters.

6.3.2 Key Uncertainties

What are the spawning and larval rearing habitats for RGSMs? This information is essential for scientific management of populations of this endangered species, especially for establishing the relationship between habitat quality and flow diversion and discharge.

6.3.3 Study Questions

Do RGSMs spawn in both channel and floodplain habitats? Do all age/size classes of fish spawn in the same habitat, or do larger fish spawn in one habitat and smaller fish in another? Is hatching success and survivorship in both habitats equal? Does spawning habitat vary with flow conditions? How does the spawning habitat vary across years given that the environment is highly variable?

6.3.4 Management Relevance

Given the endangered status of this species and the potentially strong link between the abundance of high quality habitat and population persistence, this information is necessary for population maintenance and habitat and flow management.

6.3.5 Measurement Variables and Key Considerations for Study Design

Measurement variables include: abundance of spawning females, size of spawning females, egg abundance, the relation of larvae abundance to habitat type (channel versus floodplain). Egg sampling in the main channel does not really indicate where these eggs were spawned. Given that eggs hatch quickly, this does give us some idea of how quickly downstream transport might occur when combined with flow data, and might allow calculation of a range of possible spawning dates, especially if they can be classified into developmental stages (uneyed, eyed, embryo development, etc.).

Quantification of where RGSMs spawn and whether or not there is differential survivorship of young produced in different habitats (e.g., floodplain versus main channel), is of fundamental importance to any successful management strategy. Habitat-specific comparisons of the reproductive parameters described above, especially fecundity and histological classifications of oocytes could be conducted and coupled with egg/larvae surveys and survivorship studies.

There is ample evidence that floodplain spawning occurs and the substantial decline in this habitat may help explain the decline in RGSM abundance, especially during low-flow periods. Consequently, such a study would involve sampling both natural and artificially-constructed floodplain habitat and the main channel before, during, and after the spawning period, for eggs and larvae. These studies should be conducted in multiple reaches of the river. In addition, it is likely that such studies could be conducted at either Los Lunas or in the large artificial stream at the Albuquerque BioPark.

6.4 What is the Fecundity of Female Rio Grande Silvery Minnow?

6.4.1 Summary of Available Information

Fecundity

There are no estimates of RGSM fecundity published in referred scientific journals, although some information exists in unpublished form (Falco et al. n.d.; Dr. Caldwell, pers. comm). Fecundity for cultured RGSMs, based on a sample size of five for each age class, ranges from just over 3,017 for age 1 fish to 15,522 for age 5 fish (unpublished data, Dr. Caldwell, pers. comm.). Because these estimates are from cultured RGSMs, it is safe to assume they approximate maximum fecundities rather than actual fecundities for wild fish. Given the health issues present in wild fish (Lusk et al. 2012), it is unlikely that wild spawners have such high fecundities. Nonetheless, they are the only extant data and represent a starting point for analyses based on age-specific modeling. Fecundity analyses also support the conclusion that RGSMs are fractional spawners, because oocytes within the ovaries were of a continuum of sizes, indicating multiple stages of development (unpublished data, Dr. Caldwell, pers. comm.). This is typical of a fractional spawning minnow (Roberts and Grossman 2001).

6.4.2 Key Uncertainties

What is the fecundity of female RGSMs? This information is essential for scientific management of populations of this endangered species, including population estimation and modeling.

6.4.3 Study Questions

Does fecundity of female RGSMs vary with female size? How does the fecundity/size relationship vary across years given that the environment is highly variable?

6.4.4 Management Relevance

Given the endangered status of this species and the potentially strong link between fecundity and population persistence, as well as its need for accurate population modeling, this information is necessary for scientific management.

6.4.5 Measurement Variables and Key Considerations for Study Design

Measurement variables include: female size and fecundity and year of collection. Prior to the reproductive season (e.g., February – April) wild females should be collected for fecundity estimates. These collections could be combined with GSI sampling/histological classification by using one lobe of the ovary used for reproductive effort estimates and the other used for fecundity estimates. Similar to the methods described previously in this chapter, these data could be compared to the same data collected from hatchery or other refugia fish, which would provide insights into the relationship between fecundity and body condition. In fact, conducting these studies on refugia "populations" held in semi-natural conditions in the Las Lunas and Albuquerque BioPark facilities would obviate the need to kill wild fish. Furthermore, controlled experiments altering food rations (treatments could include full rations, half rations and quarter rations) for hatchery/refugia fish could be conducted to determine how food rations affect fecundity. These experiments could be conducted concurrently with those proposed in Section 6.1 of this chapter to determine how condition/rations affected fecundity and potential population growth. Fecundity estimates could be conducted using the methods of Erickson and Grossman (1986) and Roberts and Grossman (1992).

7 SAMPLING METHODOLOGIES

In this chapter, we address three specific questions for which generation of unambiguous answers will require careful attention to issues that we group under the general heading of "sampling methodologies". In lay language, these three questions can be expressed as: 1) When do RGSMs spawn?, 2) What is the age composition of the RGSM population?, and 3) Is the CPUE a valid index of abundance? These questions may be re-expressed in more explicit terms that are more directly related to the sampling methodologies theme of this chapter: 1) What is the temporal distribution of RGSM spawning activity?; 2) How can the age distribution of the population be unbiasedly estimated?; and 3) Is the October CPUE metric, as currently calculated, a valid index of abundance?

The first question (When do RGSM spawn?) is addressed in the Reproductive Biology chapter of this report. The second question (What is the age composition of the RGSM population?) is considered in the Population Dynamics chapter of this report. The third question (Is CPUE a valid index of abundance?) is a fundamental issue for population dynamics modeling and is also central to a large number of analyses, including assessment of RGSM status, decision-making regarding augmentation (needed or not, etc.), and determination of flow regimes that appear to favor production of RGSMs. Although the CPUE issue was previously evaluated in depth by an expert panel (Hubert et al. 2016), we believe it is worth revisiting this issue given the continued reliance on the currently calculated CPUE under an assumption that it is a valid index of abundance.

7.1 Issue I. When Do Rio Grande Silvery Minnow Spawn: What is the Temporal Distribution of Rio Grande Silvery Minnow Spawning Activity?

7.1.1 Management Relevance

Knowledge of the temporal distribution of RGSM spawning activity is of fundamental importance for population dynamics modeling, for understanding the reproductive biology of the RGSM, and central to evaluation of possible flow manipulations that might enhance spawning success.

7.1.2 Summary of Available Information

The temporal distribution of spawning activity has been inferred from expanded collections of RGSM eggs in MECs and has been described in "Spawning Periodicity" reports produced on an almost annual basis since 1999 (e.g., Platania and Dudley 2006, 2011; Dudley and Platania 2010, 2013, 2014; Dudley et al. 2012). Similar methods for expansion from collections of eggs made in MECs were apparently used by Medley et al. (2007) and Widmer et al. (2010). Expanded egg collections have been used to infer relative abundance/flow of RGSM eggs through time, thereby presumably providing a valid but somewhat time-delayed (by unknown number of days since release of eggs) index of the temporal distribution of spawning activity.

Worthington et al. (2013a) examined the performance (efficiency of egg collection) of MECs in an experimental flume at a variety of discharges, and Worthington et al. (2013b) examined performance of MECs in a field setting. In both studies, performance of MECs was assessed based on release of known numbers of semi-bouyant gellan gum beads, assumed to have characteristics similar to RGSM eggs, and the recovery rate of the gellan beads in egg collectors.

Based on observations of RGSM eggs and young juveniles in constructed floodplain habitat (Gonzales et al. 2014), and RGSM larvae (Magaña 2012) in floodplain or floodplain-like habitat, we hypothesize that RGSMs spawn and release eggs in floodplain areas when such habitat becomes available. Therefore, whenever flows during the typical April-June period of spawning are sufficient to allow access to such habitats, inferences concerning spawning activity generated from main channel collections of RGSM eggs in MECs will largely exclude floodplain spawning activity. In years of relatively high flows that allow continued access to floodplain-like habitat, it is possible the majority of spawning activity takes place in such habitat and inferences based on main channel egg collections may not provide a valid index of the temporal and spatial distribution of spawning activity.

7.1.3 Methods Used to Expand Eggs Collected in Moore Egg Collectors to Total Egg Passage

According to Dudley and Platania (2011, 2014), MECs (developed by Altenbach et al. 2000) used for assessment of the temporal distribution of spawning activity have been deployed primarily at two locations in the MRG: 1) a site below the San Marcial Railroad (RR) Bridge (river mile [RM] 55.0), just above Elephant Butte Reservoir (2001-2004, 2006-2014); and 2) a site about 4.8 RM upstream of the San Acacia Diversion Dam (RM 121.0; 2006-2011). Based on the most recent Dudley and Platania (2014) report concerning reproductive effort, it appears that the upstream site has not been used since 2011. One or two MECs have been deployed at each site, with two collectors typically used at the San Marcial location. MECs have apparently been deployed from about mid-April through mid-June since 2002 (Figures 2-6 in Dudley and Platania 2014).

Total daily egg passage has been calculated according to the following two-step scheme used since 2002 (Dudley and Platania 2014):

1. Density of RGSM eggs is calculated as $D=N/V$, where D = number of eggs per cubic meter (m^3), N= number of eggs collected, and V = volume of water (m^3) sampled by the egg collector(s) according to an attached mechanical flow meter.
2. The total number of eggs passing a site on a given day, E, is estimated by expanding the density of eggs by the mean daily discharge, Q (m^3 per second [m^3/s]), at the nearest upstream USGS gauging station: $E=DQ*86{,}400$, where 86,400 is the number of seconds in a day (USGS 2017).

Details of deployment and operation of the MECs are not described fully in Dudley and Platania (2014). Extensive photos of MECs as deployed in the MRG are available (Platania and Dudley 2002). Dudley and Platania (2011) report a daily expansion factor of 4, not explicitly included in the second step above, to expand from the 6-hour total daily period in which egg collectors were operated: two hours each during morning, noon, and afternoon. Our impression is that field personnel are usually continuously present when MECs are deployed, collecting eggs as they appear and periodically removing any collected debris.

We did not find an explicit listing of assumptions for the expansion procedure in the reports by Dudley and Platania (2011), though they may have been provided in these or other related reports. Medley at al. (2007), in an experiment expanding from MEC collections of gellan beads, assumed that "beads were uniformly distributed across the channel as with the simple one dimensional models frequently used to describe solute and particle transport". Medley et al. (2011) also expanded from density (eggs collected per m^3) to total daily passage based on mean daily discharge. We found no publication or report that provided any measure of precision for the estimated values of egg passage or that described sources of error in the expanded values.

7.1.4 Sampling Efficiency and Spatial Variability in Egg Collections using Moore Egg Collectors

Sampling Efficiency (Worthington et al. 2013a)

Known numbers (1,000 beads per trial) of gellan beads were released into a 29.3-meter (m) long experimental flume with a width (w) of 1.83 m under five discharge (Q) scenarios (0.14, 0.28, 0.71, 1.42, and 2.12 m^3/s). In each trial, 1,000 beads were released at a point on the channel cross section (apparently at cross section distances 0.46 m, 0.92 m, and 1.38 m). The MEC was mounted in the center of the flume 28 m from the upstream end of the channel. The entire opening of the egg collector was submerged, and the upper crossbar was approximately at surface water level. The mean water depth (d) in the channel was 103 centimeters (cm), regulated by a downstream gate of adjustable height.

The MEC was suspended so that it protruded to 34.3 cm below the surface of each flow, so essentially the upper one-third (34.3 cm/103 cm) of the water column was being sampled. But since the average cross sectional velocity ($v=Q/wd$) varied from 0.06 to 0.84 m per second (m/s), and the MEC itself would provide a strong resistance to flow, the proportion of the flow travelling below the collector must have varied substantially (order of magnitude?) across discharge scenarios.

Their first flume result (Figure 3 in Worthington et al. 2013a) showed that at low flows (Q=0.14, 0.28), the collectors captured no eggs; the number of eggs captured increased substantially from Q= 0.71 to Q=1.42, but thereafter declined slightly. Our interpretation of this result is that at low discharges the eggs are suspended close to the channel bed, and as discharge increases the eggs become more uniformly distributed through the vertical profile. Plots of the theoretical vertical distributions of gellan beads for the Worthington flume experiment (Figure 10), based on the traditional Rouse equation (used to model sediment transport), and assuming that particles have a settling velocity of one cm/s (see Medley and Shirey 2013, re-settling velocities of RGSM eggs), are consistent with this interpretation.

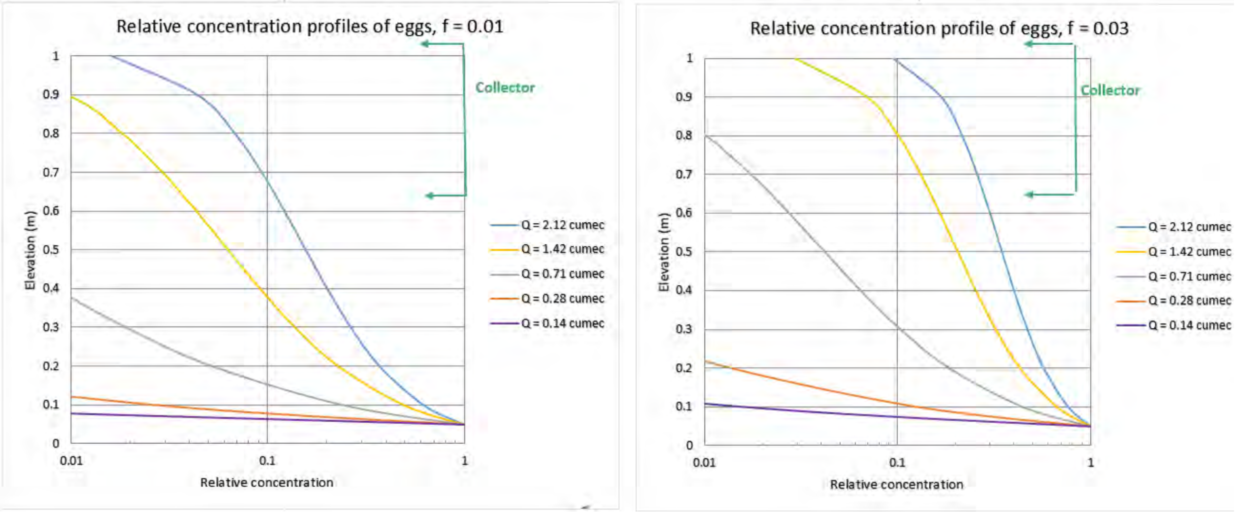

Figure 10. Calculated theoretical relative concentration profiles for Rio Grande silvery minnow eggs as a function of elevation above the bed. Based on application of the tradition Rouse equation (used to model sediment transport) in the setting of the Worthington flume experiments, assuming that Rio Grande silvery minnow eggs have a settling velocity of one cm/s (adapted from Worthington et al. 2013a, Medley and Shirey 2013).

Figure 10 displays calculations of the theoretical vertical distribution of eggs for the Worthington flume experiment based on the traditional Rouse equation describing the vertical distribution of particles with a settling velocity of one cm/s (similar to RGSM eggs according to Medley and Shirey 2013). The vertical axes display the full channel depth (1.03 m vertical distance above channel bed) and the depth range of the MECs (water surface to about 34.3 cm) are shown on each panel. The horizontal axis indicates the relative density of RGSM eggs at a given vertical depth above the channel, with a value of 1 indicating maximum concentration.

The left-hand panel uses a Darcy-Weisbach friction factor of 0.01 to obtain the shear velocity (required in the Rouse equation). This value would be appropriate for a relatively smooth sand bed, similar to the concrete bed in the Worthington experiment (Julien 2002, p. 93). The prediction is that eggs would ride sufficiently high in the water to be trapped by the collector only at the two higher flows in the experiment, which is essentially what was recorded in Figure 3 of Worthington et al. (2013a). To capture the full behavior recorded by the experiments (namely that a small number of eggs were recorded in the third-highest flow (0.71 m^3/s), we used a value of 0.03 for the friction factor (right hand panel). Choice of this factor reflects extra hydraulic roughness imposed on the flow by the experimental conditions, namely that both the collector and the downstream head control at the end of the flume added flow resistance would increase the upward diffusion of eggs away from the bed.

Worthington et al. (2013a) deployed a 12-cell (three vertical rows of four cells) grid net to collect beads at the lower end of the channel to allow characterization of the spatial distribution of eggs at different flows. Grid counts of the spatial distribution of eggs across the grid net demonstrated results consistent with the MEC collections of gellan beads: 95.7% of gellan beads were collected in the bottom row of grid cells at low flow (0.28 m^3/s), whereas 51.4% of beads were collected in the top two of three rows at high flow (0.71 m^3/s). At low flows, gellan beads were concentrated in the center grids (because the velocity was higher there), but at the high flow, there was little difference in horizontal concentration of gellan beads across cells, although highest counts were again made in cells closest to the bed.

Spatial and Temporal Variation in Efficiency (Worthington 2013b)

Three MECs were deployed in "high velocity zones" in each of four reaches of the channel of the South Canadian River (wetted channel widths ranging from 30-109 m) because "Gellan beads travel downstream in areas of concentrated discharge (Worthington et al. 2013b)". MECs were placed in locations ("left", "center", "right") where "discharge was greater than the surrounding areas." Discharges ranged from six to 10 m^3/s. Batches of 100,000 eggs were released "in an area of concentrated discharge" 500 m upstream of each set of three collectors. Overall capture efficiencies (number of beads collected at all three MECs compared to beads released) ranged from about 0.5-2% across sites and there were large differences between numbers of gellan beads collected across individual MECs at some sites (see Figure 1 in Worthington et al. 2013b).

What is Known?

1. Based on the experimental flume experiments and field deployments of MECs when known numbers of gellan beads are released above deployed MECs, it is clear that the vertical and horizontal distribution of RGSM eggs is likely to be complex, with eggs concentrated near the bed, below MECs, at low flows and becoming more evenly distributed at high flows.
2. Under a "high flow" assumption of uniform distribution of RGSMs across the channel, the flux of eggs will be greatest in areas of highest velocity and it is in these areas that MECs are often deployed so as to maximize collections of eggs.
3. Worthington et al. (2013b) provides strong evidence that substantial between-MEC variation in collections of RGSM eggs is to expected, presumably reflecting a complex interaction between MEC location-specific velocity and the unknown vertical and horizontal distribution of eggs across the channel.
4. Existing methods for expansion of egg collected from MECs appear to assume a uniform vertical and horizontal distribution of RGSM eggs across the channel. There is no existing empirical information which would support such an assumption, though an approximately uniform distribution, with substantial local variability, would be theoretically expected once flows and associated velocities are sufficiently high.
5. No attempts appear to have been made to attach any errors of estimation to expanded estimates of daily total passage of RGSM eggs or of total passage of RGSM eggs over the full period of MEC deployment (typically mid-April through mid-June). Therefore, the accuracy of these estimates is at present completely unknown.

Key Uncertainties

1. How does the vertical and horizontal distribution of RGSM eggs vary as a function of MRG discharge and channel cross-section?

2. How can collections of RGSM eggs at MECs be used to generate an unbiased estimate of total egg passage?
3. How can variability in collections of RGSM eggs across MECs and across time be used to calculate a meaningful error of estimation for an unbiased estimator of total egg passage?
4. In the absence of a solid understanding of the above three key uncertainties, it is impossible to judge whether or not the current expanded RGSM egg collections provide a reasonable picture of the temporal distribution of RGSM spawning activity.

Recommended Studies

1. A team consisting of a geomorphologist (with expertise in the hydraulics of particle flow), a statistician (with expertise in estimation and sampling theory), and a field biologist (with expertise in deployment and operation of MECs) need to work together to develop the theoretical and statistical framework from which an unbiased estimator of total egg passage could be generated from counts of eggs collected from MECs, and so that an associated error of estimation could also be calculated. Any variance estimator developed should account for uncertainty due to at least the following causes: a) variability in egg counts across deployed MECs within a given 2-hour sampling period, b) variability in mean MEC egg counts across sampling periods within a day, and c) expansion from the very small amount of flow sampled to total daily discharge. If an estimate over the full duration of sampling (mid-April through mid-June) is desired, then the day-specific variance estimates should be summed to generate a variance estimate for total egg passage. If discharges during the egg collection season are sufficiently high to justify an assumption of uniform vertical and horizontal distribution of eggs across the channel, then variability in vertical and horizontal density of eggs must also be addressed as a factor affecting uncertainty of estimated total passage of eggs.
2. Given the likely gradient in vertical density of RGSM eggs, especially at low flows, it seems likely that development of an unbiased estimation scheme will require, at least in low-flow years, development of modified egg collection gear that can provide the equivalent of a “vertically integrating” sample of eggs (i.e., that can sample the full vertical column).
3. Whenever high flows prevent safe deployment and operation of MECs, it is obvious that it is impossible to make any statements concerning passage of RGSM eggs.

7.2 Issue 2. What is the Age Composition of the Rio Grande Silvery Minnow Population: How can the Age Distribution of the Population be Unbiasedly Estimated?

7.2.1 Management Relevance

Knowledge of the age distribution of the RGSM is critical for at least the following purposes: a) generating an unbiased estimate or index of age 0 recruitment, b) generating an unbiased estimate or index of age 1 and older adults, and c) analyses related to population dynamics and response of the population to controlled or uncontrolled variation in flow regimes that rely on use of the two metrics (age 0 recruitment and adult abundance).

7.2.2 Summary of Available Information

Because RSGMs are not routinely aged from hard parts such as scales or otoliths, assessment of age composition of the population must be done indirectly via analysis of length frequency data. Extensive length frequency data have been collected annually in the long-term monitoring program using beach seine gear deployed in various mesohabitat types. Fine mesh seines (1.0 m x 1.0 m with 1.5 milimeter [mm] mesh) have been used to capture (primarily) larval RGSMs, and small mesh seines (3.1 m x 1.8 m with 5.0 mm mesh) have been used to capture age 0 juveniles and age 1-3 adults. Collected RGSMs are assigned to age classes "based on reach-specific standard length and age-length relationships during the same time of year [Dudley et al., 2009; Horwitz et al., 2011]" (Dudley et al. 2016a). (We have not been able to establish exactly how Dudley et al. (2009) assigned fish of known lengths to unknown ages. They provided site and month-specific distributions of length at age 0 in two years, but it is unclear how these distributions may have been used to separate age groups. Our guess is that these distributions were used to generate "cut-offs" lengths to separate age 0 fish from older ages, but that is just conjecture.)

Gonzales et al. (2012) used a "paired gear" approach to compare total catches and length frequency distributions of RGSMs in different gear types (fyke net, bag seine, beach seine, backpack electrofishing unit) in different habitat types (floodplain, main channel). Catches of RGSMs were correlated among gear types in floodplain and side channel habitats, but not in main channel locations. When samples sizes were sufficient, statistical comparisons of length frequencies of RGSMs collected in floodplain areas using different gear types showed that mean length of RGSMs collected in fyke nets exceeded mean length of RGSMs from electrofishing and beach seines. In addition, "the relative proportion of fish larger than 62 mm was greater… with fyke nets (28%) than backpack electrofishing (14%) and beach seines (14%)" (Gonzales et al. 2012). For that reason, they suggested that fyke nets may be more useful for describing the length frequency distribution of RGSMs. Unfortunately, the proportion of RGSMs found in the floodplain is highly variable due to variation in floodplain access, and fyke nets were found not suitable for collection of RGSMs in the main channel.

7.2.3 What is Known?

1. Beach seine gear used in the annual monitoring surveys, from which extensive length frequency data are generated, is size-selective. In particular, beach seines, as used in the MRG, are less efficient at capture of large RGSMs which are therefore underrepresented (relative to their true abundance) in collected length frequency data. (Beach seines may also underrepresent the smallest age 0 fish, especially during summer months.)
2. Underrepresentation of large RGSMs must in turn lead to underrepresentation of age 2 and age 3 RSGMs.
3. The Horwitz et al. (2011) aging study, based on monthly collections of age 0 juveniles in the long-term monitoring program, and lengths at age of VIE-marked fish recovered in surveys (see Archdeacon [Workshop Presentation, Session 4]) all provide extensive evidence of: a) very substantial variation in length at age, and b) substantial overlap in lengths of age 0 and age 1 fish by October "census" surveys and in lengths at older ages.

4. When there is substantial overlap in length frequency distributions at ages, use of "cut-off" lengths to separate age groups can lead to substantial bias in calculated proportions at age (age distribution), even when there is no size-selection against larger and older individuals (see MacDonald and Pitcher 1979).

7.2.4 Key Uncertainties

1. Size-selection with small mesh beach seine gear used to collect RGSMs in annual monitoring surveys is poorly understood, but knowledge of gear selection is essential for adjustment of collected length frequency data so that it better represents the true length frequencies in the population.
2. Absence of a large sample of aged individuals means that age composition must be estimated from length frequency data. Bias in age composition due to methods currently used to separate age groups (length cut-off points) is unknown, but is likely substantial.

7.2.5 Recommended Studies

1. **Gear Selection Study.** Quantitative comparisons of length frequencies of fish captured in two gear types when fished over the same size composition of fish can, in principle, be used to establish the selective properties of one gear if the other can be assumed non-selective with respect to length. It is possible that such a study could be carried out in floodplain areas, using fyke nets and beach seines, if flow and depth were similar to that in the main channel "backwater" mesohabitat type. If so, then size selection results from flood-plain areas could be used to adjust (for gear selection) data collected from beach seines fished in main channel backwater habitat.
2. **Mixture Distribution Separation for Age Composition.** The R package *mixdist* provides functions that allow estimation of age-specific mean lengths, corresponding variances, and proportions of age groups from an unknown mixture of age groups given different assumed distributional forms of length frequencies at age (see MacDonald 1987, 2015). We recommend that use of this software be explored for analysis of RGSM length frequency data collected in the long-term monitoring program either: a) after adjustment for gear selection (see Study 1, above), or b) incorporating truncation of age 2 and age 3 groups in the *mixdist* algorithms.

7.3 Issue III. Is Catch-Per-Unit-Effort a Valid Index of Abundance: Is the October Catch-Per-Unit-Effort Metric, as Currently Calculated or if Instead Calculated Using Only Data from the Small Mesh Seines, a Valid Index of Abundance?

7.3.1 Management Relevance

Throughout our review of reports, journal publications, and other materials concerning various aspects of RGSMs, we noted the large number of analyses that relied on use of the CPUE metric generated from the long-term population monitoring program. We recognize that a previous independent expert panel (Hubert et al. 2016) recently produced a report addressing possible improvements that could be made to the population monitoring program. However, we wish to express some of our own recommendations concerning use of the CPUE data generated from this program. Because CPUE has been used as if it were a consistent index of the abundance (more accurately, density) of RGSMs, and because so many inferences concerning effects of environmental variables such as flow are based on use of CPUE as the response variable, we believe it is appropriate to again address this issue, notwithstanding the Hubert et al. (2016) expert panel review. This topic does not lend itself to a "What is Known", "Key Uncertainties", and "Recommended Studies" format, so we adopt a different format here. (Note that our discussion below assumes that age 0 fish can be separated from older fish based on observed lengths, an assumption that may be violated by the date of the October long-term monitoring surveys.)

Catch-Per-Unit-Effort Issues 1: Properties and Flaws of the Current Catch-Per-Unit-Effort Metric

For a selected study section of the MRG, we consider only the "small mesh" seine (designed to catch age 0 and older RGSM). We define the following terms:

i = mesohabitat type,

j = seine haul,

n_i = number of seine hauls taken in mesohabitat type i,

m_{ij} = total area (m^2) covered by haul j in mesohabitat type i,

$C_{0,ij}$ = catch of age 0 RGSMs in haul j in mesohabitat type i,

$C_{1+,ij}$ = catch of age 1 and older RGSMs in haul j in mesohabitat type i,

q_i = "catchability" in mesohabitat type i (probability that a fish present in the area of a seine haul is captured),

$D_{0,I}$ = density (number of fish per 100 square m [m^2]) of age 0 RGSMs in mesohabitat type i,

$D_{1+,I}$ = density of age 1 and older RGSMs in mesohabitat type i, and

M_i = total area (m^2) of mesohabitat i within the selected study section.

We assume that areas are measured in units of 100 m^2 will be consistent with apparent practice.

Given the above definitions, the total number of age 0 and age 1 and older RSGMs present in all *k* mesohabitat types within a selected study section would be:

$$N_0 = \sum_{i=1}^{k} D_{0,i} M_i \text{ and } N_{1+} = \sum_{i=1}^{k} D_{1+,i} M_i ,$$

and the densities (fish per 100 m^2) of age 0 and age 1 and older RSGMs within a selected study section would be:

$$D_0 = \frac{N_o}{\sum_{i=1}^{k} M_i} = \frac{\sum_{i=1}^{k} D_{0,i} M_i}{\sum_{i=1}^{k} M_i} \text{ and } D_{1+} = \frac{N_o}{\sum_{i=1}^{k} M_i} = \frac{\sum_{i=1}^{k} D_{1+,i} M_i}{\sum_{i=1}^{k} M_i} .$$

Omitting age-specific subscripts to simplify notation, the "aggregated CPUE" metric that is calculated for a particular selected unit is of the form:

$$CPUE = \frac{\sum_{i=1}^{k} \sum_{j=1}^{n_i} C_{ij}}{\sum_{i=1}^{k} \sum_{j=1}^{n_i} m_{ij}} \text{ and has the approximate expected value: } E(CPUE) \approx \frac{\sum_{i=1}^{k} \sum_{j=1}^{n_i} q_i D_i m_{ij}}{\sum_{i=1}^{k} \sum_{j=1}^{n_i} m_{ij}} .$$

For the expected value of this aggregated CPUE measure to be directly proportional to the true density of RGSMs over the entire selected unit, as is required for a valid and useful "index", the following conditions must be met:

1. Catchability must be identical for all *k* mesohabitat types (i.e., $q_1 = q_2 = \ldots = q_k = q$), and
2. The total area seined over the n_i hauls within each mesohabitat type must be the same proportion, γ, of the total area of each mesohabitat type.
   That is:

$$\sum_{j=1}^{n_i} m_{ij} = \gamma M_i \text{ for all } k \text{ mesohabitat types.}$$

Substitution of Conditions 1 and 2 above into the expression for the expected value of CPUE gives:

$$E(CPUE) \approx \frac{\sum_{i=1}^{k}\sum_{j=1}^{n_i} q_i D_i m_{ij}}{\sum_{i=1}^{k}\sum_{j=1}^{n_i} m_{ij}} = \frac{q\sum_{i=1}^{k} D_i \sum_{j=1}^{n_i} m_{ij}}{\sum_{1=1}^{k}\sum_{j=1}^{n_i} m_{ij}} = \frac{q\sum_{i=1}^{k} D_i \gamma M_i}{\sum_{i=1}^{k} \gamma M_i} = qD \text{, where } D = \frac{\sum_{i=1}^{k} D_i M_i}{\sum_{i=1}^{k} M_i}$$

Whenever catchability varies by mesohabitat type, i.e., whenever $q_i \neq q$ for all *k* habitat types, and whenever different mesohabitat types are seined at different rates, i.e., whenever $\sum_{j=1}^{n_i} m_{ij} / M_i \neq \gamma$ for all *k* habitat types, then the aggregated CPUE will not provide a consistent index of true density of RGSMs.

As noted below, it seems obvious that:

- catchability using seines must vary by mesohabitat type.

It is clear from the description of routine monitoring activities and was pointed out by Hubert et al. (2016) on the population monitoring program that:

- mesohabitats are surveyed at different rates.

Therefore, the aggregated CPUE values produced from the routine monitoring surveys cannot provide a consistent index of the true density of RGSM.

The above points were implicit in the Hubert et al. (2016) population monitoring program review, but they did not provide an explicit analytic representation of the flaws in the current CPUE measure.

Recommendations

1. Separate CPUE values for selected channel segments based on catches made in small mesh seines should be calculated for age 0 RSGMs and for age 1 and older RGSMs. (Catches from the fine mesh seine designed to collect larvae should be excluded, as suggested by Hubert et al. [2016].) CPUE for age 0 fish in August might be used as a metric suitable for an indication of reproductive success (recruitment of age 0 fish) in the current year. The CPUE for age 1 and older fish in October could be used as an index of surviving adult densities, later augmented (in some years) by hatchery-reared fish.

2. The CPUE should not be aggregated across mesohabitat types within units because catchability varies across mesohabitat type and because mesohabitat types are not sampled at the same rates. Instead, CPUE should be based instead only on seine catches and areas of seine hauls made in the most abundant "preferred" habitat. Highest catch rates consistently are made in "backwater" habitats, which appear present in all sampling units (the Hubert et al. [2016] report noted that temporal trends in mesohabitat-specific CPUE were similar across all habitat types, but this does not imply that the aggregated CPUE metric would have a similar pattern given the extreme variation in densities among mesohabitat types; see Figure 11 in Dudley et al. 2016a). Below we refer to these recommended CPUE calculations, carried out separately for age 0 and for age 1 and older fish, as "modified CPUE" values.

3. There is no "clearly correct" method for aggregating unit-specific CPUE values across the full set of standard units or across a subset of those units (e.g., all standard reaches that fall within the Angostura Reach) absent a formal sampling design which would account for the total amount of habitat of a given type within each selected unit (see Dudley et al. 2012). The most natural estimator that might be used in the absence of a formal sampling design would appear to be a ratio (of means) estimator of "overall" CPUE:

$$R = \frac{\sum_{l=1}^{n}\sum_{i=1}^{k}\sum_{j=1}^{n_i} C_{lij}}{\sum_{l=1}^{n}\sum_{i=1}^{k}\sum_{j=1}^{n_i} m_{lij}},$$

   where *l* denotes one of the *n*=20 sampled units that have fixed locations in the several reaches of the MRG. This measure will suffer from many possible flaws that have been previously discussed in the context of calculating a meaningful CPUE index for a single unit, including variation in catchabilities across units (due, for example, to differences in flows, velocities, channel complexity) as well as differences in sampling rates of preferred habitat type(s) across units. However, it would probably be an improvement over current usage.

Catch-Per-Unit-Effort Issue 2: Our Panel's Concerns and Recommendations for use of the Aggregated Catch-Per-Unit-Effort Metric

Concerns

1. We have observed extensive reliance on the currently calculated CPUE index as the dependent variable for most analyses relating to flow. As noted above, the CPUE index from the population monitoring program is: a) an inappropriate and highly variable mixture of catches of age 0, 1, 2 RGSMs from two seine types; and b) in many contexts it would be highly desirable to separate age 0 from other ages because age 0 fish are a direct reflection of the current year's recruitment success. (For illustration, note that Valdez tried to use monthly age 0 CPUE to get at survival of RGSMs during the first year of life. See slide 13, Valdez [Workshop Presentation, Session 3].)

2. Analyses of the effects of flow on “abundance” of RGSMs are illustrative of our concerns. First, most flow analyses appear to have used the aggregated CPUE, not age 0 CPUE, as the response variable. Second, almost all analyses of the effects of flow make no attempt to account for spawning season abundance of adult RGSMs. Thus, in a sense, analysis methods implicitly assume an impossible situation: that “flow” in year t directly produces recruitment in year t, as well as adults surviving from previous years. Instead, it is some (unknown) interaction between flow and adult abundance that together produces recruitment. If no adults were present at time of spawning, then otherwise suitable flow conditions would produce no recruitment. (Note that Goodman [2009] does make an attempt to account for the influence of adult population on recruitment and uses an estimate of “per capita recruitment” [recruits per adult] as a dependent variable that might logically be affected by flow.)

Recommendation

A team consisting of a geomorphologist and a fisheries biologist should be charged with developing reasonable alternative theoretical flow-related physical mechanisms that might trigger RGSM spawning activity. These alternative physical mechanisms should be used to motivate statistical models relating apparent timing of spawning activity (inferred from improved expansions of eggs collected at MECs) and/or apparent success of spawning (via recruitment) to an appropriate flow “metric” and possibly also water temperature. (Fish certainly do not react to a “proportional change in flow”, but they may react to increased flow velocities as flows increase.)

8 PHYSICAL HABITAT OF THE MIDDLE RIO GRANDE SILVERY MINNOW

8.1 Physical Habitat Background and Changes

The original habitat of the RGSM comprised the channel and floodplain water bodies of the MRG valley, created by geomorphological processes of sediment transport and sedimentation and the hydrological regime provided by the regional climate. Development of natural resources, along with emerging climatic trends, have changed the factors that generate the modern habitat, and therefore have altered various habitat features to varying degrees.

8.1.1 Geomorphology

The MRG between Cochiti Dam and Elephant Butte Reservoir flows in the Rio Grande Rift Valley, which has been a locus of sediment accumulation for millions of years. The major sediment sources derive from the Rio Chama, Rio Puerco, Rio Salado, and arroyos and gullies flanking the valley. Geologically imposed variations of valley gradient, valley width, and sediment supply along the Rio Grande Rift Valley created a succession of reaches with varying channel and floodplain form. There was an irregular trend from a relatively narrow valley with a multi-thread channel and floodplain between Cochiti and Socorro to a generally wider valley with a braided channel and more complex floodplain downstream. The channel changed dramatically during large floods through shifting and avulsion into new paths across the valley floor (Massong et al. 2010). The mean and maximum channel width generally increased downstream with high variability. Accumulations of fine-grained sediment, reinforced by riparian forest vegetation, locally stabilized the banks and confined the otherwise braided channel into a single thread. The floodplain, constructed of sediment conveyed out of the main channel by diffuse overbank flows and by diverging channels, originally consisted of a topographically complex surface including extensive water bodies and wetlands.

8.1.2 Climatology and Streamflow Regime

The valley received runoff from two major sources: the melting of snow packs in the southern San Juan Mountains of southern Colorado, mainly in springtime, and from thunderstorm rainfall in the middle reach itself in New Mexico, mainly in summer and fall. The former snowmelt streamflow source was usually larger in volume and peak flow; mean daily flows exceeding 20,000 cfs were recorded at Albuquerque before the construction of Cochiti Dam in 1973 (USGS 2017). Stream flow peaks supplied by thunderstorms were generally lower. These annual high flows inundated the floodplain extensively in most years, and portions of the channel also dried up in some summer-fall periods.

8.1.3 Effects of Development on the Modern Habitat

Humans have altered the sediment and water supplies to the MRG, especially since 1800. Beginning in the 1930s, significant reconstruction of the water management infrastructure of the watershed and its valley floor were undertaken to ensure greater reliability of water supplies and reduction of water losses through evaporation within the frequently waterlogged floodplains. These management activities involved building diversion dams, trans-basin diversions, levees to reduce valley floor inundation and channel migration, and wastewater disposal systems from settlements, as well as an extensive water delivery and drainage system for irrigated agriculture. Reservoirs were constructed for flood control, water storage, and sediment control, the largest of them on the Rio Chama in 1935 and 1963, and Cochiti Dam on the Rio Grande itself in 1973.

Reduction of the sediment supply to the MRG through reservoir storage, superimposed on a natural background trend towards landscape stabilization, has led to coarsening, narrowing, and lowering of the channel bed and simplification of the channel's multi-thread pattern and cross-section form (Massong et al. 2010), especially between Cochiti Dam and Albuquerque where the bed material now ranges from gravel to coarse sand. Farther downstream, sediment influxes from tributaries maintain a finer sandy bed, and large pulses of sediment at tributary junctions sometimes constrict the Rio Grande channel, but slight incision has extended downstream to Socorro over the past 70 years (Massong et al. 2006). It is not clear from the descriptions we have read whether channel complexity in this reach has been reduced. There have been several feet of channel bed lowering at various places along the MRG, varying from up to six feet (ft) between Cochiti Reservoir and Angostura to two or three ft through the Albuquerque reach. Where the channel has incised, some parts of the original floodplain have been abandoned and converted to terraces several to more than 10 ft above "normal high water level" (Massong et al. 2006). By contrast, the channel bed has risen over the same period in the reach between Socorro and Elephant Butte Reservoir, a reach which Massong et al. (2006, p. 4) refer to as the "active floodplain". Because of the lack of a formal definition of the term "floodplain", in the rest of this document we will use the term for any surface within the levees that becomes inundated in the current range of river elevations, which vary along the MRG (see below). Of course, this range and the elevation of the riparian surface itself change as channel bed elevations continue to evolve and as the high-flow regime of the river changes with trends in climate or reservoir management.

Although reservoirs have diminished the amount of sediment in transport, suspended sediment concentrations measured at Albuquerque, for example, exceed 1,000 milligrams/liter (mg/L) in high flows throughout the year and exceed 10,000 mg/L during occasional high flows in summer and fall. Farther downstream, sediment from tributaries and from the incising bed generate higher sediment concentrations, which frequently rise above 10,000 mg/L at San Marcial, for example. Sand continues to be transported along the bed during most of the year.

Before human intervention, the floodplain of the MRG was topographically complex and rendered relatively wet by frequent inundation and low channel depths. Levees, channelization projects, and the orientation of diversion dams have constrained the floodplain width to 200-400 ft in the vicinity of Albuquerque and to 800-4,900 ft in the Bosque del Apache reach. Since the 1930s, the construction of jetty jacks, the associated spread of riparian forest, and the general reduction in flood peaks have narrowed the channel, which now increases irregularly downstream between 300 ft and 600 ft, especially in the Bosque del Apache reach where the river flows across the widening and growing (but fluctuating) sediment fill upstream of Elephant Butte Reservoir. Channel deepening leads to a general drying of the floodplain through reduced frequency and duration of inundation and through lowering of the dry-season water table.

The modern channel generally has a large width-depth ratio and displays a braiding habitat to varying degrees along its length with mid-channel bars and bank-attached alternate bars. The more active of these bars remain unvegetated where they are inundated with frequencies varying from about one or two years to most of the year, depending to their height. At several locations along the Angostura and Isleta reaches, some of these bars have been artificially re-graded to lower elevations to increase the frequency and duration of inundation, but riparian plant encroachment favors sediment trapping that tends to gradually counter the engineered lowering. The river banks are now reinforced by riparian woody vegetation and resist erosion and channel migration. The channel incision has led to a relative elevation of the floodplain and a reduction in the frequency of inundation. It has also allowed vegetation to encroach upon and stabilize bars within the channel, converting submerged braid bars into enduring mid-channel islands or bank-attached accretions to the floodplain. A similar process of vegetation encroachment and stabilization occurs in the downstream aggrading reach during multi-year sequences of low flows. Most of the channel change in the lowermost reach results from either the rising of the bed reducing the flow conveyance capacity or from avulsion when fine-grained sediment plugs, reinforced by vegetation growth large enough to re-direct high flows (Julien and Rainwater 2014). Although the channel has a generally wide and planar bed, pools are scoured out at high flows, but we have no systematic information about their frequency, depth and distribution.

Three diversion dams separate the MRG channel into four reaches: Cochiti – Angostura (Cochiti reach); Angostura - Isleta (Angostura reach); Isleta - San Acacia (Isleta reach); and San Acacia-San Marcial RR bridge (San Acacia reach). The reach between the San Marcial RR Bridge and Elephant Butte Reservoir is also designated as the San Marcial reach. The diversions make local changes to the channel bed, substrate conditions (bedrock exposure), and hydraulic conditions (shallow, fast flow that is not trafficable by fish) that reduce migration potential. But surprisingly little definitive information on migration is available despite claims that long-distance upstream migration is a crucial life-history component.

