Final Report

Ecohydrological Relationships along the Middle Rio Grande of New Mexico for the Endangered Rio Grande Silvery Minnow

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Draft Report to the US Army Corps of Engineers under WP912PP-08-D-0009-0-20, Task Order 20, Task 5

1. Introduction

Reducing ongoing risks to survival and reproduction and enhancing the recovery of endangered or threatened species requires an understanding of basic chemical and physical habitat attributes. Previous studies have concluded that water quality has not been the primary habitat attribute linked to the endangerment of Rio Grande silvery minnow (*Hybognathus amarus*; silvery minnow) in the Middle Rio Grande (MRG) of New Mexico (Marcus et al. 2005, 2010; New Mexico Environment Department 2009). As such, this assessment provides additional focus on physical habitat features (specifically, key ecohydrological constraints) that appear to place silvery minnows at continued risk for population decline in the MRG.

1.1. Study Goals and Objectives

The US Army Corps of Engineers (USACE) contracted Tetra Tech to develop a reach-wide baseline evaluation of endangered species habitat availability and quality to determine the state of the system along the San Acacia Reach of the MRG. Subsequently, in consultation with the USACE project manager for this task, this assessment was expanded to produce a system-wide analysis for additional reaches of the MRG, including the Albuquerque (Angostura) and Isleta reaches, as well as the San Acacia Reach. The resulting assessment provides information to help in the identification of future restoration and management opportunities and priorities for the MRG Endangered Species Act Collaborative Program (Collaborative Program).

Two subtasks are included under this contract task, one addressing silvery minnow habitat and one addressing the endangered Southwestern willow flycatcher (*Empidonax traillii extimus*, flycatcher) habitat. This report addresses the first of the two subtasks and focuses on silvery minnow. As specified by the USACE contract, this habitat quality assessment is to include an analysis of silvery minnow habitat (where possible) in the form of seasonal wetted surface area (based on River Eyes observations), geomorphology (channel form and gradients, embayments/outfalls); overbank flows/bank elevations, seasonal flow velocities, deep pool formation and longevity, the supplemental water program including the location of refugial pumps, salvage locations, and sediment descriptors. The following sections present background information, methods, results, and recommendations from this work.

1.2. Assessment Approach

Tockner and Stanford (2002) emphasize the importance of floodplains in the structure and function of riverine ecosystems. In North America and Europe, up to 90% of large river floodplain habitats have been impacted in a significant way (Tockner and Stanford 2002) and alteration of the natural flow regime (or hydrology) is a key determinant in the character and magnitude of such impacts (Bunn and Arthington 2002, Poff et al. 2007). In this assessment, we build upon the work of Medley and Shirey (2013) in evaluating hydraulic characteristics of the MRG using two discrete hydraulic models of the MRG: one for in-channel habitat and one for floodplain habitat. The functional separation of in-channel and floodplain habitats, allows us to quantify the relative contribution each provides in terms of a spatial and temporal perspective and can help guide future modeling and restoration efforts.

In the following sections, we present a series of maps and tables that characterize the modeled extent and location of silvery minnow habitat for both in-channel study sites and the floodplain of the MRG. In addition, our approach considers key life stages separately in order to gain a better understanding of the silvery minnow's flow-ecology relationships (or ecohydrology).

2. Background

2.1. Rio Grande Silvery Minnow Status and Distribution

In 1994, the silvery minnow was listed as endangered under the Endangered Species Act (ESA; 58 FR 36988; U.S. Fish and Wildlife Service [USFWS] 1994). It also has been listed as endangered by the State of New Mexico (19 NMAC 33.1; New Mexico Department of Game and Fish 1988), the State of Texas (Sections 65.171 - 65.184, Title 31 T.A.C; Texas Parks and Wildlife Department 2003), and the Republic of Mexico in 1994.

Historically, this fish species reportedly occupied the Rio Grande from near the Gulf of Mexico upstream into the upper reaches of the Pecos River and the Rio Grande to the Rio Grande Gorge and into the Rio Chama. Listing documents indicate that the silvery minnow currently occupies only a 280 km (174 mi) reach of the Middle Rio Grande (MRG) in New Mexico, from Cochiti Dam the headwaters of Elephant Butte Reservoir, including a short reach of the lower Jemez River a Rio Grande tributary north of Albuquerque (USFWS 1994). Limited fishery surveys since 1994, however, have not collected silvery minnow upstream of Cochiti Dam or in the Rio Chama downstream of Abiquiu Dam, suggesting that the species is no longer present in these reaches or occurs in very low densities (USFWS 2010, Torres et al. 2008). As such, this species is also presumed to be extirpated from the Rio Grande drainage upstream of Cochiti Dam (Platania and Dudley 2003, Buntjer and Remshardt 2005). In an ongoing effort since late 2008, the silvery minnow has been reintroduced into a reach of the Rio Grande near Big Bend, Texas as an experimental, non-essential population under Section 10(j) of the ESA.

2.2. Key Life-cycle and Habitat Relationships

Silvery minnow have been characterized as a *pelagic spawning fish species* since at least the mid-1990s (e.g., Platania 1995, USFWS 2010). A more recent assessment, however, states "that the [silvery minnow] is primarily a *demersal, floodplain spawning species* [italics added] that evolved eggs that are secondarily buoyant in high-sediment environments rather than a main channel, pelagic broadcast-spawning species with an evolved long-distance, downstream drift phase" (Medley and Shirey 2013). The eggs become increasingly buoyant as they harden post-spawn (>1 hr) and more buoyant with increasing suspended sediment concentrations (Cowley et al. 2009, Medley and Shirey 2013). Most spawning occurs during May to June, accompanying spring runoff; in some years spawning may occur earlier and may also occur during heavy monsoonal runoff pulses during the summer. It appears that flow spikes produced by runoff or elevated reservoir discharges are the most direct stimulus to produce a spawn by silvery minnow, but the minimal magnitude of the flow spike required to stimulate a spawn remains undefined. An artificial flow spike of 1,800 cubic feet per second (cfs; 51 m^3/second) for 24 hours released from Cochiti Dam on May 19, 1996 apparently stimulated a spawning event; flow spikes accompanying summer storms also have been documented as producing spawns (USFWS 2003a, page 24). As such, it would appear that spring flows somewhere in the range to 1,500 to greater than 2,000 cfs are likely to stimulate silvery minnow spawning.

A single 1- to 2-year old female silvery minnow can produce 3,000 to 6,000 semi-buoyant, non-adhesive eggs during a spawning event, with these eggs could passively drift with the current while developing (Platania 1995, Platania and Altenbach 1998). Such a high fecundity in young fish, from the view of basic ecological theory (e.g., Andrewartha and Birch 1982, Ricklefs 1973, Reznick et al. 2002), is indicative of a species characterized as having high fluctuations in population numbers, able to take advantage of intermittently favorable environmental conditions to produce greatly expanded populations. This is in contrast to species that produce relatively few gametes and offspring to maintain relatively consistent population sizes allowed by the average carrying capacity of their environments.

The reproductive strategy of spawning eggs that are or rapidly become buoyant to semi-buoyant in a river during spring and storm flows unfortunately exposes those eggs to hazards of downstream drift and displacement from their natal reach. As initially suggested by Platania (1995) and frequently reiterated by others since, eggs and new hatched larva suspended in the flow could drift for a hundred miles or more downstream following a flood stimulated spawning, until the larva become sufficiently mobile to escape the flow. This is particularly true for regulated rivers having modified channels that are disconnected from their floodplains, as occurs with the MRG. To return to their natal areas, such a downstream drift of eggs and larval fish would require the displaced fish to migrate equally long-distances upstream during their lifetimes. Such upstream migrations by silvery minnow have not been documented (Medley and Shirey 2003). In addition, where the river channel has become entrenched due to river maintenance and/or drought conditions, and when and where spawn-inducing flows are insufficient to produce overbanking of the river into the floodplain, minimal quiet water refugial habitat results. Such conditions exacerbate the likelihood that newly spawned eggs and hatching larvae will remain continuously exposed to strong river currents, minimizing their potential survivorship.

In acknowledging the population recruitment limitations that accompany the spawning strategy by silvery minnow in the confined channel of the MRG, the Collaborative Program members have given focus to developing habitat restoration projects that enhance the floodplain connectivity to the MRG river channel as a fundamental habitat restoration action needed to benefit silvery minnow. Many of these projects include relatively limited restoration areas and produce disconnected features.

As a preview to the assessment results presented below, the best in- and off-channel habitat for silvery minnow include larger areas with a diversity of connected, relatively low-velocity features that enhance upstream retention of eggs and larva, enhanced food supplies for both young and post-spawn adult fish, warmer water, and improved growth and survival for individual fish, with likely increases in population viability and opportunities for recovery. In particular, Section 6.1.1, below, presents results from studies that offer support to the hypothesis that the most logical basis for the development of spawning semi-buoyant eggs during early stages of flood flows was to enhance the abilities of the adapted fish species to exploit the considerable advantages that newly inundated floodplain habitats provide, especially during springtime snowmelt flood flows. That is, the historical Rio Grande was famous for its spring floods that often extended in places a mile or more over the river's historic floodplain (Scurlock 1998). Such flood events led to the development of extensive and costly jetty-jack and levee systems along its banks and upstream flood-control reservoirs, both intended to constrain the extent of the river's lateral flows (e.g., Berry and Lewis 1997). While floods in the MRG often did negatively affect human communities occupying floodplains, they concurrently produced ecosystem conditions that provided highly favorable spawning and rearing habitats to fish producing buoyant or semi- buoyant eggs during high volume spring and storm flows.