Since 1973, Cochiti Dam has limited flood peaks to less than 10,000 cfs. The USGS flow records indicate that before impoundment, the 2-year and 10-year flood peaks at Albuquerque were approximately 6,600 cfs and 13,000 cfs respectively; there are only 5,000 cfs and 8,500 cfs in the post-dam record (USGS 2017). The 2-year and 10-year peak flows at San Marcial are unknown before construction of Cochiti Dam, but have been approximately 3,400 cfs and 6,400 cfs in the post-dam era. These reductions reflect both reservoir operations and recent climatic trends. Inter-annual variation in flood peak magnitude is now diminished to some extent through the efforts by water managers to ensure levee stability and to release a snowmelt flood wave to favor fish habitat condition. Recent trends towards climate warming have resulted in earlier snowpack melting and lower water yields as a result of higher evapotranspiration (Llewellyn 2016). The frequency of bank-full and higher discharges has become particularly low since the year 2000 (USGS gauging records [USGS 2017]), and the near-term trends are difficult to anticipate. If this most recent period of record is used to estimate flood frequencies, the 2-year flood estimate declines to 3,810 cfs and the 10-year flood estimate to 5,600 cfs. However, such estimates for the most recent period should be interpreted with caution because of the short length of the record and uncertainty about whether the reduction reflects only a short-term fluctuation which could be reversed by another natural fluctuation. With a similar caveat, the post-2000 estimate of the 2-year flood is 2,690 cfs and the 10-year flood is about 5,600 cfs.

At the other end of the scale of flow magnitude, storage of water in reservoirs and releases from municipal and agricultural return flows have increased low flows so that the frequency and duration of dry channel bed conditions have decreased.

Despite continual efforts by water managers to accommodate environmental flows within their other responsibilities, declines in water availability strongly affect the amount of water available for habitat. There is less total water available for maintaining flow within the channel and for providing sufficiently high flows to inundate the floodplain. Changes in the timing of high flows may also have affected species that evolved in the original flow regime. From water managers' perspective, the decreases in total inflow to reservoirs has diminished their operational flexibility. Projected trends in regional hydroclimatology indicate the necessity to plan for even more diminished flow resources in the absence of policy changes.

Most of the changes to water availability and to channel morphology and behavior appear to be irreversible because of the reduction of both sediment supplies and the lowering of flood peaks and seasonal flow volumes, at least upstream of Socorro. Some local bed aggradation might occur downstream of tributaries that episodically can deliver extraordinary sediment supplies after large monsoonal rainstorms. In those cases, the channel bed in some reaches may rise, bars grow, and floodplain inundation may be enhanced. Some changes to riparian morphology and inundation may also be effected through engineered lowering of riparian surfaces and creation of channels. Downstream of Socorro, it is likely that aggradation, channel bed elevation, island formation, and channel avulsion will also continue, although the fluctuating level of Elephant Butte Reservoir is likely to cause alternation of periods channel degradation and simplification with periods of channel filling, avulsion, and enhanced complexity.

8.2 Habitat Components

Quantitative understanding of the roles of habitat characteristics in the life history of the RGSM is hampered by lack of a generally agreed-upon spatio-temporal conceptual model of where and when critical life-history processes occur, including spawning, egg and larval drift and maturation, juvenile rearing, and migration by juveniles and adults. It is unlikely that there is a one-to-one correspondence between the total area of habitat for each life stage and fish production because the habitat quality also influences biological outcomes. Thus, predictions of habitat availability and significance have to be linked to specific biological processes through the quantification of growth and mortality. However, it is important to emphasize that the demise of the RGSM is unlikely to have been caused by any fundamental changes in the biology of the fish. Instead, the reduction in the fish population occurred in association with radical changes in the availability of high-quality habitat resulting from changes in land management, water operations, and climatic trends. Any amelioration of the fish's status will presumably require that some changes be made in the availability and quality of habitat. It is therefore important to establish and quantify the relationships between fish biology and habitat abundance and quality, as well as the relationship between the habitat characteristics and environmental conditions related to resource management and climate.

The habitat for the RGSM can be classified into components with different degrees of significance for various life stages:

i) main channel;
ii) channel margins;
iii) in-channel bars (mid-channel or bank-attached);
iv) in-channel pools;
v) floodplain surfaces, including channels and pools; and
vi) irrigation drain outlets.

The extent of each of these components varies between the four major reaches between diversion dams, as do their connectivity and their responses to gauged flow magnitude and duration.

The ecological role of each habitat component is acknowledged to at least some degree by most of the literature and briefings that the panel received, although there is no agreement on the relative importance of all components for production rates, growth rates, or survival rates at various life-history stages.

8.3 Status of Knowledge about the Role of Habitat

We are not aware of any published, systematic study of RGSM habitat preferences or use, so knowledge of the amount and ecological significance of each habitat component is based on a few local field surveys and expert opinion, summarized as follows:

i) Main Channel

The Porter and Massong (2006) report states, on the basis of electrofishing and seining surveys, that RGSMs "have broad habitat preferences" in the MRG and are associated with the "widespread presence of algal mats in shallow water." However, Tetra Tech (2014), after consultation with fishery scientists, concluded that resting and growth habitat within the main channel is limited to areas with flow depths less than or equal to 1.5 ft and velocities less than or equal to 1.5 feet per second (fps), and they compiled results of a 2D flow model (RMA2) to map the maximum extent of such areas in short (five to seven channel widths) sample portions of various reaches along the MRG. In most of that area, adequate food would be limited because the downward-directed mouth of the minnow seems suited to bottom feeding, and the bed is sandy, mobile, and free of organic detritus across most of the main channel, which is presumably why RGSMs associate themselves with algal mats. Moreover, Tetra Tech did not assess the energetics of holding in such flows balanced against the food availability. Thus, the proportion of the channel considered to comprise high-quality feeding and rearing habitat was defined to have flow depths less than or equal to 1.5 ft and velocities less than or equal to 0.5 fps. These in-channel zones are not only bioenergetically more favorable, but the beds of at least some of these areas have been observed to have silty texture and to contain organic detritus, which forms at least part of the RGSM diet. When the 2D flow model was used to map these conditions, very small (and therefore unreliably modeled and ecologically isolated) areas of such habitat were predicted to occur in the main channel, except at its margins (see below). The minimum size of such a high-quality feeding zone for effective rearing does not seem to have been established.

The other roles of the main channel in the life history of the fish that have been proposed as important are: a) egg release, fertilization, and downstream drift of eggs and larvae; and b) upstream migration of adult fish.

If the average mainstream velocity at low flow is roughly one fps and rises to (say) three fps during the spring flood, then eggs and passive larvae would travel downstream at 16-48 miles/day during egg maturation, and 80-245 miles during the minimum of five days when the larvae cannot swim to shelter (Wilde 2016). Since the maturing eggs have the settling velocity of very fine sand (0.062-0.125 mm; Medley and Shirey 2013), which is not widely represented in the bed even in the lowest-gradient reach of the MRG (Julien and Rainwater 2014, p. 11), there is little or no chance of them settling onto the bed in high flows, and if eggs did so, they would encounter a highly mobile and abrasive substrate.

Widmer et al. (2010) conducted a set of experiments on egg retention rates per unit length of channel in the Angostura and Isleta reaches. Large numbers of artificial eggs were released within the channel, and their arrival at downstream collection points was interpreted through a model that assumed initial release locations based on the mapped distribution of gravid fish and an assumed exponential spatial distribution of egg retention. The results indicated that egg retention should be highest in discharges that were interpreted to access the floodplain, or at least vegetated islands and riparian margins (3,400 and 4,900 cfs depending on the reach), and in reaches with more complex geometry, including vegetated, inundated islands. Retention was computed to be lowest in discharges that were either too low to access the floodplain or during times when water was flowing from the floodplain to the channel. Egg retention has apparently not been studied downstream of San Acacia and Socorro, where the channel complexity and frequency of overbank flow are higher.

The current role of the main channel in providing upstream passage for adult fish is limited by the Isleta and San Acacia diversion dams, which separate the MRG into three reaches 30-50 miles in length.

The main channel is also where egg production is monitored, and since the fate of eggs released into the water column is essentially a problem in suspended particle transport there are some physical aspects of the channel and the flow that need to be considered when designing an egg monitoring program and interpreting its results. We do not have a map of where the egg collection sites are, and we do not know certain (easily acquired) hydraulic features of the MRG channel approaching the egg sampling sites. However, descriptions of the monitoring equipment and its deployment in other rivers by Worthington et al. (2013 a, 2013b) indicates that its sampling efficiency at early rising flows is low (presumably because the suspended eggs at low-flow velocities travel below the sampling depth of 34 cm), that the vertical gradient in egg concentration within the flow makes it difficult to obtain an index of egg concentrations that is linearly proportional to the total number in transport, and that cross-channel variability in flow velocity in wide, shallow channels requires deployment of a number of samplers per site that has not yet been determined. More detail on this methodological issue is presented in Chapter 7.

ii) Channel Margins

Shallow areas along the margins of the main channel (usually within 50 ft of a bank), as well as very small areas of mid-channel bars, were also predicted by the flow modeling studies to have sufficiently slow flow (less than or equal to 0.15 fps) for feeding and rearing of RGSMs. However, such zones were highly restricted in all of the sampled subreaches except in the lower-gradient Bosque del Apache. Some, but not all, of these shallow areas are located along vegetated banks, but the Tetra Tech (2014)modeling did not incorporate the role of this characteristic in the habitat modeling, and it is not clear how extensive channel-edge vegetation is along the whole MRG at flow stages characteristic of the early phase of hydrograph rise, as opposed to at bankfull stage.

Pease et al. (2006) measured the occurrence and food sources of larval and juvenile fish of several species, including very low numbers of the RGSM, in low-velocity zones of the braided channel in the Bosque del Apache National Wildlife Refuge reach of the MRG. Habitats investigated included backwaters, isolated pools, disconnected side channels, and main channel margins. Of these environments, the isolated pool was by far the densest occupied habitat, and fish numbers in side channels and main channel margins were particularly sparse. However, the study took place during a year of intense drought with discharges far below those of average years, even for the diminished flow conditions of the past two decades. Thus, although the authors concluded that "low-velocity habitats created during floodplain inundation (high flow) … provided important nursery areas for Rio Grande fishes", that conclusion appears to be an extrapolation from the association between fish use and low-flow velocities, and could not be applied in a quantitative manner to assess the potential yield of inundated floodplains or of the frequency and duration of fish access to inundated floodplains in the various reaches along the MRG.

Porter and Massong (2004 p. 437) report (without documentation) that eggs settle out of the river flow along gradually sloping channel margins where flow velocity declines almost to zero even in rising spring flows, and especially where inlets create low-velocity flow. Massong et al. (2004) also reported that natural and constructed inlets at the mouths of tributary arroyos and diversion channels provide a drift zone with vanishingly low velocities connecting directly to the main channel flow from which eggs and larvae can diffuse and settle, and free-swimming fish can also hold. The mouths of perennially wet channels entering the MRG are particularly attractive low-velocity zones. However, the mouths of ephemeral, sediment-rich channels tend to build fans that constrict the main channel and do not provide habitat except during brief high flows when their outer margins operate like fragments of low floodplain roughly 30-50 ft wide. The US Army Corp of Engineers (USACE) has constructed other inlets at various locations along the MRG, and have measured (but not reported by Massong et al. 2004) their effectiveness at capturing and retaining artificial eggs and the duration of the inlets' inundation. At other locations, such as the Los Lunas restoration site, lowering of a narrow strip of floodplain and the shaping of a number of islands with intervening inlet channels created some potential for egg retention, but apparently with mixed results.

It is not known at this time how many adult and maturing juvenile fish inhabit these shallow, near-bank areas, but presumably it is in these locations that at least some fish are present when they first sense an increase in discharge during the spring. There is some consensus that this proximate trigger is a spring-time discharge increase (as low as 100-200 cfs was reported anecdotally to Tetra Tech and at the workshop), possibly accompanied by a change in water temperature. The reality and role of a temperature trigger have not been established, though the data to resolve that issue would be easy to collect, and probably exist already.

In most years, the flow increase is much larger than 100-200 cfs, and occurs from a baseflow of a few hundred to 1,000 cfs (USGS gauge records at Albuquerque [USGS 2017]). It is not known whether, given the opportunity, fish holding in the shallow, channel-margin habitat when flow increases attempt to move into more sheltered floodplain habitat before releasing eggs. If they release eggs at flow increases as low as a few hundred cfs, they have no access to the floodplain and the eggs must be released into fast-moving water, where they might or might not be recorded as a sharp rise in egg concentration in the upper 34 cm of the water column (in a MEC described by Worthington et al. 2013a at the regular monitoring sites).

The flow at the Albuquerque USGS gauge typically takes about one month to rise from 1,000 cfs to the 2,500 cfs flow (USGS 2017), which would allow gravid fish to access sheltered, vegetated channel margins, and bank-attached bars, but not extensive floodplain areas before spawning. According to Tetra Tech (2014), lab studies indicate that about seven days of increased flow at temperatures more than 20 degrees C are necessary to trigger spawning. They also report that their modeling indicates that 1,500 cfs at the Central Avenue reach "provide some inundated habitat", but their maps show that this inundated area must be no larger than one or two acres on the right bank of the river. Nevertheless, they report that such a threshold (1,500 cfs) "appears to be correlated with years with successful recruitment." In years of particularly successful recruitment, flow increases to above 3,000 cfs usually require at least a month. So, it is not clear whether spawning fish, confined to channel margins at the start of flow rises, delay their spawning until the flow is high enough for them to access the broader floodplain.

It is not clear where in the channel fish are located when they release eggs. There are only very small (approximately one acre) patches of near-bank habitat where velocities of less than or equal to 0.05 fps exist, which Tetra Tech (2014) claim is required for egg deposition and larval development, even at low flow, and thus certainly not during the hydrograph rise.

iii) In-Channel Bars (Mid-Channel or Bank-Attached)

Unvegetated and vegetated sand bars in mid channel and attached to the banks cause slowing of flow, and the bank-attached bars provide an increase in channel margin length, and possibly organic-rich substrate, so they expand slightly the extent of high-quality rearing habitat and even of inundated areas where eggs and larvae might be retained, according to the flow modeling. Large woody debris along the channel margins also expands the favorable habitat locally. These shallow zones are most extensive in the Bosque del Apache reach. Farther upstream where the channel is narrower and simpler, even these small areas where eggs and larvae might be retained are unvegetated and smooth, and become unfavorable as flow increases above 500-600 cfs, according to the Tetra Tech (2014) habitat suitability maps based on hydraulic modeling. The predicted patches favorable for egg retention within side channels are so small (a few hundred square ft), that it is not clear whether eggs could settle within them before being accelerated by the faster moving water downstream.

There is a small increase in the inundation of vegetated lateral bars as flow rises above 1,000 cfs before it enters the floodplain. However, the strongly limited extent of habitat favorable to spawning, larval development, and juvenile rearing within even those channel reaches that contain bars makes it difficult to understand how the fish could prosper if it were confined to these areas without access to floodplain habitat in most years. When flow is confined to the channel, the extent of favorable habitat for all life stages within the channel and along its margins actually shrinks as flow increases, vitiating any expectation of a positive relationship between flood size and population responses.

iv) In-Channel Pools

In-channel pools provide refuges for fish in the MRG during summer and fall when flow becomes intermittent in some years in the lower river. These pools are exploited by agency managers for salvaging fish, which are then re-located upstream where the channel retains water. We have not seen any maps of the distribution and size of such pools, which in some other sand-bed rivers become scoured larger and deeper in large floods and then tend to become filled in during smaller floods, particularly in the presence of significant sediment influxes like those from tributaries of the MRG.

Pease et al. (2006) established that an isolated pool in a braided zone of the Bosque del Apache reach of the MRG could act as a more productive habitat for fish and their food resources compared to nearby faster flowing zones of the channel, but the study was carried out in an intense drought and lacked context and scalability to the whole river. We do not have enough data to estimate the amount of rearing and refuge habitat in pools along the MRG, and thus the role of pools in supporting populations under the inter-annual variability of summertime flows in the MRG. The amount of this habitat and its significance for population dynamics presumably varies between reaches and from year to year. Some form of cheap and quickly deployable remote sensing technology, such as drones with digital video, would facilitate such censuses. Analysis of the field sampling associated with the current salvage program might be useful to quantify the biological response to the availability of pool habitat.

v) Floodplain Surfaces, Including Channels and Pools

The area of ecologically functional floodplain has shrunk dramatically within the past century because of two developments. The first is the draining and development of most of the valley floor for agriculture and settlement. The second is the levee construction which now limits the floodplain width, even in large floods, to 700-1,100 ft, within which the channel itself occupies 20-50%. Again, there appear to be systematic, if irregular, trends in these magnitudes along the river, with the floodplain downstream of the San Acacia diversion being much wider than that in the reaches upstream of the Isleta diversion.

The USACE (2010) used the FLO-2D numerical model to map floodplain inundation at a range of flows from less than 200 cfs to 10,000 cfs. The computations were calibrated to topographic surveys and observations of inundation extent in 1992 and 2002. More floodplain area was inundated for a given river discharge based on the 2002 survey than on the 1992 survey because the Rio Grande channel diminished in width and flow capacity between the two field surveys. There was no floodplain inundation unless the annual flood peak rose to 4,000 cfs in 1992 and to only 2,500 cfs in 2002, although the geographical extent of this inundation was not specified in the report. In both cases, however, the inundated floodplain area increased in a roughly linear fashion with increasing discharge, so that at 6,000 cfs, for example, about 8,000 acres were inundated based on the 1992 survey and about 11,000 acres based on the 2002 survey. The two calibrated models were then used to estimate the inter-annual variation of total inundated area in each reach from the 5-day maximum discharge of each year. The results showed that floodplain inundation is severely episodic with no overbank flow occurring in 45% of all years in the 2-decade period of the simulations.

Tetra Tech (2014) used the same FLO-2D numerical model results to illustrate hydraulic aspects of the habitat quality of the floodplain for short (five to seven channel widths) sample reaches of the floodplain. The spatial resolution of topographic data used as input to the flow modeling is 500 ft x 500 ft (250 ft x 250 ft in another case) and we do not know its vertical resolution and accuracy. Thus, it is not yet clear how accurate are the predictions of the nature of the inundated habitat, such as its flow depth variability, flow concentrations, and floodplain channels since the models provide only a single average value for flow depth and velocity for each 500 ft x 500 ft cell in the digital map of model results. However, the results are very useful for indicating broad trends in habitat availability with discharge, as well as important differences between reaches. The field surveys conducted to calibrate the flow modeling in 1998 and 2003 probably yielded some observations of the detailed nature of the inundation and possibly of fish distributions at the time of the inundations, which might yield qualitative insights about biological processes in the inundated floodplain, but we did not discover any published reports of such knowledge.

Gradual recognition that floodplains might provide critical habitat for the RGSM has led in the past decade to engineered reconfiguration of small areas of floodplain to re-establish more natural frequency and duration of inundation during the spring snowmelt runoff. Gonzales et al. (2014) conducted trapping surveys of adult fish, eggs, and larvae in eight of these reconfigured floodplain patches in the Angostura reach and in one natural floodplain in the Isleta reach during the inundation periods of 2008 and 2009. The surveys were conducted for several weeks in each year after the gauged MRG flow at Albuquerque had risen above 3,500-4,000 cfs (USGS 2017). The results established that both the reconfigured and natural floodplains support breeding adults, egg production, and larvae, but since the study was only designed to establish the presence of adult RGSM activity, few other measurements were reported. The Gonzales et al. (2014) publication refers to other studies of water depth, velocity, and flooding duration, colonization by plants, as well as use by the fish community, but we have not seen such reports, nor any attempt to scale the results to assess population-level contributions or the feasibility of affecting populations by this floodplain engineering method. Magaña (2012) documented habitat use by the silvery minnow of a 40-acre patch of reconfigured channel margin near Los Lunas. The site had been lowered to a level that was inundated at discharges exceeding 2,500 cfs, and configured with a network of small channels. Observations were made during the 44-day recessional phase of a controlled flow release from Cochiti Reservoir, which peaked at about 7,000 cfs. The study documented that larval RGSMs and other fish occupied the reconfigured floodplain, but also noted that floodplain inundation at the same site was relatively rare in the modern flow regime.

The Los Lunas annual report by Tave and Hutson (2012) also anecdotally describes a demonstration of RGSM spawning and growth response to a simulated overbank inundation event. The results were encouraging, but difficult to scale up to natural conditions because of the complexity of the simulation conditions and the lack of reported ancillary measurements of environmental conditions. More recent studies and peer-reviewed data analysis may yield scalable information.

vi) Irrigation Drain Outlets

Irrigation return flows and floodplain drainage channels were referred to occasionally in the public presentations and literature as providing summer and fall refuge for RGSM, but there does not appear to be any systematic mapping of this potential habitat, and therefore of its contribution to population maintenance. It probably has a longer and more secure duration than natural floodplain wetlands.

8.4 Key Uncertainties

The extensive technical literature, webinar briefings (Donnelly 2016, Gensler 2016, Harvey 2016, Llewellyn 2016, Schmidt-Peterson 2016, Wilde 2016), and presentations to the February science panel meeting indicated that a large number of uncertainties exist about the ecological role of habitat in affecting the various life stages of the RGSM population. The following outline is structured to highlight questions from the perspective of the various habitat components.

i) Main Channel

a. How extensively do juvenile and adult fish use the main channel when flow declines below floodplain access level?
b. To what extent do they occupy (a) channel margins or (b) pools as flow declines?

c. If the RGSM's life history plays out dominantly in the channel, why is there a positive correlation between spring flow magnitude and production if high flows make the channel a more unfavorable place to be a fish, egg, or larva?

d. Is the proximate trigger for spawning some aspect of the flow, and if so what is it? Answering this question is going to require examining the temporal resolution of the egg monitoring data. Assuming that these data are of sufficient temporal resolution, the question needs to be asked: what is the amplitude, timing, and duration of the signal for egg production?

   To test the hypothesis that water temperature is the proximate trigger, the water temperature records for the reach could be examined. The strongest temperature signal in water temperature is likely to be the diurnal one, and it should change gradually each day.

   If the trigger is water velocity (currently referred to as discharge) it might be sensed as drag on the fish's body, causing the fish to work harder to stay in place or to sense that it should move towards shelter in a lower-velocity zone, perhaps the channel margin or floodplain if possible.

e. As flow rises, where do adult fish move to? Are they in control of their movements or are they swept into lower-velocity zones, including overbank? When the flow rises, do RGSMs get washed downstream into the monitoring equipment? If not, then either there are very few in the reach or they have headed for low-velocity shelter or been swept overbank. Having evolved in this environment, the fish must have had flow refuges in times of high flow, but not necessarily in the channel itself. If the modern flow regime reduces or delays their escape from high in-channel flow velocities, the fish might be confined to habitat with lower quality and safety.

f. How soon after flow rises do the fish release eggs? The following (Figure 11), showing a randomly selected sequence of annual hydrographs, indicates the time lag between the first rise of the flow in spring and the onset of discharges high enough to allow floodplain access in vicinity of the Albuquerque reach (red line indicating flows greater than 2,500 cfs) and in the vicinity of the San Marcial reach (green line indicating flows greater than 1,500 cfs). The ticks on the abscissa of the graph indicate months. The time lag from initial rise to floodplain accessibility varies from about four to seven weeks in the vicinity of Albuquerque, to one to six weeks in the vicinity of San Marcial. The graph is meant only to sketch the nature of the uncertainty. The analysis could be refined with a longer data series, which could also indicate whether bed degradation trends in the various reaches are altering the lag time between initial flow rise and floodplain accessibility.

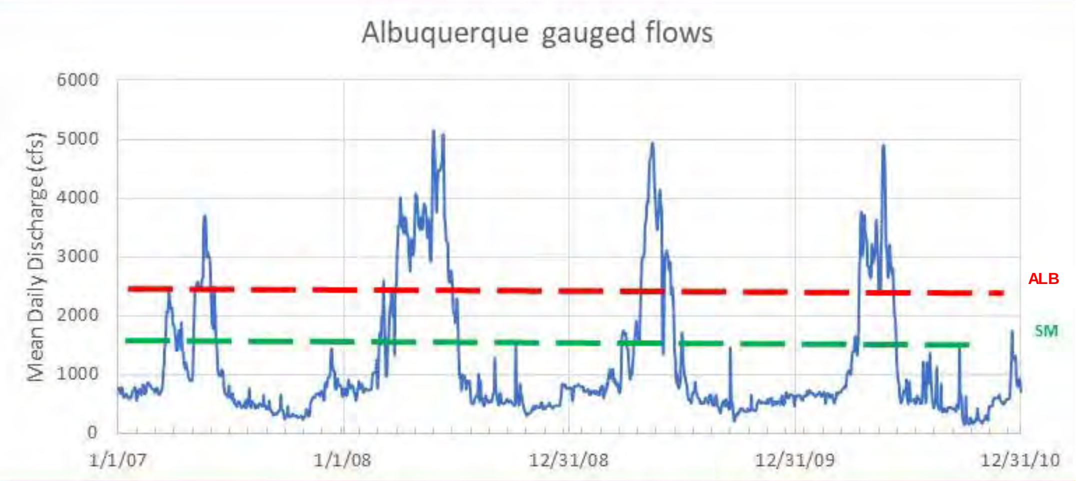

Figure 11. Albuquerque gauge flows from January 1, 2007, to December 31, 2010 (USGS 2017).

g. Do eggs settle from suspension in side channels? Since the settling velocity of eggs is known, this can be answered by the Rouse equation from hydraulics where flow depth and velocity or gradient are known. Can it be verified with field measurements of eggs settling onto traps on the stream bed? Has the texture, organic content, and mobility of the bed in these side channels been sampled? Even before any of these field measurements are made, it would be worth systematically mapping the occurrence of side channels (see the generalizing Figure 5 of the Tetra Tech [2014] report) to conclude whether such side channels could provide quantitatively significant egg and larval retention areas.

h. What is the amount and contribution to the population potential of upstream passage within each reach between dams? The only impediment to this passage, apart from the dams themselves, appears to be spatial intermittency of flow at various seasons, which could be mapped from records of drying that are currently available.

i. There are significant complexities in using egg collectors to obtain a reliable quantitative index of egg production that is even linearly related to the actual numbers. Careful planning of egg monitoring could probably improve the quantitative reliability of this measure of ecological functioning (see Chapter 7).

ii) Channel Margins

a. The extent of low-velocity habitat along channel and bar margins is not known, but could be mapped with a combination of field measurements at sample cross-sections and 2D flow modeling with higher resolution topographic/bathymetric data. Such data might have been used for the in-channel flow modeling described by Tetra Tech (2014), but is not referenced there. Such an analysis would quantify the extent of holding habitat and how the area would shrink as discharge rises, and it could also be used to examine the significance of riparian vegetation and large woody debris in creating slow-velocity zones (see below on floodplains).

b. The extent of the use of channel margin habitat by RGSM is not known, although anecdotal reports of fish sampling from river banks was presented in the workshop. Such documentation could confirm or refute the hypothesis that channel margin habitat constitutes significant rearing habitat and whether it comprises the locations from which egg dispersal originates.

c. Can eggs and larvae survive to maturity in channel margins? An indication of the answer to this question would be obtained by mapping substrate texture and organic matter occurrence in channel margins. Where the substrate is coarser than 0.125 mm (the upper size limit of very fine sand, which has the same settling velocity as RGSM eggs [Medley and Shirey, 2013]), eggs would not settle to the bed but would be transported downstream. Also, organic material in the substrate could be an indicator of food availability for developing larvae until they can move to more favorable sites.

d. If there are significant rearing zones within channel-margin habitat, what is the minimum effective size of such areas that would allow juvenile fish to occupy an area in which they would be secure and would not be swept downstream if they strayed into faster water?

e. If the RGSM's life history plays out dominantly in the channel, why is there a positive correlation between spring flow magnitude and production if high flows make the channel margin an unfavorable place to be a fish, egg, or larva?

f. What is the potential occupancy density (number per acre) for egg retention, larval survival, juvenile rearing, and adult holding of constructed or artificially enhanced channel margin habitat (inlets, lowered channel margins, or bank-attached bars)?

g. What is the total potential for constructing channel margin habitat as inlets, lowered channel margins, or bank-attached bars, and what is the likely contribution to fish production from those investments?

h. At what rate do artificially lowered channel margins recover their original elevations through sedimentation?

iii) In-Channel Bars (Mid-Channel or Bank-Attached)

The uncertainties about the habitat role of in-channel and bank-attached bars are essentially the same as those for channel-margin habitat.

iv) In-Channel Pools

a. What is the distribution, size and inundation status of pools that serve as rearing and refuge for RGSM in the dry season? How does the hydrology, water quality, and biology of pools relate to the probability of channel drying?

b. Are there pools, supported by groundwater discharge, irrigation return flows, or floodplain drain outfalls, that reliably form refuges even if the channel dries up?

c. Does pool habitat play any significant role in supporting fish production originating from fall spawning?

v) Floodplain Surfaces, Including Channels And Pools

a. What is the extent and nature of floodplain habitat that is hydraulically connected to the channel in each of the three reaches between dams?

b. How do those areas vary between years with the magnitude and duration of high flows?

c. At what threshold flow does the floodplain habitat become accessible to adult fish that have been holding in the main channel?

d. Do adults move into the floodplain before spawning?

e. Do eggs released in the channel get swept into the floodplain by overbank flow? What is the relative magnitude of this egg flux compared to the egg flux that can settle into favorable maturation sites within the main channel and its margins?

f. What is the nature of the substrate in inundated parts of the floodplain (organic detritus, diatom-rich, bare sand, silt)?

g. What is the rearing potential per unit area of inundated floodplain, and how does it compare with a unit area of main channel habitat?

h. Can rearing fish be systematically observed and their distribution quantified in the floodplain?

i. How does the duration of floodplain accessibility vary from year to year with the magnitude and shape of the spring hydrograph?

j. What is the total potential area for engineered lowering of floodplain to increase sites for egg and larval retention and rearing? Where are the main opportunities for this intervention?

8.5 Suggestions for Resolving Uncertainties

Some of these uncertainties can be resolved through experimentation. Others are unlikely to be subject to experimentation, but uncertainties about them can be reduced through systematic inductive investigations.

8.5.1 Quantifying the Productive Capacity of Channel, Riparian Margin, and Floodplain

Question: What is the potential for RGSM production in each MRG reach if the annual peak flow, and thus the range of available habitat, is limited during a particular year?

The question could be addressed in two ways.

i) Field Based Approach

The first step would be to identify years in the USGS flow records when the annual peak flow indicated that habitat access was:

a) confined to the sandy channel and unvegetated bars;

b) included (a) and also vegetated islands and sloping riparian zones described informally in various reports (these could include recently regraded surfaces); or

c) included (a) and (b) and also extensive floodplain areas.

The threshold discharges for each of these conditions will vary between reaches, typically being lower in the reach downstream of Socorro and higher near Albuquerque. The discharges could initially be defined from USGS gauging records, possibly with interpolation between gauging stations with flow modeling. For example, the peak mean daily flow at the USGS Albuquerque gauge was 1,240 cfs in water year 2002 and 1,260 cfs in water year 2003 (USGS 2017), implying that all fish would have been confined to the sand- bed channel and (mainly unvegetated) bars. Egg and fish production data for these and similar years should allow analysts to converge on an upper limit for the productive capacity of the channel alone. The process could be repeated for downstream reaches. Similar segregation of years with flows in the range between (say) 1,500 cfs and the threshold discharge for more extensive floodplain inundation, estimated to be 2,500 cfs for the Albuquerque reach in 2002 (Tetra Tech 2014), could be used to estimate the additional level of egg and fish production gained when the vegetated in-channel and riparian zone is inundated. Finally, a suite of years with extensive floodplain inundation with discharges exceeding (say) 3,000 cfs in the Albuquerque reach and lower threshold values in downstream reaches could be used to define a lower bound on the productive value of floodplain inundation. The duration of overbank flow might add significant inter-annual variance to production data from these years, but the important first analytical target would be whether a lower bound on floodplain production could be recognized. Currently available monitoring data from these years could be used to make a first assessment of egg production and larvae and fish counts.

Segregation of data analysis by flow years in this way highlights a potentially significant complication for interpreting census data. For example, in years when many or most fish have access to the floodplain for spawning and rearing, the main channel monitoring data may have little correspondence with egg and larva production, though presumably October census data would provide a useful metric of total recruitment from all habitats where spawning had taken place. This observation is made only to illustrate the value of developing a spatially registered analysis of where critical life stages occur and also the value of quantifying the degree to which changes to habitat availability influence the fish population. This issue is the critical link between fish populations and water management operations in a changing climate.

The analysis of field production rates would also need to take account of well-understood forms of variability, such as the duration of overbank flow or whether channel-bed elevation changes have altered the threshold stage for inundation. There are standard hydraulic and geomorphological techniques, such as specific gauge height analysis, for doing this. The purpose of the segregation of census data interpretation by flow years would be merely to estimate some broad limits on the production capacity of at least the channel and perhaps of the riparian zone, and a lower limit of production for the floodplain.

In addition to statistical analysis of past monitoring data segregated by flow year, field studies of habitat selection and resulting growth could be expanded by using the trapping techniques and food source studies utilized, for example, by Magaña (2012) and Gonzales et al. (2014). However, to construct a quantitative model of how the quantity and quality of habitat varies with flow, the studies would have to be replicated in more overbank environments and in a variety of flow years. As far as we can tell from the literature, only a single natural floodplain has been surveyed in this way and in a single flow year.

ii) Experimental Approach

In order to avoid some of the obvious complicating factors in field studies and to obtain other data on the biological processes responsible for different population responses to habitat availability, experiments could be designed to isolate the same environmental constraints in the Los Lunas or Albuquerque BioPark facilities. Los Lunas has already been used to demonstrate that RGSMs could be successfully reared in a partially naturalized channel-riparian system with off-channel water bodies and native plants in the surrounding overbank area (Hutson et al. 2012, Coleman et al. 2011). However, the overbank area (apart from the off-channel water bodies) was not inundated in this study. Tave and Hutson (2012) described anecdotally a demonstration of fish spawning and growth response to a simulated overbank inundation event in the Albuquerque BioPark experimental facility. The report is difficult to scale up to natural conditions because of the complexity of the simulation conditions and the lack of reported ancillary measurements of environmental conditions.

In one set of experiments, fish could be confined to the channel and their condition and (for example) spawning responses to rapid flow increase could be monitored continually throughout a spawning season. The success of egg maturation, larval and juvenile development could be monitored, along with food availability, growth rates, site selection within the flow field, and the energetics of growth. A parallel set of experiments with higher discharges could allow fish access to an experimental floodplain of sufficient extent. Egg release, larval and fish growth rates, stomach contents, and life-history processes could again be tracked continuously to measure whether there is incremental production under floodplain conditions. Environmental conditions of both channel and floodplain, along with such factors as food availability and water temperature, could be characterized in detail. Follow-up experiments might begin with fish in the channel, suddenly supplied with a rapid increase in discharge that would give them access to the channel, so that it could be observed whether the eggs are released while the fish are in the channel and then carried into riparian zones by the overbank flow, or whether the fish prefer to access the floodplain before releasing eggs if they have the necessary time. Other experiments could quantify the effects of duration of floodplain access and whether stranding is a quantitatively significant factor at the population level.

8.5.2 Quantifying the Extent and Quality of Habitat at Various Flow Levels

Question: How does the extent and quality of physical habitat change with river discharge in each of the reaches of the MRG between pairs of diversion dams?

Initial work on modeling the extent, threshold discharge, and the duration of floodplain inundation and in-channel hydraulic conditions summarized by Tetra Tech (2014) is valuable, but finer-resolution characterization of topography, vegetation, and substrate together with 2D flow modeling would facilitate a clearer, quantitative assessment of the amount and quality of the habitat at various streamflows. Such results would provide a more reliable mechanistic perspective on floodplain accessibility, the area and quality of habitat for egg and larva retention and maturation, food resources, juvenile rearing, and prospects of fish stranding during falling water. The modeling of the relationship between streamflow and habitat extent is also required for calculating the duration of floodplain inundation under various managed flow releases and unanticipated floods in the current hydrological regime, and under various climatic scenarios expected in the future.

The modeling would also characterize in-channel conditions, including velocities and depths, and the magnitude and distribution of pool refuges, although presumably these pools change from year to year more substantially than do floodplain features. The mapping and modeling would develop only a snapshot of pool habitat status, but one which would still characterize the ecological role of these features more systematically than we have seen in the literature and presentations.

Thus, the characterization and modeling of channel and floodplain habitat could be a flexible tool for habitat assessment, and would allow the assessment of competing hypotheses concerning the necessary conditions for each life stage of the RGSM. It could also be used to predict the extent and connectivity of artificially lowered and planted areas of rejuvenated floodplain habitat at various streamflows, as well as the habitat potential of engineered channel modifications to diversion inlets, banklines, and drain outfalls (Massong et al. 2004), and thus to assess their potential contribution to population maintenance.

The higher resolution habitat characterization would require a one-time aerial survey with standard topographic lidar. A recent paper by Stone et al. (2017, in press) reports on the implementation of such a high-resolution flow model for the channel and floodplain along 32 km of the MRG in the vicinity of Albuquerque, using lidar-generated topographic data with a spatial resolution of a few m, already provided by the New Mexico Interstate Stream Commission. Details of the procedure are reported only sparsely in the paper, so it is not clear where subaqueous channel topography came from, how the model was validated, and why ecologically more interesting reaches downstream could not be modeled, but the paper provides a useful pointer to advances that could be made in habitat characterization along the MRG. It would be preferable to simultaneously map flow depth with bathymetric lidar, which can penetrate to one Secchi depth, if this is possible at the season of lowest turbidity in the MRG. Otherwise bathymetry would have to be obtained separately with some ground-based utility, such as boats equipped with sonar and global positioning system (GPS). If the lidar survey were conducted at extreme low stage, which would minimize uncertainty in bed elevation, even channel cross-sections surveyed with a ground-based RTK-GPS could probably be interpolated with sufficient confidence. The 2D flow modeling could then be carried out with greater spatial resolution than has been done for the lower MRG in the past, yielding a more reliable template for modeling a wide range of scenarios.

Because the channel of the MRG changes on annual and longer time scales (Massong et al. 2006, 2010; Makar and AuBuchon 2012), and the downstream reach responds to fluctuations of Elephant Butte reservoir levels and can even become plugged and redirected in the lowermost reach (Julien and Rainwater 2014), it is important to consider whether such changes would vitiate the use of a high-resolution spatial model of habitat quality.

Secular changes such as a trend of channel bed lowering or rising relative to the floodplain surface would have to be identified from at least the USGS gauge sites through the standard techniques of stage-discharge analysis, and if sufficiently large might trigger new lidar surveys as happened between 1992 and 2002. However, it is not always necessary to undertake new surveys simply to keep up with the details of habitat changes, so long as the essential features of the ecosystem are understood, the likely magnitudes of biological responses to habitat change are known, and some simple indicator of changing conditions can be easily monitored.

A spatial model of habitat extent and characteristics of the kind proposed would produce a much more concrete basis for analysis of the fish's life cycle and its reaction to habitat change than is currently available. The model could serve as a template for many characterizations of biological response, such as location of fish, fate of eggs, pool salvaging, evidence for upstream migration, etc. It could be used, for example, when designing spatially representative surveys referred to under (i) above to establish habitat preferences and growth responses. Some of the biological response studies would probably be conducted in experimental flumes because of convenience, but results from the Los Lunas experimental facility would probably have greater natural value. Whether the biological characterizations of habitat preference and quality were conducted experimentally or from field surveys, the spatial model would provide the integrating template and allow issues of scalability and representativeness to be evaluated.

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10 LIST OF ACRONYMS AND ABBREVIATIONS

2D	2-dimensional
B.S.	Bachelor of Science
BOR	Board of Review
C	Celsius
CFM	constant fractional marking
cfs	cubic feet per second
cm	centimeter
CPUE	catch-per-unit-effort
ES	Executive Summary
ES	Executive Summary
ESA	Endangered Species Act
fps	foot per second
ft	foot
GPS	global positioning system
GSA	GeoSystems Analysis, Inc.
GSI	gonadosomatic index
Los Lunas	Los Lunas Silvery Minnow Refugium
m	meter
m/s	meter per second
m^2	square meter
m^3	cubic meter
m^3/s	cubic meter per second
MEC	Moore egg collector
mg/L	milligrams per liter
mm	millimeter
MRG	Middle Rio Grande
NMSU	New Mexico State University
Panel	The independent science panel consisting of Drs. Noon, Hankin, and Dunne, and Prof. Grossman,
pers. comm.	personal communication
Program	Middle Rio Grande Endangered Species Collaborative Program
PVA	Population viability analysis
Recovery Plan	*Rio Grande Silvery Minnow Recovery Plan, First Revision*
RGSM	Rio Grande silvery minnow
RM	river mile
RR	railroad
SL	Standard length
SME	subject matter expert
UNM	University of New Mexico
USACE	US Army Corps of Engineers
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey
VBGE	von Bertalanffy growth equation
VBGM	von Bertalanffy growth model
VIE	Visible implant elastomer
YOY	young-of-year

APPENDIX A
RIO GRANDE SCIENCE PANEL AGENDA AND SESSION PRESENTATIONS

MIDDLE RIO GRANDE ADAPTIVE MANAGEMENT PROGRAM

INDEPENDENT SCIENCE PANEL: RIO GRANDE SILVERY MINNOW LIFE HISTORY

Location:
Tamaya Resort and Spa
1300 Tuyuna Trail Santa Ana Pueblo, New Mexico, USA, 87004

February 1-2, 2017 (Open Session)
February 3, 2017 (8:30 am-12:30 pm) (Executive Session)

AGENDA

Meeting Objectives/Desired Outcomes:

- Review the available science that addresses how population characteristics (e.g. abundance, density, and occupancy) relevant to the recovery of Rio Grande Silvery Minnow (RGSM) vary over space and time and what environmental factors best explain this variation.
- Identify aspects of the species' life history that are characterized by significant uncertainty and those that are sufficiently well understood to inform management decisions.
- Provide recommendations for priority studies that address key uncertainties relevant to management decisions, either within an adaptive management framework or supplemental to it.

Wednesday, February 1, 2017

8:30-9:00 Informal Gathering

9:00-9:40 Welcome, Introductions, Meeting Objectives and Agenda

Dr. Barry Noon, Professor, Department of Fish, Wildlife, and Conservation Biology, Colorado State University *(Chair)*
Gail Bingham, President Emeritus, RESOLVE *(facilitator)*

9:40-10:00 Background
Objective: Review activities to set the stage for the workshop.

Gail Bingham, *facilitator*

10:00-12:00 *w/break* Session I: Scientific Perspectives on Spawn Timing
Objective: Review the scientific evidence related to spawn timing.

Suggested Questions:

- What are the proximate and ultimate environmental cues for RGSM spawning? How well known is the association between these cues and spawning?
- How time sensitive are these cues and are they effective over a narrow time frame (days to weeks) or over a wider period?

Presentations (20-25 min with 10-15 min each for questions from the panel)
Thomas Archdeacon, *USFWS*
Dr. David Cowley, *New Mexico State University*

Follow up questions from the Panel [~30 min]
[and from management representatives of Collaborative Partners if time permits]

12:00-1:15 LUNCH

1:15-3:00 Session II: Scientific Perspectives on Spawning and Larval Development
Location(s)

Objective: Review the scientific evidence related to where spawning and larval development occurs in the Middle Rio Grande River system.

Suggested Questions:

- Where (main channel, backwater channels, floodplain, etc.) does RGSM spawning, egg development and larval development occur?
- What are the key physical, chemical, and biological/hydrological attributes of these habitats?

Presentations (20-25 min with 10-15 min each for questions from the panel)
Dr. David Propst, *University of New Mexico*
Dr. Richard Valdez, *SWCA Environmental Consultants*

Follow up questions from the Panel [~30 min]
[and from management representatives of Collaborative Partners if time permits]

3:00-3:15 BREAK

3:15-5:00 Session III: Scientific Perspectives on Relationships between Hydro-Geomorphic Attributes and RGSM Population Response

Objective: Review available science exploring relationships between hydrologic attributes of flow magnitude and duration and channel morphology with RGSM density, abundance and spatial distribution through the Middle Rio Grande.

Suggested Questions:

- How do population characteristics relevant to RGSM recovery (e.g., density, abundance, occupancy, etc.) vary over space and time and what hydrologic and/or geomorphic factors best explain this variation?
- What models, data, or analyses are available to support these relationships?
- How does channel morphology interact with discharge to create appropriate spawning and nursery habitat?

Presentations (20-25 min with 10-15 min each for questions from the panel)
Joel Lusk, *USFWS*
Dr. Rich Valdez, *SWCA*

Follow up questions from the Panel [~30 min]
[and from management representatives of Collaborative Partners if time permits]

5:00-5:15 Day One Wrap Up and Adjourn

5:30-6:30 Executive Session: Review Information Presented

Thursday, February 2, 2017

9:00-10:45 Session IV: Scientific Perspectives on Adult Survivorship

Objective: Review the scientific evidence relating to factors affecting lifespan and implications for population age structure.

Suggested Questions:

- What physical, chemical, ecological and hydrological factors limit survival of adult RGSM?
- How do these factors affect longevity and population age structure?

Presentations (20-25 min with 10-15 min each for questions from the panel)
Thomas Archdeacon, *USFWS*
Dr. David Cowley, *New Mexico State University*

Follow up questions from the Panel [~30 min]
[and from management representatives of Collaborative Partners if time permits]

10:45-11:00 BREAK

11:00-12:45 Session V: Scientific Perspectives on Intermittency of Flow for Adult Survivorship

Objective: Review the scientific evidence relating to the importance to adult survivorship of maintaining wetted habitat during low flow periods.

Suggested Questions:

- What characteristics of wetted habitat are supportive of adult survival during low water years, e.g., linear distance of wetted river, specific refugial areas and where they should be located, key attributes of habitat, volume of habitat etc., are important for adult survival? Also, what metric(s) is (are) used to measure survival?
- How is adult survival through periods of intermittent flow affected by wetted habitat size?
- What role do~~es~~ physical and chemical aspects of water quality play in adult survival?

Presentations (20-25 min with 10-15 min each for questions from the panel)
Joel Lusk, *USFWS*
Mike Hatch, *New Mexico State University*

Follow up questions from the Panel [~30 min]
[and from management representatives of Collaborative Partners if time permits]

12:45-1:45 LUNCH

1:45-3:30 Session VI: Scientific Perspectives on Connectivity and Fish Passage

Objective: Review the scientific evidence relating to the contributions of connectivity and fish passage for RGSM population viability.

Suggested Questions:

- What are the important science questions in increasing fish movement between reaches (San Acacia, Isleta, Angostura, and Cochiti) for improving RGSM population status? Why?
- What are the functional benefits (e.g., genetic diversity, to escape channel drying, reoccupation of upstream reaches, other) to RGSM from fish passage? What are the uncertainties, and how can we test them?

Presentations (20-25 min with 10-15 min each for questions from the panel)
Dr. David Propst, *University of New Mexico*
Dr. Mickey Porter, *USACE*

Follow up questions from the Panel [~30 min]
[and from management representatives of Collaborative Partners if time permits]

3:30-3:45 BREAK

3:45-5:00 Session VII (discussion only): Water Management on the Middle Rio Grande
Objective: Understand the reservoir water operations decision criteria and process with respect to endangered species, obligations under the Rio Grande Compact, and satisfaction of water rights and other water supply demands.

Homework in advance of the workshop: Watch video presentation by Carolyn Donnelly on water operations in the Middle Rio Grande, including the 2016 El Vado coordinated spring pulse as an example.

Suggested Questions:

- What monitoring or other information is used in making decisions about timing and magnitude of releases?
- What is the decision space or latitude for adjusting flows for RGSM?
- How are tradeoffs between water demand, compact deliveries and flow releases for endangered species handled? Using what criteria or information?

Questions/discussion with water managers:
Carolyn Donnelly, *US Bureau of Reclamation*
David Gensler, *Middle Rio Grande Conservancy District*
Nabil Shafike, *New Mexico Interstate Stream Commission*
Ryan Gronewold, *USACE*

5:00-5:15 Day One Wrap Up and Adjourn

Friday, February 3, 2017 (Executive Session)

8:30-10:00 Initial Findings
Objective: Discuss the evidence presented. What conclusions about the life history of the Rio Grande Silvery Minnow are substantiated by the evidence?

What uncertainties remain which have significant implications for management action? How might these uncertainties be addressed either within or supplemental to an adaptive management framework?

Topics *[~20-30 min each]*:

1. Spawn timing
2. Spawning, nursery location(s)
3. Hydro-geomorphic relationships
4. Adult survivorship / age classes
5. Relationship of flow intermittency on adult survivorship
6. Connectivity and fish passage
7. Other?

10:00-10:15 BREAK

10:15-11:30 Executive Session: Initial Findings *[continued]*

11:30-12:30 Executive Session: Next Steps
Objective: Review initial draft table of contents for report and schedule. Discuss writing/review assignments. Determine need / schedule for follow-up conference call(s).

12:30 Adjourn

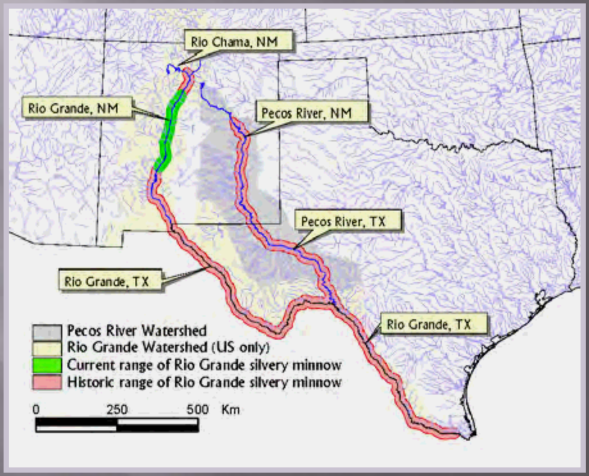
SESSION 1
SCIENTIFIC PERSPECTIVES ON SPAWN TIMING

SCIENTIFIC PERSPECTIVES ON TIMING OF RIO GRANDE SILVERY MINNOW REPRODUCTIVE EFFORTS

Thomas P. Archdeacon
New Mexico Fish and Wildlife
Conservation Office

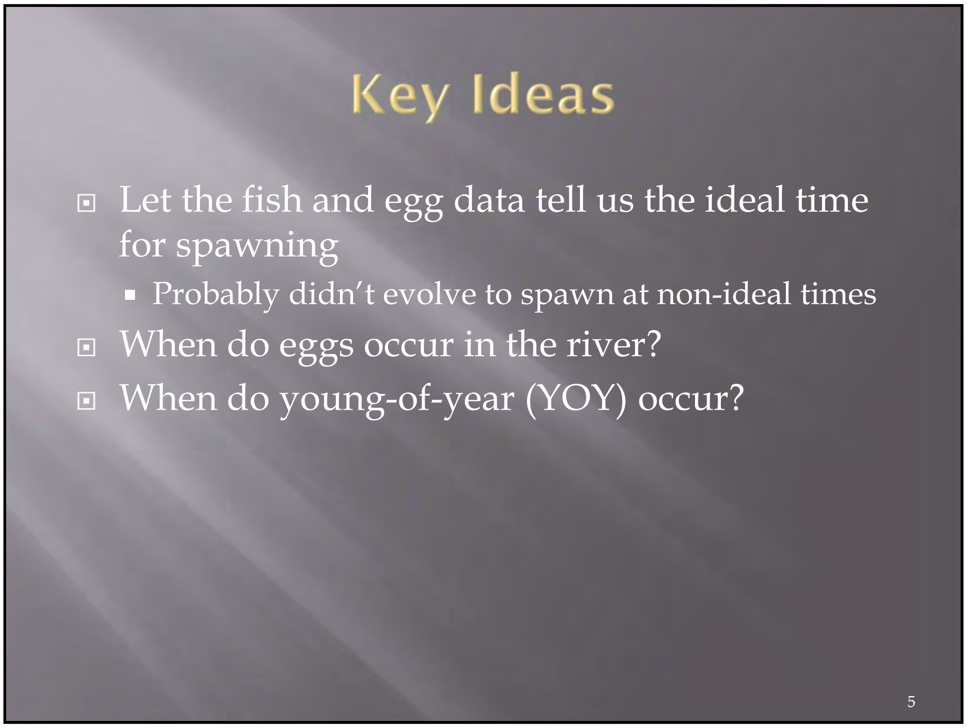
Rio Grande Silvery Minnow

Rio Grande Basin
New Mexico and Texas



Ideal timing or able to spawn?

- What are the proximate/ultimate cues?
- How sensitive to cues?
  - (days to weeks)
  - wider period?
- Evidence of monsoonal spawning



Key Ideas

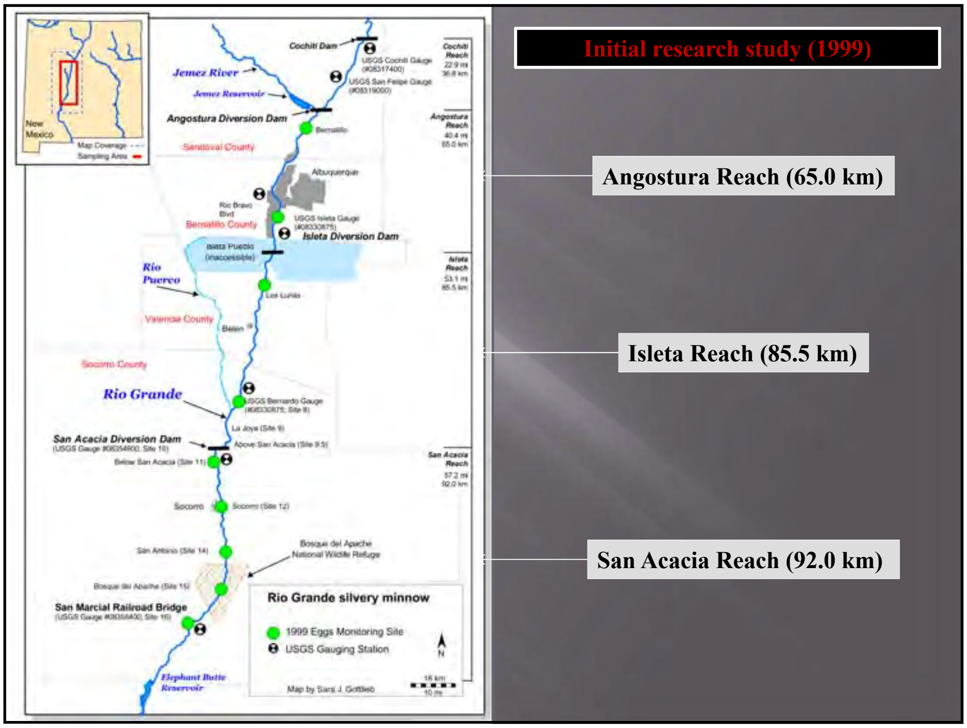
- Let the fish and egg data tell us the ideal time for spawning
  - Probably didn’t evolve to spawn at non-ideal times
- When do eggs occur in the river?
- When do young-of-year (YOY) occur?

Able to spawn

- Some eggs collected as late as July and even August 2002 (Smith 2003)
- 1 Egg collected in March (ASIR)
- April to July, maybe August
- Presence of small YOY in August and beyond might suggest monsoonal spawning
- Current egg monitoring is funded for 50 days
  - from mid-April to mid-June

Ideal spawning time

- Based on 9 years of larval collections, spawning begins in mid-May, +/- 2 weeks (Turner et al. 2010, Krabbenhoft et al. 2014)
- Majority of eggs (millions) are collected in May
  - Some in late April, some in early June

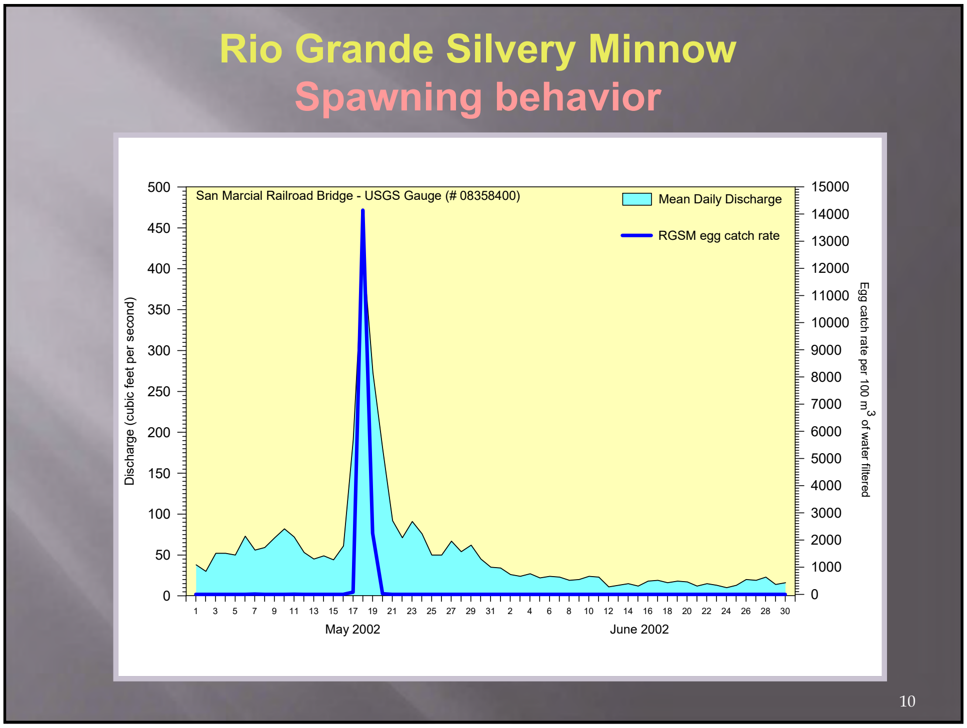


Initial research study (1999)

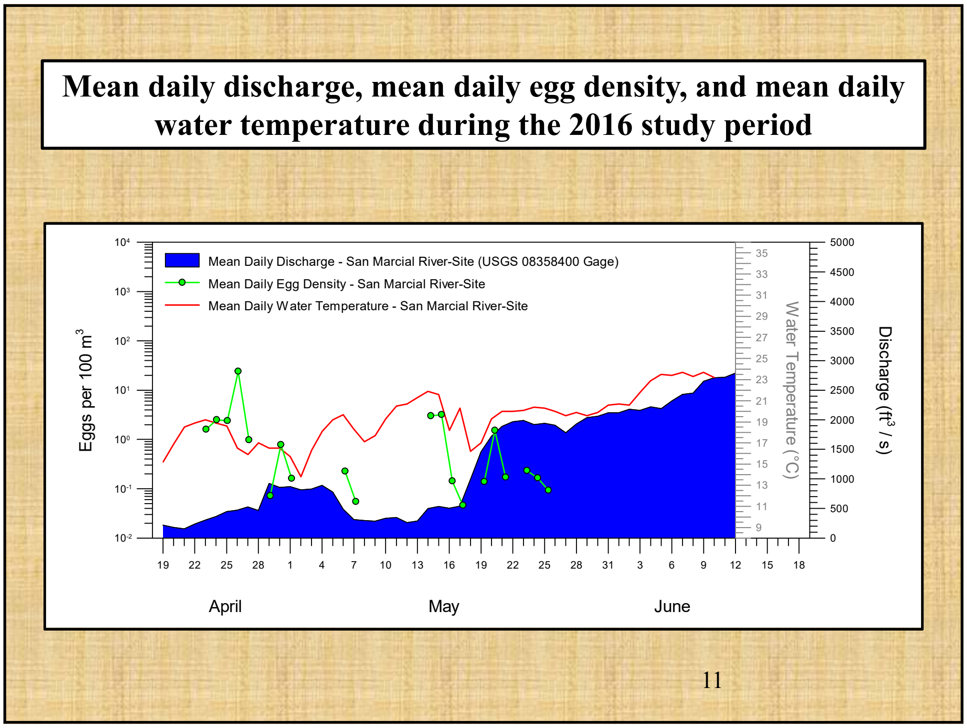
Angostura Reach (65.0 km)

Isleta Reach (85.5 km)

San Acacia Reach (92.0 km)



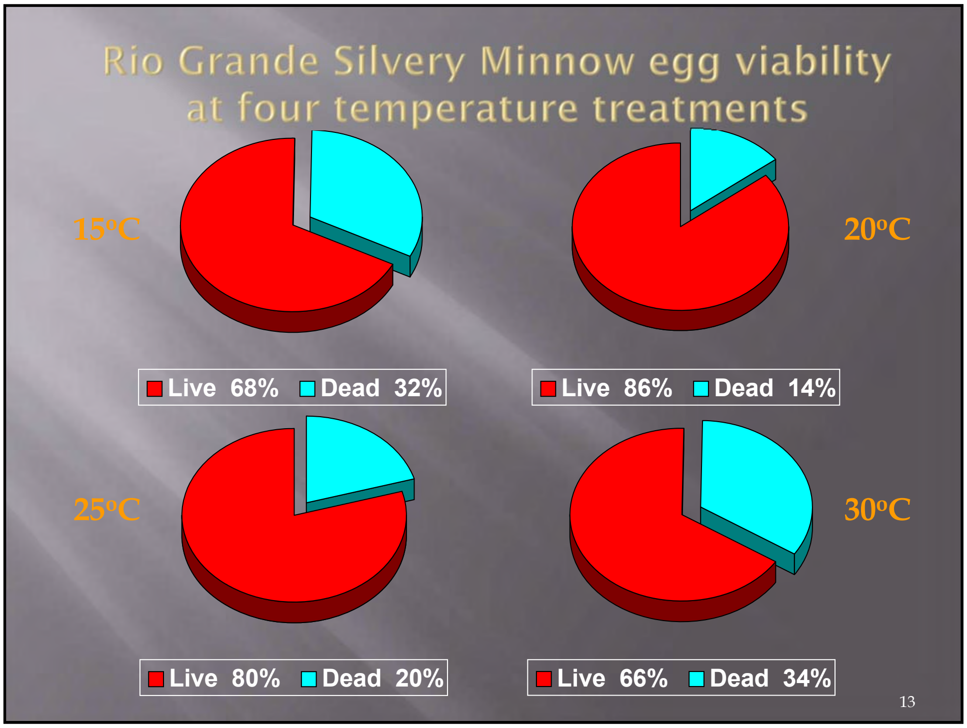
Rio Grande Silvery Minnow
Spawning behavior



Mean daily discharge, mean daily egg density, and mean daily water temperature during the 2016 study period

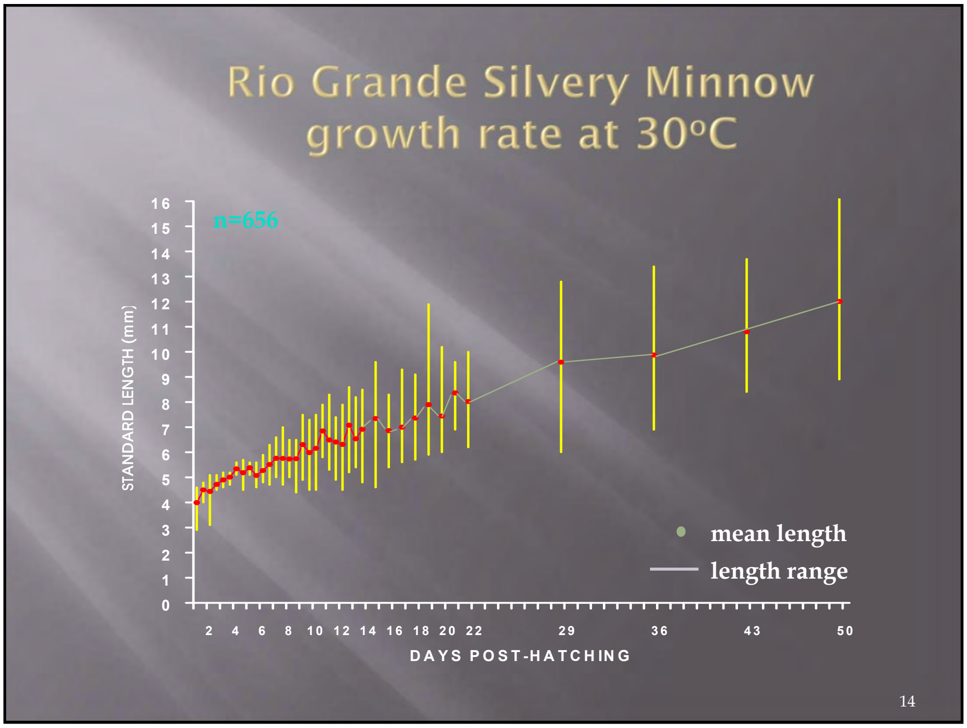
Ideal spawning time

- Earlier is potentially too cold, slows hatching and growth (Platania 2001, Dudley and Platania 2007, Mapula et al. 2008)
- Later potentially overlaps river intermittency, water temperatures >30 C (FWS)
- Best egg survival and larval growth about between 20 and 25 C (Platania 2001)
- Each year is different, but across many years spawning is centered on May



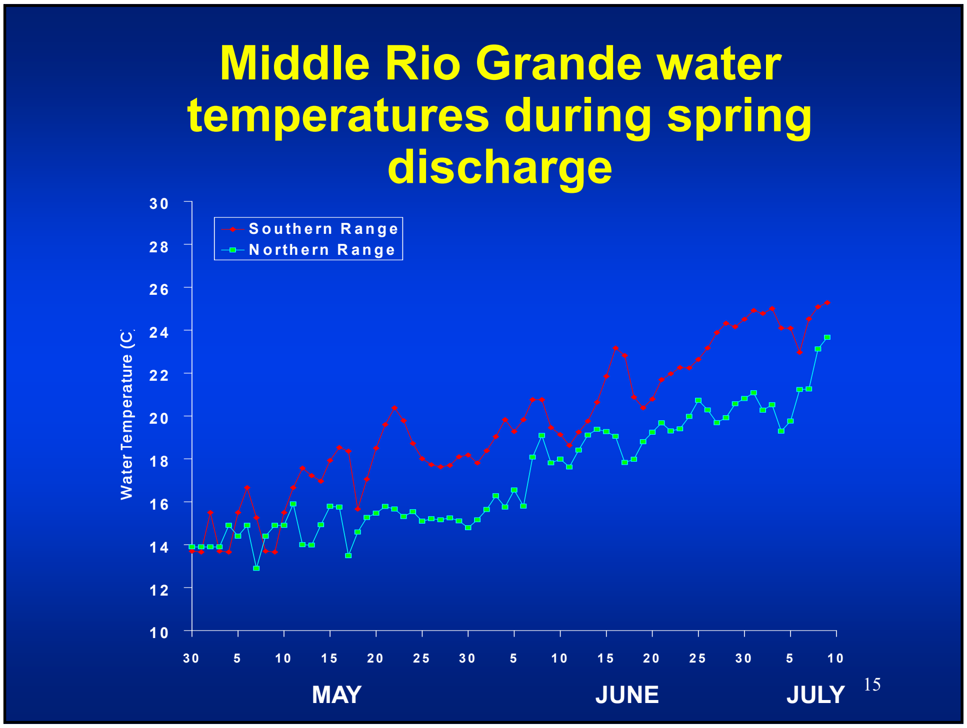
Rio Grande Silvery Minnow egg viability at four temperature treatments

13



Rio Grande Silvery Minnow growth rate at 30°C

14

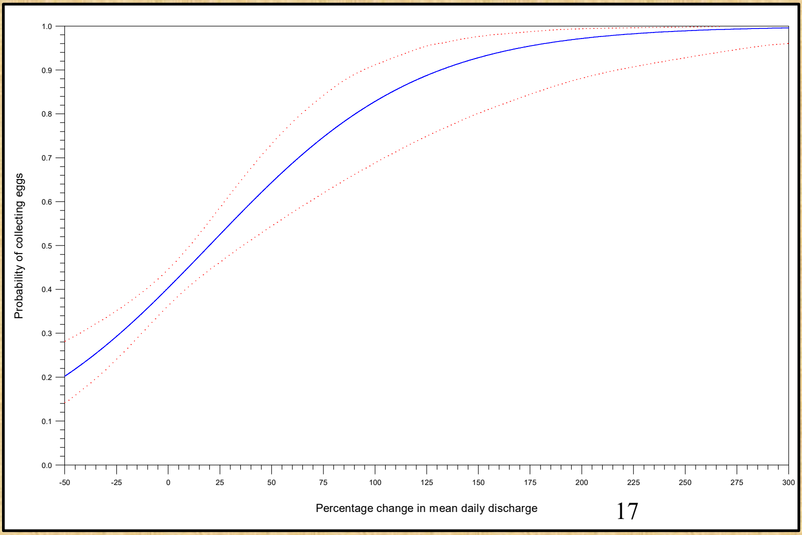


Middle Rio Grande water temperatures during spring discharge

Cues

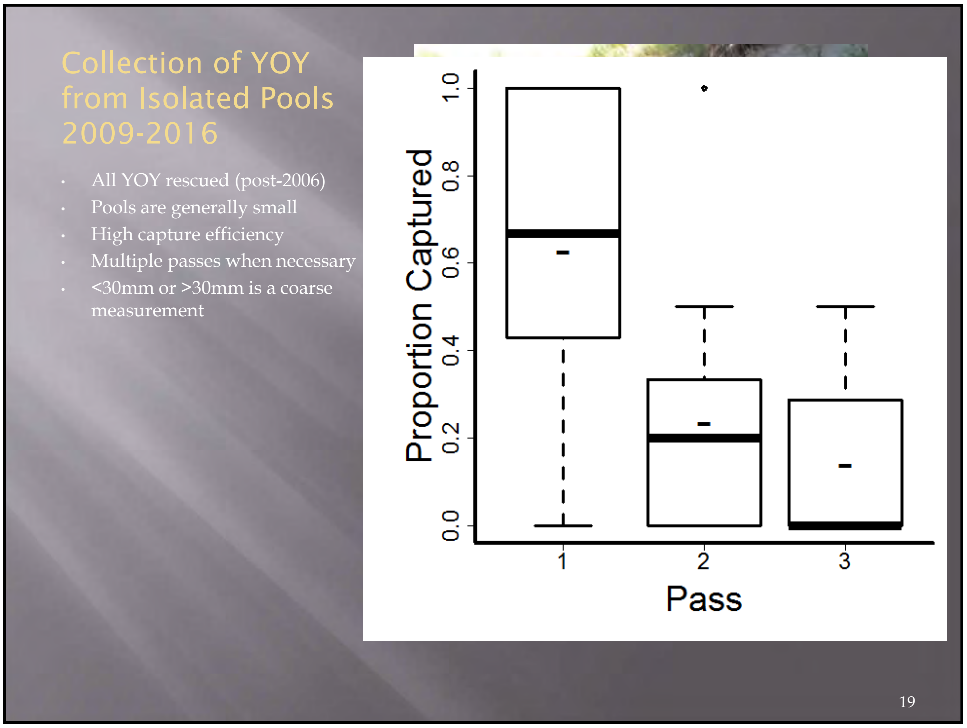
- Ultimate
    - Temperature
    - Photoperiod
- Proximate
    - Change in stage

Logistic regression plot, using San Marcial Site data (2003–2016), illustrating the probability of collecting eggs as a function of the percentage change in mean daily discharge



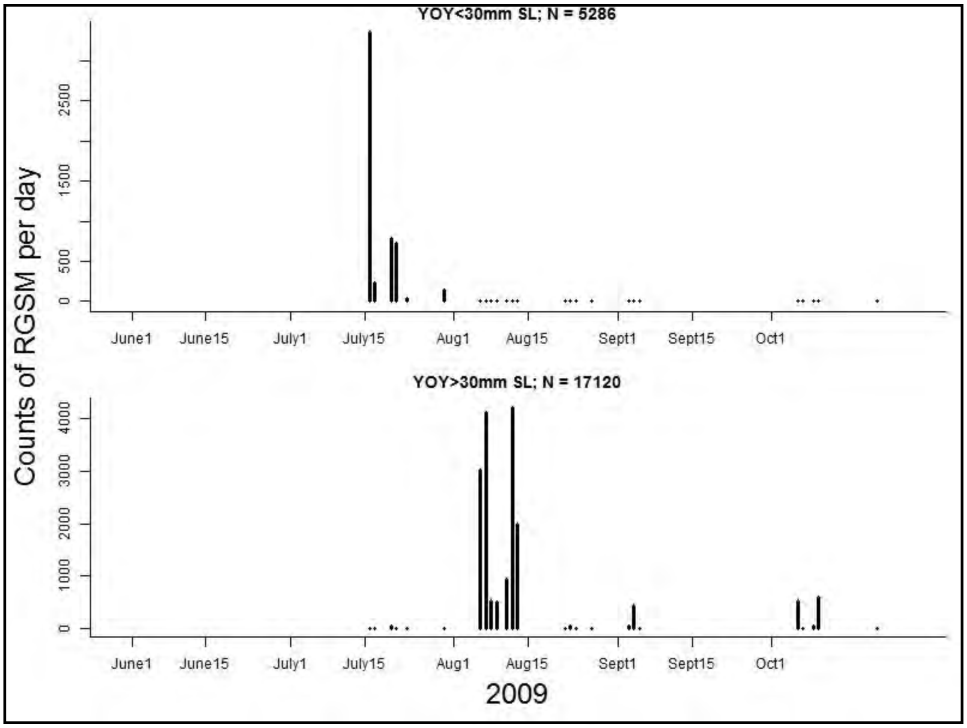
Evidence of monsoonal spawning

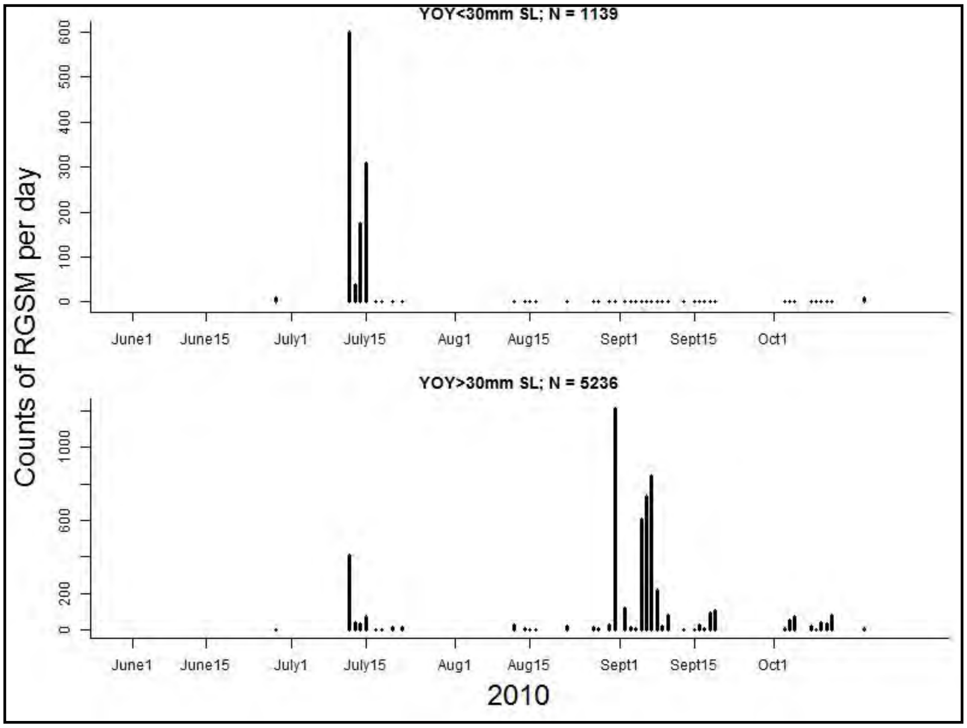
- July/August egg collections
  - Do they recruit?
- Collection of a few small YOY late in year
  - Spawn date unknown without otoliths
  - Population outliers? Within observed range of growth experiment
- Lack of distinct cohorts from monsoonal spawning in larval collections (ASIR)
  - Larval silvery minnow (<15mm) not collected later than August



Collection of YOY from Isolated Pools 2009-2016

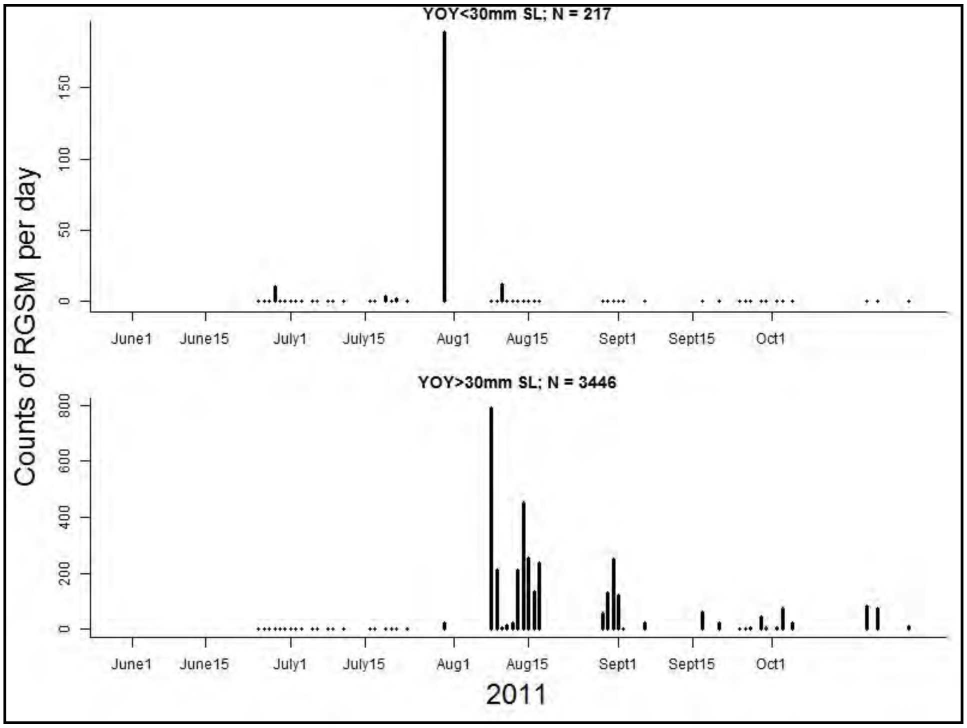
- All YOY rescued (post-2006)
- Pools are generally small
- High capture efficiency
- Multiple passes when necessary
- <30mm or >30mm is a coarse measurement





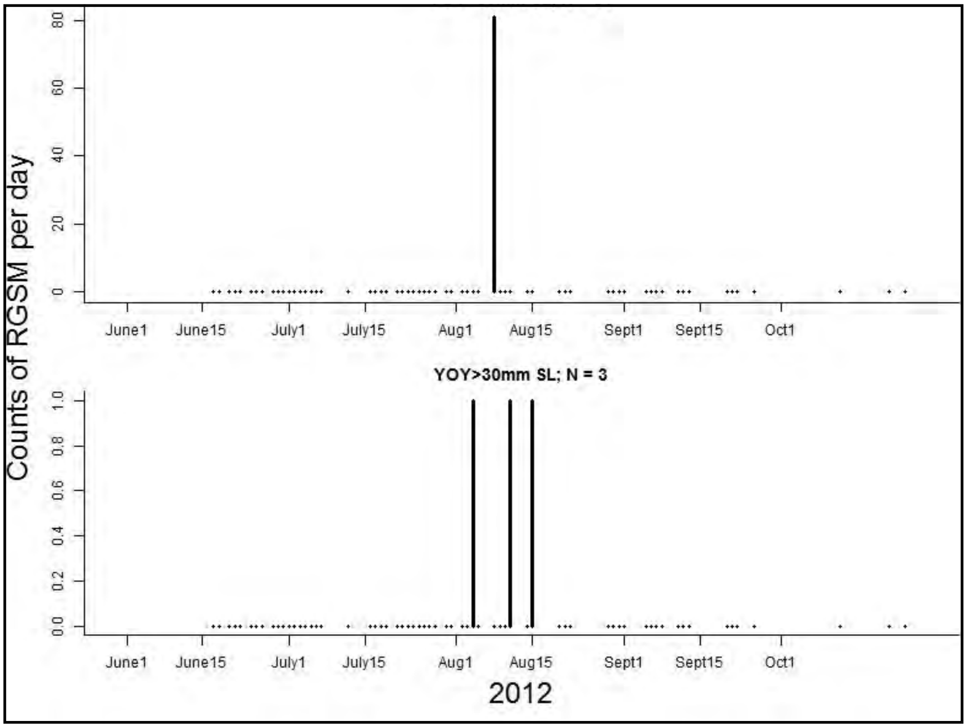
YOY<30mm SL; N = 1139

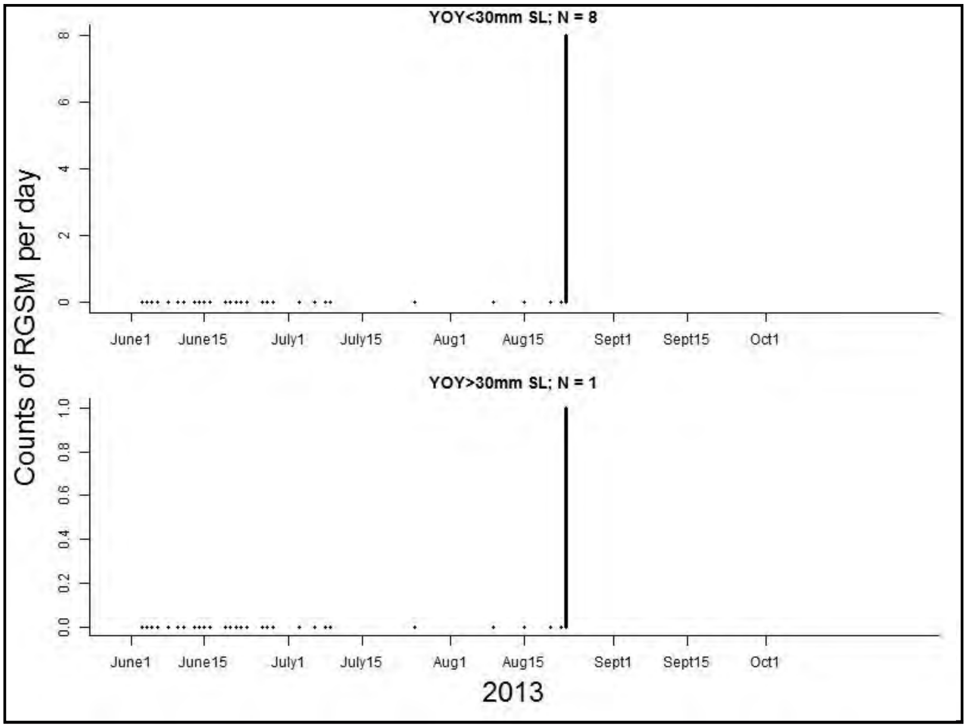
YOY>30mm SL; N = 5236

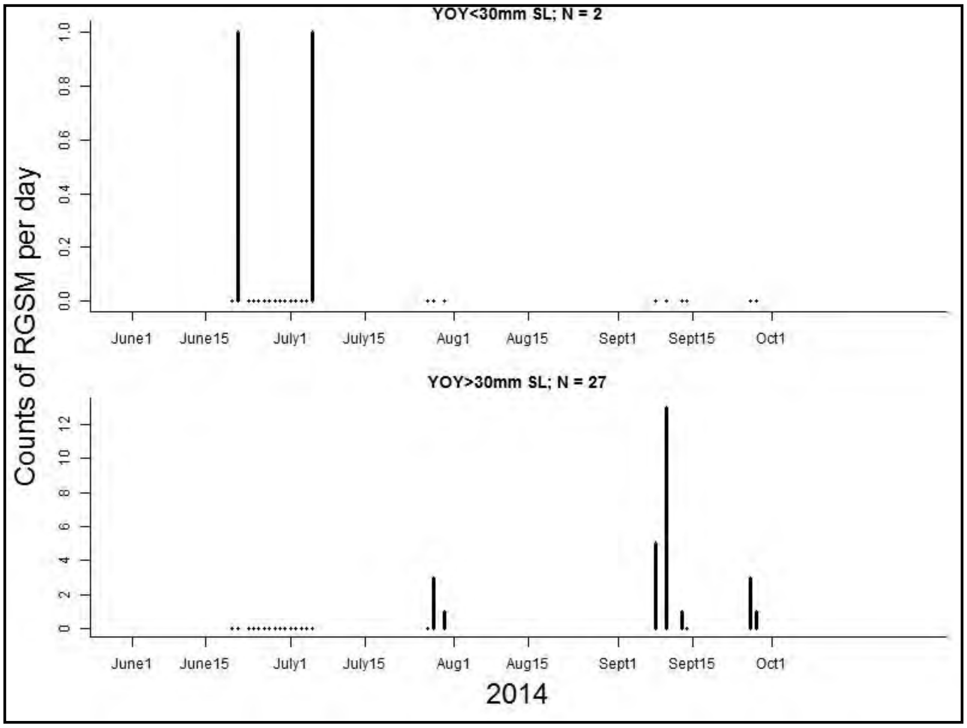


YOY<30mm SL; N = 217

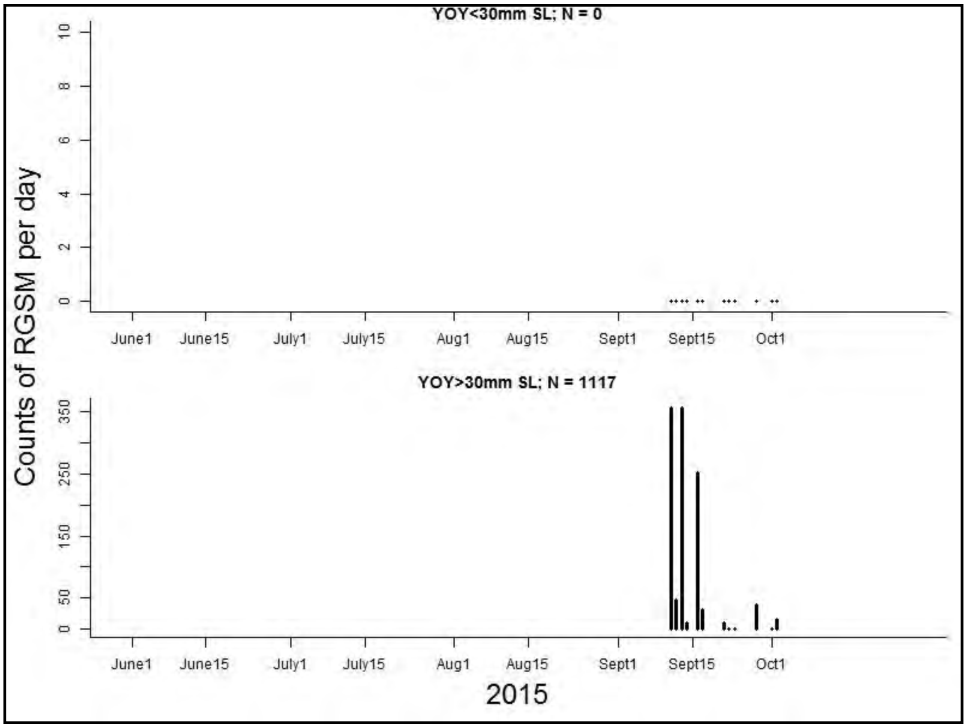
YOY>30mm SL; N = 3446


Counts of RGSM per day
0
20
40
60
80
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
YOY>30mm SL; N = 3
0.0
0.2
0.4
0.6
0.8
1.0
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
2012