2.3. Historic Provisions of the 2003 Biological Opinion

On March 17, 2003, the USFWS issued a Biological Opinion (BO) on the effects of actions associated with the "Programmatic Biological Assessment of Bureau of Reclamation's Water and River Maintenance Operations, U.S. Army Corps of Engineers' Flood Control Operations, and Related Non-Federal Actions on the Middle Rio Grande, New Mexico" (USFWS 2003a).

Historically, the 2003 BO presented numerous Reasonable and Prudent Alternatives (RPAs) intended to avoid the likelihood of jeopardizing the continued existence of the silvery minnow and flycatcher and of destruction or adverse modification of critical habitat for silvery minnow. Many of these RPAs specified water operations and flows for habitat maintenance and restoration. The first 15 RPAs addressed water management operations that vary depending on dry, average, or wet water year conditions (USFWS 2003a). A dry year is defined as those years when the Natural Resource Conservation Service (NRCS) April stream flow forecast at the Otowi Gage is less than 80 percent of average, and a wet year is one where it is 120 percent higher than average. Average water years are between these extremes. In addition, the 2003 BO RPAs included a section of habitat improvement elements specifically intended to benefit silvery minnow (USFWS 2003a).

The 2003 BO was modified in 2006, which only included revisions to effects of the action on critical habitat for flycatcher and for the Incidental Take Statement for silvery minnow (USFWS 2006a). A subsequent BO has not been issued by USFWS, however, RPAs contained in the 2003 BO are presented herein as reference.

2.4. Critical Habitat Requirements for Silvery Minnow

In designating *Critical Habitat* for the silvery minnow, the USFWS (2003b) stated, "[t]he various life history stages of the silvery minnow require shallow waters with a sandy and silty substrate that is generally associated with a meandering river that includes sidebars, oxbows, and backwaters." They went on to designate approximately 157 mi (252 km) of the Rio Grande in New Mexico from Cochiti Dam to north of Elephant Butte Reservoir at rivermile (RM) 62.1 and to include the areas bounded by existing levees or, in areas without levees, 300 ft (91.4 m) of riparian zone adjacent to each side of the bank full stage of the MRG (68 FR 8088; USFWS 2003b). With the exception of Cochiti and San Felipe Pueblos, Pueblo lands downstream of

Cochiti Dam are excluded from the critical habitat designation (USFWS 2003b). No critical habitat for silvery minnow was defined upstream of Cochiti Reservoir.

Areas other than the MRG were excluded from the designation of critical habitat for silvery minnow under section 4(b)(2) of the ESA. The USFWS (2003b) reported that the benefits of excluding these areas from critical habitat designation outweighed the benefits of including them. Areas they analyzed for possible inclusion as silvery minnow critical habitat included the middle Pecos River from immediately downstream of Sumner Dam to Brantley Dam, New Mexico, and the Rio Grande from the upstream boundary of Big Bend National Park to the Terrell/Val Verde county line, Texas.

In defining these critical habitat requirements, the USFWS (2003b) stated, "various life history stages of the silvery minnow require shallow waters with a sandy and silty substrate that is generally associated with a meandering river that includes sidebars, oxbows, and backwaters. … Adult silvery minnow occur in shallow braided runs over sand substrate, but rarely in habitat with substrate of gravel or cobble."

The critical habitat designation included four primary elements for the silvery minnow (FWS 2003b):

1. A hydrologic regime that provides sufficient flowing water with low to moderate currents capable of forming and maintaining a diversity of aquatic habitats, including backwaters, shallow side channels, pools, eddies, and runs.
2. The presence of eddies created by debris piles, pools, or backwater, or other refuge habitat with unimpounded stretches of flowing water of sufficient length to provide a variation of habitats with a wide range of depth and velocities.
3. Substrate of predominately sand and silt.
4. Water of sufficient quality to maintain natural daily and seasonally variable water temperatures in the approximate range of greater than 1°C (35°F) and less than 30°C (85°F) and reduce degraded conditions (e.g., "decreased dissolved oxygen, increased pH").

2.5. Recovery Plan Criteria for Silvery Minnow

In 2010, the USFWS (2010) released the final, *Rio Grande Silvery Minnow, Recovery Plan, First Revision*, updating an earlier (1999) version. The 2010 update established three goals for the recovery of the Rio Grande silvery minnow. These goals are presented below and the criteria listed to support each goal are presented in Table 1:

1. Prevent the extinction of the Rio Grande silvery minnow in the middle Rio Grande of New Mexico.
2. Recover the Rio Grande silvery minnow to an extent sufficient to change its status on the List of Endangered and Threatened Wildlife from endangered to threatened (downlisting).
3. Recover the Rio Grande silvery minnow to an extent sufficient to remove it from the List of Endangered and Threatened Wildlife (delisting).

Table 1. Silvery Minnow Recovery Plan Goals and Criteria (USFWS 2010)

RECOVERY GOALS AND CRITERIA

Recovery Goal 1. Prevent the extinction of the Rio Grande silvery minnow in the middle Rio Grande of New Mexico.

Recovery Objective 1-A. A middle Rio Grande population at a level sufficient to prevent extinction as defined by criteria related to distribution and reproduction, measured through annual monitoring of the population.

> **Recovery Criterion 1-A-1.** Using the standard sampling protocol (Appendix E), and sampling at a minimum of 20 sites distributed throughout the middle Rio Grande in New Mexico, document the presence of Rio Grande silvery minnow (all unmarked fish) at three-quarters of all sites, per reach, sampled during October.
>
> Habitat fragmentation has subdivided the extant population into three distinct sub-reaches, and diversions limit genetic exchange to the downstream direction. The presence of silvery minnow in all three reaches demonstrates reasonable certainty that the remaining genetic makeup of the species has been preserved and that the population can withstand a catastrophic event in any one reach.
>
> **Recovery Criterion 1-A-2.** Annual reproduction in the middle Rio Grande below Cochiti Reservoir, as indicated by the presence of young-of-year at three-quarters of all sites, per reach, sampled during October.

Recovery Objective 1-B. A captive population sufficient to prevent extinction.

> **Recovery Criterion 1-B-1. A** captive population of 50,000 to 100,000 fish with a composition and distribution (among facilities) consistent with the recommendations of the Rio Grande Silvery Minnow Genetics Management and Propagation Plan (USFWS 2007).

Recovery Goal 2. Recover the Rio Grande silvery minnow to an extent sufficient to change its status on the List of Endangered and Threatened Wildlife from endangered to threatened (downlisting).

Demographic Criteria:

Recovery Objective 2-A. Three populations, including a stable middle Rio Grande population and at least two additional populations that are self-sustaining (see box p. 3), in the Rio Grande silvery minnow's historical range, as defined by criteria related to population distribution, annual reproduction and extinction risk.

> **Recovery Criterion 2-A-1.** Using the standard sampling protocol (Appendix E), and sampling at a minimum of 20 sites distributed throughout the middle Rio Grande in New Mexico, document for at least 5 consecutive years, an October catch per unit effort (CPUE) from all monitoring sites within each reach of > 5 fish/100 m2 .
>
> **Recovery Criterion 2-A-2.** Annual reproduction in the middle Rio Grande below Cochiti Reservoir, as indicated by the presence of young-of-year from three-quarters of the monitoring sites, per reach, for at least five consecutive years.
>
> **Recovery Criterion 2-A-3.** Two additional populations of Rio Grande silvery minnow, in the historical range of the species but outside the middle Rio Grande of New Mexico, that each demonstrate (by quantitative analysis) a probability of extinction in the wild of less than 10% within 50 years.

Threats-based Criteria:

Recovery Objective 2-B. Habitat sufficient to support three such populations, as defined by criteria related to river base flow, hydrographs, and habitat and water quality (Factors A, C, D, and E).

> **Recovery Criterion 2-B-1.** Base flow within occupied habitat sufficient to generate survival rates necessary to achieve Criteria 2-A-1. Wetted habitat represents the overall carrying capacity of a particular area for Rio Grande silvery minnow and influences survival rates for the population. The amount and distribution of base flows necessary for recovery can be informed by a PVA.
>
> **Recovery Criterion 2-B-2.** Recruitment flows that generate population growth rates necessary to achieve Criteria 2-A-1.
>
> **Recovery Criterion 2-B-3.** Habitat of sufficient quantity and quality to generate recruitment and survival rates that meet Criteria 2-A-1. Quantity and quality will vary by site but each location is likely to need increased nursery habitat and overall channel complexity. These increases can be achieved through restoration, flow management, and removing impediments to river migration, such as giant cane in the Big Bend area.
>
> **Recovery Criterion 2-B-4.** Improve water quality within occupied areas and reintroduction sites to support recruitment and survival rates necessary to achieve Criteria 2-A-1.

RECOVERY GOALS AND CRITERIA (USFWS 2010) - continued

Recovery Goal 3. Recover the Rio Grande silvery minnow to an extent sufficient to remove it from the List of Endangered and Threatened Wildlife (delisting)

Demographic Criteria:

Recovery Objective 3-A. Three self-sustaining populations within the Rio Grande silvery minnow's historical range, as defined by criteria related to population size, distribution and extinction risk.

> **Recovery Criterion 3-A-1.** 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.

Threats-based Criteria:

Recovery Objective 3-B. Habitat sufficient to support three such populations, as defined by criteria related to river base flow, hydrographs, and habitat and water quality (Factors A, C, D, and E).