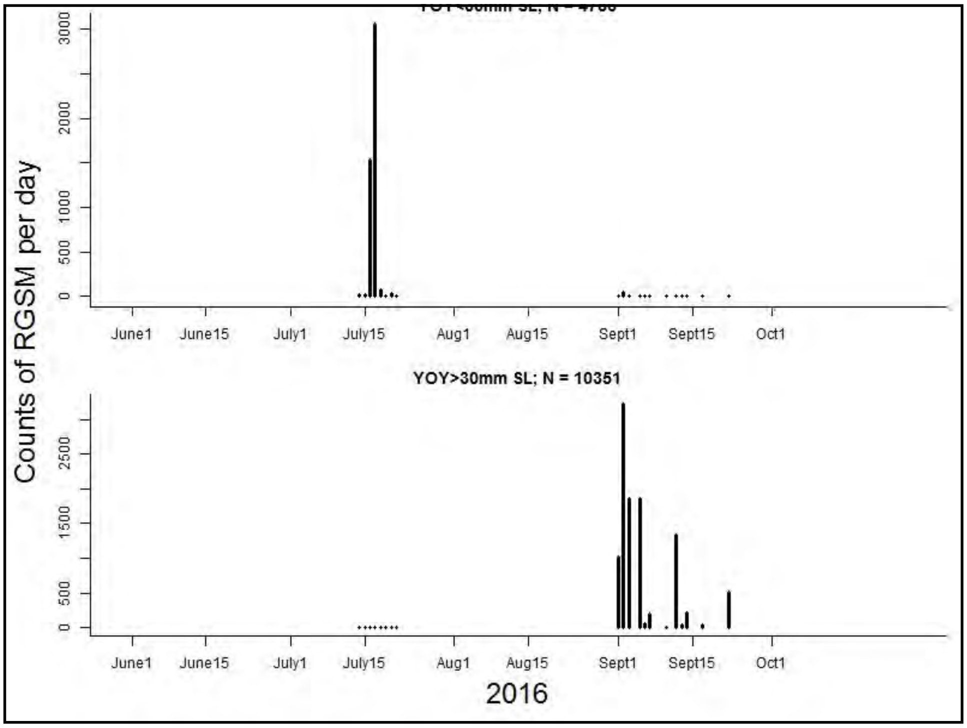

YOY<30mm SL; N = 8
Counts of RGSM per day
0
2
4
6
8
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
YOY>30mm SL; N = 1
0.0
0.2
0.4
0.6
0.8
1.0
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
2013

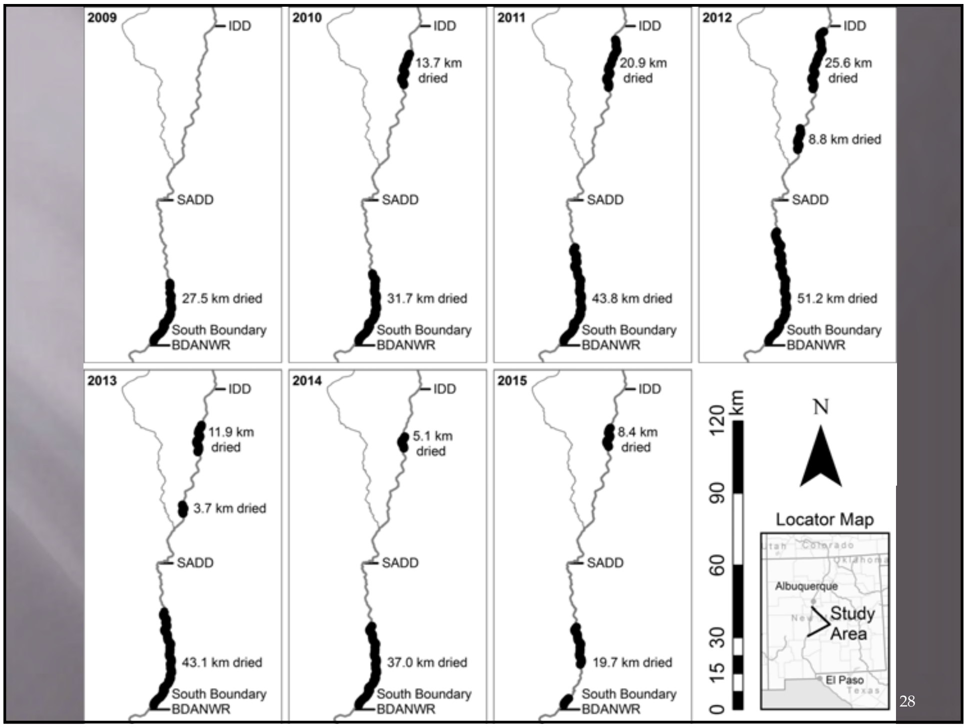


YOY<30mm SL; N = 2
Counts of RGSM per day
1.0
0.8
0.6
0.4
0.2
0.0
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
YOY>30mm SL; N = 27
12
10
8
6
4
2
0
2014



YOY<30mm SL; N = 0
Counts of RGSM per day
10
8
6
4
2
0
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
YOY>30mm SL; N = 1117
350
250
150
50
0
2015


Counts of RGSM per day
0
500
1000
2000
3000
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
YOY>30mm SL; N = 10351
0
500
1500
2500
June1
June15
July1
July15
Aug1
Aug15
Sept1
Sept15
Oct1
2016

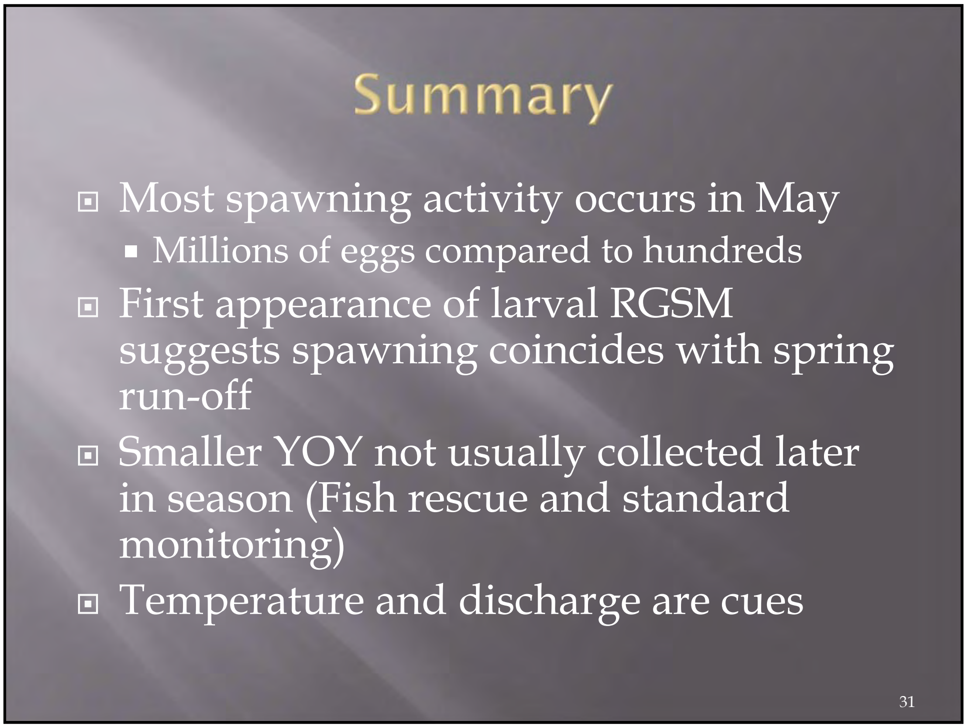

2009
IDD
SADD
27.5 km dried
South Boundary
BDANWR
2010
IDD
13.7 km dried
SADD
31.7 km dried
South Boundary
BDANWR
2011
IDD
20.9 km dried
SADD
43.8 km dried
South Boundary
BDANWR
2012
IDD
25.6 km dried
8.8 km dried
SADD
51.2 km dried
South Boundary
BDANWR
2013
IDD
11.9 km dried
3.7 km dried
SADD
43.1 km dried
South Boundary
BDANWR
2014
IDD
5.1 km dried
SADD
37.0 km dried
South Boundary
BDANWR
2015
IDD
8.4 km dried
SADD
19.7 km dried
South Boundary
BDANWR
km
0
15
30
60
90
120
N
Locator Map
Utah
Colorado
Oklahoma
Albuquerque
New
Study Area
El Paso
Texas
28

Spearman Rank Correlation 2009-2016

Flow metric (Aug-Sept)	YOY per mile	October RGSM density
Mean	-0.48	-0.29
Median	-0.50	-0.35
R-B Flashiness	-0.67*	-0.65*

How regular is monsoonal spawning?

- Egg collection in July/August (one time)
- Almost no collections of late-season small YOY
  - 58 Sept-Oct small YOY, ~49,000 total YOY
- Collection of pre-juvenile YOY in August
  - Does not rule out a spring spawn date based on experimental growth data
- September and October larval seining does not collect larval RGSM (but does collect many larval fish)



Summary

- Most spawning activity occurs in May
  - Millions of eggs compared to hundreds
- First appearance of larval RGSM suggests spawning coincides with spring run-off
- Smaller YOY not usually collected later in season (Fish rescue and standard monitoring)
- Temperature and discharge are cues

Reproduction

David E. Cowley, Professor
Fish, Wildlife & Conservation Ecology
New Mexico State University

Evidence of Protracted Spawning

- 14 Aug 2006, Bridge Blvd cottonwood snags
  - ABQ gage peaked previous night @ 2000 cfs
  - 12 RGSM: 7, 13, 19, 20, 24(2), 28(2), 31, 32, 33, 36 [SL]
  - smallest fish likely produced 23 July-10 Aug
    - length @ hatching 3.5-4, attained in ~48 h post-fertilization
  - size gaps suggest multiple later spawning events in 2006
  - drifting eggs were documented in July 2006 (M. Hatch)

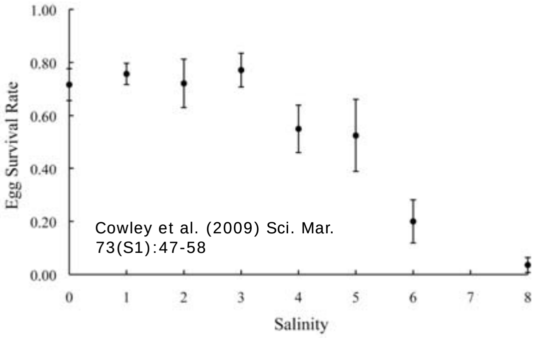
Spawning Period

- evidence suggests greatest intensity of spawning is late May - early June
- I agree; however
  - potential spawning period ≥ **2 months**
  - could be 6 months in duration
- **knowledge deficits, data needs**:
  - 1) field observations for spawning April-September
  - 2) does *H. amarus* delay spawning if snowmelt flow variations are too small?
  - 3) what effects might occur by creating a captive stock with truncation selection on spawning period?

Floodplain Conditions, 1 June 2005

Isleta Reach, 20 locations

salinity 0.2 - 11.2



Cowley et al. (2009) Sci. Mar. 73(S1):47-58

Conclusion: some wetted areas of the floodplain are unsuitable for *H. amarus* egg hatching

Initiation Cues for Spawning

- egg maturation is probably affected by spawning photoperiod
  - BUT, photoperiod may not be the cue that causes minnows to engage in spawning behavior & release eggs
- elevated discharge seems a correlate, but may not be the signal perceived by the minnow that causes spawning
- data deficit: articulation of hypotheses is needed to stimulate data collection

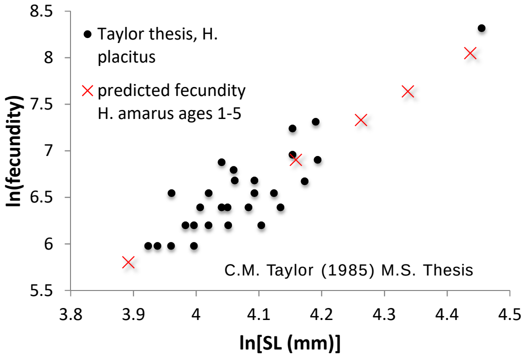
Possible Cues (some correlated)

- current velocity, turbulence
- dissolved O_2, temperature
- turbidity, sediment load
- aquatic foam, elevated organics
- higher discharge aggregates gravid fish
- ...

Simulation of Population Size

- a reach-scale model extensible to a metapopulation of adjacent reaches is needed
- Leslie matrix
  - age-specific reproductive outputs
  - age-specific survival rates
- Data deficit:
  - large sample (N ≥ 100) counts of mature ova for contemporary age-validated *H. amarus* spanning the reproductive size range (38 - 90 mm SL)

Age-specific Reproductive Output



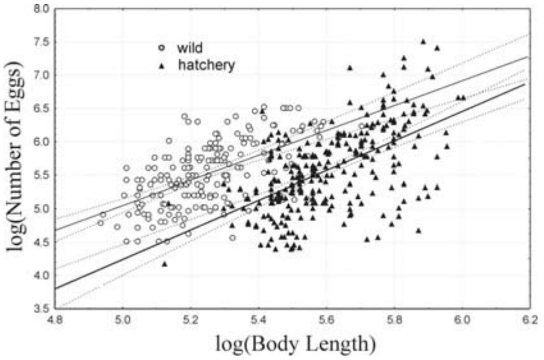
C.M. Taylor (1985) M.S. Thesis

Age	exp(predicted)
1	332
2	997
3	1528
4	2079
5(+)	3131

Conclusion: use of proxy data for *H. placitus*, which includes size at all documented ages of *H. amarus* (Cowley et al. 2006), seems to be a reasonable substitute.

Ova Counts on Hatchery Fish

- I expect fecundity at size for hatchery fish to substantially differ from that for wild fish



Rio Grande cutthroat trout, wild (9 populations), hatchery (7 Springs)

SESSION 2

SCIENTIFIC PERSPECTIVES ON SPAWNING AND LARVAL DEVELOPMENT

Scientific Perspectives
on Spawning & Larval Development Locations

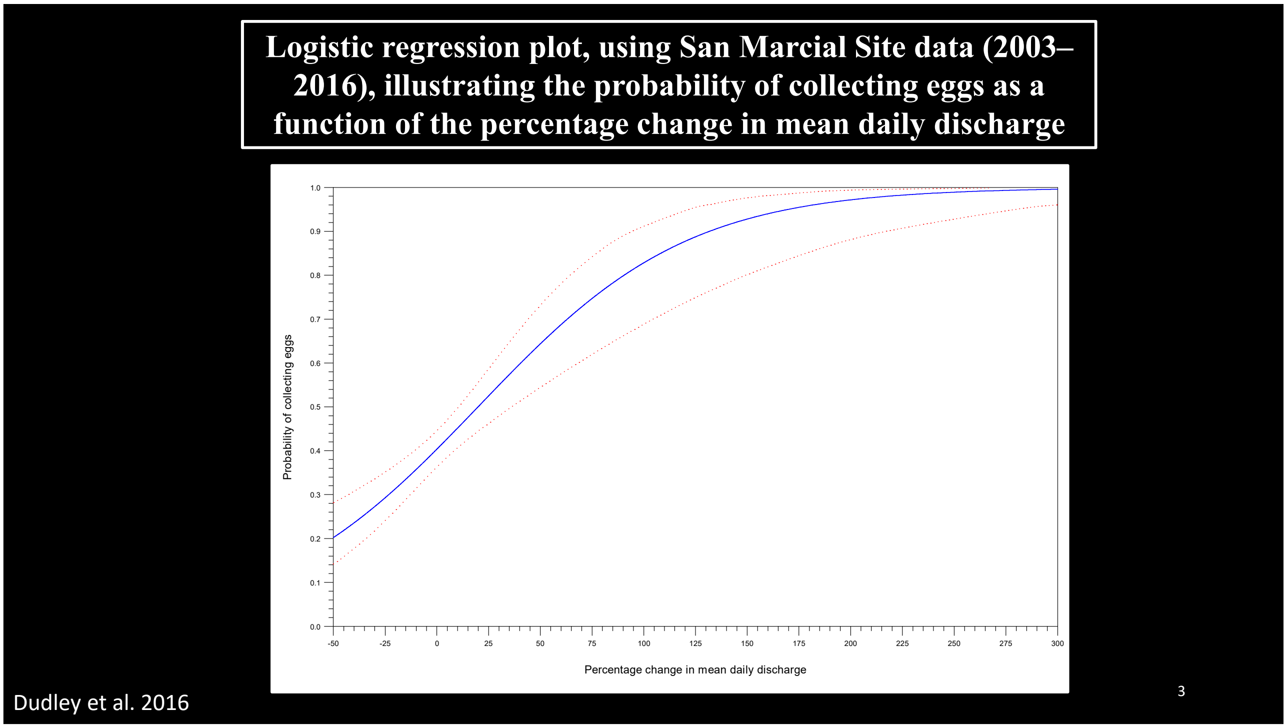
Photo by Tom Kennedy

Courtesy R Dudley

David Propst
University of New Mexico

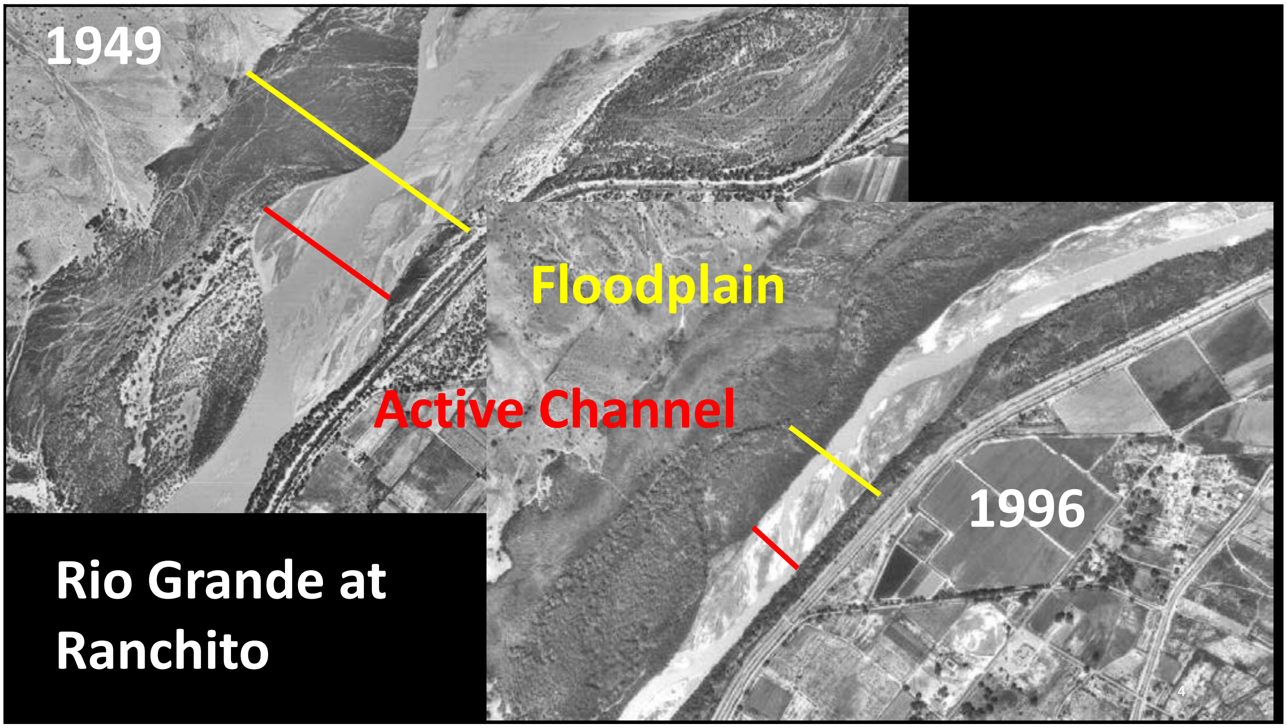
Rio Grande Silvery Minnow Spawning

- Spawning Conditions
  - Temperature—18-20℃
  - Water Velocity—10-20 cm/s
  - Water Depth—10-20 cm
  - Flow pulse



Logistic regression plot, using San Marcial Site data (2003–2016), illustrating the probability of collecting eggs as a function of the percentage change in mean daily discharge

Dudley et al. 2016



Rio Grande at Ranchito

Image from
SWCA.2008

Floodplain Spawning?

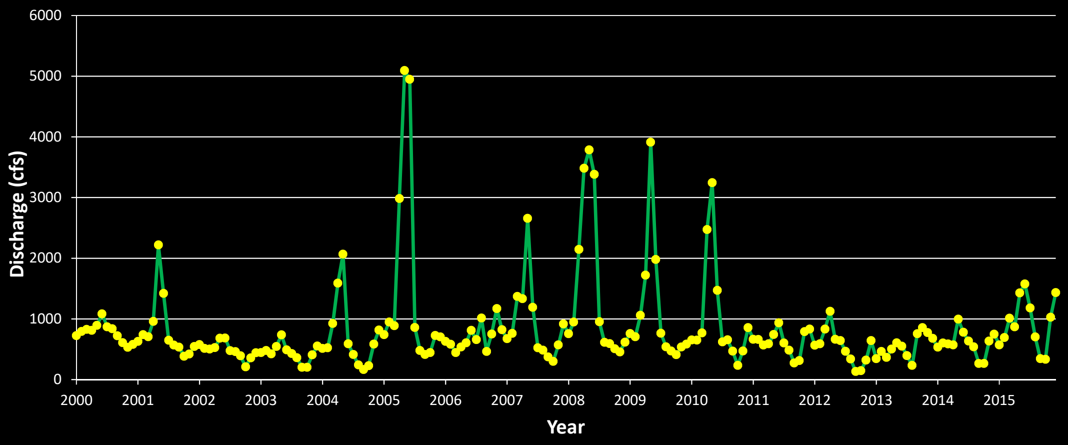
- Evidence
  - Hatch & Gonzales 2008
  - Hatch & Gonzales 2010
  - Gonzales et al. 2012
  - Magana 2012
  - Medley & Shirey 2013
- Under suitable conditions likely?
  - Velocity & depth
- Contribution?

From
Dudley & Platania.
2015, in part

San Marcial
Mean Daily Q

Year	Eggs Present	Eggs Absent	Max Daily Den (#/100m^3)	Mean Daily Q (cfs)	Max Daily Q (cfs)
2003	18	28	475.63	107	347
2004	3	43	0.09	819	2780
2005	NS	NS	NS	3204	4920
2006	10	36	289.33	42	83
2007	39	7	90.13	977	2400
2008	3	43	5.1	2560	4260
2009	13	34	8.05	1727	3560
2010	15	32	9.47	1215	3230
2011	39	17	2334.93	124	456
2012	18	30	466.71	314	1860
2013	13	37	61.00	41	84
2014	25	25	560.22	44	94
2015	30	20	423.00	331	902

Mean Monthly Discharge
Albuquerque USGS Gage



Rio Grande Silvery Minnow Nursery Habitat -Wetted Channel-


Courtesy Thomas Archdeacon

- **11-20 mm SL (metalarvae)**
  - **Water velocity <20 cm/s**
  - **Depth <30 cm**
  - **Silt substrate**
  - **Pool (main & side channel)**
- **21-30 mm SL (juveniles)**
  - **Water velocity 0 cm/s for 70%, <30 cm/s for 98%**
  - **Depth 11-20 cm for 68%, <50 cm for 99%**
  - **Silt substrate**
  - **Mainly backwater (58%), pool & run (40%)**
- **Temperature**
  - **Longitudinal & seasonal increase**

Dudley & Platania 1997, Dudley pers. com.

Rio Grande Silvery Minnow Nursery Habitat -Wetted Floodplain-

- Mean water temperature: 19℃, range 15.5-24.9℃
- Water velocities: <30 cm/s
- Dissolved Oxygen: 4-6 mg/L
- Specific conductance: 220-234 µS/cm

Hatch & Gonzales 2010


Courtesy Thomas Archdeacon

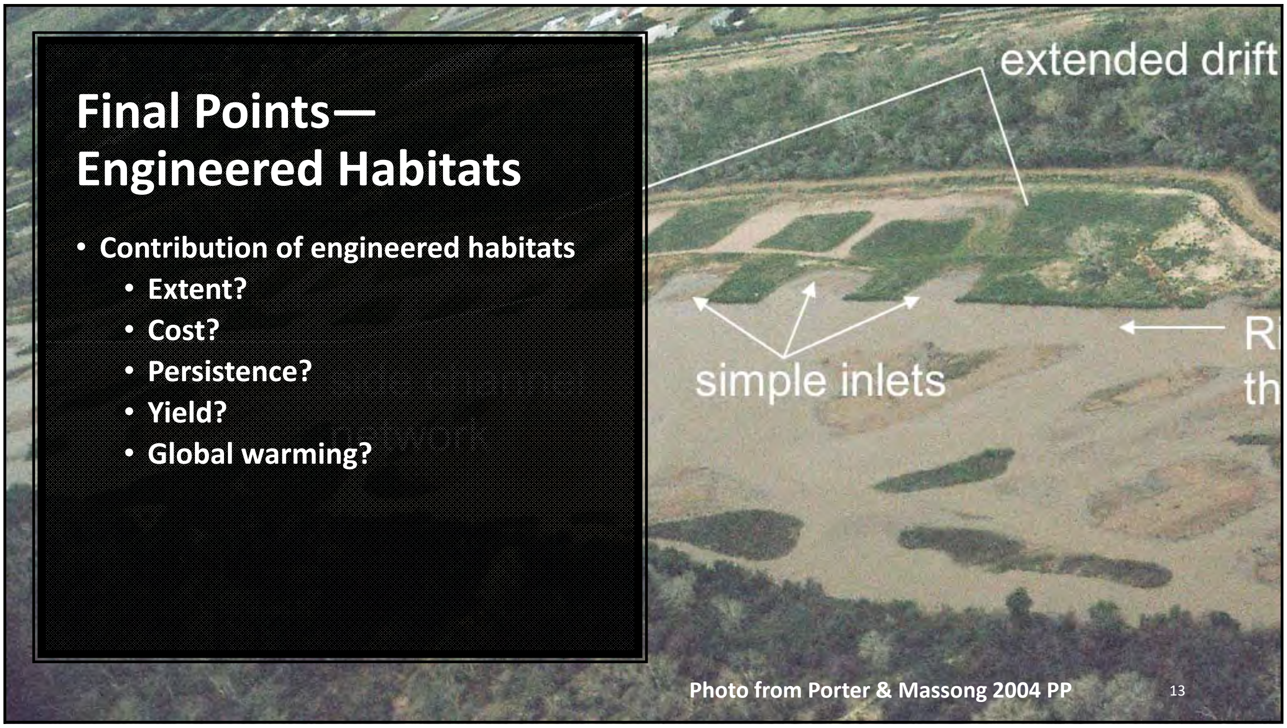

Courtesy J Lusk & P Tashjian

Rio Grande Silvery Minnow Nursery Habitat

- **Stable isotope analysis suggests low velocity habitats (del Apache)**
  - **Epibenthic algae (Pease et al. 2006).**
- **Gut contents suggests low velocity habitats (Los Lunas)**
  - **Diatoms (Magana 2013)**

Final Points--Spawning & Nursery Habitats

- **Spawning**
  - **Where depth <30 cm & velocity <30cm/s**
  - **Inundated floodplain also provides food & cover**
- **Nursery**
  - **Water velocity & depth**
  - **Food**
  - **Cover**
    - **Vegetation & debris**
    - **Turbidity**
- **Extent**
  - **Temporal**
  - **Spatial**

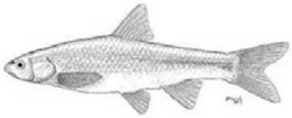


Final Points—Engineered Habitats

- Contribution of engineered habitats
  - Extent?
  - Cost?
  - Persistence?
  - Yield?
  - Global warming?

Photo from Porter & Massong 2004 PP

Session II



Does spawning and larval development of RGSM occur in the main channel or on the floodplain and in certain channel features?

1. RGSM in the historical and contemporary river channel
2. Egg drift and entrainment hypotheses
3. Spawning guild of RGSM
4. RGSM in habitat restoration sites
5. Conceptual RGSM spawning model

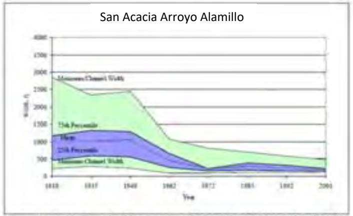
Richard A. Valdez, Ph.D.
SWCA
Rio Grande Silvery Minnow Independent Science Panel
Santa Ana Pueblo, New Mexico
February 1, 2017

RGSM in the Historical and Contemporary River Channel

- Historical spawning habitat undescribed; fish in spring and summer in braided channels over sandy-silt bottoms (Sublette et al. 1990; Bestgen and Platania 1991).
- RGSM evolved in a river with braided channels and an expanded floodplain during spring snowmelt runoff.
- Contemporary river channel is narrow, confined, incised, and vegetated—a very different river!
- Maximum channel width has decreased by ~82% (1918 to 2001; Holmquist-Johnson 2004).

Rio Grande at Central Avenue, Albuquerque, NM (1933; MRGCD)

Rio Grande at Albuquerque, NM (2015)



San Acacia Arroyo Alamillo

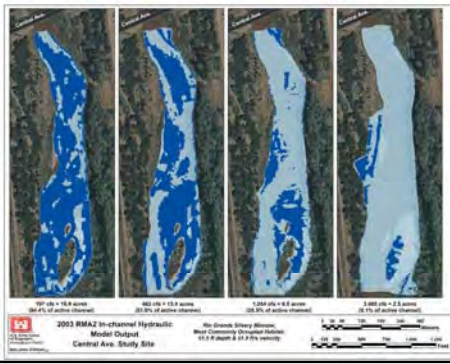
Figure 11: Channel widths - San Acacia Diversion Dam to Arroyo Alamillo (1918 to 2001). (Holmquist-Johnson 2004)

RGSM Habitat in Contemporary Channel (Albuquerque Reach)

≤1.5 ft depth; ≤1.5 ft/sec velocity = 🟦

- Habitat increases with flow in reaches with islands and old braided channels.

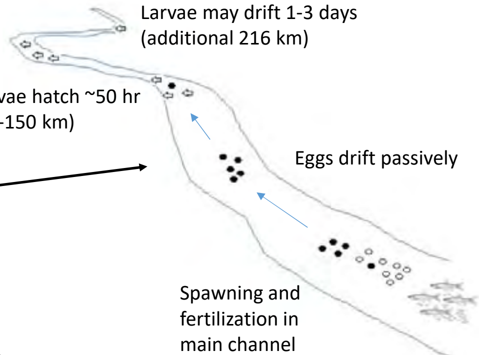
- Habitat decreases with flow in reaches with single channel.



USACOE 2003

Egg Drift and Entrainment Hypotheses

1. <u>Most Eggs and Larvae are Transported Downstream</u>: (Platania 1995).



Larvae may drift 1-3 days (additional 216 km)

Larvae hatch ~50 hr (72-150 km)

Eggs drift passively

Spawning and fertilization in main channel

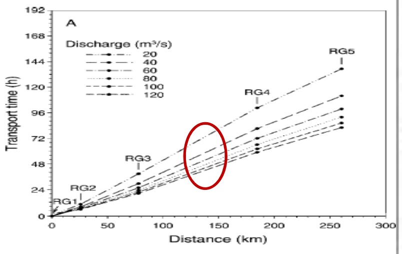
2. <u>Eggs and Larvae Retained in Irregularities and Floodplains</u>:

- Nursery habitat determined by high spring runoff inundating arroyo inlets, floodplain depressions, old side channels, constructed sites (Porter and Massong 2004).
- Channel incision has resulted in degraded nursery areas, but constructed sites can provide egg entrainment at lower flows (Porter and Massong 2006).
- Larvae found primarily in isolated pools, backwaters, and former channels; i.e., floodplains (Pease 2004).

Drift of RGSM Eggs (2 key studies)

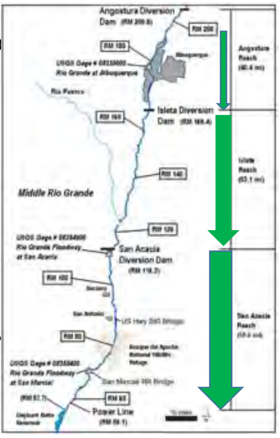
1) Dudley and Platania (2007)

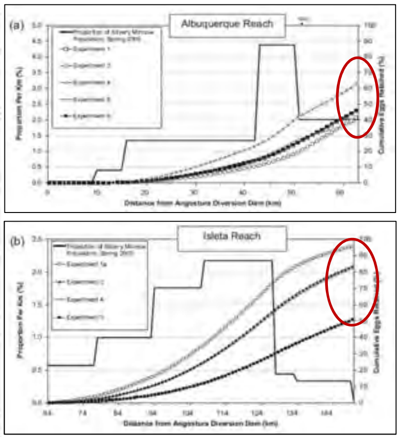
- Mean transport of N-beads = 138.7 km.
- Transport time = 44.4 hr.
- Small percent of eggs and embryo retained in reaches <100 km.



2) Widmer et al. (2010)

- Retention a function of channel complexity.
- Highest retention on rising limb of flow.
- 40-63% of G-beads retained in Albuq R. (65 km)
- 50–96% of G-beads retained in Isleta R. (85 km)

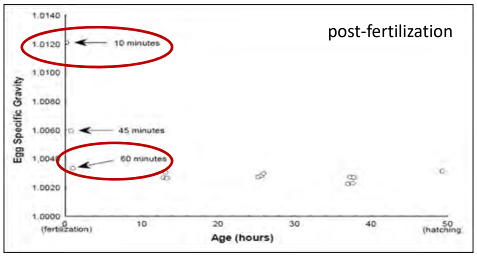




Specific Gravity of Eggs

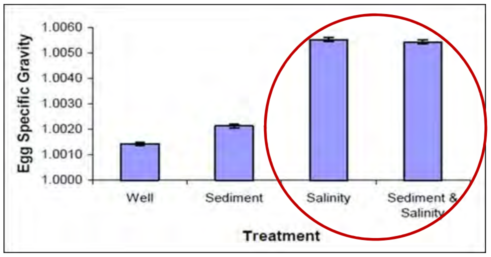
Egg SG changes with post-fertilization time (Cowley 2005).

- Newly fertilized eggs are heaviest and tend to sink.
- Eggs are lightest after ~1 hr post-fertilization and are more buoyant.

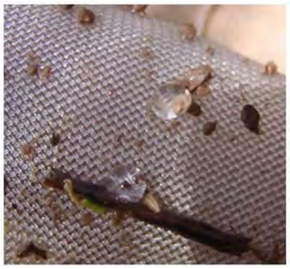


Egg SG increases with salinity and salinity/sediment (Cowley 2005).

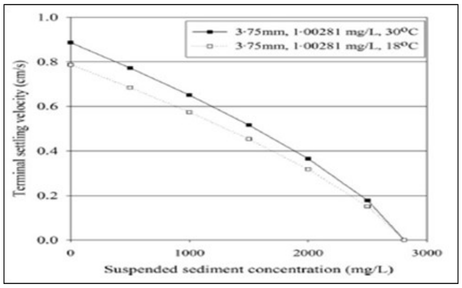
- But—at high salinity/sediment, SG of water is greater and eggs remain suspended.
- Eggs less likely to be suffocated in bottom sediment.



RGSM Reproductive Ecology
(Medley and Shirey 2013)

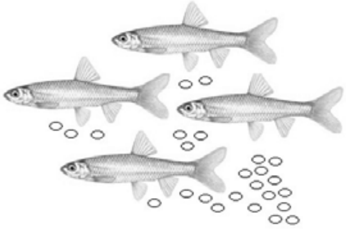


- *"Location and timing of spawning, ontogenic stage of egg development, and habitat-specific differences in sediment and temperature that influence egg-settling rates interact to (1) prevent egg suffocation, (2) promote egg entrainment in clear, warm, productive floodplain habitats, and (3) limit downstream population displacement."*
- Recommend conservation actions to restore historic channel form and reconnect low-velocity backwater and floodplain habitats.



Medley and Shirey (2013)

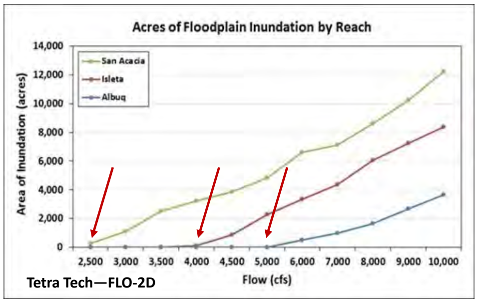
Spawning Guild of RGSM



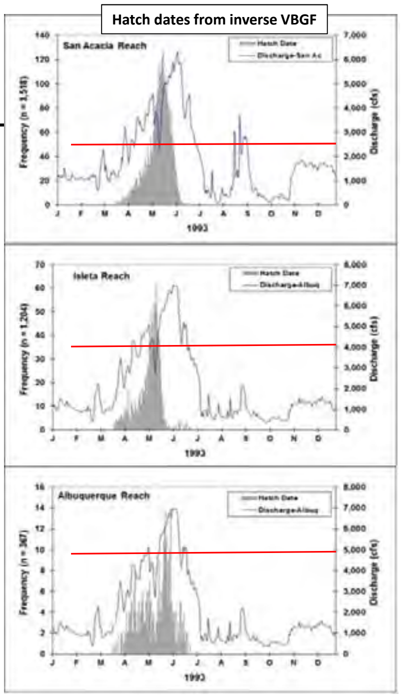
1. RGSM are **<u>pelagic-broadcast spawners</u>** that produce nonadhesive, semi-buoyant eggs (Platania and Altenbach (1998), susceptible to long-distance downstream drift (Dudley and Platania 2007).
2. RGSM is primarily a **<u>demersal, floodplain spawning species</u>** with eggs that are secondarily buoyant in high-sediment environments; high magnitude of egg drift is an artifact of contemporary river management and channelization, leading to reduced lateral connectivity and floodplain abandonment (Medley and Shirey 2013).

Hatch Times and Floodplain Availability

- Flow to inundation relationship differs by reach.
- Hatch dates span a range of flows below and above floodplain inundation levels.
- In moderate to high flow years, spawning can occur in mainstem or in inundated floodplains—or both.



Tetra Tech—FLO-2D



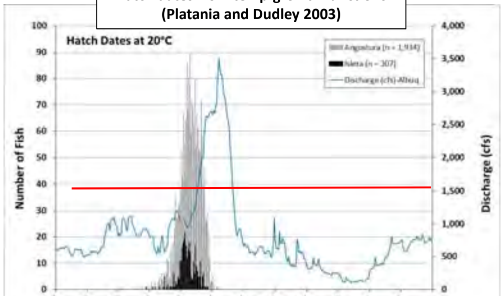
Hatch dates from inverse VBGF

Hatching Times—2016

(NMISC and SWCA)

- Restored sites began to inundate at ~1,500-2,000 cfs (Albuq & Isleta).
- Ripe and gravid adults were caught moving onto restored sites.
- Spawning probably took place in main channel and in floodplains.

Hatch dates from temp-growth functions
(Platania and Dudley 2003)

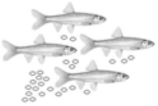


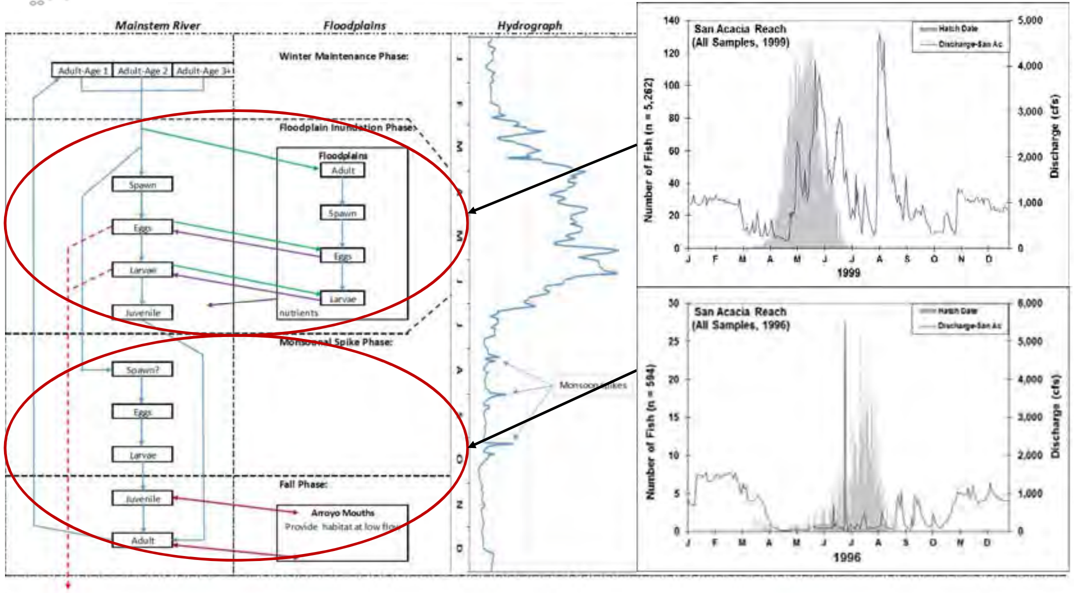
M. Marcus photo

RGSM in Restored Sites (prior studies)

- Extensive use of constructed and natural sites when flows are sufficient to inundate (Gonzales and Hatch 2009).
- RGSM moved onto and from HR sites (Gonzales et al. 2012); 1st or 2nd most common species (Gonzales et al. 2014).
- 2008: of 9,545 RGSM, 108 females expressed eggs (Gonzales et al. 2013).
- 2009: of 2,057, 48-55% of females were gravid (Gonzales et al. 2013).
- Spawning in floodplains indicated by occurrence of eggs and abundance of RGSM adults (Gonzales and Porter 2011).

Conceptual RGSM Spawning Model





Summary


Egg-bearing female RGSM

1. Spawning probably takes place in low-velocity habitat where communal groups can gather and egg-bearing females can maintain position.
2. RGSM spawn in available habitat (main channel or floodplain), but eggs and larvae must be entrained in sheltered productive habitat near natal areas.
3. Ripe and gravid fish, as well as eggs and larvae, in floodplains suggests that spawning is taking place in inundated off-channel habitats.
4. Positive relationships between CPUE and high flow indicate that survival and recruitment of eggs and larvae are highest when off-channel habitat is available.

Recommendations for Priority Studies

1. Quantify depth, velocity, substrate, cover, and temperature at which spawning occurs.
2. Determine flow stage and change when entrainment of eggs and larvae is maximized.
3. Evaluate hydrology and geomorphology of reconstructed floodplain sites for effective spawning, egg/larval entrainment, and larval rearing.
4. Determine time of edge periphtyon development and zooplankton chronology at first inundation and with stage changes.
5. Use larval lengths to estimate hatching dates for retrospective analysis of relationships of spawning, survival, and recruitment to hydrology.

Los Lunas Refugium

- RGSM tend to school in large numbers.

- During artificial flood, fish moved from high velocity main channel to low velocity “floodplain.”

Thank you—Questions?

SESSION III

SCIENTIFIC PERSPECITVES ON RELATIONSHIPS BETWEEN HYDRO-GEOMORPHIC ATTRIBUTES AND RGSM POPULATION RESPONSE

U.S. Army Corps of Engineers' and GeoSystems Analysis' independent peer review for development of an Adaptive Management Framework workshop. February 1, 2017, Santa Ana Pueblo, New Mexico

Session III: Spring runoff magnitude, timing, duration, and channel inundation relationships to the estimated densities of Rio Grande Silvery Minnow (RGSM) in the October census (Oct Log10(E(x)+1)).