> **Recovery Criterion 3-B-1.** Base flows within occupied habitat sufficient to generate survival rates necessary to achieve Criteria 3-A-1.
>
> **Recovery Criterion 3-B-2.** Recruitment flows that generate population growth rates necessary to achieve Criteria 3-A-1.
>
> **Recovery Criterion 3-B-3.** Habitat of sufficient quantity and quality to generate recruitment and survival rates that meet Criteria 3-A-1.
>
> **Recovery Criterion 3-B-4.** Water quality within occupied areas and reintroduction sites to support survival rates of Rio Grande silvery minnow necessary to achieve Criteria 3-A-1.

For this recovery plan, the USFWS defined a self-sustaining population "as one that can sustain a specified population level without augmentation with captive-bred fish," whereas, a "managed population is one that requires some augmentation to sustain specified population number." Additionally, the USFWS stated that Goal 2 may only be "considered when the criteria have been met resulting in three populations (including at least two that are self-sustaining) that have been established within the historical range of the species and have been maintained for at least five years." Also, Goal 3 may be considered only "when the criteria have been met resulting in three self-sustaining populations that have been established within the historical range of the species and have been maintained for at least ten years."

The USFWS listed five categories of actions that would be needed to achieve recovery:

1. Develop a thorough knowledge of the Rio Grande silvery minnow's life history, ecology, and behavior, and the current status of its habitat.
2. Restore, protect, and alter habitats as necessary to alleviate threats to the Rio Grande silvery minnow.
3. Ensure the survival of the Rio Grande silvery minnow in its current habitat and reestablish the species in suitable habitats within its historical range.
4. Implement and maintain an adaptive management program so that appropriate research and management activities are implemented in a timely manner to achieve recovery of the Rio Grande silvery minnow.

5. Design and implement a public awareness and education program.

2.6. Supplemental Water Program

Supplemental water requirements were included among the historical key water management RPAs in the 2003 BO (USFWS 2003a).

- **Spawning Spike -** Between April 15 and June 15 of each year, the action agencies, in coordination with parties to the consultation, shall provide a one-time increase in flows (spawning spike) to cue spawning. The timing, magnitude, and duration of this flow spike will be determined in coordination with the USFWS.

- **Maximum Persisting Habitat Reach -** In coordination with the USFWS, USBR and the USACE shall release any supplemental water in a manner that will most benefit the listed species, i.e., produce the maximum persisting habitat reach.

  Channel Desiccation and Minnow Rescue - USBR, in coordination with parties to the consultation, shall conduct routine monitoring of river flow conditions when flows are 300 cfs or less at San Acacia, and report information regularly to the USFWS through the water operations conference calls and meetings.

- **Continuous River Flow from November 16 to June 15 (all years)** -Action agencies, in coordination with parties to the consultation, shall provide continuous river flow from Cochiti Dam to the southern boundary of the silvery minnow critical habitat from November 16 to June 15. In wet years, the target flow is 100 cfs at the San Marcial Floodway gage.

- **Year-round Continuous Flow from Cochiti to Isleta (all years)** - Action agencies, in coordination with parties to the consultation, shall provide year-round continuous river flow from Cochiti Dam to Isleta Diversion Dam with a minimum flow of 100 cfs at the Central Bridge gage in dry years, and 150 cfs in wet and average years.
- **Ramp Down the Flows (wet and average years) -** Action agencies, in coordination with parties to the consultation, shall, from June 16 to July 1 of each year, ramp down the flow to achieve a target flow of 50 cfs over San Acacia Diversion Dam through November 15 in average years, 100 cfs in wet years.
- **Year-round Continuous Flow from Cochiti to Isleta (wet and average years) -** Action agencies, in coordination with parties to the consultation, shall provide year-round continuous river flow from Cochiti Dam to Isleta Diversion Dam with a target flow of 100 cfs over Isleta Diversion Dam in average years, 150 cfs in wet years.
- **Managed River Recession/Low Flow Conveyance Channel (LFCC) Pumping -** USBR shall pump from the LFCC if needed to manage river recession and maintain in-channel connectivity when and where possible. The pumping capacity must meet or exceed the total capacity of pumps used in the 2002 irrigation season (150 cfs). Pumping

> shall continue when it will benefit the flycatcher and its habitats in dry and average years, and to maintain river connectivity in wet years.

The Supplemental Water Program (Supplemental Program) is funded by USBR (2006). It includes, (1) leasing of available San Juan Chama (SJ-C) water from willing water contractors; (2) concurrence with waiver requests; (3) the pumping and conveyance of water from the LFCC to the Rio Grande, including the operation of an outfall near Escondida; and (4) the implementation of water conservation practices by water contractors and municipal and industrial users. A goal of the Supplemental Program is to provide continuous flows in the MRG from Cochiti Dam downstream to Elephant Butte Reservoir. However, environmental conditions and the availability of water constrain attainment of this goal (USBR 2006).

Leasing of Available SJ-C Water from Willing Contractors: Fifteen entities have repayment or water service contracts with USBR for SJ-C project water. This diverted trans-basin water supply goes to municipal, industrial and irrigation uses. Some have been willing to temporarily lease back to USBR some of this contracted water to accommodate needs for recreation, fish and wildlife, and endangered species.

Concurrence with Waiver Requests: This part of the Supplemental Program relates to USBR policy on SJ-C contractors requesting temporary waivers of the contract requirement to take delivery of the annual allocation of project water prior to December 31 of each year and instead modify the date of their water delivery into the following calendar year. This allows flexible management of water releases to benefit the silvery minnow. Such waivers generally allow SJ-C water to remain in Heron Reservoir beyond April 30 of a particular year.

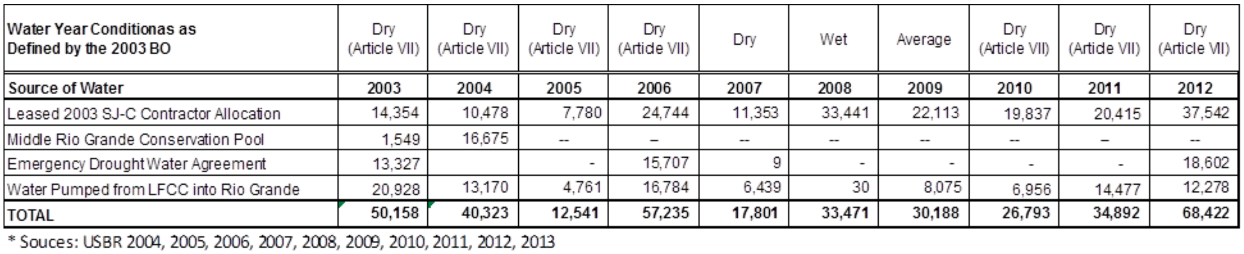
Pumping and Conveyance of Water from the LFCC to the Rio Grande: USBR, as required under the 2003 BO, reinstalled pumps at four locations along the LFCC adjacent to the Rio Grande that are used to move supplemental water from the LFCC to the Rio Grande in order to benefit silvery minnow and flycatcher. Pump sites are located at Neil Cupp, the northern and southern boundaries of the Bosque del Apache Wildlife Refuge (BdA), and at Fort Craig (Figure 1). Each location may require different actions before initiation of pumping or to maintain the facility integrity and operations. An additional pumping site in the Middle of the BdA was decommissioned in 2004 due to a lack of water in the LFCC and has not been used since.

Water Conservation Measures: Much of this part of the Supplemental Program deals with increasing irrigation efficiency by the Middle Rio Grande Conservancy District (MRGCD) under Reclamation's Water 2025 Supplemental Program. Other options for additional water conservation savings along the MRG include restricting water available for landscaping and household use (e.g., low-flow shower heads and toilets, and efficient clothes washers and dishwashers), and use of recycled water in industrial processes and for irrigation.

Table 2 summarizes the water used in the Supplemental Program from 2003 through 2012, based on annual reports from USBR to the Collaborative Program. Most years in this period of record have been classified as dry years because Article VII of the Rio Grande Compact was in place that restricts the storage of water in upstream reservoirs. Of note, a “dry” year’s supplemental water use (e.g., 2005 and 2007) can be less than a “wet” year’s water use (i.e., 2008) because carry over water could be stored in a wet year not under Article VII of the Rio Grande Compact.

The maximum supplemental water use occurred in 2012 (Table 2). This consumption is broken down in Table 3 to show water use by month for that year by pumping location, total pumping, and water released from Abiquiu Reservoir. Maximum pumping from the LFCC to the MRG occurred in June and July, and maximum discharge from Abiquiu occurred in June and September, with secondarily high discharges in May and October. The May and June discharges were linked to spawning flow requirements as well as channel drying, and September and October releases were linked to fall drought conditions.

Table 2. Supplement Water Used 2003 through 2012 to augment MRG flows (ac-ft).*



Water Year Conditionas as Defined by the 2003 BO	Dry (Article VII)	Dry (Article VII)	Dry (Article VII)	Dry (Article VII)	Dry	Wet	Average	Dry (Article VII)	Dry (Article VII)	Dry (Article VII)
Source of Water	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Leased 2003 SJ-C Contractor Allocation	14,354	10,478	7,780	24,744	11,353	33,441	22,113	19,837	20,415	37,542
Middle Rio Grande Conservation Pool	1,549	16,675	--	–	--	--	--	--	–	--
Emergency Drought Water Agreement	13,327		-	15,707	9	-	-	-	-	18,602
Water Pumped from LFCC into Rio Grande	20,928	13,170	4,761	16,784	6,439	30	8,075	6,956	14,477	12,278
TOTAL	**50,158**	**40,323**	**12,541**	**57,235**	**17,801**	**33,471**	**30,188**	**26,793**	**34,892**	**68,422**

* Souces: USBR 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013

Table 3. Approximate Annual 2012 Volume (ac-ft) by LFCC Pumping Location and supplemental water released from Abiquiu Reservoir (USBR 2013).

Pumping Location	**Neil Cupp**	**North Boundary Bosque del Apache NWR**	**South Boundary Bosque del Apache NWR**	**Fort Craig**	**TOTAL**	**Monthly Release from Abiquiu Reservoir**
No. of Pumps	4	3	5	3	**15**	
March Volume	0	0	0	0	**0**	**0**
April Volume	0	0	0	0	**0**	**0**
May Volume	439	569	535	0	**1,543**	**9,007***
June Volume	0	815	2,185	0	**3,000**	**14,082****
July Volume	0	0	2,376	0	**2,376**	**2,033**
August Volume	0	0	1,990	0	**1,990**	**6,834**
September Volume	0	0	1,616	0	**1,616**	**14,453**
October Volume	0	0	1,560	0	**1,560**	**9,735**
November Volume	0	0	193	0	**193**	**0**
Annual vol (ac-ft)	**439**	**1,384**	**10,455**	**0**	**12,278**	**56,144**

* release from El Vado; ** release from El Vado and Abiquiu

USBR (2013) reported the following about the 2012 supplemental water operations:

> The first instance of drying in 2012 occurred on June 16. The segment that traditionally dries first has always been in the Bosque del Apache just above the South Boundary pumping station. The river quickly dries upstream of the pumps to the North Boundary pumping station. Further north of this point, recession of the river usually proceeds at a much slower pace. During 2012 the

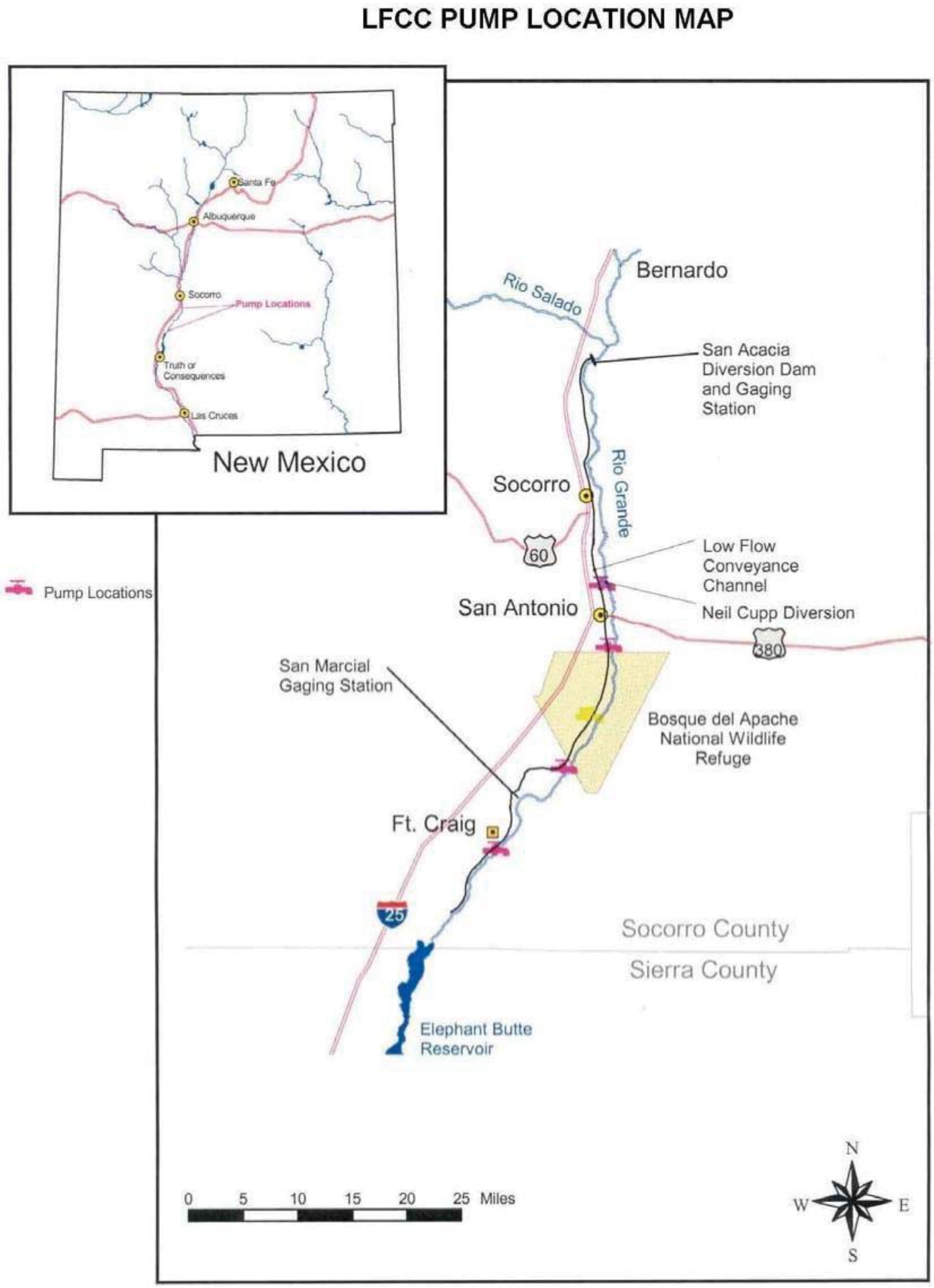


Figure 1. Low Flow Conveyance Channel Pumping locations (figure from USBR 2012).

maximum amount of drying in this reach was just over 32 miles which occurred in mid-August. Rainfall events caused small arroyos to flow throughout the summer, which led to re-wetting of previously dried channel.

Drying also occurred in the Isleta Reach to the north. In this reach most of the drying happened just above the Peralta Wasteway, and then proceeded upstream as flows were reduced below Isleta Dam. In 2012 there were actually 2 segments which dried in the Isleta Reach. There was the reach from just south of the Peralta Wasteway to the north, but there was also an additional segment some 13 miles to the south just above the Highway 60 Bridge. The maximum amount of drying in the entire reach was about 22.5 miles which occurred in mid-August. This included 16.5 miles in the northern segment and 6 miles in the southern.

2.7. “River-eyes” Monitoring of Channel Drying

During the irrigation season, whenever flows are less than 300 cfs at the Rio Grande Floodway at San Acacia stream gage (USGS 08354900), RPA Element C of the now expired 2003 BO required daily monitoring of MRG reaches to assess drying (USFWS 2003a). This monitoring has continued after the 2003 BO expired and is called *RiverEyes.* During times of channel drying, it provides daily updates on river flows and river-reach drying. This information allows the federal and state agencies to adjust daily water operations along the MRG to minimize channel drying and to forecast needs for silvery minnow rescue. This effort also includes site-specific flow measurements conducted by the personnel contracted under the RiverEyes. This occurs at times when it is safe to wade, within allotted time and budgetary constraints. The measurements have included sites in the MRG channel to verify gage accuracy, within irrigation wasteways to determine the volume of water being returned to the Rio Grande, and at other locations requested by water operations personnel (Hatch et al. 2013).

While RiverEyes monitoring generally has been limited to the summer and fall of most years, in some years it has started as early as April when flows at San Acacia have dropped to less than 300 cfs. Typically, monitoring extends through the end of October, the end of the irrigation season. Conditions are documented at half-mile intervals or less (Hatch 2010, 2011; Hatch et al. 2013). Over the past several decades channel drying has been limited to the Isleta and San Acacia reaches, with varying locations and durations of channel drying. Factors influencing the drying patterns include spring runoff, recent storm events, irrigation and drinking water diversions, and the elevation of the streambed relative to the local groundwater levels and their prevailing flow gradients.

Reach drying during 2012 was one of the driest periods on record (Hatch et al. 2013). In 2012, similar to most years monitored, channel drying was limited to the Isleta and San Acacia reaches. Drying in the San Acacia Reach began on June 16, 2012 and in the Isleta Reach began on July 4, 2012. On the last day of monitoring (October 31, 2012), two subreaches in the Isleta Reach extending for 11.29 miles and one 13.11-mile subreach in the San Acacia Reach “remained dry or reduced to isolated pools” (Hatch et al. 2013). With the end of irrigation diversion after October 31, 2012 the dry Isleta and San Acacia subreaches were expected to rapidly rewet.

Figures 2 and 3 show the extent of river drying in two reaches of the MRG during each month channel drying occurred between 2009 and 2013. The patterns observed during this period may be representative of future conditions projected due to climate change , where regional water supplies may be reduced by about 8.5 to greater than 50 percent (Bui 2011, Figure 4).