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U.S. Fish and Wildlife Service
New Mexico Ecological Services
Albuquerque, New Mexico

*With an emphasis on Conservation Biology

Increased densities of RGSM in October were positively associated with prolonged spring runoff

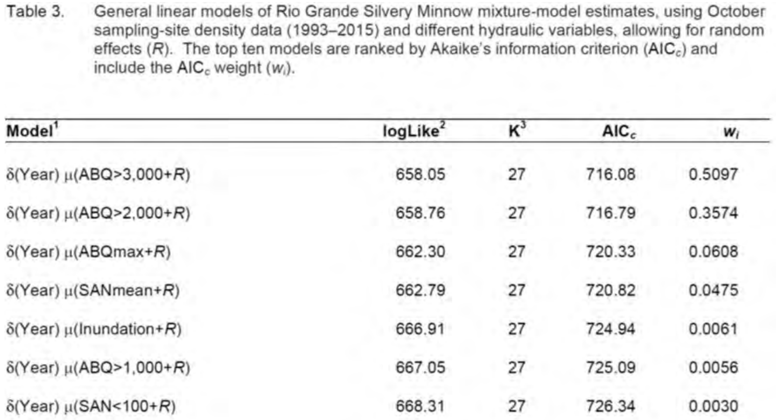
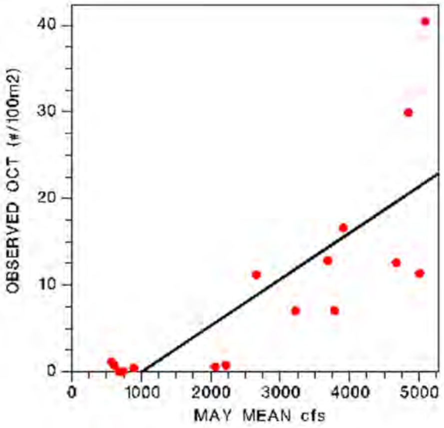


Table 3. General linear models of Rio Grande Silvery Minnow mixture-model estimates, using October sampling-site density data (1993–2015) and different hydraulic variables, allowing for random effects (*R*). The top ten models are ranked by Akaike's information criterion (AIC_c) and include the AIC_c weight (w_i).

Model[1]	logLike[2]	K[3]	AIC_c	w_i
δ(Year) μ(ABQ>3,000+*R*)	658.05	27	716.08	0.5097
δ(Year) μ(ABQ>2,000+*R*)	658.76	27	716.79	0.3574
δ(Year) μ(ABQmax+*R*)	662.30	27	720.33	0.0608
δ(Year) μ(SANmean+*R*)	662.79	27	720.82	0.0475
δ(Year) μ(Inundation+*R*)	666.91	27	724.94	0.0061
δ(Year) μ(ABQ>1,000+*R*)	667.05	27	725.09	0.0056
δ(Year) μ(SAN<100+*R*)	668.31	27	726.34	0.0030

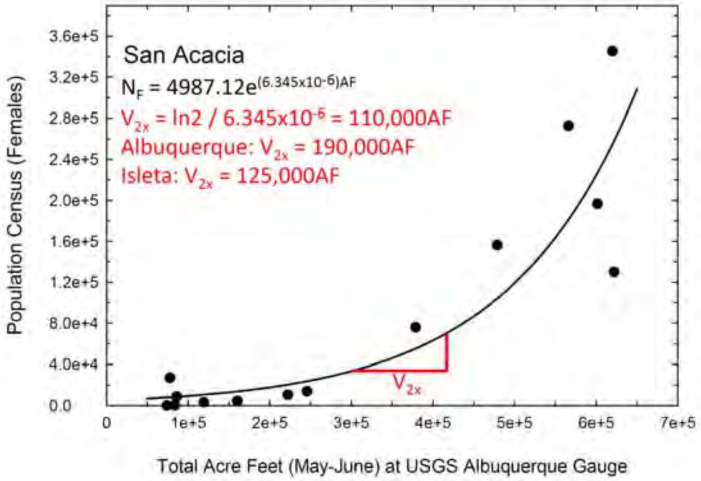
Dudley et al. (2016): "General linear models of [RGSM] mixture-model estimated revealed variation in μ . . . was reliably predicted by changes in hydraulic variables over the period of study (1993-2015)". "Thus, prolonged high flows during spring were most predictive of increased density . . . of [RGSM] over the study period."

Using different methods with same data, similar findings were reported by Goodman (2011)



"October census observed recruits predicted by May mean cfs at Albuquerque. Correlation is 0.790; jackknife cross validation R^2 is 0.4706; n=16; there are 5 years in the cluster < 1000 cfs. The high outlier is 2005."

Using population modeling, similar findings were reported by Miller (2012)



Archdeacon (2016): different data; spring runoff affects density of RGSM/km in isolated pools

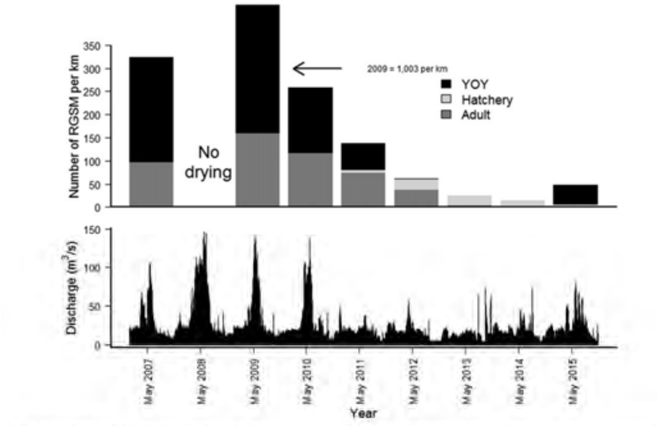
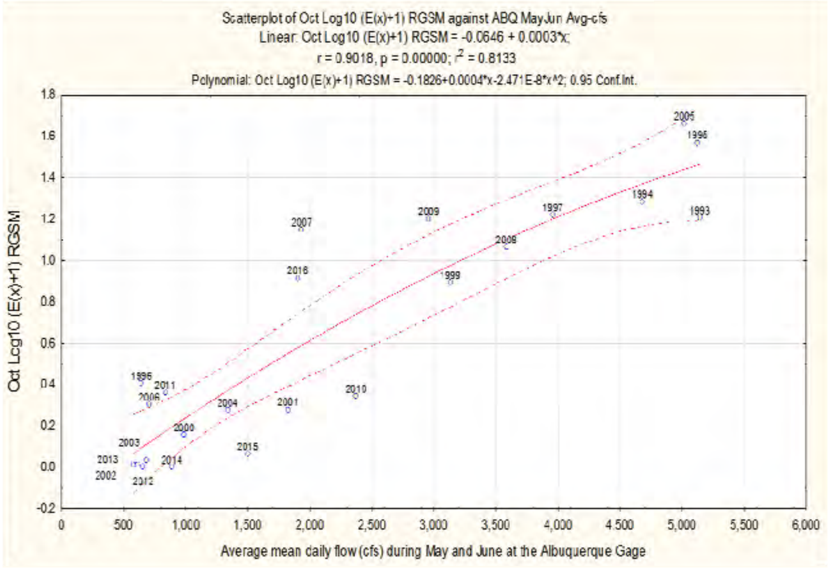


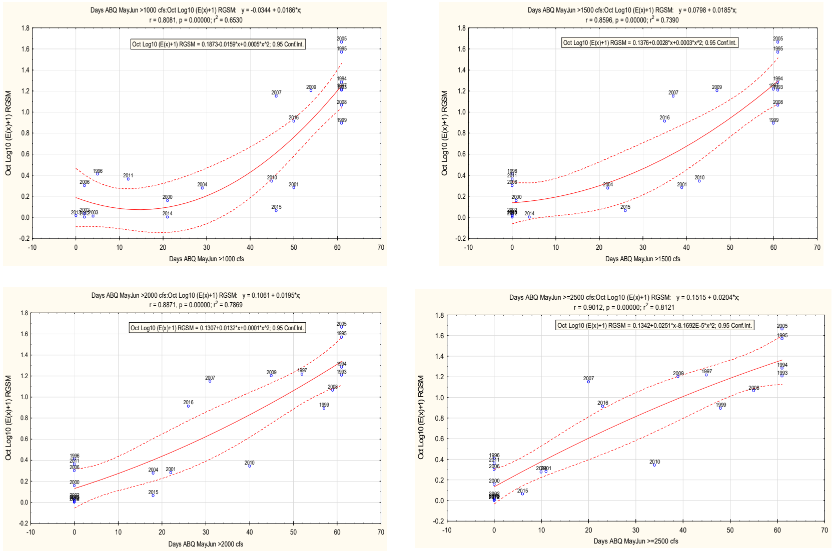
FIGURE 4. Number of adult, hatchery-reared adult, and young-of-year (YOY) Rio Grande Silvery Minnow (RGSM) collected per kilometer of dried river from the Middle Rio Grande, New Mexico, June through October 2007–2015 (upper plot) compared with mean daily May discharge measured at Albuquerque, New Mexico (lower plot).

- Archdeacon (2016): Generalized linear mixed-effects model parameter estimates and standard error predicts number of adult and Age-0 RGSM captured in isolated pools that increased with May discharge at Albuquerque

Using same data, we found similar relationships between spring runoff and Oct RGSM densities

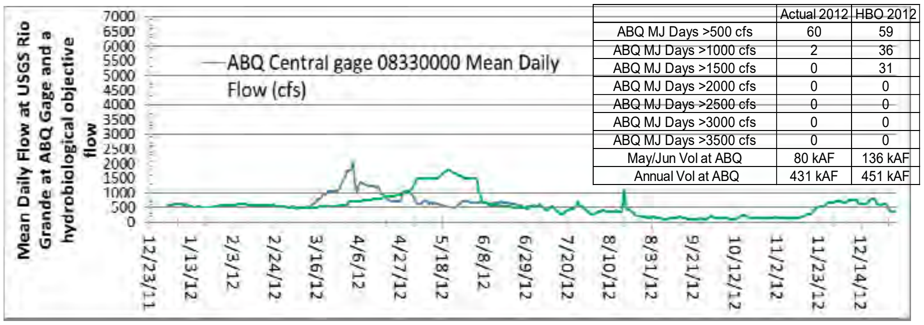

Scatterplot of Oct Log10 (E(x)+1) RGSM against ABQ MayJun Avg-cfs
Linear: Oct Log10 (E(x)+1) RGSM = -0.0646 + 0.0003*x;
$r = 0.9018$, $p = 0.00000$; $r^2 = 0.8133$
Polynomial: Oct Log10 (E(x)+1) RGSM = -0.1826+0.0004*x-2.471E-8*x^2; 0.95 Conf.Int.

Managing days spring runoff elevated will be positively associated with increased est. densities of Oct RGSM



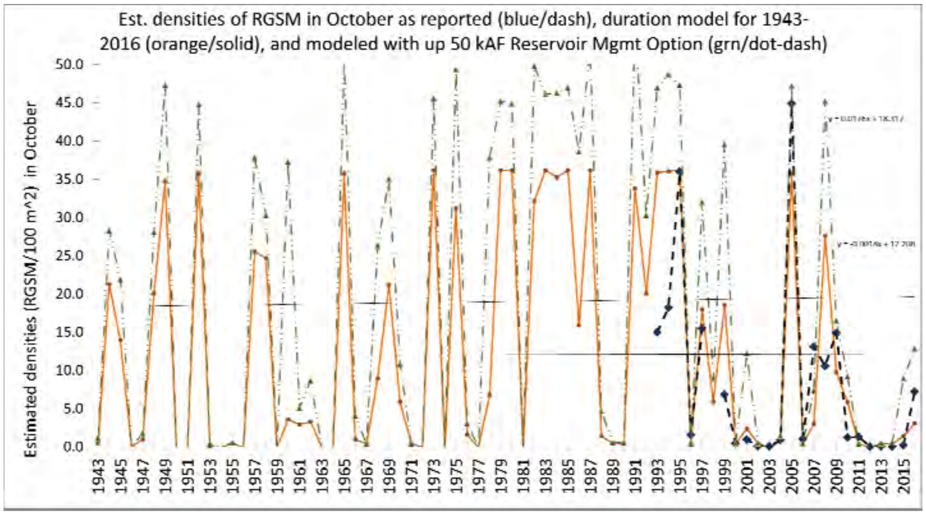
Key uncertainty 1 - how spring runoff could be managed to optimize Oct RGSM recruitment

- If reservoirs options and potentially available water was 20kAF, then one could adaptively manage the number of days at certain flows (1,500 to 2,500) to attempt to optimize October RGSM recruitment. For example:
- 2012 hydrograph, (blue, 80kAF in May-June)=density of <u>**0.0** RGSM/100 m^2</u>
- If we could manage spring runoff (move 56kAF to May/Jun), add 20kAF to make year whole) for a prolonged runoff (green line), then we'd expect an est. RGSM density in October of <u>~ **0.4 to 1.0** RGSM/100 m^2</u>

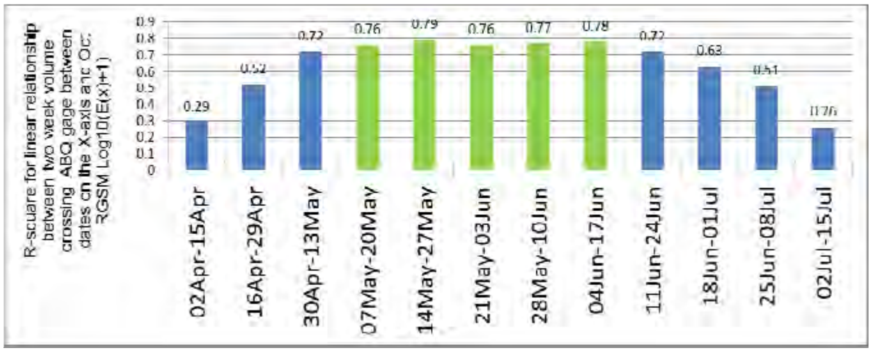


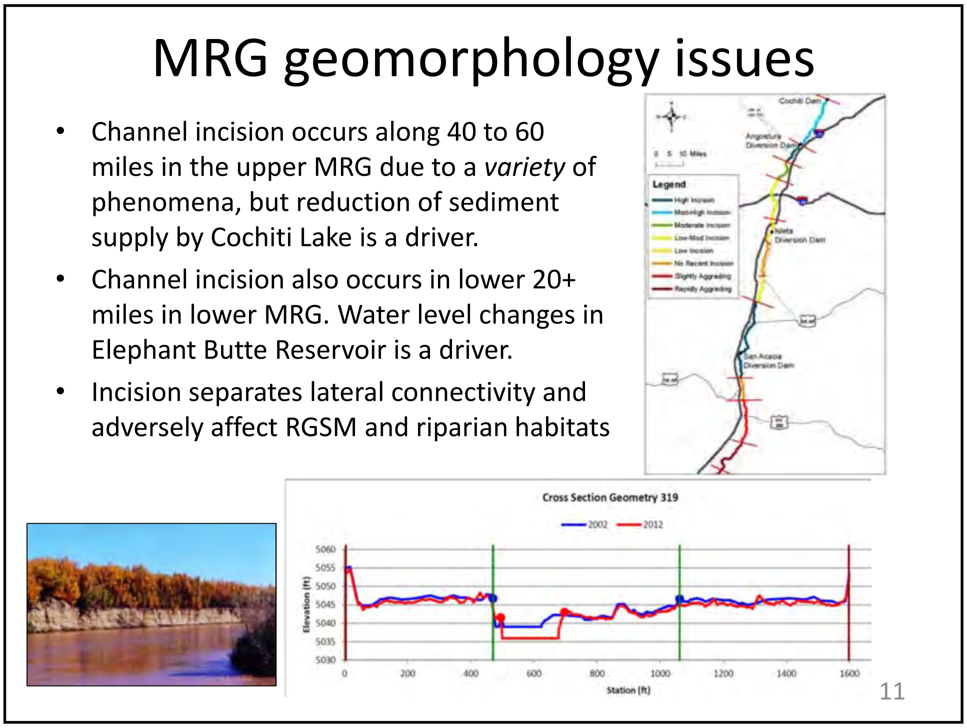
	Actual 2012	HBO 2012
ABQ MJ Days >500 cfs	60	59
ABQ MJ Days >1000 cfs	2	36
ABQ MJ Days >1500 cfs	0	31
ABQ MJ Days >2000 cfs	0	0
ABQ MJ Days >2500 cfs	0	0
ABQ MJ Days >3000 cfs	0	0
ABQ MJ Days >3500 cfs	0	0
May/Jun Vol at ABQ	80 kAF	136 kAF
Annual Vol at ABQ	431 kAF	451 kAF

Using up to 50 kAF reservoir mgmt options to increase runoff duration & est. Oct RGSM model



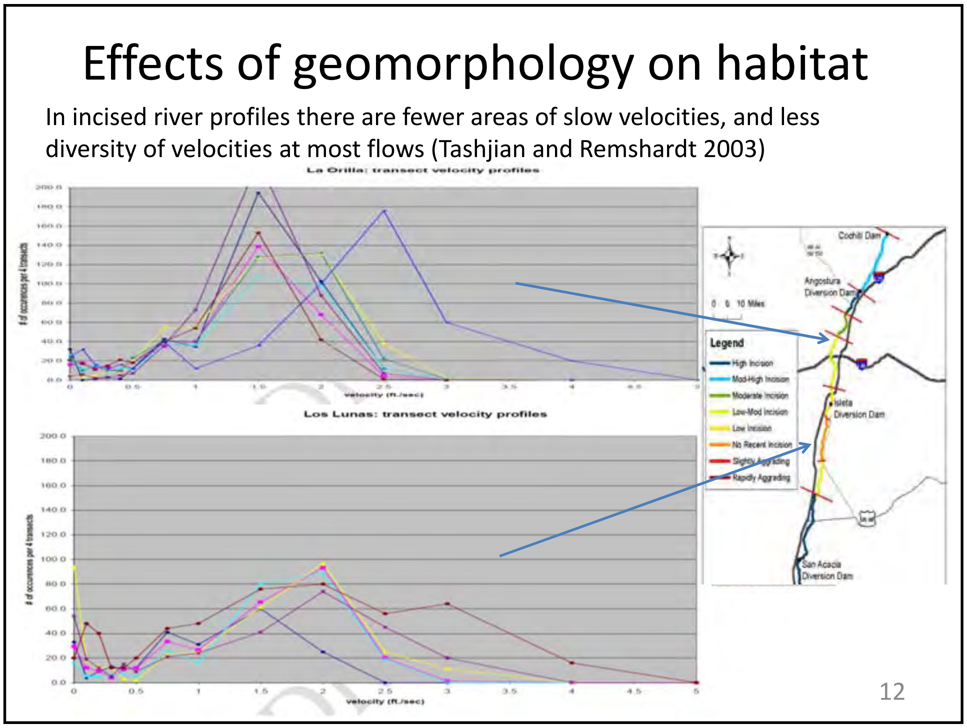
Spring runoff during May-June was strongly related to est. densities of RGSM in October





MRG geomorphology issues

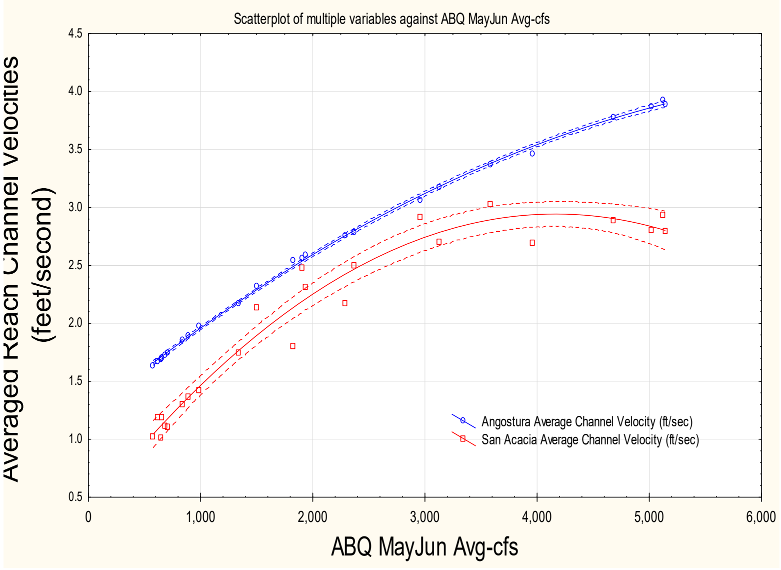
- Channel incision occurs along 40 to 60 miles in the upper MRG due to a *variety* of phenomena, but reduction of sediment supply by Cochiti Lake is a driver.
- Channel incision also occurs in lower 20+ miles in lower MRG. Water level changes in Elephant Butte Reservoir is a driver.
- Incision separates lateral connectivity and adversely affect RGSM and riparian habitats



Effects of geomorphology on habitat

In incised river profiles there are fewer areas of slow velocities, and less diversity of velocities at most flows (Tashjian and Remshardt 2003)

Modeled, average channel velocity (feet/second) by river reach



Ongoing reduction of active channel in MRG

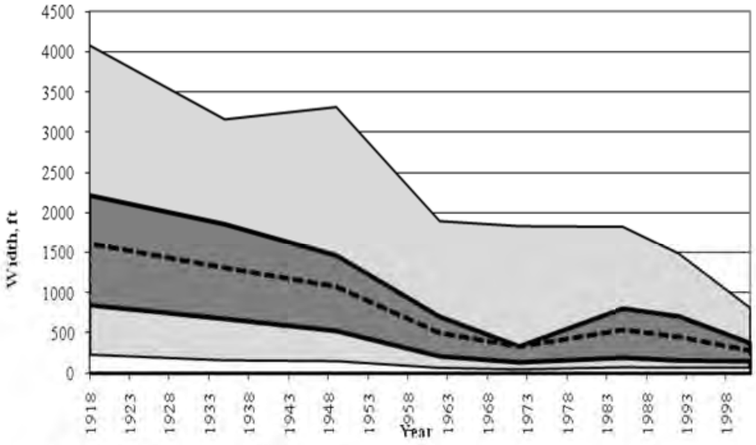


Figure 8. Average channel width over time between San Acacia to San Marcial

Bui (2014) described a conceptual basis for Reclamation’s habitat restoration goals

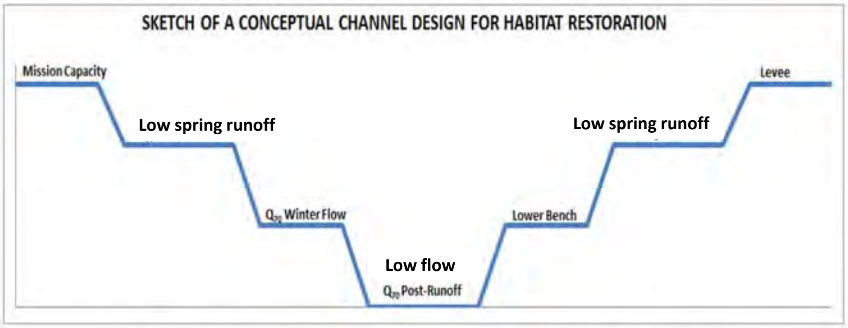
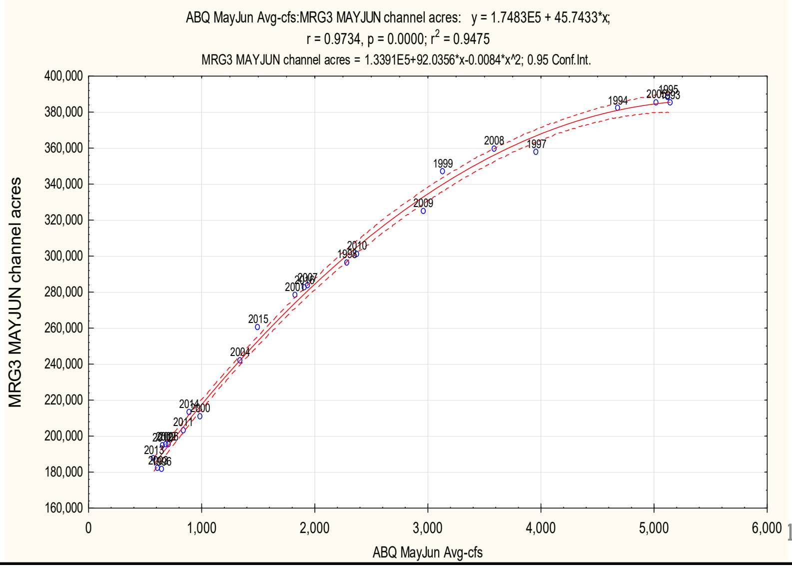
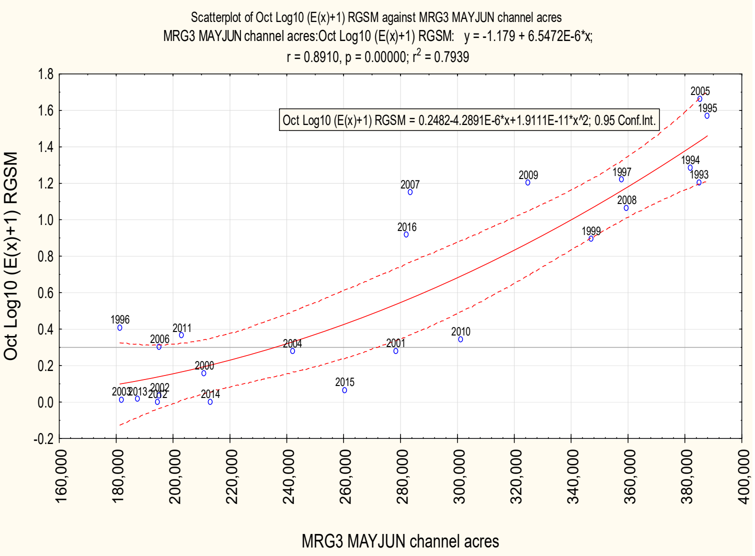


Figure 18: Conceptual Channel Design for Habitat Restoration

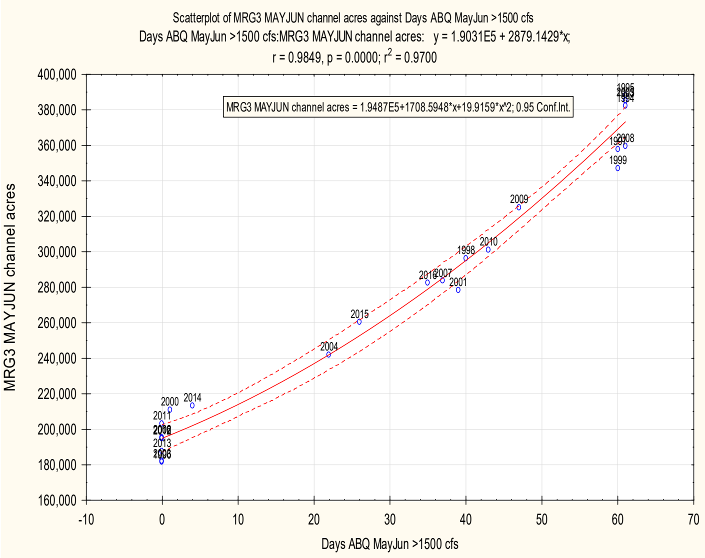
Inundated channel area during May through June is related to the average mean daily flow at the Albuquerque Gage during May through June



Increased inundated channel area during May through June (by flows) is associated with increased est. densities of RGSM in October



Key Uncertainty 2: Habitat Restoration Project Planning is a uncertainty for RGSM management



Conclusions

- Prolonged spring runoff during May through June was most predictive of RGSM recruitment in the fall.
- Key Uncertainty 1: how water management agencies will use available water and any modified reservoir authorities to meet needs while adaptively managing spring runoff duration for fall RGSM recruitment.
- Ongoing geomorphic phenomena are limiting habitat and limiting Habitat Restoration project effectiveness.
- Key Uncertainty 2: Current Habitat Restoration efforts lack clear purpose and goals for RGSM and riparian species habitat management. The potential costs are likely higher than reservoir management options.

Slides below are for reference <u>only</u>

Dudley et al. (2016) complete Table 3

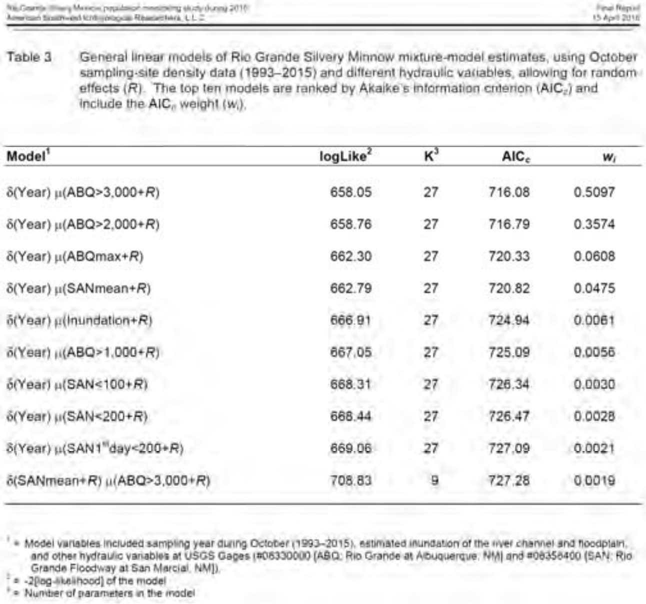


Table 3 General linear models of Rio Grande Silvery Minnow mixture-model estimates, using October sampling-site density data (1993–2015) and different hydraulic variables, allowing for random effects (*R*). The top ten models are ranked by Akaike's information criterion (AIC$_c$) and include the AIC$_c$ weight (w_i).

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δ(Year) μ(ABQ>1,000+*R*)	667.05	27	725.09	0.0056
δ(Year) μ(SAN<100+*R*)	668.31	27	726.34	0.0030
δ(Year) μ(SAN<200+*R*)	668.44	27	726.47	0.0028
δ(Year) μ(SAN1stday<200+R)	669.06	27	727.09	0.0021
δ(SANmean+*R*) μ(ABQ>3,000+*R*)	708.83	9	727.28	0.0019

[1] = Model variables included sampling year during October (1993–2015), estimated inundation of the river channel and floodplain, and other hydraulic variables at USGS Gages (#08330000 [ABQ: Rio Grande at Albuquerque, NM] and #08358400 [SAN: Rio Grande Floodway at San Marcial, NM]).

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

[3] = Number of parameters in the model

Location of USGS stream gages

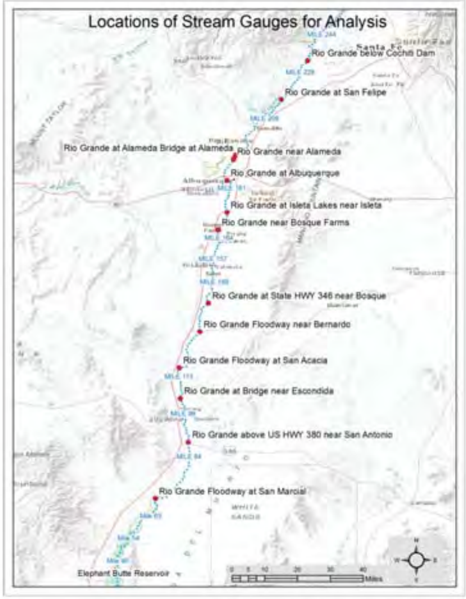


Figure 1: Stream Gauges from Cochiti Dam to Elephant Butte Reservoir for the Analysis

Rio Grande at San Felipe Gage

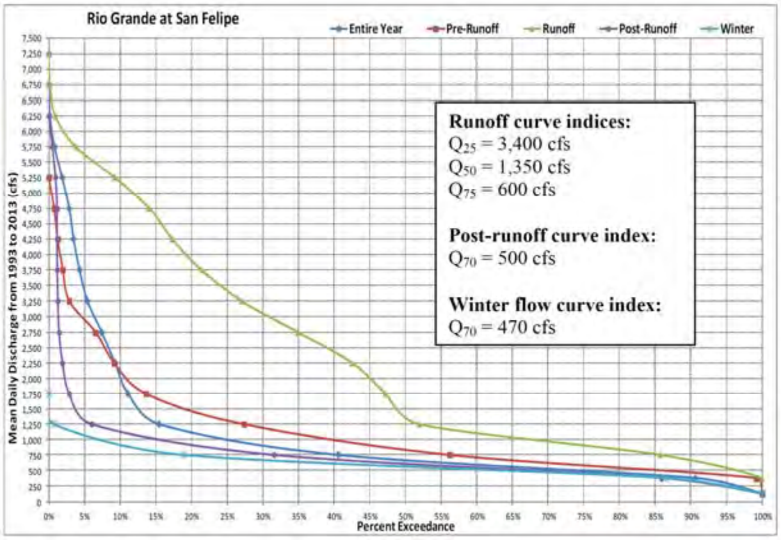


Figure 6: Flow Duration Curve of the Rio Grande at San Felipe

Rio Grande at Albuquerque Gage

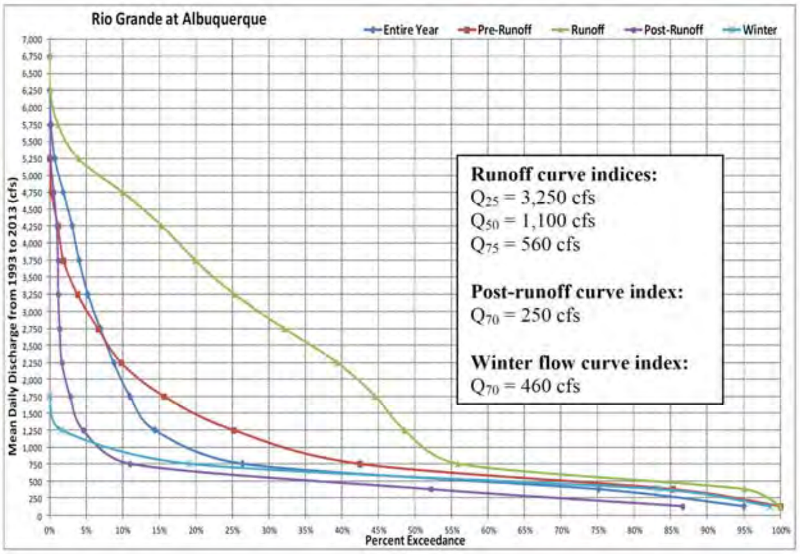
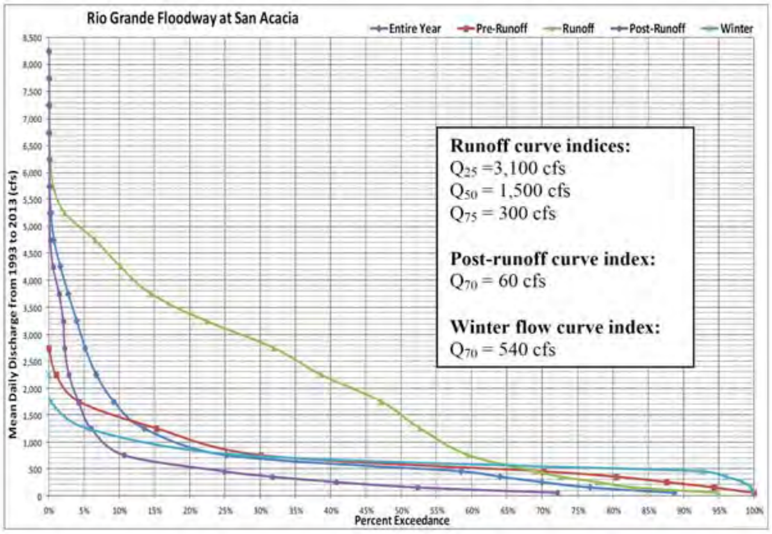


Figure 9: Flow Duration Curve of the Rio Grande at Albuquerque

Rio Grande at San Acacia Gage



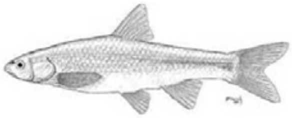
Runoff curve indices:
Q_{25} =3,100 cfs
Q_{50} = 1,500 cfs
Q_{75} = 300 cfs

Post-runoff curve index:
Q_{70} = 60 cfs

Winter flow curve index:
Q_{70} = 540 cfs

Figure 14: Flow Duration Curve of the Rio Grande Floodway at San Acacia (Downstream of San Acacia Diversion Dam)

Session III



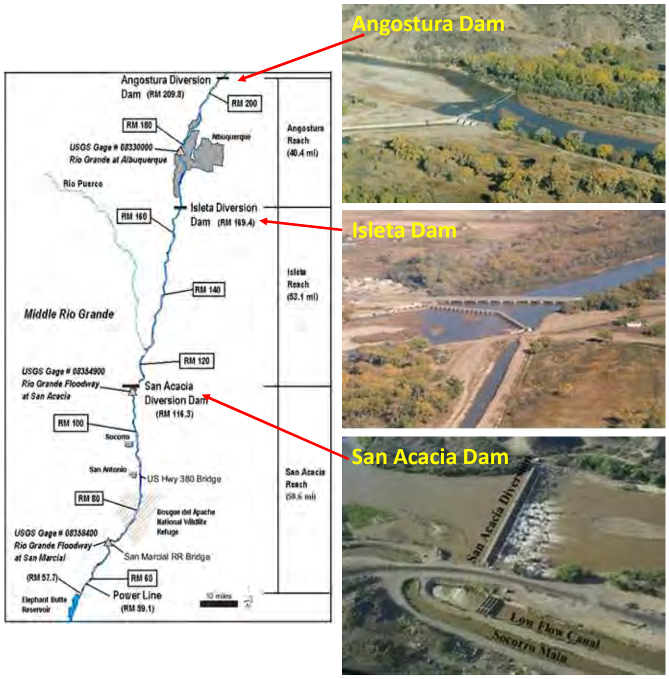
What is the relationship between hydrology and channel morphology with RGSM density, abundance, and spatial distribution?

1. Reach fragmentation
2. Hydrologic variables and CPUE
3. Relationship of hydrology to spawning time
4. Middle Rio Grande habitat restoration
5. 2016 coordinated spring flow

Richard A. Valdez, Ph.D.
SWCA
Rio Grande Silvery Minnow Independent Science Panel
Santa Ana Pueblo, New Mexico
February 1, 2017

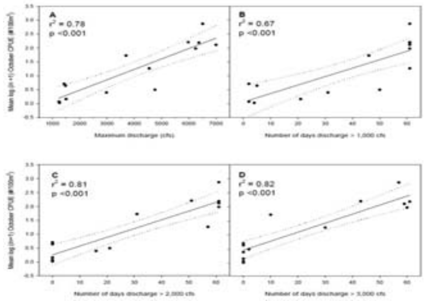
Reach Fragmentation

- RGSM is a broadcast spawner that releases nonadhesive, semi-buoyant eggs into the water column (Platania and Altenbach 1998).
- Drifting eggs and larvae transported downstream of diversions that impede upstream return = fragmentation.
- RGSM less abundant in upper-most reach (Angostura) and most abundant in lower-most reach (San Acacia).



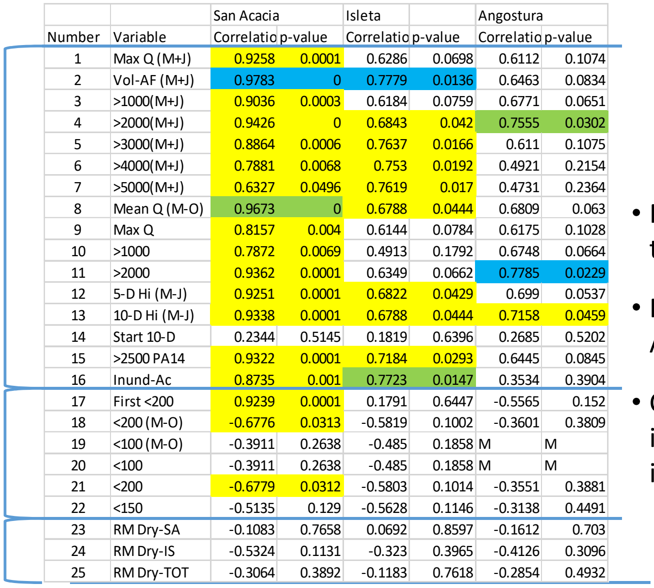
Hydrologic Variables and CPUE

- Relationship between high flow variables and Oct CPUE (Dudley and Platania 2008).
- Correlation shows most variables that describe high river flow are positively related to RGSM CPUE in Oct.



Dudley and Platania (2011) regressed October CPUE against ten "hydrologic variables" for two gages		
1	Max Q (M+J)	Maximum discharge (cfs) (May - June)
2	>1000(M+J)	Number of days discharge > 1,000 cfs (May - June)
3	>2000(M+J)	Number of days discharge > 2,000 cfs (May - June)
4	>3000(M+J)	Number of days discharge > 3,000 cfs (May - June)
5	>4000(M+J)	Number of days discharge > 4,000 cfs (May - June)
6	>5000(M+J)	Number of days discharge > 5,000 cfs (May - June)
7	First <200	First date with discharge < 200 cfs (after 1 June) Julian Date
8	Mean (M-O)	Mean daily discharge (cfs) (March - October)
9	<200 (M-O)	Days with discharge < 200 cfs (March - October)
10	<100 (M-O)	Days with discharge < 100 cfs (March - October)
Goodman (2009) noted relationships between October CPUE and nine "flow indices" for two gages		
11	Max Q	Maximum discharge cfs (year-around)
12	>1000	Number of days of discharge > 1,000 cfs (year-around)
13	>2000	Number of days of discharge > 2,000 cfs (year-around)
14	<100	Number of days of discharge < 100 cfs (year-around)
15	<200	Number of days of discharge < 200 cfs (year-around)
Lusk (Service's Hydrologic Objectives) uses five "hydrologic variables" for two gages on the MRG		
16	5-D Hi (M-J)	Mean 5-day peak daily flow (May-June)
17	>2500 PA14	Number of Days of Mean Daily Flow > 2,500 cfs after April 14
18	<150	Number of Days Mean Daily Low Flows <150 cfs
19	RM Dry-SA	River Miles Dry - San Acacia Reach (Valdez 2011 and Lusk 2013)
20	RM Dry-IS	River Miles Dry - Isleta Reach (Valdez 2011 and Lusk 2013)
21	RM Dry-TOT	River Miles Dry - Total (Valdez 2011 and Lusk 2013)
Valdez (added for this analysis)		
22	10-D Hi (M-J)	Mean 10-day peak daily flow (May-June)
23	Start 10-D	First date of 10-day peak flow (May-June) Julian Date
24	Vol-af(M+J)	Volume of river in May+June
Tetra-Tech Flow Inundation		
25	Inund-Ac	Acres of total inundation at a given flow (HEC2 + Flow 2-D)

Pearson Correlation (variable vs Ln [CPUE+1] for 1993-2014)



		San Acacia		Isleta		Angostura	
Number	Variable	Correlatio	p-value	Correlatio	p-value	Correlatio	p-value
1	Max Q (M+J)	0.9258	0.0001	0.6286	0.0698	0.6112	0.1074
2	Vol-AF (M+J)	0.9783	0	0.7779	0.0136	0.6463	0.0834
3	>1000(M+J)	0.9036	0.0003	0.6184	0.0759	0.6771	0.0651
4	>2000(M+J)	0.9426	0	0.6843	0.042	0.7555	0.0302
5	>3000(M+J)	0.8864	0.0006	0.7637	0.0166	0.611	0.1075
6	>4000(M+J)	0.7881	0.0068	0.753	0.0192	0.4921	0.2154
7	>5000(M+J)	0.6327	0.0496	0.7619	0.017	0.4731	0.2364
8	Mean Q (M-O)	0.9673	0	0.6788	0.0444	0.6809	0.063
9	Max Q	0.8157	0.004	0.6144	0.0784	0.6175	0.1028
10	>1000	0.7872	0.0069	0.4913	0.1792	0.6748	0.0664
11	>2000	0.9362	0.0001	0.6349	0.0662	0.7785	0.0229
12	5-D Hi (M-J)	0.9251	0.0001	0.6822	0.0429	0.699	0.0537
13	10-D Hi (M-J)	0.9338	0.0001	0.6788	0.0444	0.7158	0.0459
14	Start 10-D	0.2344	0.5145	0.1819	0.6396	0.2685	0.5202
15	>2500 PA14	0.9322	0.0001	0.7184	0.0293	0.6445	0.0845
16	Inund-Ac	0.8735	0.001	0.7723	0.0147	0.3534	0.3904
17	First <200	0.9239	0.0001	0.1791	0.6447	-0.5565	0.152
18	<200 (M-O)	-0.6776	0.0313	-0.5819	0.1002	-0.3601	0.3809
19	<100 (M-O)	-0.3911	0.2638	-0.485	0.1858	M	M
20	<100	-0.3911	0.2638	-0.485	0.1858	M	M
21	<200	-0.6779	0.0312	-0.5803	0.1014	-0.3551	0.3881
22	<150	-0.5135	0.129	-0.5628	0.1146	-0.3138	0.4491
23	RM Dry-SA	-0.1083	0.7658	0.0692	0.8597	-0.1612	0.703
24	RM Dry-IS	-0.5324	0.1131	-0.323	0.3965	-0.4126	0.3096
25	RM Dry-TOT	-0.3064	0.3892	-0.1183	0.7618	-0.2854	0.4932

High-flow events

Low-flow events

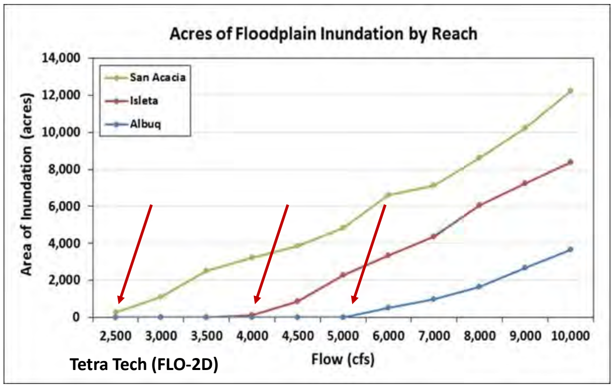
Drying events

Correlation (α ≤ 0.05):

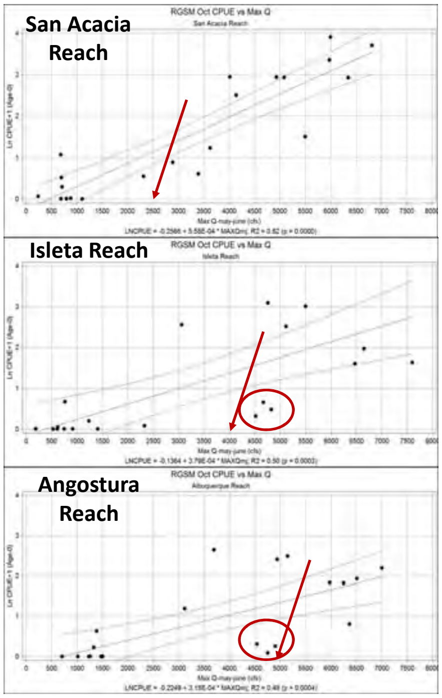
🟦	1 (highest)
🟩	2
🟨	3

- Most high-flow variables correlate to CPUE in San Acacia Reach.
- Fewer correlations for Isleta and Angostura.
- Correlations reflect greater incision and less lateral expansion in Isleta and Angostura.