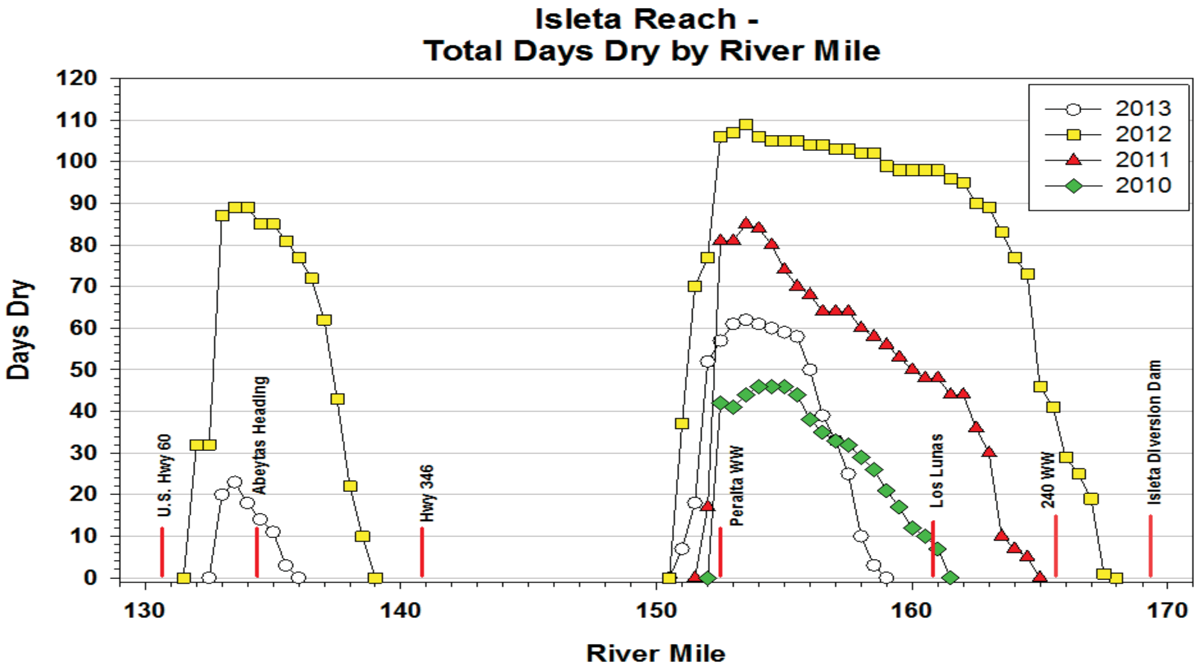


Figure 2. Number of days of channel drying by river mile within the Isleta Reach of the Middle Rio Grande for 2009 through 2013. Note: No drying was observed in the Isleta Reach during 2009. (summary graphic of RiverEyes data from M. Hatch, SWCA, unpublished, 2014).

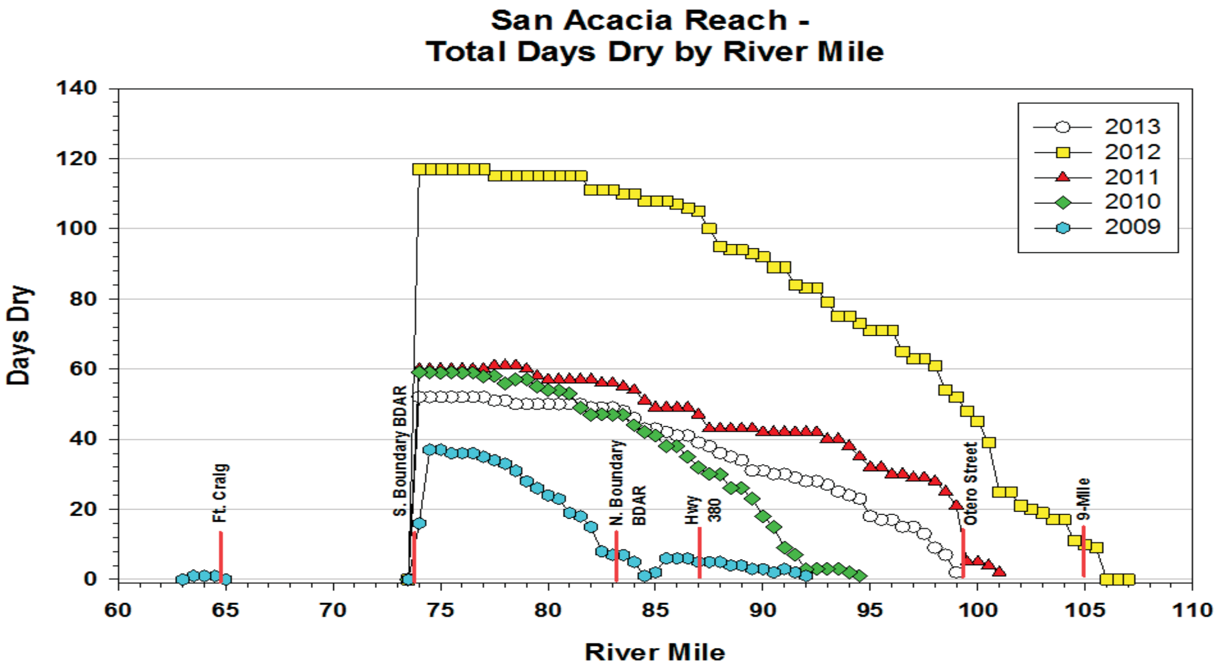


Figure 3. Number of days of channel drying by river mile within the San Acacia Reach of the Middle Rio Grande for 2009 through 2013. (summary graphic of RiverEyes data from M. Hatch, SWCA, unpublished, 2014).

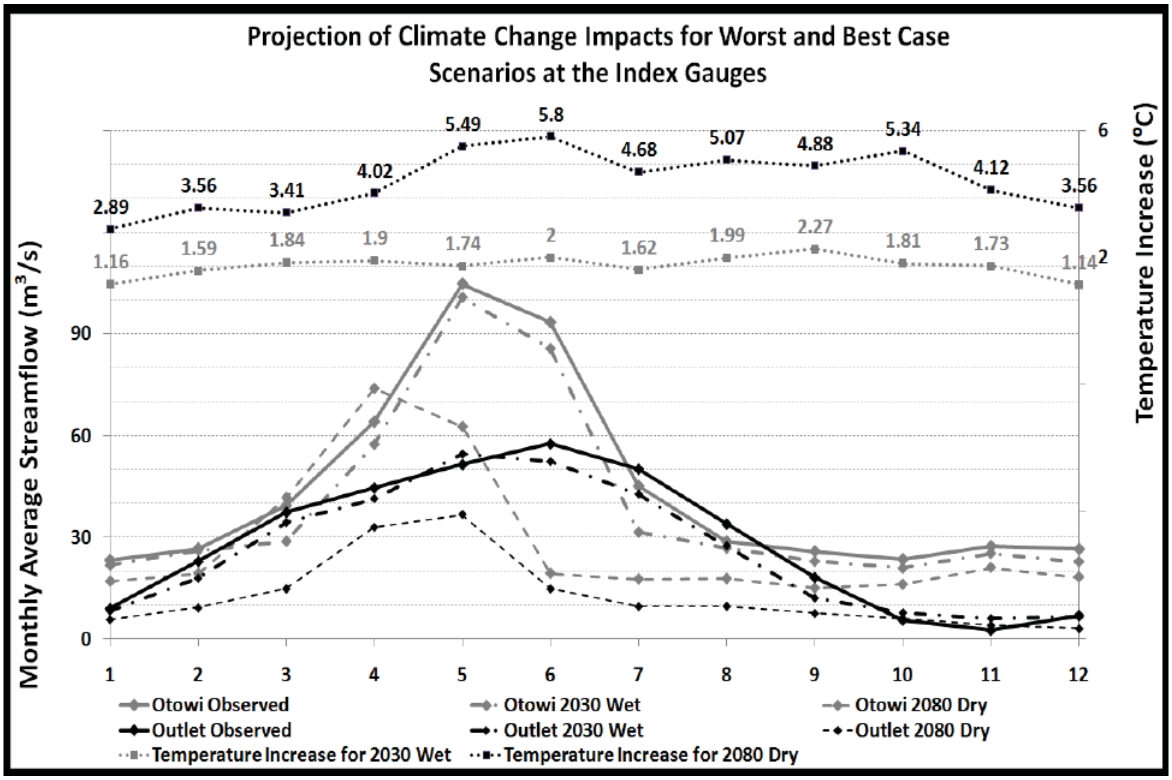


Figure 4. Projection for worst and best case scenarios by month (1 to 12) at index gauges at the Otowi Bridge and Elephant Butte Dam outlet (Figure from Bui 2011).

2.8. Silvery Minnow Rescue

Silvery minnow mortality accompanies channel drying during times of drought, with the possible impacts altered by water operations. Intermittent drying has affected as much as 68.0 miles (45 percent) of the current range for silvery minnow, between Isleta Diversion Dam and Elephant Butte Reservoir (Archdeacon and Remshardt 2012).

As a consequence of possible mortalities, the now expired 2013 BO established a basis for an annual incidental take limit for silvery minnow greater than 30 mm standard length (SL; i.e., from tip of snout to base of tail; USFWS 2003). Incidental take of post embryonic silvery minnow is defined for two size classes, i.e., for those shorter than or equal to 30 mm standard length and those longer than 30 mm. All smaller sized post embryonic silvery minnow (less than or equal to 30 mm standard length) that are presumed to be taken are linked to the MRG water operations, when the river dries downstream of Isleta Diversion (Archdeacon and Remshardt 2012).

Salvaging, or rescuing, silvery minnow from drying pools along the channel can help reduce silvery minnow mortality and incidental take during times of channel drying. Silvery minnow salvage is led by USFWS staff biologists and has occurred every year since 2001, except for 2008. The salvage efforts progress in synchrony with river recession, with priority given to river reaches in which the death of silvery minnow due to prevailing water operations would be considered incidental take.

Table 4 summarizes the total silvery minnow salvaged, incidental take, and total river channel miles dried for the years 2005 through 2012. During this period the incidental take was within the allowable limits. Salvage methods were altered in 2007 to focus salvage only on those silvery minnow within the drying channel. This was justified under the view that off channel stranding of silvery minnow is due to natural processes, therefore not included in *take* under the ESA; whereas in-channel stranding in isolated pools was due to water user manipulation of natural river flows, which could produce take (USFWS 2007, Remshardt 2008). In previous years salvage included fish on drying floodplains and off-channel pools. These include locations where the greatest numbers of silvery minnow have been removed for relocation to reaches having perennial stream flow (USFWS 2006b). This makes results from the early efforts not directly comparable to the post 2008 results.

Table 4. Total silvery minnow salvaged, incidental take, and total river channel miles dried for the years 2005 through 2012

Year	Total Number Salvaged	Incidental Take	Total Miles of Channel Drying
2005	626,444	5,640	28.5
2007	13,953	92	30.0
2009	18,473	1,694	20.0
2010	9,667	95	28.2
2011	8,244	116	40.0
2012	4,251	304	51.0

Data Source: Remshardt 2008, 2010; Remshardt and Archdeacon 2011a, b; Archdeacon and Remshardt 2012

A specific example of salvage actions comes from Archdeacon and Remshardt (2012). Between June 16 and October 22, 2012, a total of 51.0 miles of the main channel MRG became intermittent, including 19.2 miles in the Isleta Reach and 31.8 miles in the San Acacia Reach. During that period 5,014 silvery minnow were observed in isolated pools and 4,251 of these were removed, transported upstream, and released alive in the same reach at locations with flowing water.

Archdeacon and Remshardt (2012) reported finding a decreasing trend in the annual numbers of silvery minnow salvaged each year from 2007-2012. They also reported that, with annual patterns of multiple wetting and drying episodes within each reach, fewer salvaged silvery minnow per mile were collected, eventually leading to local extirpation in dried areas. For example, in the San Acacia reach, local extirpations of silvery minnow occurred over large areas after the fifth re-wetting and drying event in 2012.

While a clear correlation exists between spring run-off and recruitment success (e.g., Dudley and Platania 2010), it is also clear that poor run-off years not only result in poor recruitment, but are also typically years when the total extent of drying is greater (Archdeacon and Remshardt 2012). Archdeacon and Remshardt (2012) observed during salvage operations that more than two episodes of drying and re-wetting clearly impact the local abundance and distribution of silvery minnow. They concluded, “further research is needed to determine the effects of river drying on the silvery minnow at the population level.”

2.9. Previous Habitat Quality Studies Related to Silvery Minnow

The quantitative habitat assessments we produced during this project are based on two separate, two-dimensional hydraulic models generated from previous efforts. While the goals and objectives for these models differed, they are both suited for assessing the salient hydraulic parameters (depth and velocity) and thus the habitat characteristics for silvery minnow. It must be noted, however, that the specific relations defined by these models are based on a MRG condition occurring approximately a decade ago; as such, the physical conditions they represent have undoubtedly changed. Nonetheless, we employed these models to demonstrate relationships and draw conclusions on silvery minnow habitat based on the assumption that average physical habitat (channel geomorphology and floodplain connectivity) continue to hold a certain representativeness of the system. A third study investigated and modeled physical habitat conditions in the southern portion of the Isleta Reach, and then linked these conditions to the defined habitat requirements for life-stages of silvery minnow. The next three subsections introduce these three studies and how their results were included in our assessments.

2.9.1. Upper Rio Grande Water Operations Review and Environmental Impact Statement (URGWOPS)

The in-channel hydrodynamic model was part of an aquatic habitat assessment for the URGWOPS analysis (USACE et al. 2007). In short, URGWOPS was a comprehensive evaluation of downstream effects possible under different storage regimes at upstream reservoirs. The aquatic habitat evaluation was an in-channel analysis located at eight study sites (six on the Rio Grande and two on the Rio Chama). We selected five of the six Rio Grande study sites (excluding Peña Blanca) that are coincident with reaches previously defined by Collaborative Program. We examine the hydraulic characteristics at various flows and quantify the extent and patterns of in-channel silvery minnow habitat for different life stages (see Section 3).

2.9.2. Rio Grande FLO-2D Hydrodynamic Model

In addition to in-channel habitat, we evaluated the location and extent of floodplain habitat using the 2006 FLO-2D hydrodynamic modeling framework. The Rio Grande FLO-2D model was originally constructed in 2001 using 500 ft. x 500 ft. (5.74 acres) grid elements and extends from Cochiti Dam to the San Marcial Railroad Bridge. The model uses light detection and ranging (LiDAR) and a variety of cross section survey data to determine grid elevations and was calibrated based on surveys during high flows in the Rio Grande in 1998. In 2006, the model was revised to use 250 ft. x 250 ft. (1.43 acre) grid elements making the model output more resolved. This model was again calibrated using 2005 runoff inundation mapping (Horner 2007) and cross section surveys (Tetra Tech 2005). The model was revised in 2010 with 2010 LiDAR data (USACE 2010) and 2009 cross section survey data in the vicinity of RM 83 (cross section data collected for the RM 83 Channel Re-alignment Project; Tetra Tech 2009).

2.9.3. USGS Streamflow and Endangered Species Habitat Study

Bovee et al. (2008) present results from the USGS collection of flow and depth data over transects at three study sites. This survey information used two-dimensional hydraulic simulation modeling to characterize habitat conditions for a range of Rio Grande flows. The three selected sites were located along the Rio Grande near the Rio Puerco confluence, adjacent to the Sevilleta National Wildlife Refuge, and near the Rio Salado confluence. Site selection was based on representativeness and access characteristics. The study's goal was to provide information relating in-stream habitat characteristics and streamflow for the Rio Grande from Salas Arroyo/Lower San Juan Riverside Drain to San Acacia Dam. Specific study objectives were to quantify changes in low flow habitat features for the endangered silvery minnow and flycatcher through this river reach. A secondary objective was to provide USBR and other stakeholders with a tool to evaluate the effects of different operational modes of the proposed Bernardo siphon on habitats and irrigation deliveries to the Middle Rio Grande Conservancy District.

As part of this study, an expert panel of 19 hydrologists and biologists, experienced with silvery minnow biology and Rio Grande hydrology, were consulted for the development of habitat suitability criteria for silvery minnow. The panel included staff from federal and state agencies, the City of Albuquerque, both of the major New Mexico universities, and selected consultants. The panel produced consensus recommendations presented in the second column of Table 5. Although many of those involved in developing these criteria also had developed criteria for the USFWS (1999) Recovery Plan for silvery minnow, Bovee et al. (2008) found that the two criteria sets differed. As such, the expert panel members were presented with the inconsistencies, as shown in the second and third columns of Table 5, and asked to revise their initial criteria set. The resulting final criteria are shown in the right most column of Table 5. Those values are a basis for some of the habitat quality assessment criteria use in assessment presented below.

Bovee et al. (2008) defined two types of habitat: (1) *hydraulic habitat* included areas of patches having suitable depths and velocities for adults and juveniles; and (2) *hydraulic habitat with large woody debris (LWD)* that included areas having suitable depths and velocities within the specified buffer distances from deposits of large woody debris (0.25 m for juveniles and 0.5 m for adults).

Bovee et al. (2008) reported that the normalized areas of hydraulic habitat tended to increase rapidly between 0 and 20 cfs for adult and juvenile silvery minnow at all three sites; the area of suitable hydraulic habitat for adults reaching maximum values at roughly the same range of flows (40 to 80 cfs) at all three sites.

The maximum hydraulic habitat area for adults varied from site to site: Maximum was attained at 40 cfs at the Rio Salado site, at 60 cfs at the Rio Puerco site, and at 80 cfs at the Sevilleta site. The maximum for the composite of all three sites occurred at 60 cfs. When the flows exceeded 150 cfs, areas of suitable hydraulic habitat for adults declined rapidly for all three sites, largely due to an increase in areas having velocities in excess of the suitable range for adult silvery minnow. For juveniles, flows producing the most habitat area ranged from 20 cfs at the Rio Salado site to 40 cfs at the Rio Puerco and Sevilleta sites. Of particular interest, the hydraulic habitat for juveniles increased slightly over the flow range from 800 to 1,000 cfs, at the Rio Puerco site. Bovee et al. (2008) concluded that this increase was probably related to the shallow inundation of point bars along the channel margin at these higher flows.

Table 5. Summary of habitat suitability criteria for the Rio Grande silvery minnow, with justification for deviations from criteria in the 1999 USFWS Recovery Plan (table reproduced from Bovee et al. 2008).

Criteria Type	**Criteria source**		
	Technical Advisory Group (Initial) June 2007	**Recovery Plan 1999**	**Technical Advisory Group (final) November, 2007**
Adult depth range	10 cm, no upper limit	50 cm, no lower limit given	5 cm[(a)]–50 cm[(b)]
Juvenile depth range	5 cm, no upper limit	50 cm, no lower limit given	5 cm[(a)]–50 cm[(b)]
Adult velocity range	0–60 cm/s	0–40 cm/s	1 cm/s[(c)]–40 cm/s[(d)]
Juvenile velocity range	0–30 cm/s	0–40 cm/s	1 cm/s[(c)]–30 cm/s[(e)]

Justification for modifications:

(a) Minimum depth set at 5 cm for habitat use at shallower depths consistent with feeding biology
(b) Maximum depth changed to 0.5 m for consistency with recovery plan
(c) Minimum velocity set at 1 cm/s to differentiate flowing water from stagnant pools
(d) Maximum velocity for adults reduced for consistency with recovery plan
(e) Maximum velocity for juveniles reduced from recovery plan to reflect sustained swimming performance of post-larval fish

Including large woody debris altered the habitat–discharge curves: (1) habitat areas associated with large woody debris were much smaller than for hydraulic habitat area alone; (2) hydraulic habitat–discharge curves were fairly similar in shape among the sites, reflecting similarities in channel structure and hydraulics; and (3) maximum areas of suitable habitat occurred at a higher ranges of discharges because deposits of LWD tended to be concentrated along shorelines and on higher elevation mid-channel bars at all three sites where as at low flows, many of these deposits were located above the water line (Table 6).