Max Q (m-j) to Age-0 CPUE by Reach (1993 – 2014)

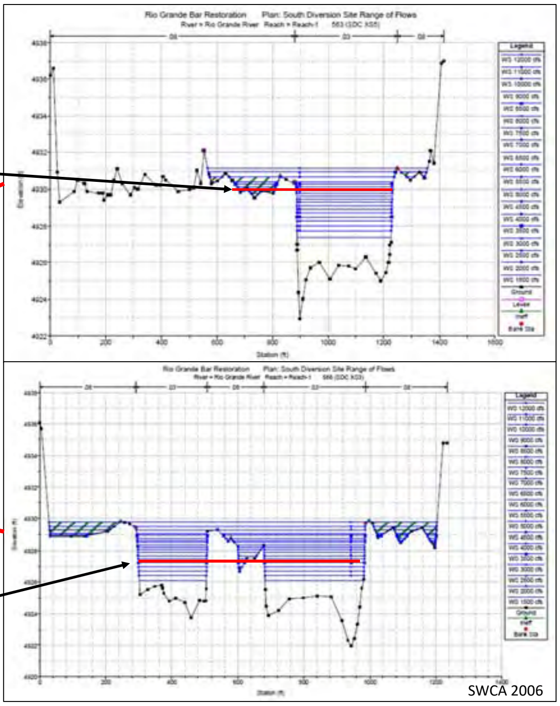


Tetra Tech (FLO-2D)



Cross Sections—Albuquerque Reach

CS without islands, inundation begins at ~7,500 cfs



CS with islands, inundation begins at ~3,500 cfs

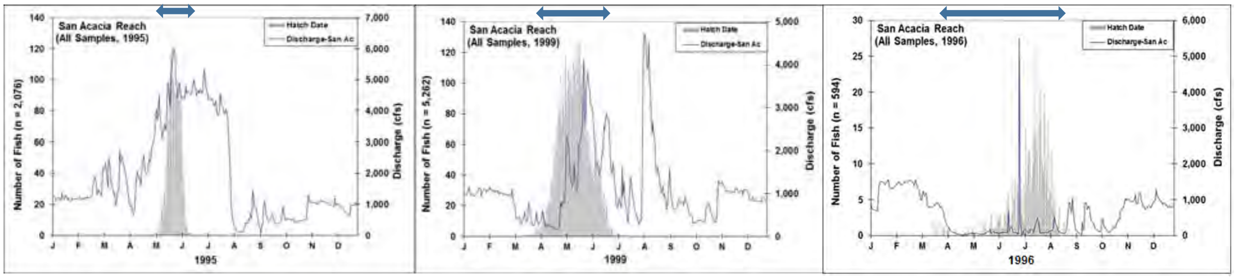
SWCA 2006

Relationship of Hydrology to Spawning Time

Single-batch spawn on spring peak
(Narrow early-spring window, May)

Single-batch spawn during extended high flow
(Expanded window, Apr-Jun)

Protracted spawning on spring peak and summer monsoons
(Protracted window, Apr-Aug)



Hatching dates computed from inverse von Bertalanffy growth function (VBGF)

Larval Developmental Phases

- Effects of downstream transport dependent on developmental rate from a drifting embryo to the free-swimming larval phase (Dudley and Platania 2007).

free-embryo

transition to larval stage

free-swimming larval phase

fully-developed fins

Protolarvae
1-day, 4 mm TL
(yolk sac, no fins)

Protolarvae
~4-day, 5 mm TL
(yolk sac nearly absorbed, no fins)

Mesolarvae (flexion)
~7-day, 7 mm TL
(yolk sac absorbed, fins forming)

Mesolarvae (post-flexion)
~10-day, 9 mm TL
(yolk sac absorbed, fins forming)

Metalarvae
~14-day, 12 mm TL
(fins formed)

Drawings courtesy of H.W. Brandenburg

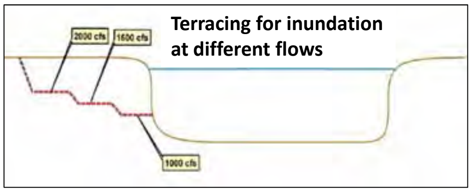
Middle Rio Grande Habitat Restoration

- Habitat restoration in response to 2003 BO.
- Ten Program partners constructed 300+ sites.
- Sites were designed to establish diverse habitats at a range of river flows—500 and 3,500 cfs.


Amphibious caterpillar terracing the bankline


Inundated terrace


Terraced bankline

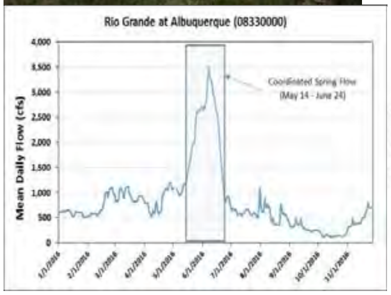

Terracing for inundation at different flows

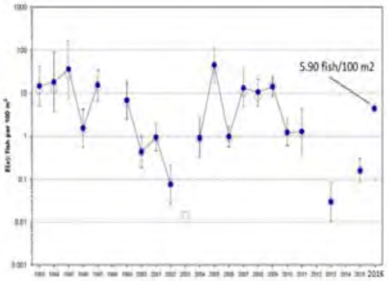
Aerial Photos Restored Sites during 2016 Controlled Spring Flow

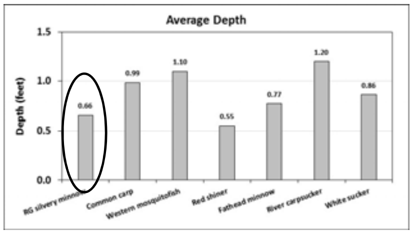
Photos courtesy of Todd Caplan

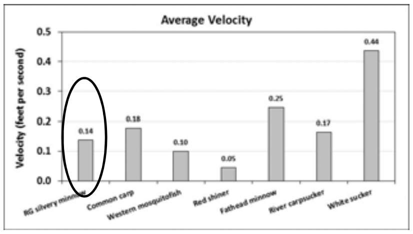
Use of Constructed Sites by RGSM 2016 Controlled Spring Flow (NMISC & SWCA)

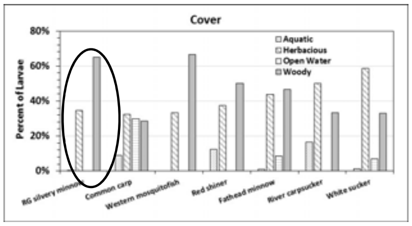
- Of 2,430 larvae, 1,758 (72%) were RGSM.
- Shallow water, low velocity.
- 98% in vegetation.
- 73% near water's edge.
- Less volume than 2015.









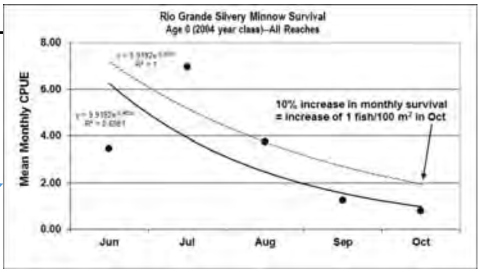


Summary

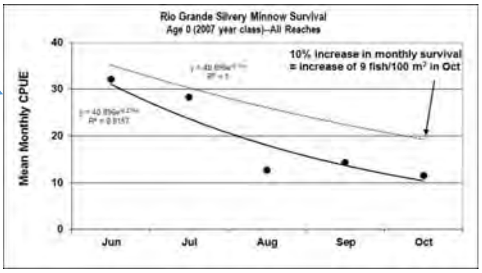
1. Annual RGSM census density (i.e., October CPUE) appears to be driven by spring flow magnitude, duration, and stage change.
2. CPUE is positively correlated with high flow and overbank inundation.
3. High flow and overbank inundation do not occur annually, but reconstructed sites can provide floodplain-like habitat at lower flows.
4. Flow of sufficient magnitude and duration is needed to create sheltered off-channel habitats that allow full fin development in larvae (10-14 days post-hatch).
5. Once flooded, floodplain habitat should be stabilized as long as possible to ensure full development of edge periphtyon and a zooplankton community as a food supply.

Survival of Rio Grande Silvery Minnow

- Higher survival in earliest life stages is critical to increasing population size.
- At low density, increase of 10% survival = increase of ~1 fish/100 m^2 in Oct.
- At high density, increase of 10% survival = increase of ~9 fish/100 m^2 in Oct.



Rio Grande Silvery Minnow Survival
Age 0 (2004 year class)--All Reaches



Rio Grande Silvery Minnow Survival
Age 0 (2007 year class)--All Reaches

Recommendations for Priority Studies

1. Continue ongoing evaluation of reconstructed sites.
2. Design a set of *a priori* optional hydrographs, at different available water volumes, with timing, magnitude, duration, and stage change that would benefit the RGSM.
3. Conduct condition-dependent coordinated spring flows.
4. Evaluate the possibility of a coordinated spring flow triggered by flow, temperature, or first appearance of eggs.

Condition-Dependent Flows

- High-Flow Experiments (HFE) from Glen Canyon Dam conserve sand and benefit resources, including humpback chub.
- Releases from Flaming Gorge Dam match Yampa River highs to provide nursery floodplains for larval razorback sucker.
- Rio Grande does not have a single control system.

Thank you—Questions?

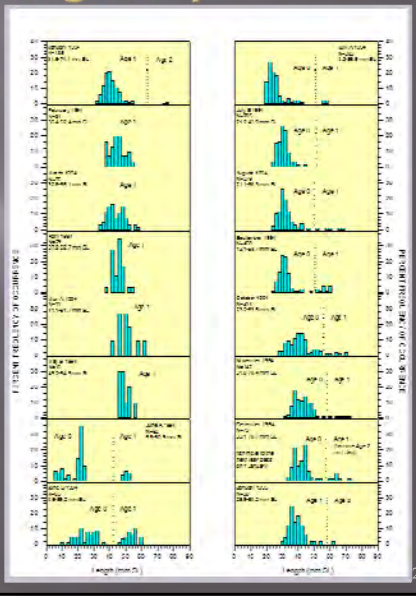
SESSION IV
SCIENTIFIC PERSPECITVES ON ADULT SURVIVORSHIP

SCIENTIFIC PERSPECTIVES ON LONGEVITY OF RIO GRANDE SILVERY MINNOW

Thomas P. Archdeacon
New Mexico Fish and Wildlife Conservation Office

Changing perspectives on silvery minnow longevity

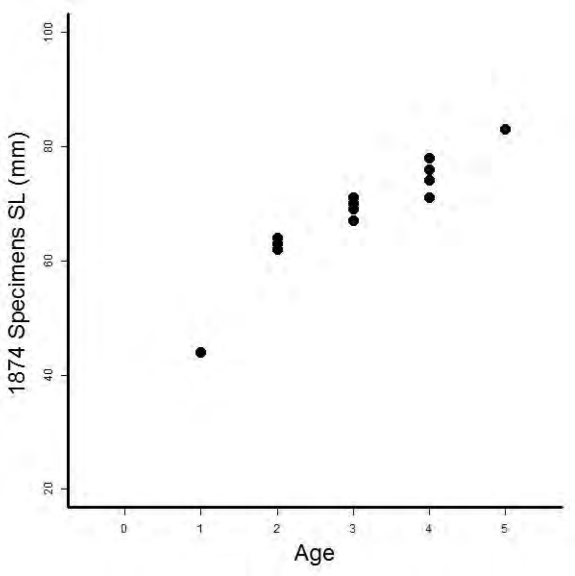
- Early analyses of length-frequency suggested two distinct cohorts with a maximum age of 2
- Not an unreasonable assumption based on the available data

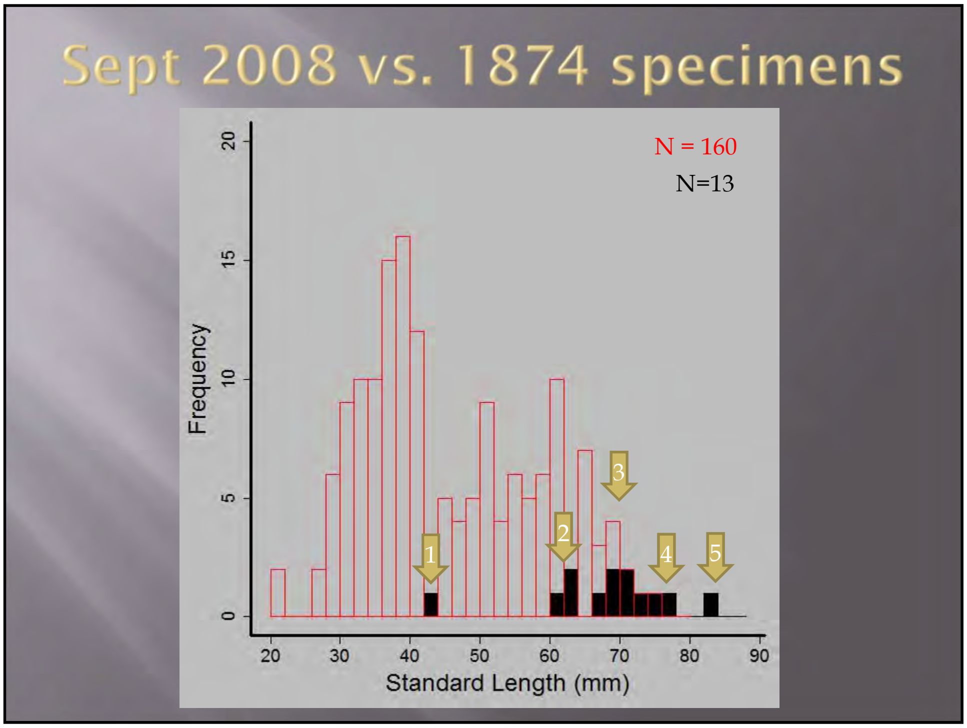


Historical collection consists of older RGSM

- Annuli on otolith laid down once per year (Lang 2016)
- Cowley et al. (2006)
  - Obtained ages of 13 specimens (by scales) from August, 1874, captured near San Ildefonso, NM
  - Found age classes 1-5
  - Historically may have been iteroparous
  - Near linear relationship between age and length

Cowley et al. (2006)
1874 Specimens





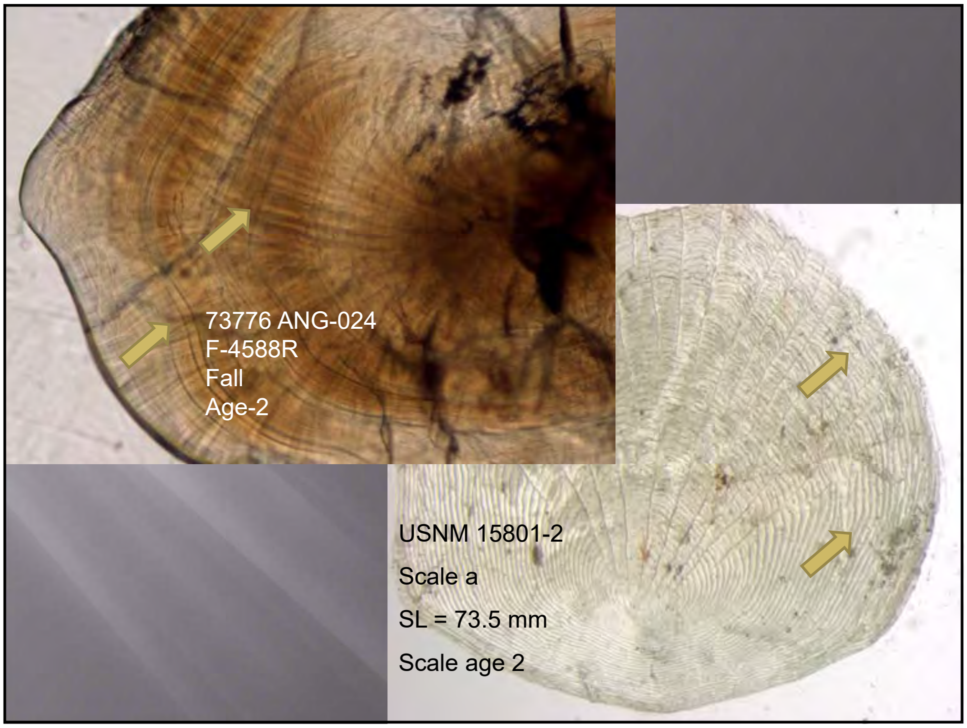
Sept 2008 vs. 1874 specimens

Contemporary RGSM

- Horwitz et al. (2011) examined 158 RGSM collected in autumn 2009 and spring 2010.
  - Over 13,000 RGSM measured to collect the 158 used for aging
  - largest individuals collected for analysis – statistically the greatest chance to observe RGSM > 2 years old
- Otoliths, scales, lengths
  - 83 in autumn 75 in spring
  - Collected in size bins, larger fish over-represented
  - Lengths fully encompass 1874 collection

Results – Horwitz et al. (2011)

- Scales biased older than otoliths
- Scales more difficult to read
- Some overlap in Age-0 and Age-1 lengths
- Complete overlap in Age-2 and Age-3 lengths



73776 ANG-024
F-4588R
Fall
Age-2

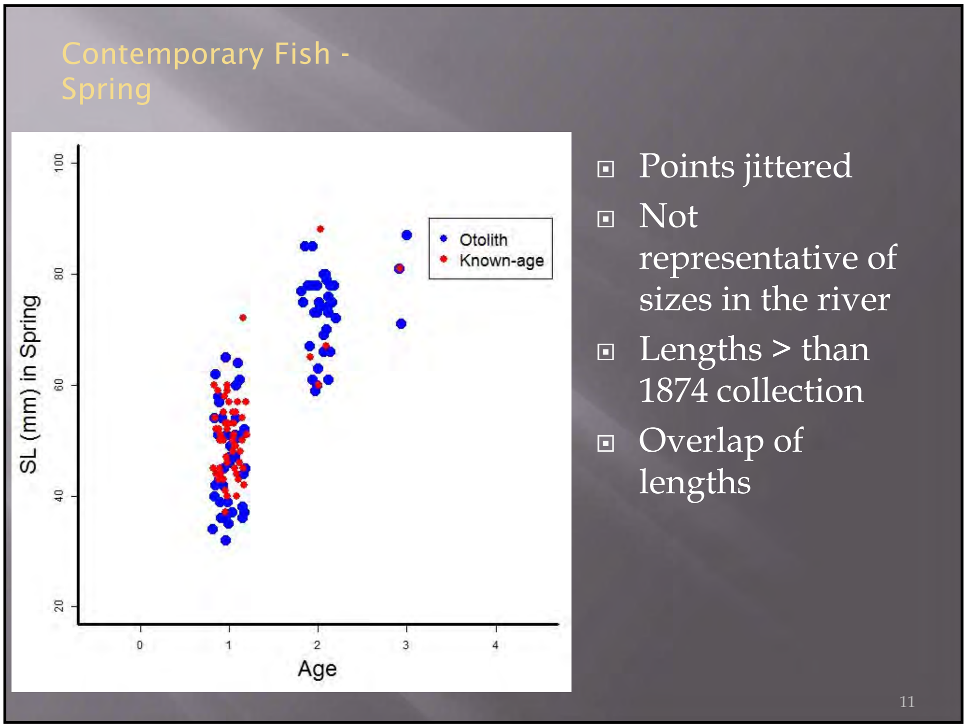
USNM 15801-2
Scale a
SL = 73.5 mm
Scale age 2

Results - Contemporary longevity

- Reported a maximum of Age-3 (Spring only)
- Reported largest fish (90 mm) was Age-2

Contemporary Ages – Known age RGSM

- USFWS -301 known-age RGSM measured for SL 2007-2016
  - VIE-marked, released as Age-0 in fall
  - 168 collected in spring (March-May)
  - 133 collected in autumn (August-Sept)

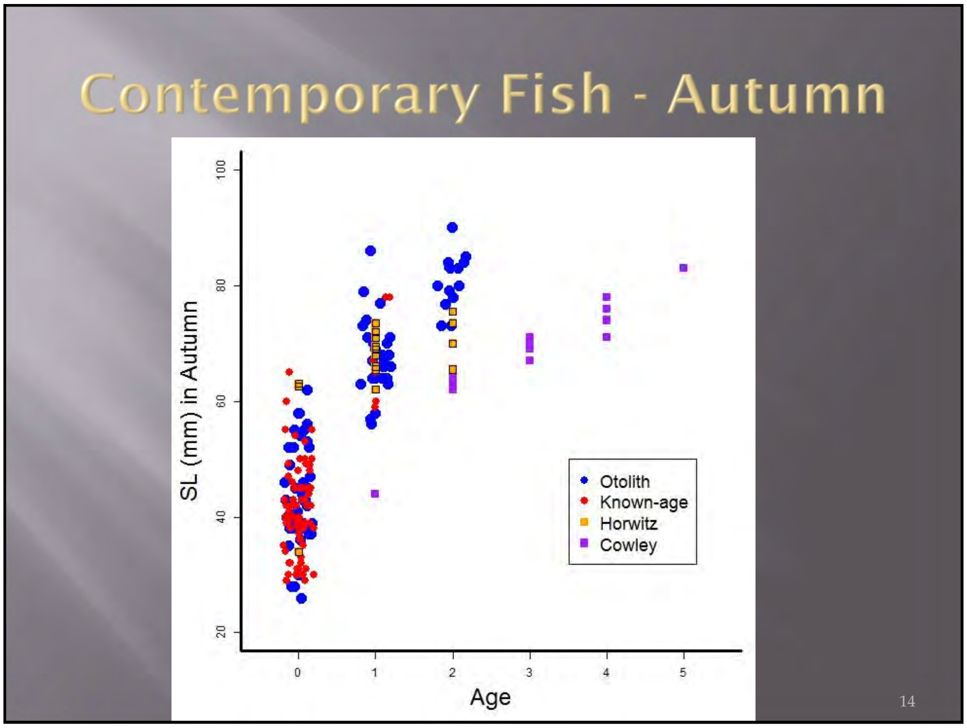


Contemporary Fish - Spring

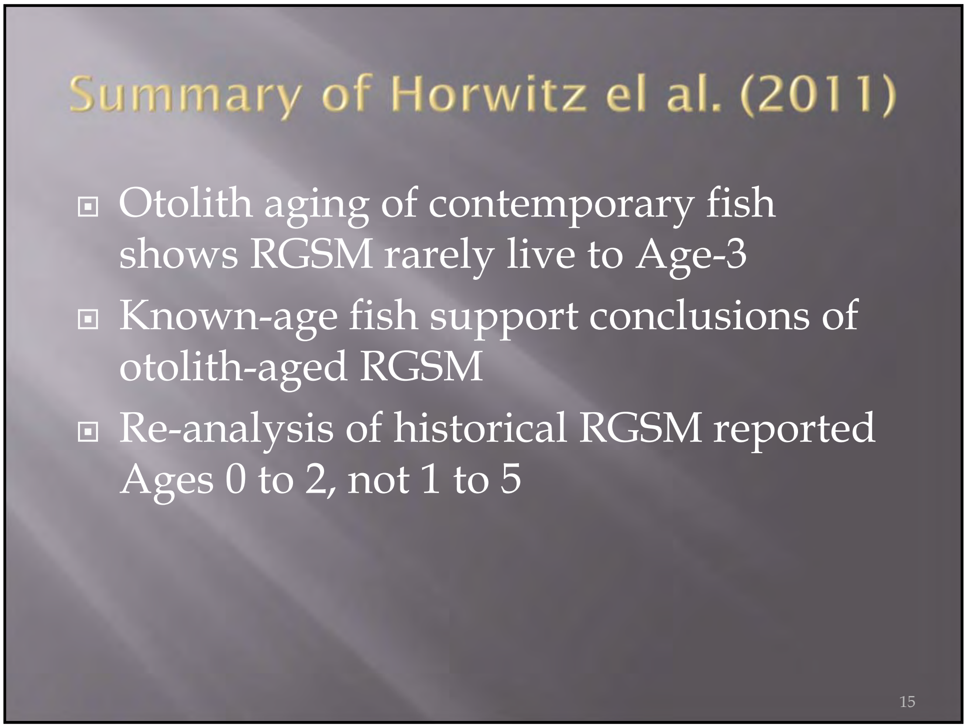
- Points jittered
- Not representative of sizes in the river
- Lengths > than 1874 collection
- Overlap of lengths

Historical Ages

- Cowley et al. (2006)
  - Reported ages 1 to 5
  - Reported lengths ~44—83mm SL (N = 13)
- Horwitz et al. (2011)
  - Reported ages 0 to 2
  - Reported lengths ~34—75.5mm SL (N = 20)



Contemporary Fish - Autumn

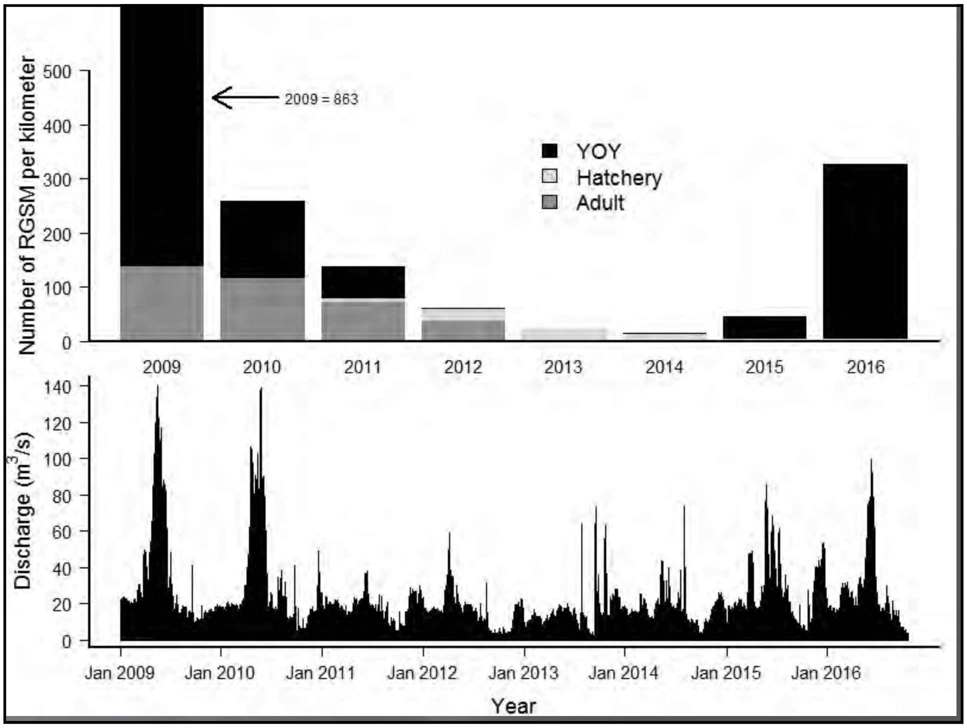


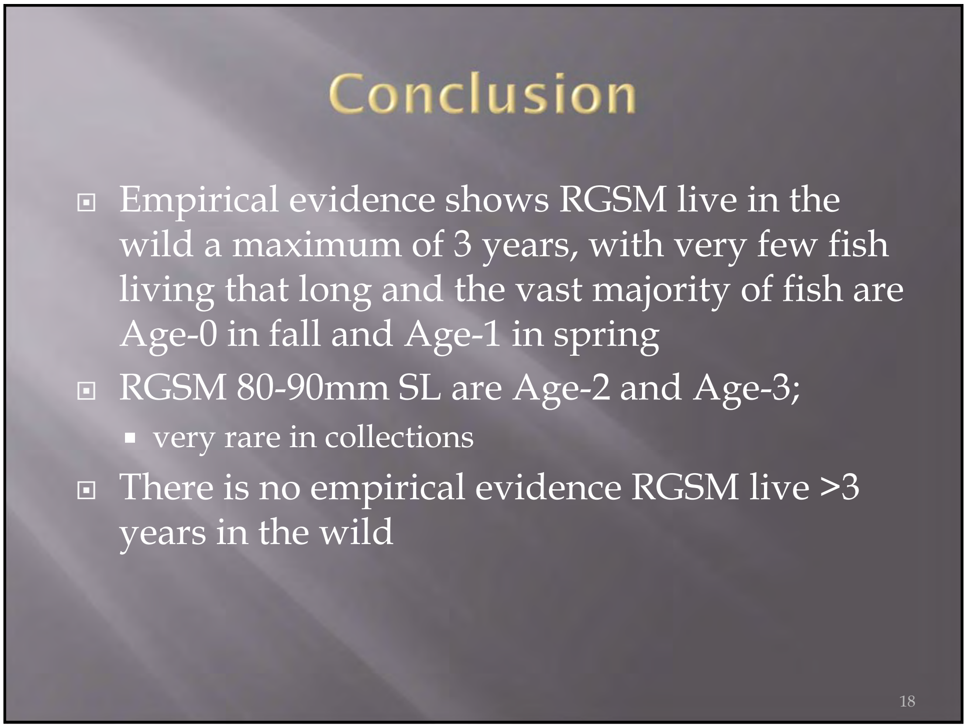
Summary of Horwitz el al. (2011)

- Otolith aging of contemporary fish shows RGSM rarely live to Age-3
- Known-age fish support conclusions of otolith-aged RGSM
- Re-analysis of historical RGSM reported Ages 0 to 2, not 1 to 5

Implications for Life history

- Iteroparity
  - Longer-lived
  - Multiple spawning
  - Resistant to consecutive years of recruitment failure (e.g. lack of spring run-off)
- Semelparity
  - Shorter-lived
  - Single-spawn before death
  - Annual recruitment is critical





Conclusion

- Empirical evidence shows RGSM live in the wild a maximum of 3 years, with very few fish living that long and the vast majority of fish are Age-0 in fall and Age-1 in spring
- RGSM 80-90mm SL are Age-2 and Age-3;
  - very rare in collections
- There is no empirical evidence RGSM live >3 years in the wild

Life Span, Age & Growth, & Some Simulation Models

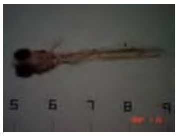
David Cowley, Professor
Fish, Wildlife & Conservation Ecology
New Mexico State University

photo by M. Marusek

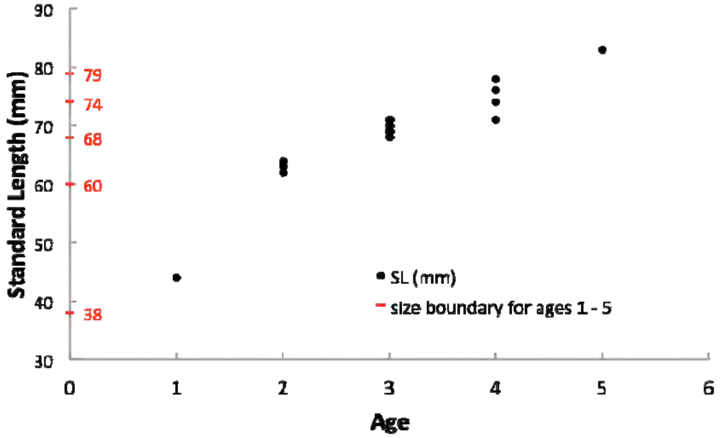
Acknowledgments & Disclaimer

- M. Hatch & M. Porter, *collaborators*
- *support*: 1) N.M. Agric. Exp. Sta., 2) Dept. of Defense, W912HZ-15-2-0016
- The content of this presentation does not necessarily reflect the position or the policy of the government, and no official endorsement should be inferred.

Don't forget us!



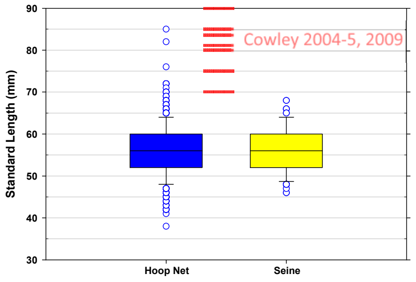
Life Span ≥ 5 years



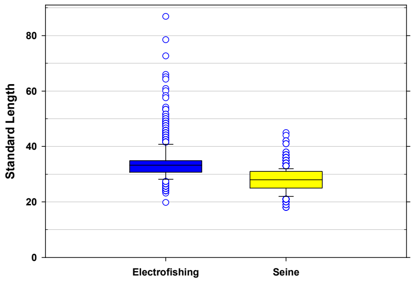
Cowley et al. (2006) Rev. Fish. Sci.14:111-125

Data Need

- age & growth data are limited (Cowley et al. 2006), more sampling data from wild fish are needed
- sampling method is important, seine samples may not cover the size range of *H. amarus*



Los Lunas Restoration, 20 May-6 Jun 2008
Hoop Net & Seine – SWCA



ABQ Reach, Aug 2007
Electrofishing – USBR, seine – UNM affiliates

A Model for *H. amarus* Demography

- Age-specific fecundity is consistent with *H. placitus*.
- Uncertainty is expected in survival rates for an endangered species, which precludes simple application of Leslie matrix methods
  - – simulations are necessary
- My model assumes age-specific survival & fecundity vary randomly every year across a 5 yr life span with reproduction @ ages 1-5.
- Simulations of my Leslie matrix model will required an estimated transition matrix
  - – each year simulated will use a stochastic realization of the transition matrix

Building a Transition Matrix

- I use surrogate fecundity data for a closely-related species (*H. placitus*)
  - the predictions of *H. amarus* fecundity were shown previously

0	332	997	1528	2079	3131
S_{01}	0	0	0	0	0
0	S_{12}	0	0	0	0
0	0	S_{23}	0	0	0
0	0	0	S_{34}	0	0
0	0	0	0	S_{45}	0

- survival rates (**S**)
  - estimated using size-at-age boundaries inferred from an 1874 sample of H. amarus

Age-Specific Survivorship

Age	N	est. survival	adj. survival
0	0		0.00172*
1	1883	0.1168	0.2868**
2	220	**1**	0.4074**
3	220	0.3909	
4	86	0.1628	
5	14	0	
Total N	2423***		

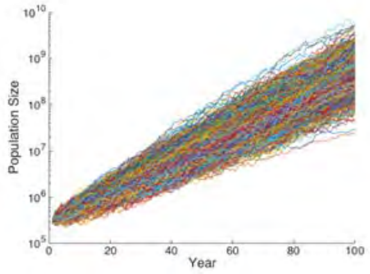
* age 0-1 survival estimated with a Leslie Matrix algorithm (Vaughn & Saila 1976) after adjusting S_{12} & S_{23}

** adjusted survivorship: 540 fish in the sample are age 2 or older, S_{12} = 540/1883, S_{23} = 220/540

*** Los Lunas Restoration Area, May 2009, hoop net

My Transition Matrix for *H. amarus*

0	332	997	1528	2079	3131
0.00172	0	0	0	0	0
0	0.2868	0	0	0	0
0	0	0.4074	0	0	0
0	0	0	0.3909	0	0
0	0	0	0	0.1628	0



With random variation in vital rates, *H. amarus* simulations increase in population size over time when the extraneous environment is benign.

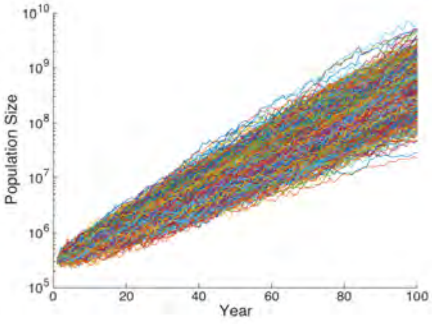
What happens in the real world?

Incorporating Unpredictable River Drying

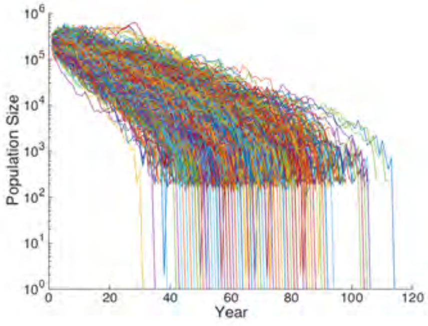
- I model unpredictable river-drying that kills minnows of all age classes equally.
- est. annual frequency of river drying (2004-15) is 0.83
  - a year with drying is simulated using uniform deviates, if deviate ≤ 0.83, then the year has drying
  - extent dried is simulated with normal deviates, scaled to 19.7 km mean extent and variance of 186.5
  - the fraction of the reach (Isleta, 85.5 km length) simulated to have dried is used to proportionally reduce the number of fish in each age class

Simulations

a) No Drying



b) River Drying

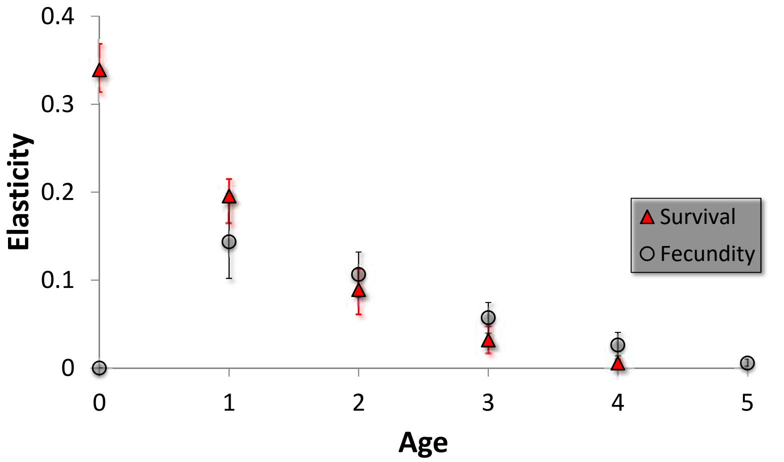


Conclusion: sustained river drying in my model causes extinction

Cowley & Hatch are simulating different transition matrices.

Will we draw the same conclusion comparing simulations with & without river intermittency?

What if life span is less than 5 years?



Conclusions: a) largest effect on population growth rate is from age ≤ 2; b) fecundity is more important than survival after age 1

Summary

- data deficits noted were identified 11 years ago (Cowley et al. 2006)
- our work is an attempt to proceed in spite of significant data deficits for *H. amarus*
- work in progress:
  - 1) comparing outcomes & conclusions between coauthors
  - 2) assessing model robustness for different shapes of the mortality-at-age curve
  - 3) identifying alternate ways to simulate environmental stochasticity
  - 4) extending the simulations to a metapopulation model of adjacent reaches

SESSION V

SCIENTIFIC PERSPECTIVES ON INTERMITTENCY OF FLOW FOR ADULT SURVIVORSHIP

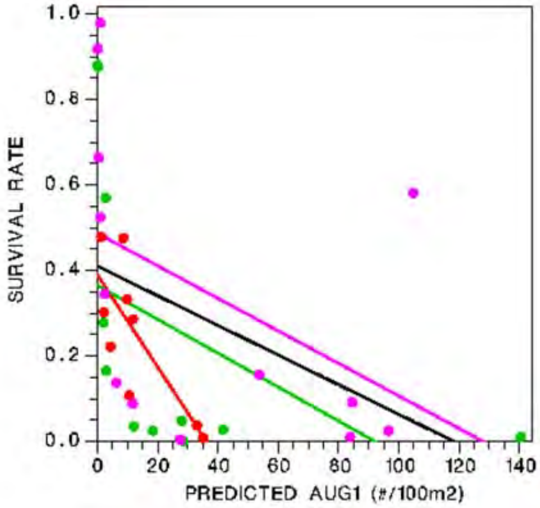
U.S. Army Corps of Engineers' and GeoSystems Analysis' independent peer review panel meeting for development of an Adaptive Management Framework.

February 2, 2017, Santa Ana Pueblo, New Mexico

Session V: Scientific perspectives on intermittency of flow for adult survivorship.