Table 6. Comparison of optimum flow ranges for silvery minnow based on hydraulic habitat alone and with large woody debris. Discharge in cubic feet per second associated with maximum habitat indicated in parentheses.

Site	**Silvery Minnow Adult**		**Silvery Minnow Adult Juvenile**	
	Optimum flow range without LWD	**Optimum flow range with LWD**	**Optimum flow range without LWD**	**Optimum flow range with LWD**
Rio Puerco	40–150 (60)	60–200 (150)	20–80 (40)	60–150 (150)
Sevilleta	40–200 (80)	80–300 (200)	20–80 (40)	60–200 (200)
Rio Salado	20–100 (60)	40–100 (40,60)	20–40 (20)	40–80 (60)
Composite	40–100 (60)	40–200 (100)	20–60 (40)	40–150 (80)

Channel connectivity increased rapidly over the discharge range from 0 to 10 cfs at all three sites, with total (100 percent) connectivity achieved at the Rio Puerco and Rio Salado sites at 80 cfs and at 150 ft3 /s in the Sevilleta site. From these flows down to 10 cfs at these sites, the main channel area was generally contiguous, but contained a few disconnected patches. Bovee et al. (2008) stressed that there may be a concern when channel connectivity is less than 100 percent if silvery minnow could become stranded in isolated pools for extended periods of time.

In summary, Bovee et al. (2008) emphasized that silvery minnow optimal habitat areas reduced from their maxima when discharges exceeded 200 cfs. They also point out that sand-bed rivers, such as the Rio Grande, often pose daunting problems for data collection and hydraulic simulations due to their continually changing topography. Large channel forming flows can produce major changes in channel alignments, plus both large and extended low flows can cause channel-bed degradation. They concluded that the overriding issue related to their study is not so much due to channel instability, but more to the continuing changes in modeled discharge-habitat relations found during this study. Noting that channel changes occur in the Rio Grande over a variety of spatial and temporal scales, they suggest that their surveys were essentially snapshots of the Rio Grande channel during a short period in 2007.

3. Ecohydrologic Definitions of Habitat Quality for Silvery Minnow

Based on observed silvery minnow distributions and on known in-stream hydraulic relationships summarized in the following three subsections, we defined three classification brackets to characterize three types of habitat quality for silvery minnow:

1. ***Most Commonly Occupied Habitat*** – Surface water and inundated floodplain areas averaging less than or equal to 1.5 feet (45 cm) depth and 1.5 ft/sec (0.45 m/sec) velocity.
2. ***Highest Quality Feeding and Rearing Habitat*** – Surface water and inundated floodplain areas averaging less than or equal to 1.5 feet (45 cm) depth and 0.5 ft/sec (0.15 m/sec) velocity.
3. ***Highest Quality Spawning and Egg/Larvae Retention Habitat*** - Surface water and inundated floodplain areas averaging less than or equal to 1.5 feet (45 cm) depth and near 0 ft/sec (i.e., less than or equal to 0.05 ft/sec [1.5 cm/sec]) velocity.

3.1. Most Commonly Occupied Habitat

The USFWS (2010) stated that the silvery minnow rarely has been found in habitats having deep and swift water velocities, including main channel runs. Specifically, silvery minnow most commonly occupied habitat having velocities of less than 0.33 feet per second (10 centimeters/second). In the summer they occupy water depths of less than 7.9 inches (20 centimeters) and in the winter they are found at water depths of 12 to16 inches (1.0 to 1.3 feet, 31-40 centimeters). Year-round, silvery minnow have rarely been collected from water with depths greater than 1.6 feet (50 centimeters) (USFWS 2003, 2010).

Bovee et al. (2008;) developed a set of habitat suitability criteria based on input of 19 experts in silvery minnow biology and Rio Grande hydrology, as described above (see Section 2.8.3). The final consensus from that group concluded that the optimal water depth range for both adult and juvenile silvery minnow was 0.16 to 1.6 feet (5 to 50 centimeters), with water velocities ranging from 0.03 feet per second (1 centimeter per second) up to 1 foot (30 centimeters) per second for juveniles and to 1.3 feet per second (40 centimeters per second) for adult silvery minnow.

3.2. Feeding and Rearing Habitat

Silvery minnow are adapted to feed primarily along the channel bottoms and across other substrates, as indicated by the placement of their mouth on the lower front (sub-terminal) portion of their head (Sublette et al. 1990). Their comparatively longer intestine for fishes of their size indicates a particular reliance on vegetative and detrital material that is more difficult to digest (Sublette et al. 1990). Organic detritus, algae, diatoms, and small invertebrates appear to be the most important foods for silvery minnow, most of which accumulate and grow along the river bottom. These benthic food sources should not be confused with their planktonic (free-floating) forms, which are not a significant food source for silvery minnow for two reasons. First, neither algae nor diatoms grow particularly well as freely suspended plankton in rivers and streams with turbulent flows. Second, the placement of the mouth on silvery minnow lack morphological adaptations to feed on suspended (planktonic) materials. (Fish best adapted to feed on plankton have terminal mouths opening on the front tip of their heads, e.g., Rio Grande chub, *Gila pandora*.) Benthic algae and diatoms, as well as the other microbial and small invertebrate communities they attract, grow best in rivers where there are relatively stable substrates that can be used for attached growth. Common examples of stable substrates in rivers and streams include gravel, cobble, and woody debris. Also, multithread channels can include shallow braids having flow rates sufficiently low to allow metastable sand beds to persist, even during some flood events. Many of these substrates can also provide locations for attachment or accumulation of drifting leaf litter and fine detritus. Such accumulations also can be, at times, important sources of food for silvery minnow.

In the contemporary channel of the MRG, sand, silts, and clays are the predominant bed material. This is also true elsewhere along the Rio Grande and was likely true for at least some reaches of its historical channel as well. As such, stable sandbed substrates, by necessity, are the predominant present-day feeding habitat for silvery minnow for most of the year in the MRG, not necessarily because it is particularly favored by this fish species, but because it is the predominate benthic substrate. Stable sandbed habitats of particular importance as feeding areas include various small ephemeral side channels that remain wet during lower flow regimes, and small backwater eddies produced within metastable sandbed ripples and dune faces that form within the main channel during low flow regimes. Drifting organic materials tend to accumulate in these small pocket eddies. These pockets and the adjacent stable sand surfaces then provide growth substrates for algae, diatom, other microbes, and small invertebrates, all of which can provide high value food for silvery minnow and various other fish, as well as habitat and food for invertebrates.

The typically high suspended sediment loads in the MRG severely limit light penetration and algae and diatom growth during much of the year to only a few inches of water depth. This is particularly true during periods of moderate to higher flows. In turn, this markedly limits the food availability for silvery minnow. Shallow side channels and channel-edge “bathtub rings” commonly provide most of the area where light can penetrate sufficiently for silvery minnow food to develop. Turbidity levels decrease during low-flow periods, leading to greater light penetration and primary productivity. At these times, greater areas of the metastable sandbeds can become available substrate for algal growth, enhancing its value as silvery minnow feeding habitat.

Unfortunately, suitable feeding habitat for silvery minnow in the MRG is very limited during much of the year when elevated flow velocities mobilize the sandbed substrate, suspend fine organic materials, and wash away the attached algae and diatom communities. Specifically, flow velocities at the bed of less than about 0.5 ft/s (15 cm/s) are required for the sandbeds of rivers to stabilize (SEPM 1984). These low flows allow detritus to accumulate and algae and diatoms to grow on the stalled surfaces whenever light penetration is sufficient. But, as flows exceed 0.5 ft/s in the MRG, much of the food supply for silvery minnow within the river channel will be mobilized and flushed downstream. In fact, fine detrital and plant materials can be stirred into motion at flows of an order of magnitude less than that velocity (Fisher et al. 1979). Therefore, to provide critical feeding habitat for silvery minnow, areas with flow velocities of ≤0.5 ft/s are required, particularly during the periods of spawning and post spawning.

Since the relationship between water depth, turbidity, and photosynthesis in the MRG has not been established, but is likely to be highly variable of the range of water velocities, we use in the following assessment a water depth equal to or less than1.5 feet as optimal for feeding and rearing of silvery minnow. This is consistent with the previous criteria and beyond which velocity in the water column would likely result in turbidity levels that would limit photosynthesis and organic accumulations. Of additional note, studies by SWCA found the highest food resource densities occurred in mesohabitats where flow velocities were <0.5 ft/s (<0.15 m/s) (Valdez and Beck 2007, Valdez et al. 2008).

3.3. Spawning and Egg Retention Habitat

Silvery minnow produce naturally buoyant eggs that, when suspended in the water column, are easily transported with the current. Section 2.2 presented consideration for retention of young in channel-attached floodplains as the long-term retention strategy for silvery minnow and other fish species whose eggs are or become buoyant. As such, maximum upstream retention would occur in waters with near-zero velocity. The previous section reported that detrital and plant materials can be stirred into motion at flows of an order of 0.05 ft/s (Fisher et al. 1979). Therefore, in the following assessment optimal egg and larval habitat is defined to have a flow velocity of ≤0.05 ft/s and a depth of ≤1.5 ft. This depth is consistent with that used for the two previous criteria.

4. Methods

Quantitative habitat quality assessments for silvery minnow projected in this study used results from two previous modeling efforts, one characterizing in-channel habitat and the second characterizing floodplain habitat. The in-channel study sites included a subset of locations comprehensively modeled as part of an aquatic habitat model used for the Upper Rio Grande Water Operations Review and Environmental Impact Statement (URGWOPS; USACE et al. 2007). The following subsections describe the methods applied to each set of model results during this assessment.