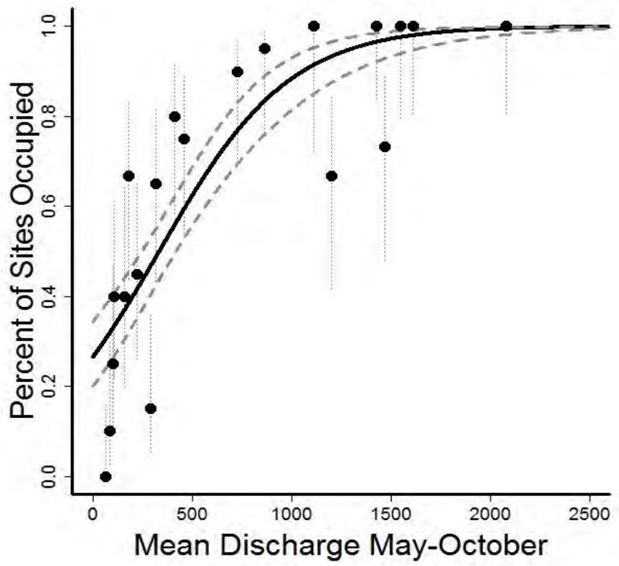
Joel D. Lusk, Fish and Wildlife Biologist
U.S. Fish and Wildlife Service
New Mexico Ecological Services
Albuquerque, New Mexico

Density-dependent mortality rate - related to runoff

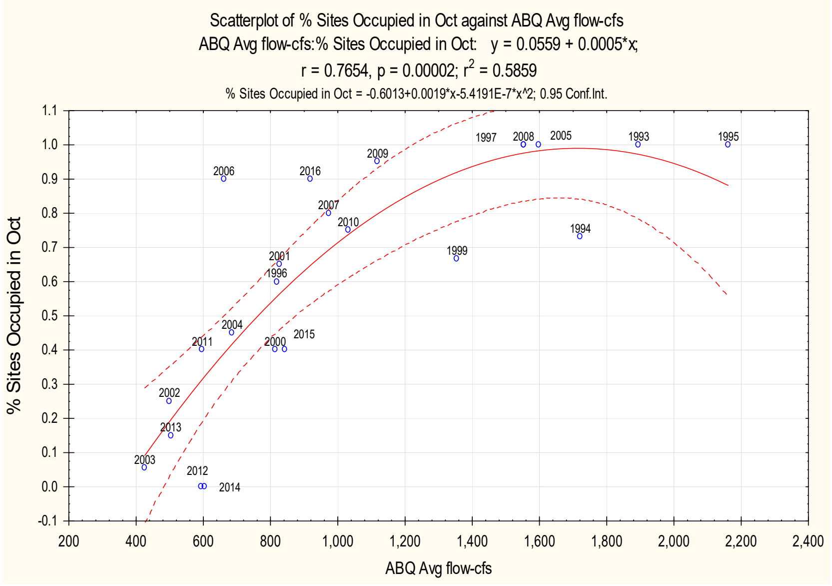


- Goodman (2011): reported that the larger the estimated number of RGSM that occur in August, the higher the mortality rate. Also, reach-specific mortality rates were highest in Angostura Reach and lowest in San Acacia.

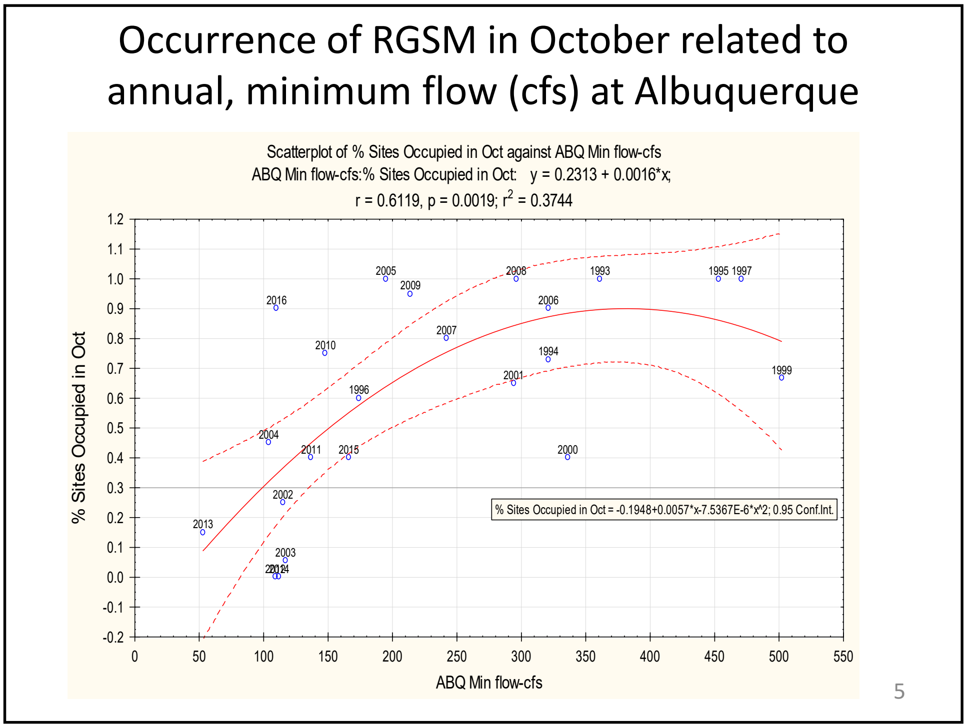
Occurrence of RGSM at Population Monitoring Program sites and flow



Occurrence of RGSM in October related to annual, average flow (cfs) at Albuquerque

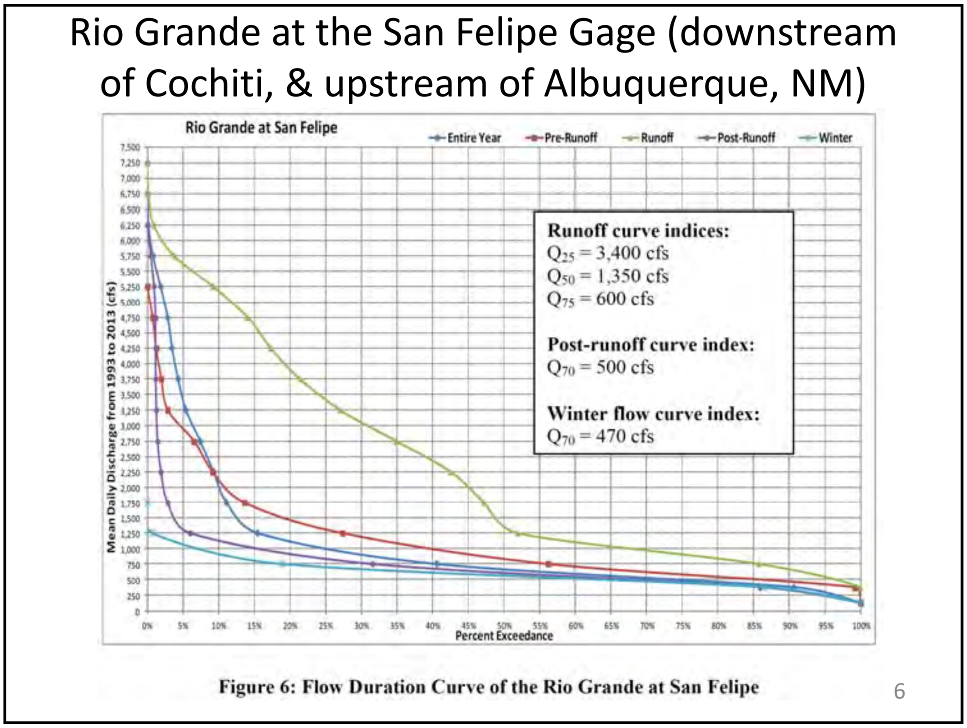


Occurrence of RGSM in October related to annual, minimum flow (cfs) at Albuquerque



5

Rio Grande at the San Felipe Gage (downstream of Cochiti, & upstream of Albuquerque, NM)



Runoff curve indices:
Q_{25} = 3,400 cfs
Q_{50} = 1,350 cfs
Q_{75} = 600 cfs

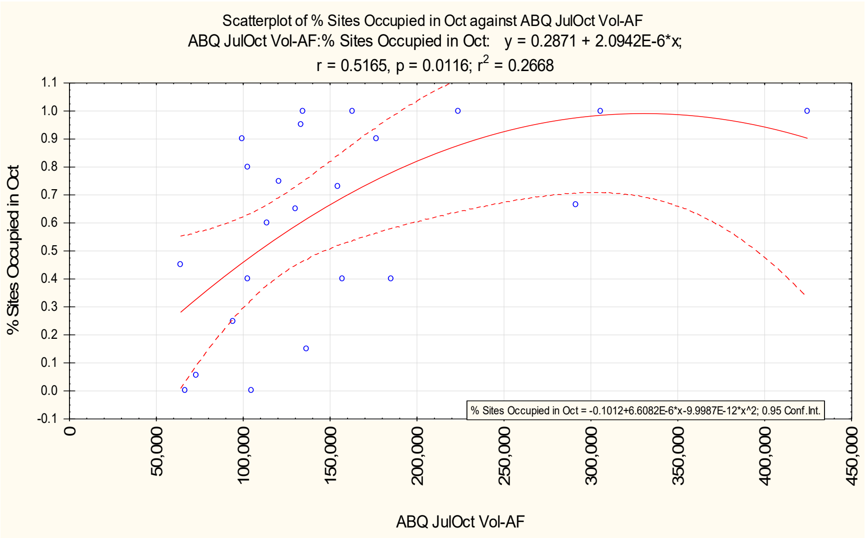
Post-runoff curve index:
Q_{70} = 500 cfs

Winter flow curve index:
Q_{70} = 470 cfs

Figure 6: Flow Duration Curve of the Rio Grande at San Felipe

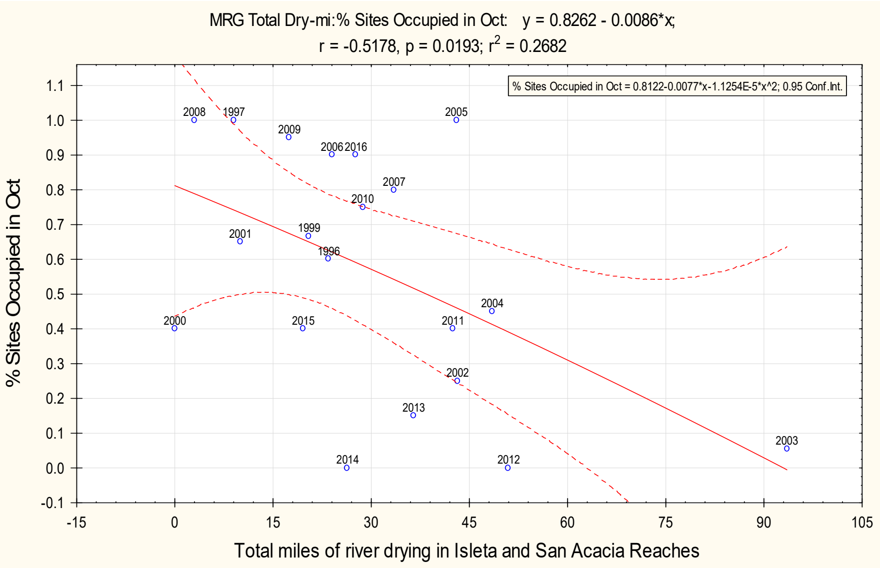
6

Forecast is for a warmer climate



Scatterplot of % Sites Occupied in Oct against ABQ JulOct Vol-AF
ABQ JulOct Vol-AF:% Sites Occupied in Oct: y = 0.2871 + 2.0942E-6*x;
r = 0.5165, p = 0.0116; r^2 = 0.2668

Miles of river drying and Occupancy



MRG Total Dry-mi:% Sites Occupied in Oct: y = 0.8262 - 0.0086*x;
r = -0.5178, p = 0.0193; r^2 = 0.2682

Prolonged low flows during summer were most predictive of increased site extinction probability during 2005-2015

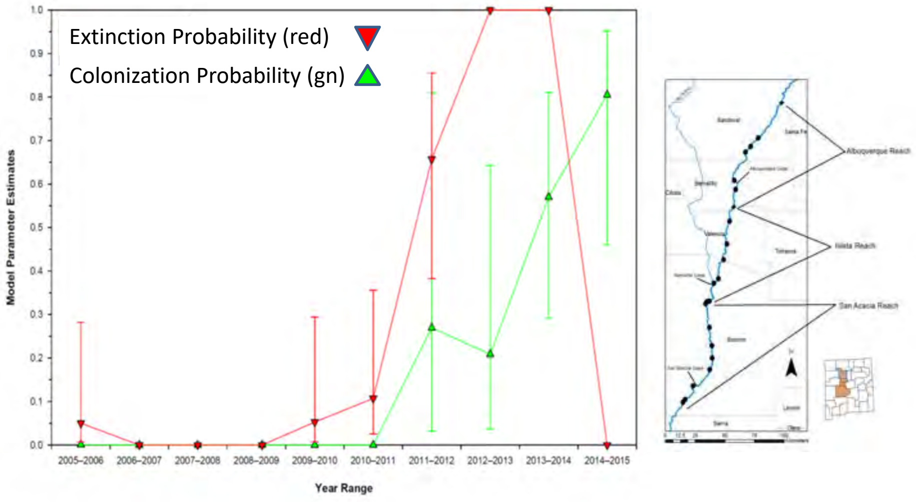
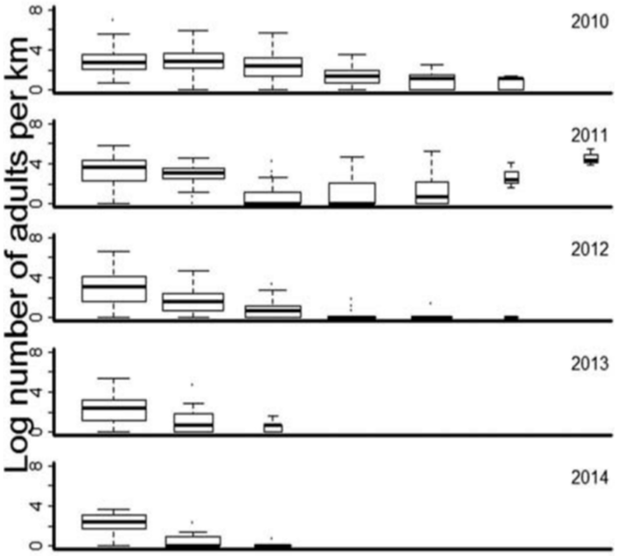


Figure B - 2. Site occupancy model estimates (extinction probability and colonization probability) for Rio Grande Silvery Minnow (all age-classes combined) based on repeated site sampling efforts (2005–2015). Symbols indicate means and capped-bars represent 95% confidence intervals.

Archdeaon (2016): RGSM need water and local extirpation often results from repeated river drying

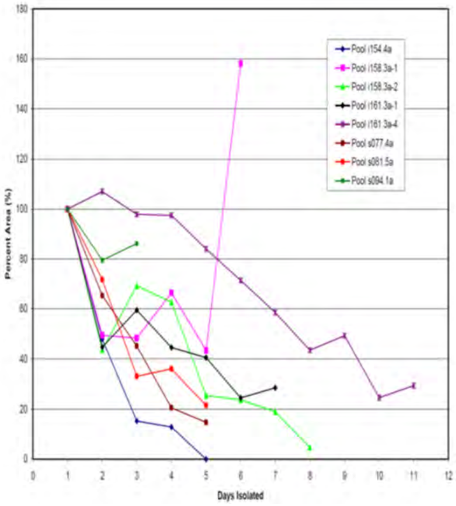


Fishkill in an isolated pool on 16 July 2016

Photography by USFWS/E. Henry

Isolated pool longevity in the MRG

- Isolated pools do not persist for long in MRG:
  - Hatch et al. (2008) selected for study larger pools. Pools dried or declined in size for 5-7 days then pools rewet.
  - Putative daily survival rates ranged from 0.6 to 0.87.
  - Archdeacon (2016; unpublished data) observed 290 pools. Ten (3%) pools lasted 20 days but shallow (0.1 to 0.25 m)then rewet. 4,729 RGSM were captured in the 290 pools, with 1.5% (70) RGSM in lasting pools.
- Bui (2011) deep, well-drained sands and gravels can infiltrate at 0.3 in/hour. (7.2 in/day; 3ft/5days).



Hatch et al. (2008) Pool s081.5 - July 2 & 6, 2007

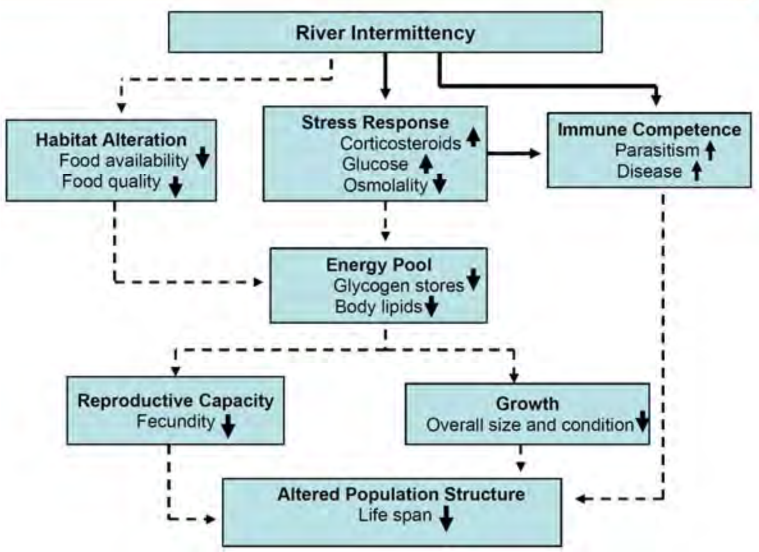
Picture J.18. First day of daily monitoring of in-stream refugia at Pool s081.5-a on July 2, 2007. This pool reconnected with the main channel on July 7, 2007. Photo taken from southern end of pool.

Picture J.21. July 6, 2007; last day on monitoring at Pool s081.5-a before it reconnected with main channel flows. Photo taken from center of pool, looking north. Pinflag depicts water's edge on July 2, 2007.

A million ways to die

- Numerous factors likely contribute to RGSM stress, harassment, injury, and death during intermittency
- Examples of physical and water quality factors
  - Most important is lack of flow – intermittency/isolation in pools - (Dudley et al. 2009; Caldwell et al. 2010; Archdeacon 2016)
  - Opportunistic disease, parasites, bacterial infections, cumulative stressors (Caldwell et al. 2010; Cho et al. 2011; Lusk et al. 2012)
  - Terrestrial predation, other interactions (Lake 2003; FWS 2010)
  - Low O_2 sat'n < NALC: larvae=24%(2mg/l); juv=23%(1.9mg/l); adult=15%(1.2mg/l) and less with surface access (Buhl 2011a)
  - Temp > NALL: larvae=33C; juv=33C; adult=30C; (Buhl 2011b)
  - Ammonia, pH, other water quality factors (Hatch et al. 2008)

Caldwell et al. (2010) described some of the effects of intermittency on RGSM



Conclusions

- RGSM mortality rates were density-dependent and were related to spring runoff conditions.
- RGSM mortality rates were higher in the Angostura Reach, perhaps associated with incision and higher velocities.
- RGSM occurrence and local probability of extinction at monitoring sites were significantly related to prolonged low flows in the San Acacia Reach during July thru October. Low flows ~ less occurrence/higher risk of site extirpation.
- Intermittency and repeated river drying kills many RGSM.
- River drying is not uncommon in lower river reaches, but there are consistently higher flows upstream in the Cochiti Reach and RGSM were historically captured there.
- Many factors are associated with RGSM mortality in pools.
- Isolated pools persistence was short in MRG/sand bed river.

Intermittency Effects on the Viability of *H. amarus* Populations

Michael D. Hatch[1], **Dr. Michael Porter**[2], **&**
Dr. David E. Cowley[1]

[1] **Department of Fish, Wildlife & Conservation Ecology,**
New Mexico State University, Las Cruces, NM, USA
[2] **U.S. Army Corps of Engineers, Albuquerque, NM, USA**

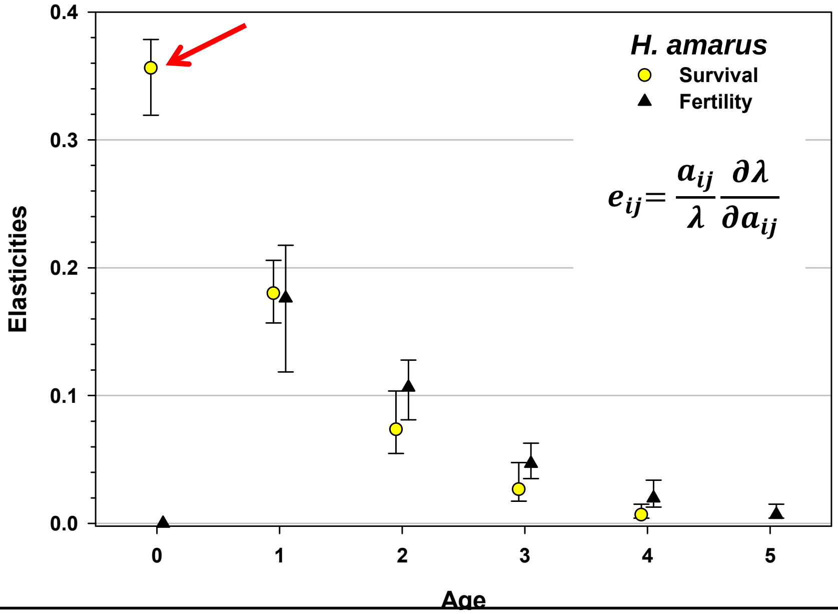
Acknowledgment and Disclaimer

- **This presentation is supported in large part by the Department of Defense, Cooperative Agreement Number W912HZ-15-2-0016.**
- **The content of this presentation does not necessarily reflect the position or the policy of the government, and no official endorsement should be inferred.**

Presentation Overview

- **Focus on a <u>process for assessing water management options</u> for achieving conservation purposes.**
  - **Emphasis on adult survivorship.**
- **Utilize a time-variant, age-based, density independent model to simulate demography. "PVA" type model.**

Proportional Time-variant Effects of Vital Rates on Population Growth



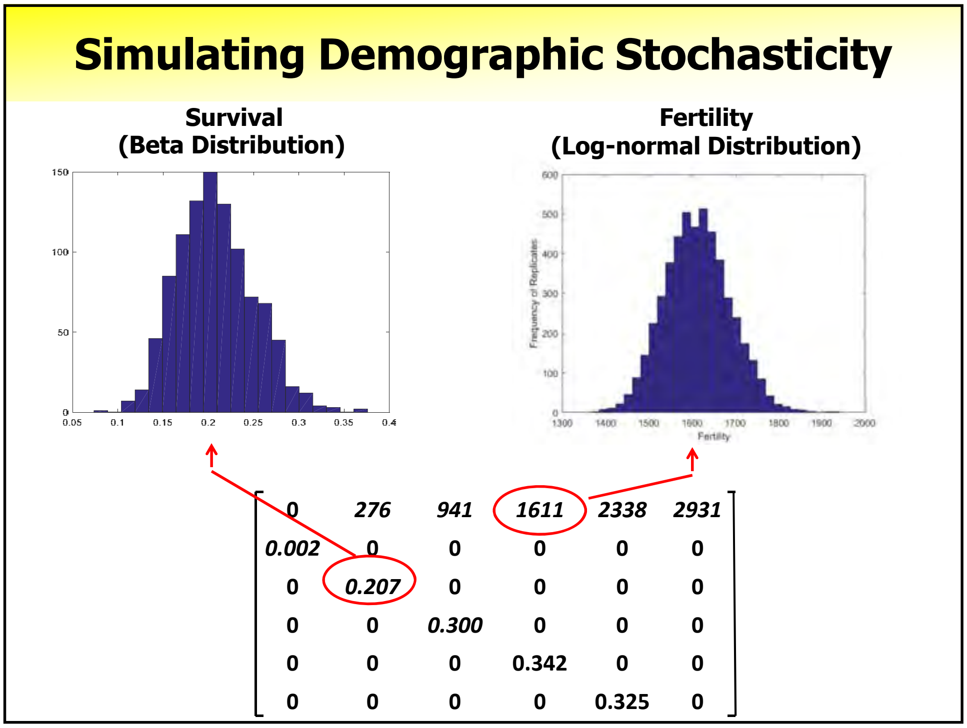
$$e_{ij} = \frac{a_{ij}}{\lambda} \frac{\partial \lambda}{\partial a_{ij}}$$

Simulation Assumptions and Caveats

- Simulations assume a simple linear decline in population size with habitat loss.
- A single set of transition parameter values may not provide an adequate basis for all simulation circumstances.
- Elasticities vary systematically with population growth rate.
  - Effective management strategies will need to be differentially tailored for declining vs. growing populations.

Input Parameters

- Years for simulation, number of replicate simulations.
- Transition matrix elements (longevity, age at maturity, mean age-specific vital rates).
- Egg fertilization / hatching rate.
- Demographic stochasticity.
- Reach-specific environmental stochasticity (annual periodicity, extent and variance of drying).

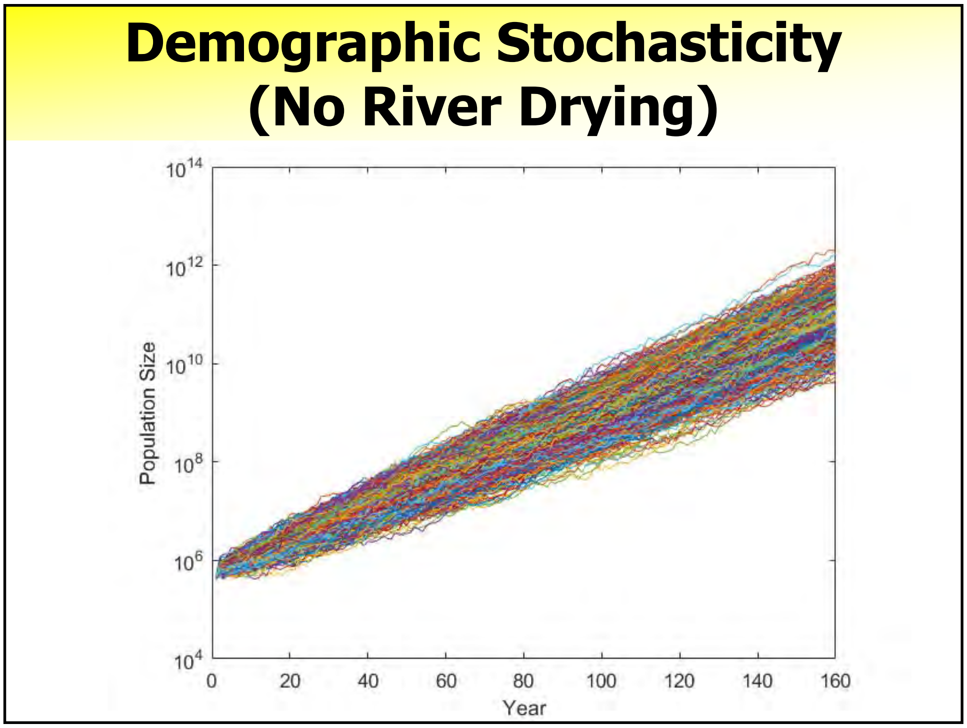


Simulating Demographic Stochasticity

Survival
(Beta Distribution)

Fertility
(Log-normal Distribution)

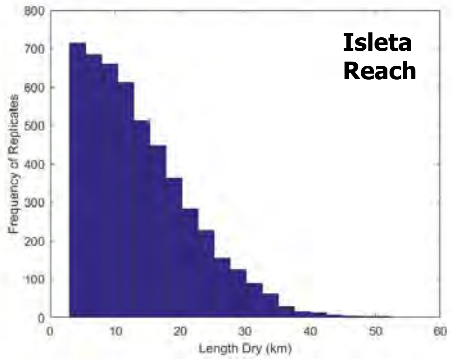
$$\begin{bmatrix} 0 & 276 & 941 & \boxed{1611} & 2338 & 2931 \\ 0.002 & 0 & 0 & 0 & 0 & 0 \\ 0 & \boxed{0.207} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.300 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.342 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.325 & 0 \end{bmatrix}$$



Demographic Stochasticity (No River Drying)

Simulating Mortality Linked to River Drying in the Isleta Reach

Reach (Total km)	**Periodicity of River Drying**	**Range** (km)	**Mean km Dry** (var.)
Isleta (85.46)	10 of 12 years (83.3 %)	44.4	**19.72** (186.5396)

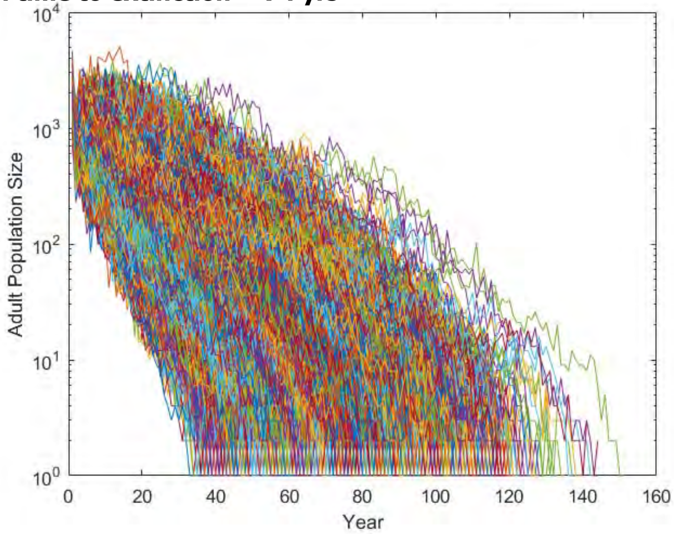


Two Long-term (180 year) Simulation Scenarios – Isleta Reach

- **Full Contemporary Effects Baseline**
  - Annual drying periodicity = 0.83
  - Annual river drying mean = 19.72 km; variance = 186.5396
- **Reduced River Drying**
  - Annual drying periodicity = 0.83
  - Annual river drying mean = 10.0 km; variance = 144.0

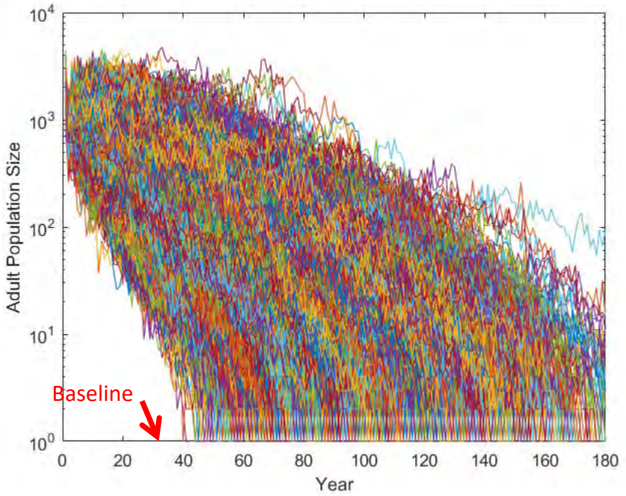
Long-term Full-effects Baseline Adult Projection

Annual drying periodicity = 0.83
Annual river drying mean = 19.72 km; variance = 186.5396
Median time to extinction = 74 yrs



Long-term Reduced Drying – Adult Projection

Annual drying periodicity = 0.83
Annual river drying mean = 10.0 km; variance = 144.0
Median time to extinction = 100.0 yrs
Probability of extinction reduced to 0.9968

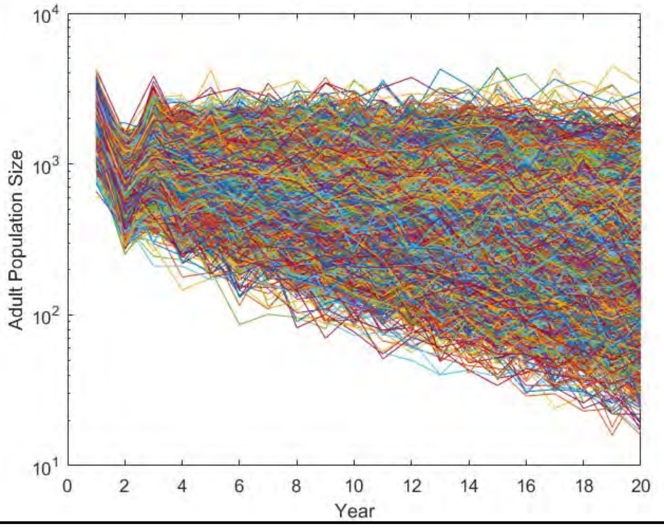


Three Short-term (20 year) Simulation Scenarios – Isleta Reach

- **Full Contemporary Effects Baseline**
  - Annual drying periodicity = 0.83
  - Annual river drying mean = 19.72 km;
    variance = 186.5396
- **Reduced River Drying**
  - Annual drying periodicity = 0.83
  - Annual river drying mean = 10.0 km;
    variance = 144.0
- **Reduced Periodicity of River Drying with Full Contemporary Effects**
  - Annual Drying Periodicity = 0.415;
  - Annual river drying mean = 19.72 km;
    variance = 186.5396

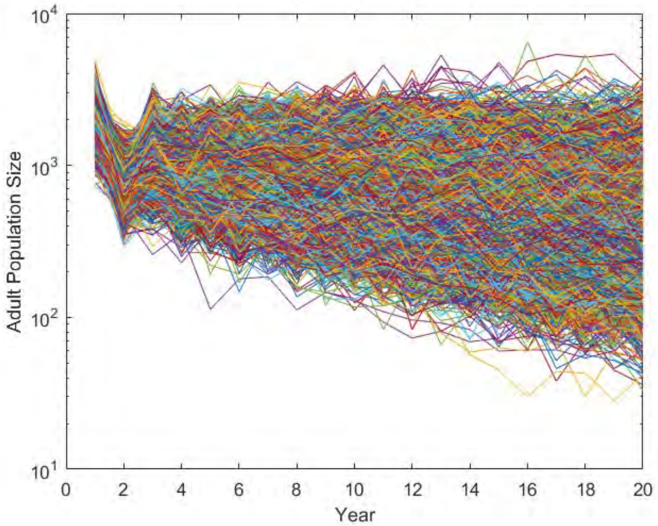
Short-term Full-effects Baseline Adult Projection

Annual drying periodicity = 0.83
Annual river drying mean = 19.72 km; variance = 186.5396
Extinction avoided – preponderance of declining trajectories



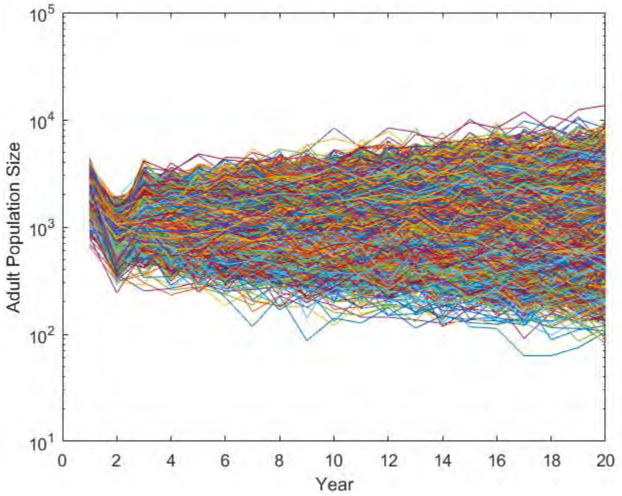
Short-term Reduced Drying Adult Projection

Annual drying periodicity = 0.83
Annual river drying mean = 10.0 km; variance = 144.0
Extinction avoided – mix of trajectories

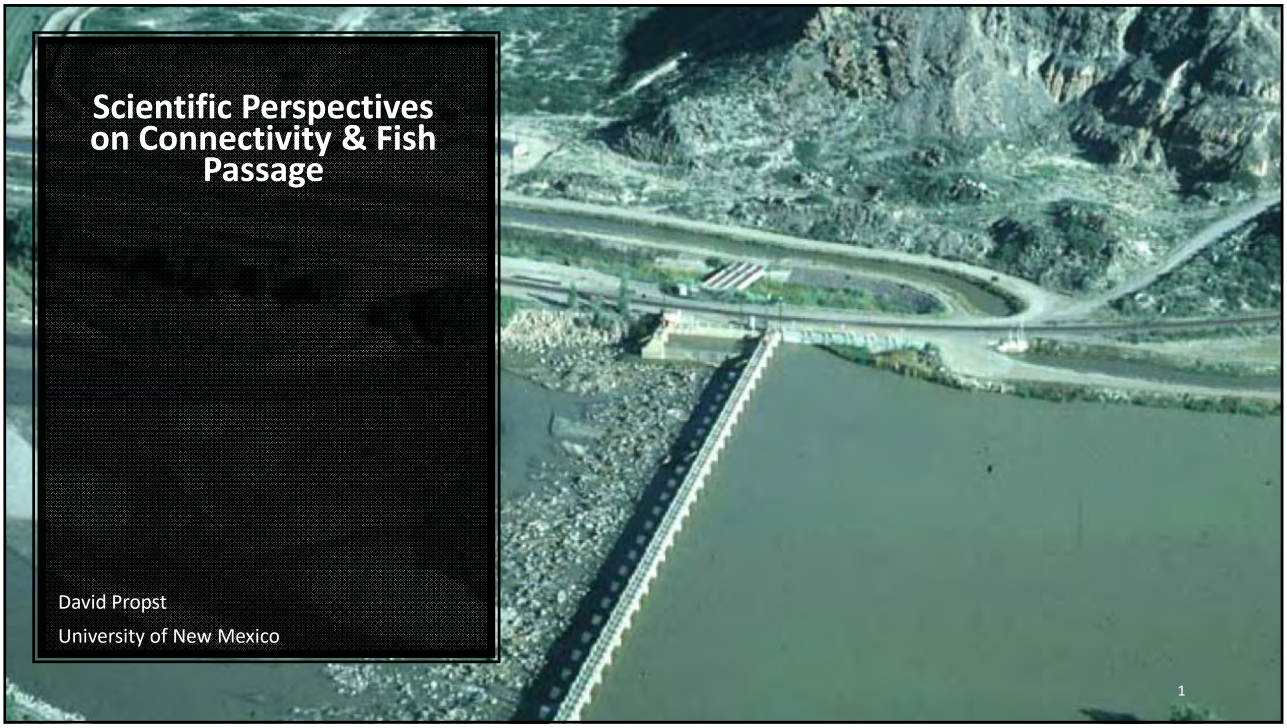


Short-term Full-effects Baseline Reduced Periodicity of Drying – Adult Projection

Annual drying periodicity = 0.415
Annual river drying mean= 19.72 km; variance = 186.5396;
Extinction avoided – preponderance of horizontal or increasing trajectories



SESSION VI SCIENTIFIC PERSPECTIVES ON CONNECTIVITY AND FISH PASSAGE



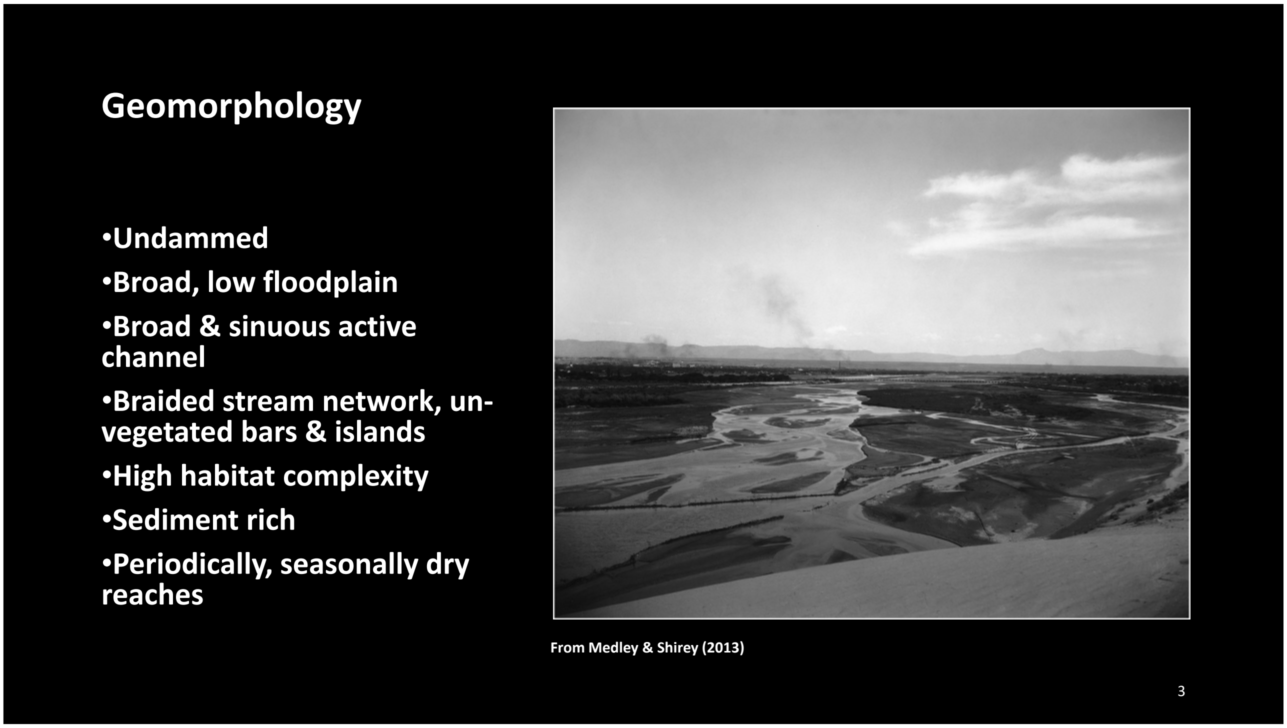
Scientific Perspectives on Connectivity & Fish Passage

David Propst

University of New Mexico

Connectivity & Fish Passage

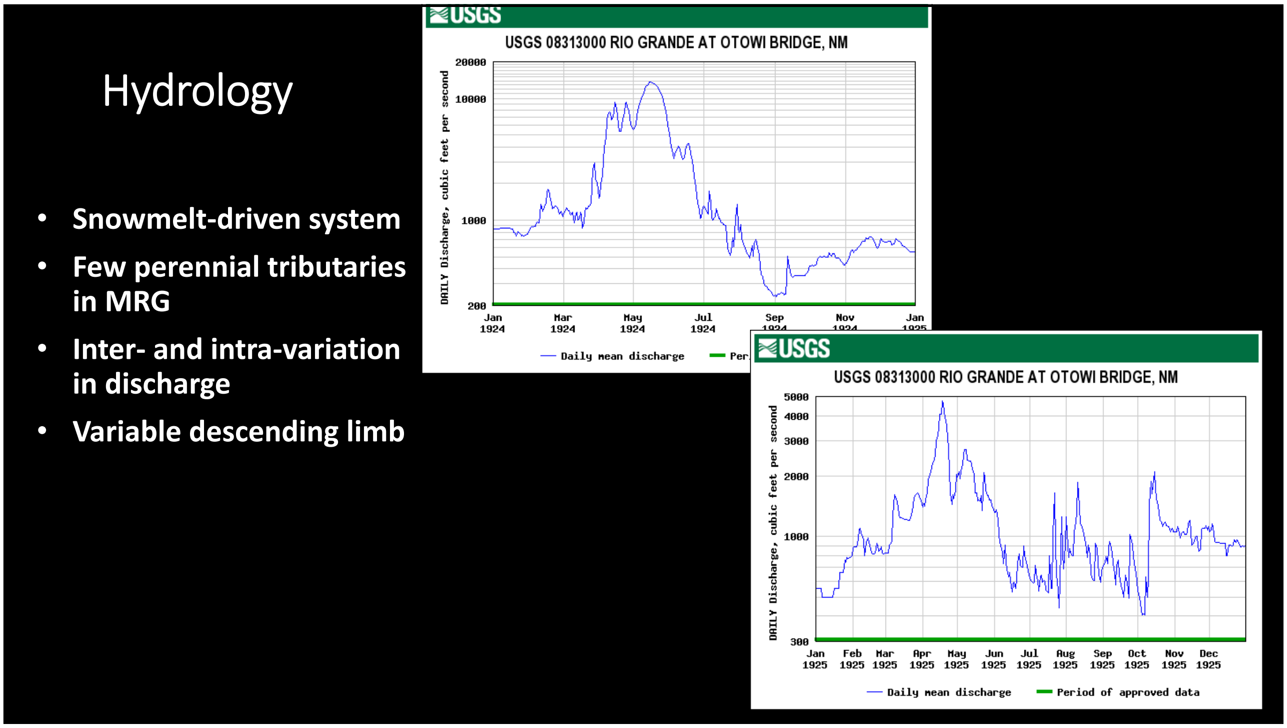
- **Background**
  - **Historical Middle Rio Grande, New Mexico**
    - **Geomorphology**
    - **Hydrology**
    - **Aquatic Fauna**
  - **Current Middle Rio Grande, New Mexico**
    - **Geomorphology**
    - **Hydrology**
    - **Aquatic Fauna**



Geomorphology

- •Undammed
- •Broad, low floodplain
- •Broad & sinuous active channel
- •Braided stream network, un-vegetated bars & islands
- •High habitat complexity
- •Sediment rich
- •Periodically, seasonally dry reaches

From Medley & Shirey (2013)

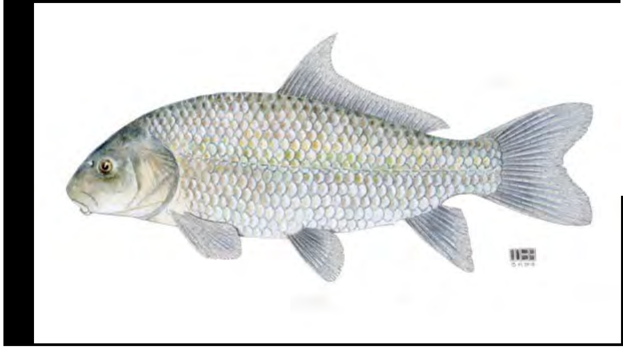


Hydrology

- Snowmelt-driven system
- Few perennial tributaries in MRG
- Inter- and intra-variation in discharge
- Variable descending limb

Native Fishes

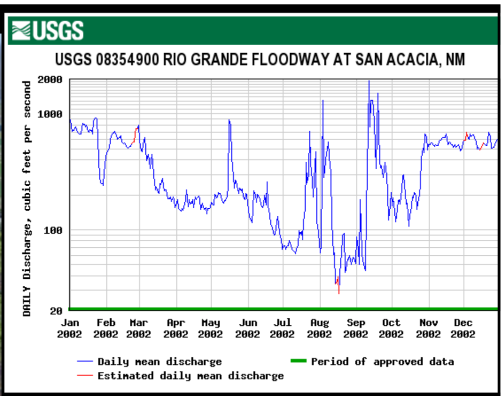
- 24+ native fishes
  - 10 families
- 4 migratory
- 5 pelagic spawners

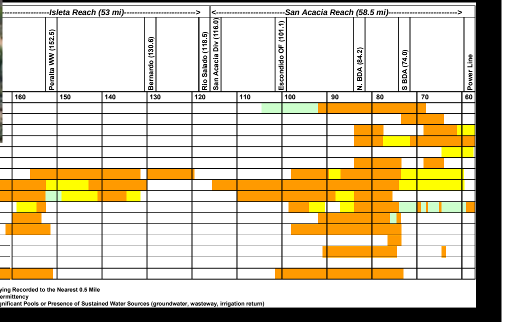


Current Middle Rio Grande

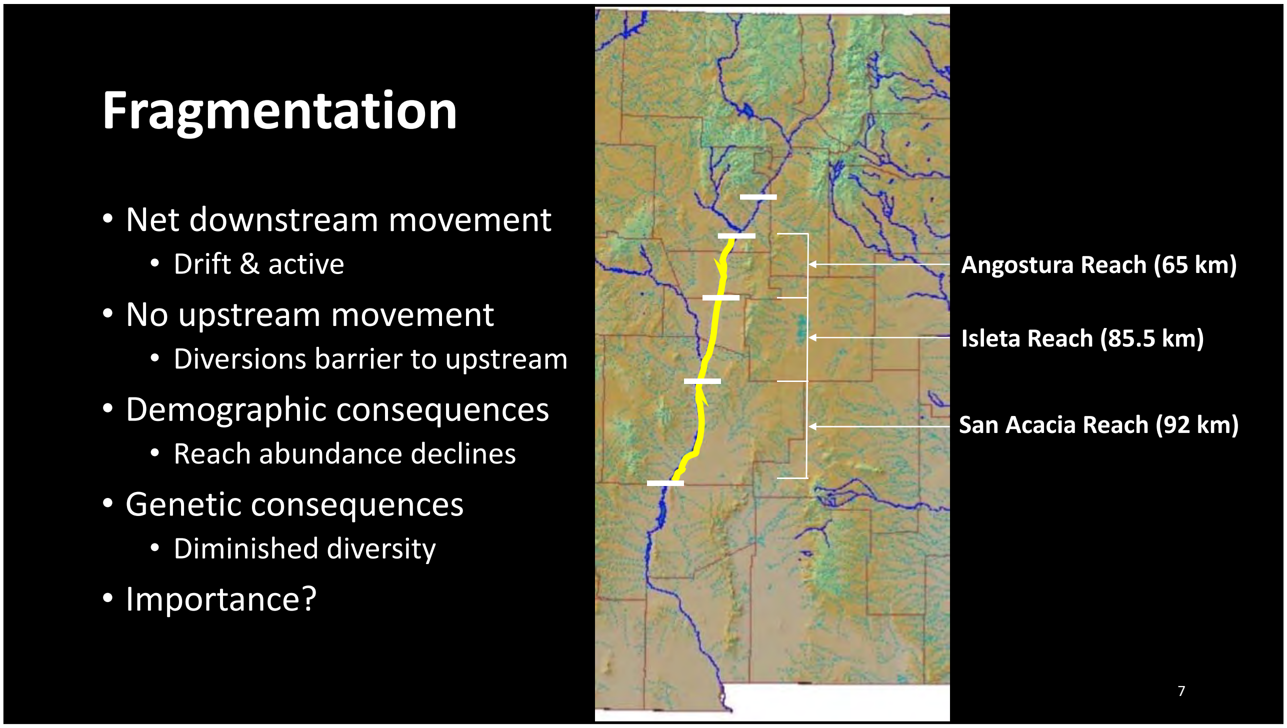
- Geomorphology
  - Narrow floodplain
  - Straight, confined channel
  - Diminished habitat complexity
  - Sediment starved in some reaches
  - Vegetated islands
- Hydrology
  - Regulated, diminished discharge
  - Loss of spring peaking flows
  - Seasonal drying extensive in many years
- Native fishes
  - 4 migratory extirpated
  - 4 of 5 pelagic spawners extirpated/extinct
  - 5 others extirpated
  - Reduced MRG range of remaining species

USBR



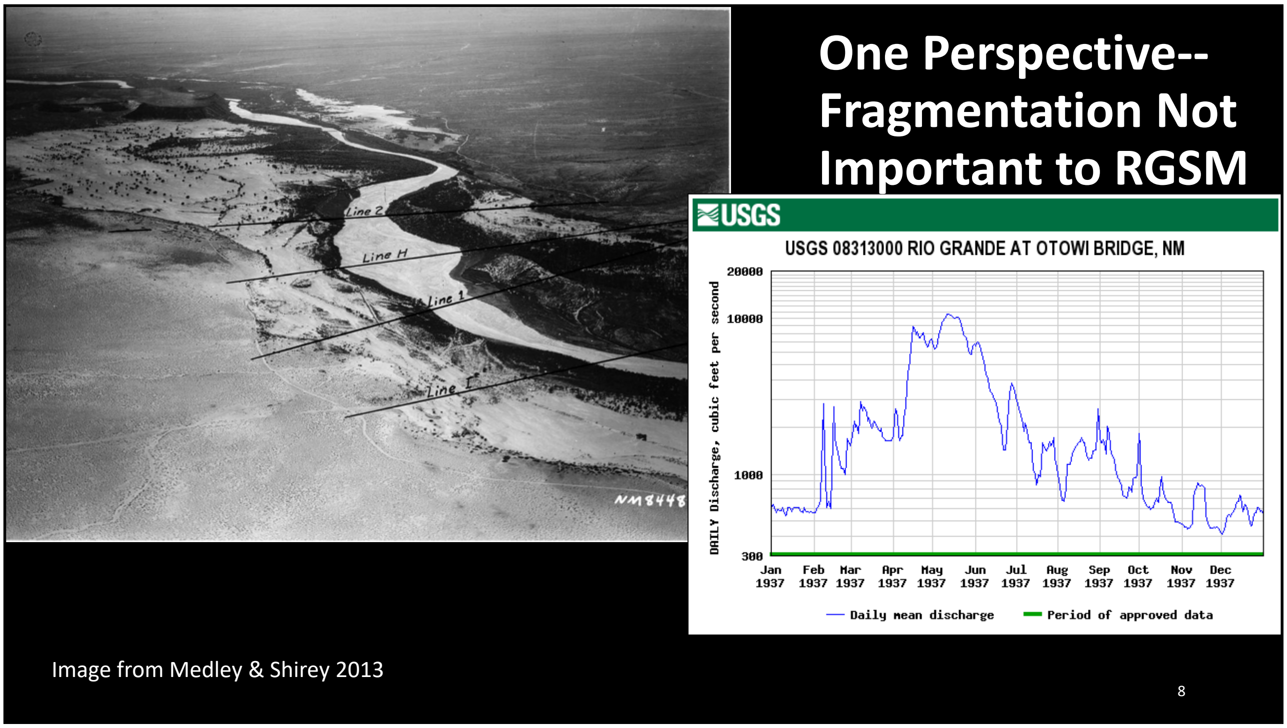


Valdez (2011) PP



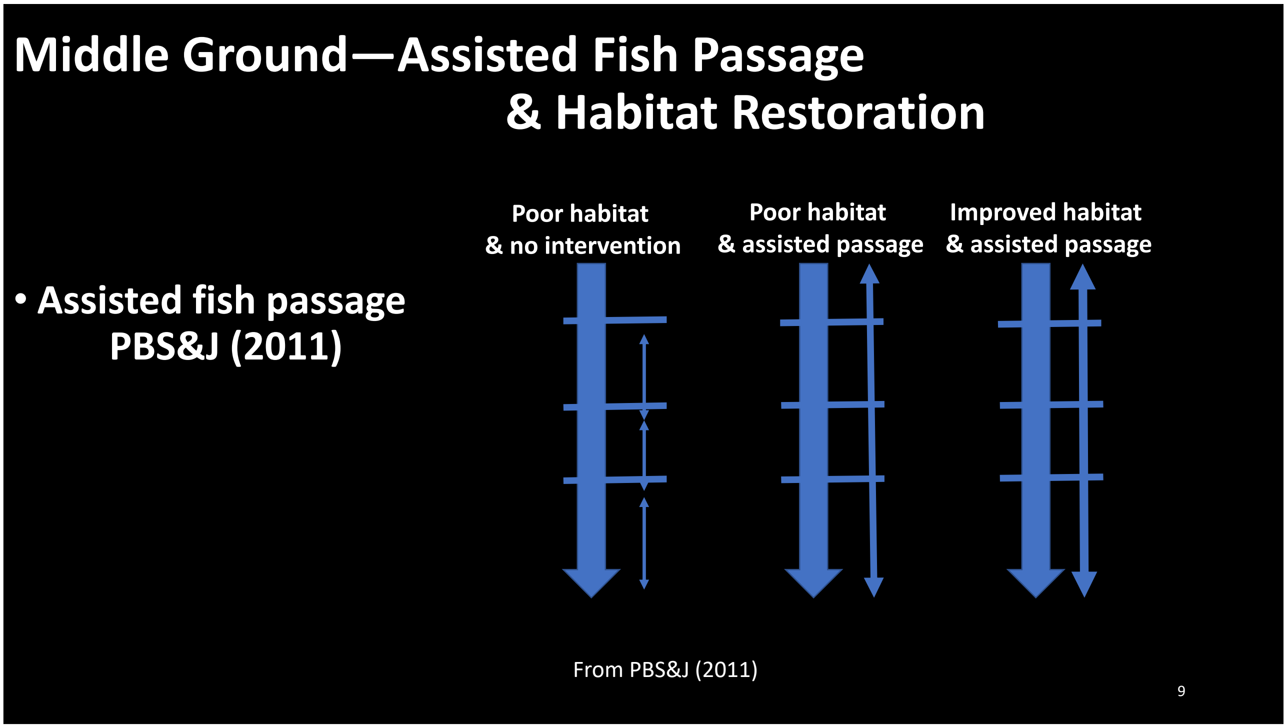
Fragmentation

- Net downstream movement
  - Drift & active
- No upstream movement
  - Diversions barrier to upstream
- Demographic consequences
  - Reach abundance declines
- Genetic consequences
  - Diminished diversity
- Importance?



One Perspective--Fragmentation Not Important to RGSM

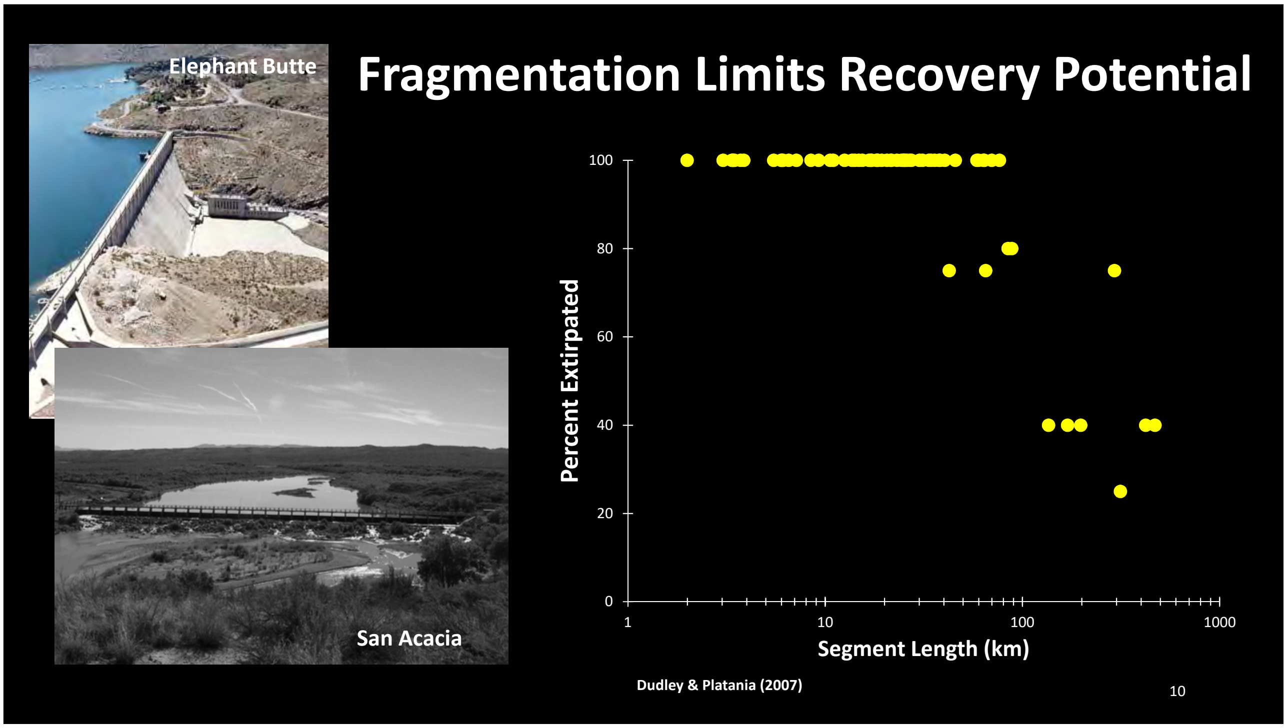
Image from Medley & Shirey 2013



Middle Ground—Assisted Fish Passage & Habitat Restoration

- Assisted fish passage PBS&J (2011)

From PBS&J (2011)



Fragmentation Limits Recovery Potential

Dudley & Platania (2007)

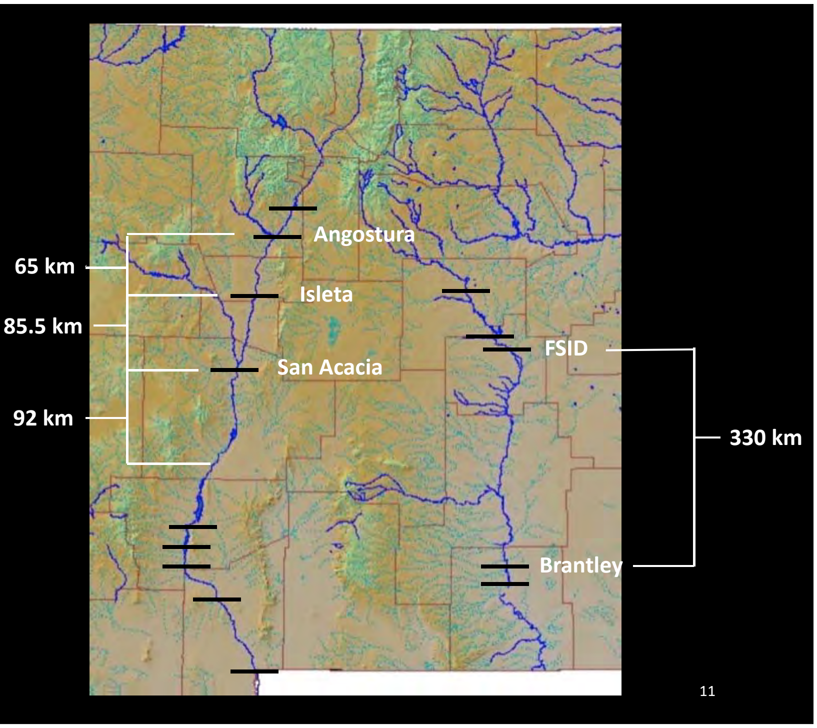
Two Rivers

Rio Grande

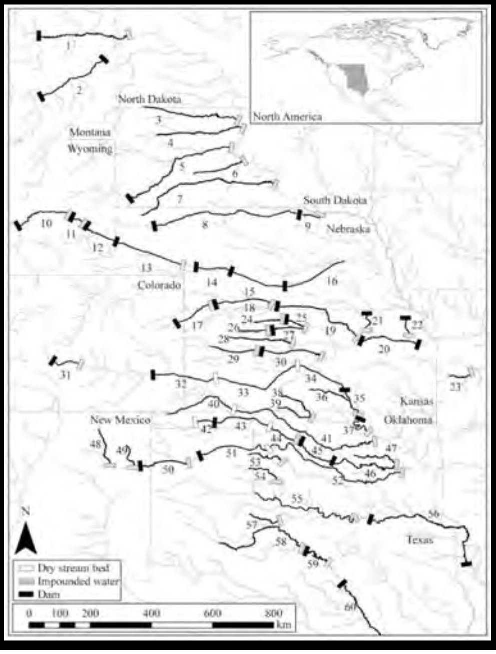
- ~~Speckled chub~~
- ~~RG bluntnose shiner~~
- ~~RG shiner~~
- ~~Phantom shiner~~
- RG silvery minnow

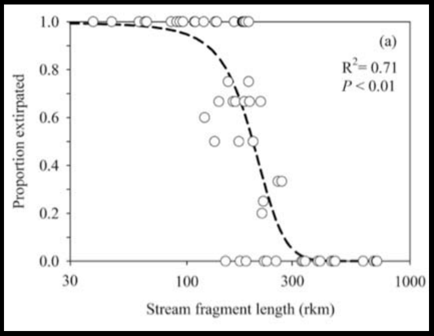
Pecos

- Speckled chub
- Pecos bluntnose shiner
- RG shiner
- ~~RG silvery minnow~~



Other Pelagic Spawner Populations





Perkin & Gido 2011

GENETIC CONSIDERATIONS

- Fragmentation, isolation, genetic drift,
- No genetic analysis of Angostura & Isleta reaches prior to augmentation
- Alo & Turner (2005)

Options

Within Segment

- **Medley & Shirey (2013)**
  - **Restoration habitat available?**
  - **Area of restored habitat?**
  - **Adequate flow to inundate?**
    - **Frequency?**
  - **Restoration costs?**
    - **Water?**
    - **Monetary?**
  - **Habitat persistence & maintenance?**
  - **Measure success?**
  - **Importance of perennial habitat?**

Mixed

- **PBS&J (2011)**
  - **Translocation mortality**
  - **Restoration costs?**
  - **Maintenance?**
  - **Measure success?**
  - **Importance of perennial habitat?**

Passage & Perennial Flow

- **Investigate**
  - **Use**
  - **Cost**
- **Fragment Length**
  - **Current max = 92 km**
  - **Connected = 242 km**
- **Optimum**
  - **300-400 km**
- **Genetic issues**
- **Perennial flows**

Archdeacon & Remshardt (2012)

Final Points

- Regardless of approach, investigation needed
  - Monetary costs
  - Contribution to recovery
  - Movement
- Perennial flow vs constructed solution

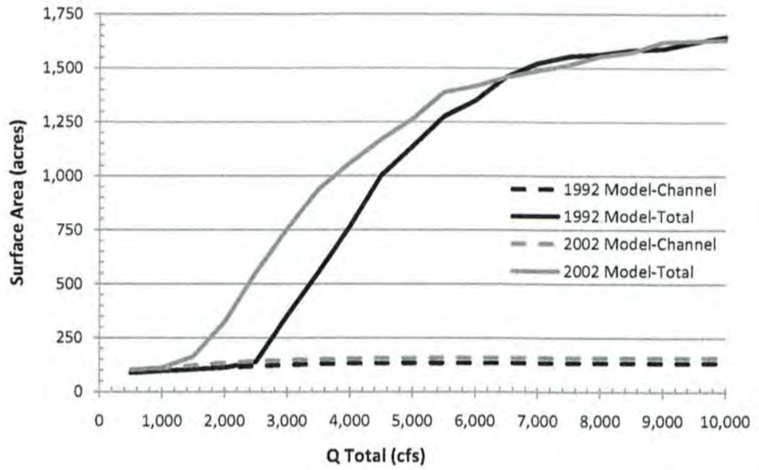
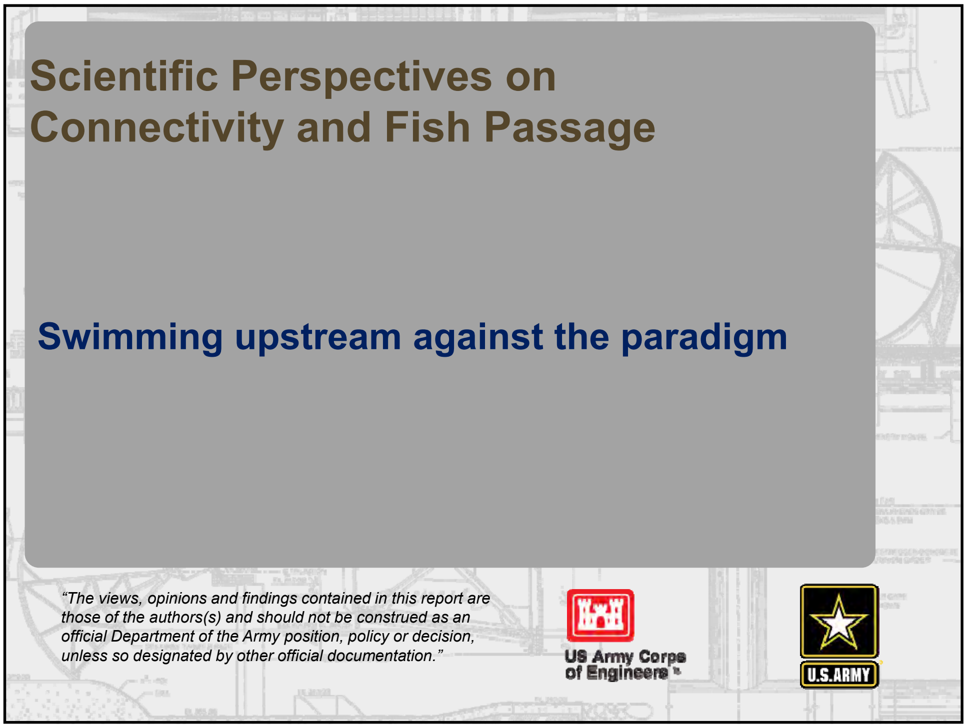


Figure 16 – Surface Area Comparisons for Reach 11

USACE (2010)



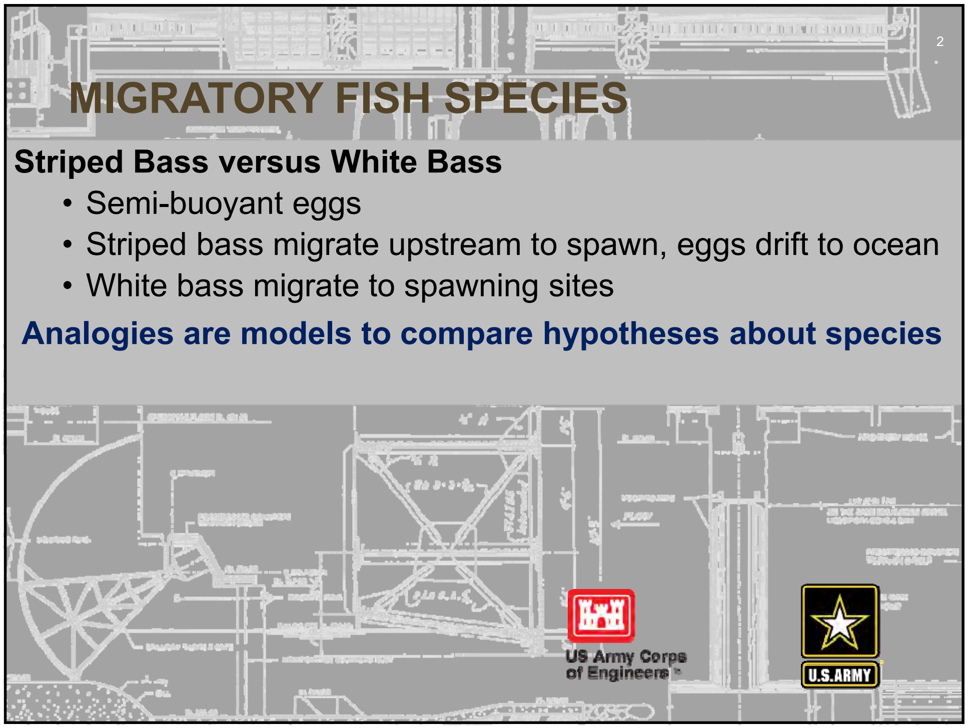
Scientific Perspectives on Connectivity and Fish Passage

Swimming upstream against the paradigm

"The views, opinions and findings contained in this report are those of the authors(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation."

US Army Corps of Engineers

U.S.ARMY



MIGRATORY FISH SPECIES

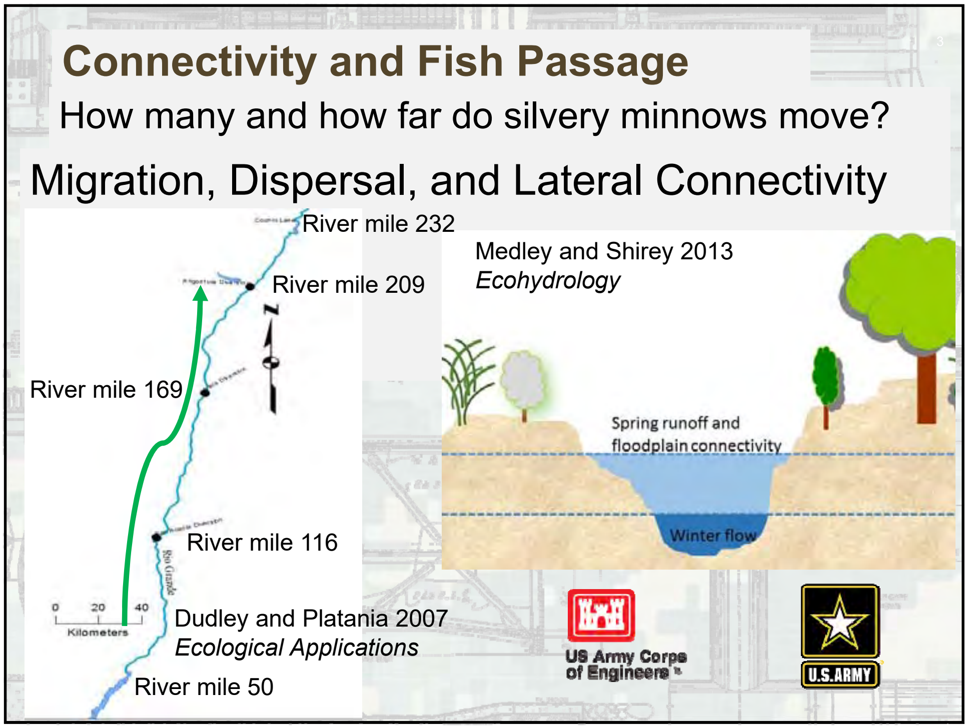
Striped Bass versus White Bass

- Semi-buoyant eggs
- Striped bass migrate upstream to spawn, eggs drift to ocean
- White bass migrate to spawning sites

Analogies are models to compare hypotheses about species

US Army Corps of Engineers

U.S.ARMY



Connectivity and Fish Passage

How many and how far do silvery minnows move?

Migration, Dispersal, and Lateral Connectivity

River mile 232

River mile 209

River mile 169

River mile 116

River mile 50

Dudley and Platania 2007
Ecological Applications

Medley and Shirey 2013
Ecohydrology

Spring runoff and floodplain connectivity

Winter flow

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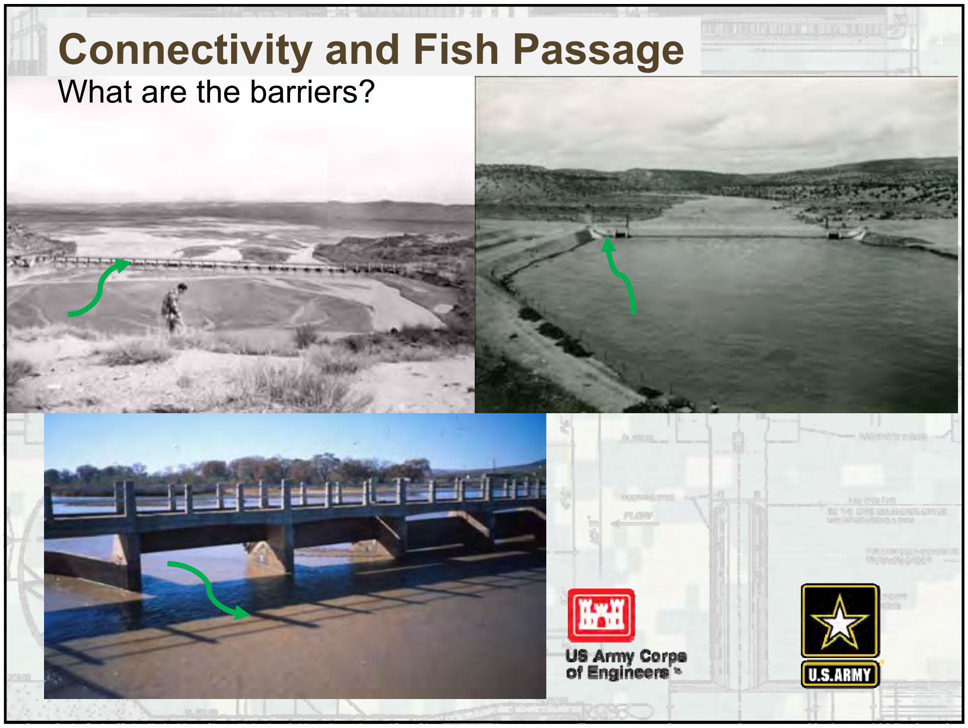

Connectivity and Fish Passage

What are the barriers?

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Fish Passage versus Lateral Connectivity

Fish passage usage						Floodplain spawning					
								Percent			
Release site	Distance (km)	Released	Count	Percent		Year	Number	Gravid	Spent	Male	Unknown
Upstream	11.87	2875	180	6%		2008	9473	29.0%	15.8%	24.3%	31.0%
Fishway	0.01	891	17	2%							
Downstream	9.07	2791	46	2%		2009	2057	50.3%	7.3%	30.3%	12.5%
		6557	243								

Archdeacon and Remshardt. 2012. *North American Journal of Fisheries Management*

Gonzales, Tave and Haggerty 2014. *Ecohydrology*

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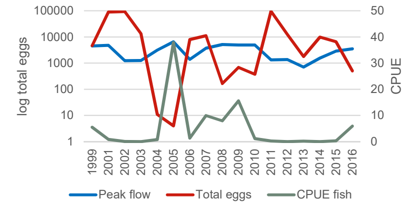
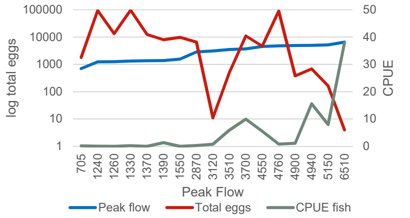
FLOW, EGGS, AND FISH

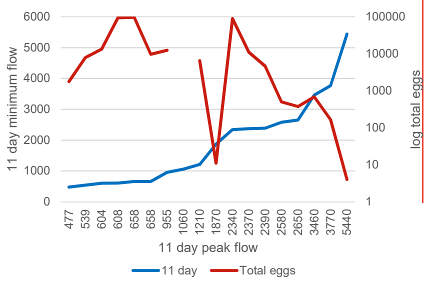
Relationship of Eggs to October Index



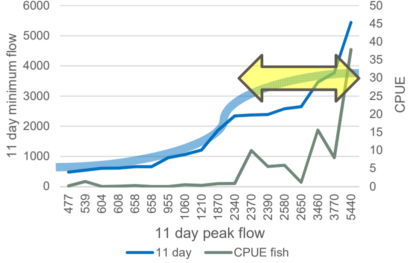
Relationship of Eggs to October Index

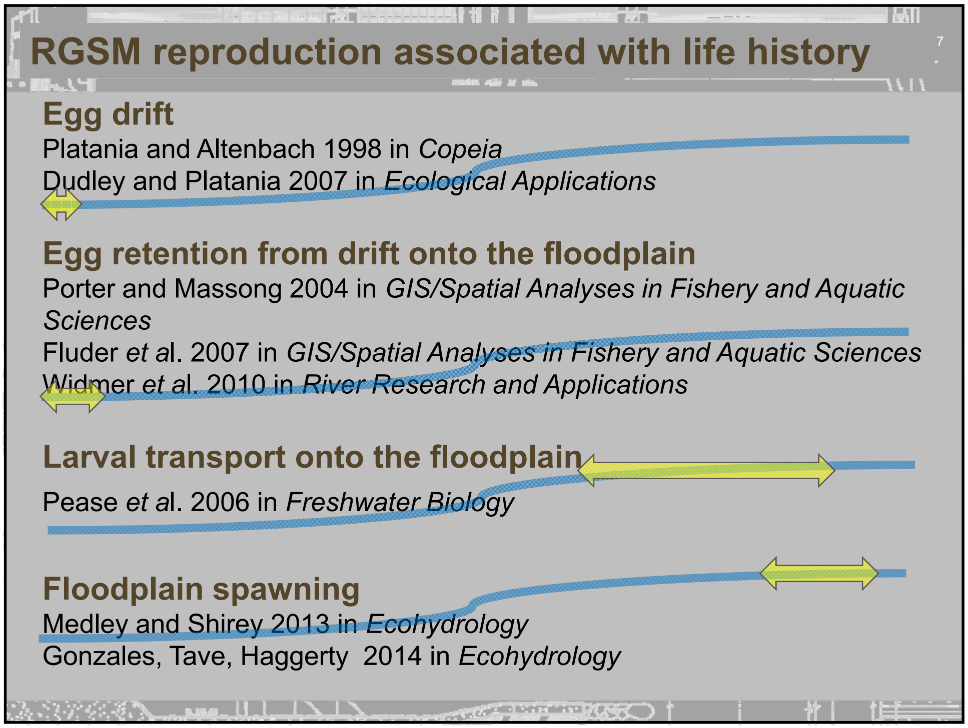


Relationship of Eggs to Flow



Relationship of Flow to October Index





RGSM reproduction associated with life history

Egg drift

Platania and Altenbach 1998 in *Copeia*
Dudley and Platania 2007 in *Ecological Applications*

Egg retention from drift onto the floodplain

Porter and Massong 2004 in *GIS/Spatial Analyses in Fishery and Aquatic Sciences*
Fluder *et al*. 2007 in *GIS/Spatial Analyses in Fishery and Aquatic Sciences*
Widmer *et al*. 2010 in *River Research and Applications*

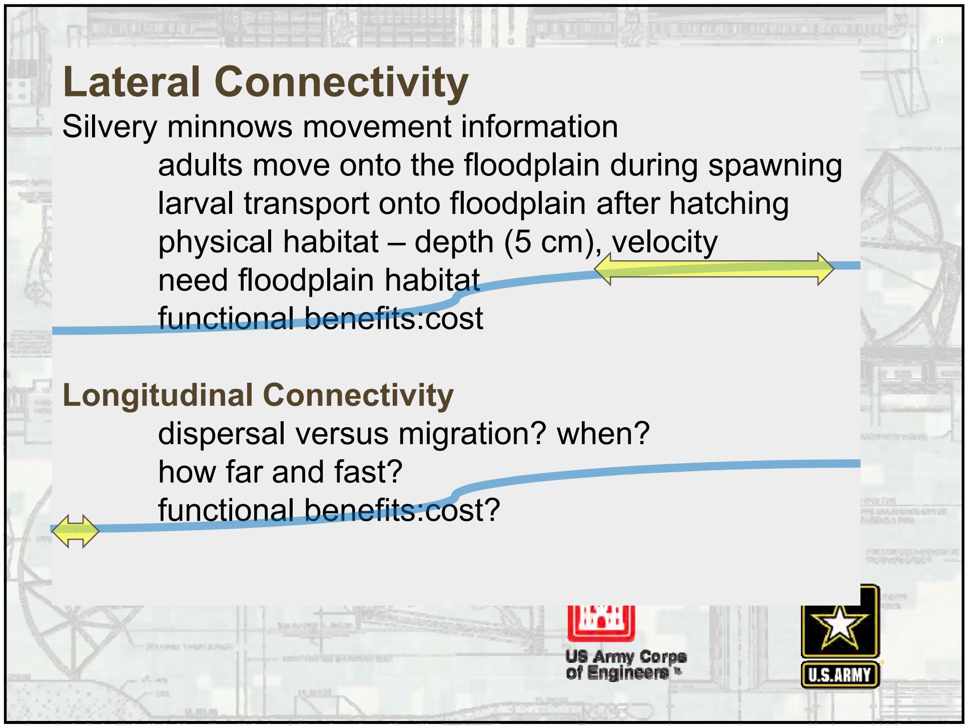
Larval transport onto the floodplain

Pease *et al*. 2006 in *Freshwater Biology*

Floodplain spawning

Medley and Shirey 2013 in *Ecohydrology*
Gonzales, Tave, Haggerty 2014 in *Ecohydrology*

SILVERY MINNOW BEHAVIOR



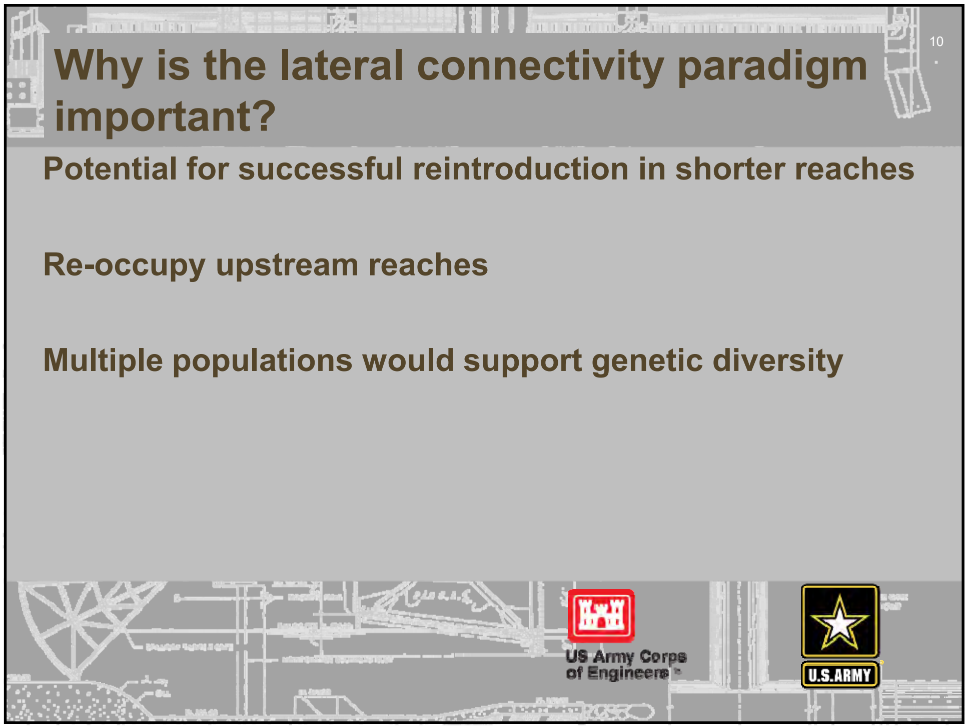
Lateral Connectivity

Silvery minnows movement information

- adults move onto the floodplain during spawning
- larval transport onto floodplain after hatching
- physical habitat – depth (5 cm), velocity
- need floodplain habitat
- functional benefits:cost

Longitudinal Connectivity

- dispersal versus migration? when?
- how far and fast?
- functional benefits:cost?



Why is the lateral connectivity paradigm important?

Potential for successful reintroduction in shorter reaches

Re-occupy upstream reaches

Multiple populations would support genetic diversity

QUESTIONS?

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255
255
255

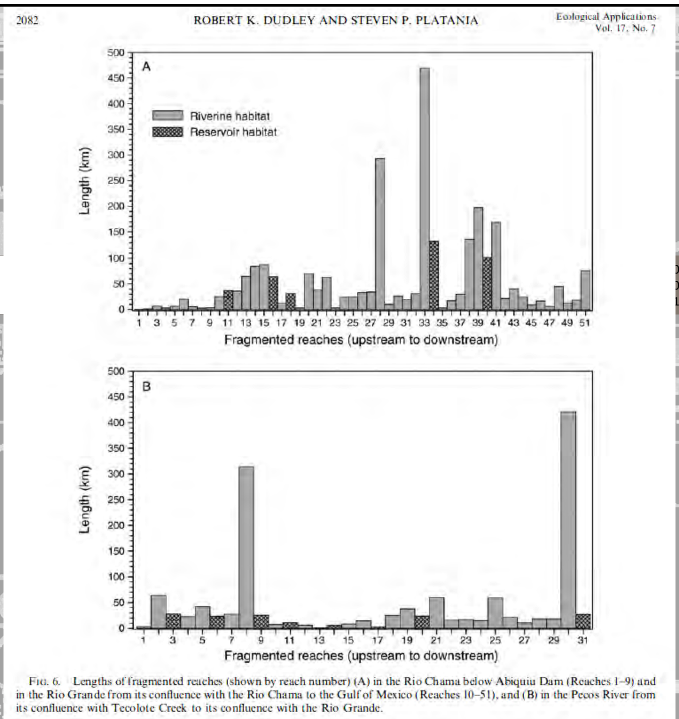

FIG. 6. Lengths of fragmented reaches (shown by reach number) (A) in the Rio Chama below Abiquiu Dam (Reaches 1–9) and in the Rio Grande from its confluence with the Rio Chama to the Gulf of Mexico (Reaches 10–51), and (B) in the Pecos River from its confluence with Tecolote Creek to its confluence with the Rio Grande.

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Appendix B. Bibliography of Scientific Articles and Reports Provided for Panel Review

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