4.1. In-channel Habitat

4.1.1. Upper Rio Grande Water Operations Review and Environmental Impact Statement (URGWOPS)

In this study, we used output from the URGWOPS aquatic habitat assessment. Although URGWOPS was officially released in 2007, cross section and other supportive data collection efforts, as well as the construction of the aquatic model itself, took place during 2002-2003. As described in Section 2.8.1, a two-dimensional hydrodynamic model was employed (RMA2 and the Surface Water Modeling System or SMS) with the capability of predicting depth and velocity values on a finite grid. For URGWOPS, the hydraulic model results were then coupled with habitat use criteria and a hypothetical hydrologic time series to derive a scenario-based, usable habitat area for a number of native and non-native fish species at eight study sites (six on the Rio Grande and two on the Rio Chama). This approach parallels flow-habitat relationships of the Instream Flow Incremental Methodology (IFIM; Bovee 1982; Bovee et al. 1998; see also Section 2.8.3).

In this study, we employ the depth and velocity values from the RMA2 hydrodynamic model to quantify the area and location of the silvery minnow habitat available as characterized under the set of three life stage criteria described in Section 3.0. This is similar to the IFIM and URGWOPS approach but differs in that we consider alternative definitions of key life stages. In addition, we consider a series of steady state flow conditions, whereas the URGWOPS approach provided a tally of adult and juvenile habitat area through a hypothetical hydrologic regime.

Five in-channel study sites are considered in our assessment:

1) *Bernalillo*, just south of the U.S. Highway 550 bridge;
2) *Central Avenue*, just south of Central Avenue bridge in Albuquerque;
3) *Bernardo*, just south of the U.S. Highway 60 bridge;
4) *Bosque del Apache National Wildlife Refuge (NWR)*, approximately 200 feet south of its north boundary; and
5) *San Marcial*, approximately 500 feet south of the railroad bridge.

For comparability, maps for these sites are presented in Appendix A that also include a segment for one of three reaches that corresponds to how we have parsed the MRG floodplain inundation modeling products (see Section 4.2 below).

4.1.2. Study Site Characteristics, Model Parameterization, and Range of Flows Assessed

The original URGWOPS study sites were selected to be representative of the geomorphic variation in the MRG (USACE et al. 2007). The linear distance of each study site (or reach) was five to seven times the channel width at the time of topographic and discharge data collection. Up to 10 separate flow profiles were modeled under the original URGWOPS analyses, ranging from low-flow conditions to approximately 3,000-4,000 cfs (although the highest flow at the San Marcial site was 2753 cfs). While the higher flow profiles may represent near bankfull conditions at some sites (mainly the southernmost reaches) they typically do not characterize the entire in-channel habitat hydrographic profile, and do not include what is currently understood to be an estimate of bankfull conditions. Nonetheless, the range of flows evaluated in URGWOPS provides a reasonable characterization of contemporary in-channel aquatic habitat conditions. In this study, we selected a subset of the URGWOPS flow profiles for each of the five study sites, including low and high flow conditions, to determine the trends of in-channel silvery minnow habitat produced over progressively increasing flows.

4.1.3. GIS Post-Processing of Model Results

The URGWOPS RMA2 model results were obtained from Bohannon Huston, Inc. (the principal aquatic habitat modeling contractor for URGWOPS) as sets of ASCII tables containing three dimension (X,Y,Z) coordinates, velocity, and depth point data for each of the discharge flow profiles. Some datasets also contained water surface elevation data. No metadata or additional documentation was provided with any of the datasets. The only background for these data was from URGWOPS documentation (USACE et al. 2007) and other supportive reports. Horizontal coordinates were determined to be New Mexico State Plane, Central (US Foot) with datums for some datasets as NAD 27 and others as NAD 83. The vertical datum is unknown for any of the datasets and we assume here that the water depth values calculated in the model output were derived as run-time calculations and not the difference between RMA2 derived water surface elevations and the underlying digital elevation model (DEM) outside of the RMA2 environment. Thus, the water depth values contained in the ASCII files are not subject to errors in or conversions of vertical datums.

Since Tetra Tech was not provided the RMA2 mesh (grid) and we sought to quantify habitat area, we used the point files to create Thiessen polygons in ArcGIS 10.1 (ESRI 2013). By construction, this process provides a set of topologically correct polygons (i.e., consistent adjacency with no gaps or overlaps) that define a spatially explicit gradient of the modeled point characteristics. We held the data processing extent of Thiessen polygon construction to the boundary (the maximum extent) of each flow profile’s output point file; a bounding polygon that encompasses all points within a given flow profile’s output. In addition, the bounding polygons, and thus the processing extent, also reflect areas where no inundation was predicted such as islands or bank attached bars. We then assigned both modeled depth and velocity values from each point to its corresponding polygon through a spatial join. The resulting dataset allows one to query by both depth and velocity thereby selecting grid cells that meet both desired conditions simultaneously. For several of the study sites, the point files contained some data points with zero depth values. While it is certainly possible to have a zero velocity point, it is not logical to have a predicted inundation with zero depth. We therefore treated these points as null and removed them before Thiessen polygon creation. Lastly, the Central Avenue point files showed an unexplainable spatial displacement of approximately 700 feet. We applied a spatial adjustment to correct this horizontal coordinate error.

After creation of the Thiessen polygons and performing the spatial joins for all five sites and flow profiles, we queried the datasets for the depth-velocity combinations for the three life stages discussed previously: (1) Most Commonly Occupied Habitat; (2) Highest Quality Feeding and Rearing Habitat; and (3) Highest Quality Spawning and Egg/Larval Retention Habitat. The query results were then exported as stand-alone geospatial datasets.

4.2. Floodplain Habitat

4.2.1. Model Description and Range of Flows Assessed

The floodplain inundation modeling results assessed came from a FLO-2D model produced for the MRG, as described in Section 2.8.2. FLO-2D is a two-dimensional hydrodynamic flood routing model that simulates channel flow and unconfined overland flow. It models a given stream discharge over complex topography and substrate roughness through the conservation of water volume. The model uses the full dynamic wave momentum equation and a central finite difference routing scheme with eight potential flow directions to predict the progression of a flow over a system of square grid elements.

The revision of the established 2010 FLO-2D model served as the framework for the creation of three stand-alone model reaches: (1) the Angostura Reach from the Angostura Diversion Dam to the north boundary of Isleta Pueblo; (2) the Isleta Reach from the south boundary Isleta Pueblo to the San Acacia Diversion Dam; and (3) the San Acacia Reach from the San Acacia Diversion Dam to the San Marcial Railroad Bridge. These reaches are consistent with those defined by the Collaborative Program and reflect reaches functionally separated by main-stem diversion dams and thus subject to an operationally unique hydrology. These reaches were also used in three previous mapping products for USACE (Tetra Tech 2012, 2013a, 2013b).

For this study and the earlier mapping products, various flows were input for model assessment at the upstream end of each reach. The model then determines how much of the flow remains in the channel and allows the excess to move out onto the floodplain. The models were allowed to run for a sufficient period of time, which varies with discharge, for the inundation on the floodplain to reach an equilibrium state. The model uses assigned grid elevation values in concert with the modeled water surface elevation at each grid element to determine a depth of inundation. Water velocity is also calculated for each grid cell.

It is important to understand that the model is only resolved, for any output variable, to the grid cell size (an unclipped grid cell is 1.43 acres, see Section 4.2.2. below,). That is, each grid cell only contains a single value for any given parameter (depth and velocity) and cannot capture the smaller scale variability within each cell. In addition, there are locations where a grid cell falls on both sides of the levee or where floodplain inundation is also shown in the river channel. In these cases, the dimensions of the grid cell simply extend beyond the floodplain and are an artifact of the underlying model grid.

For the purposes of the mapping products, steady state flows of 2,000, 3,500, 5,000, 7,000 and 10,000 cfs were chosen by the ESA Collaborative Program HRW to cover the range of flows anticipated in the MRG. 10,000 cfs is the maximum allowable release from Cochiti Dam although 7,000 cfs is the maximum that has been released since 1985 due to concerns about channel capacity and damage to infrastructure. The FLO-2D output for these flow profiles were adopted for this study.

4.2.2. GIS Post Processing of Model Results

Geospatial representations of the floodplain inundation model results were exported using the FLO-2D mapper module, where each variable (e.g., depth and velocity) is output as a distinct ESRI shapefile. All shapefiles were then projected to New Mexico State Plane, Central (US

Foot), NAD83 for use in geospatial analysis. Similar to the in-channel post-processing, a spatial join was used to create a single shapefile containing both depth and velocity attributes for each reach and flow profile. Although, water surface elevation is also available as an output attribute, it was not included in the geospatial post-processing. The resulting shapefiles were clipped by the lateral floodplain extent (defined by levees and bluffs) to eliminate the overestimation of area where certain grid cells span the outer boundary of the floodplain. The clipping process reduced the area of some boundary grid cells, by varying amounts, but produced a more accurate account of overall inundation as well as silvery minnow habitat extent. Life stage queries, identical to those used in the in-channel habitat analysis, were then run on each dataset to locate and quantify silvery minnow habitat.

5. Results

5.1. In-channel Habitat

5.1.1. In-channel Flow Relationships and Habitat Quality Projections

Results for the in-channel study sites are provided in Appendix A where a table is presented for each of the five study sites. Each table presents for each of the channel discharge profiles and for each of the three life-stage habitat criteria assessed, the total area of the classified habitat (ft^2), percent of total active channel, mean depth (ft), and mean channel velocity (ft/s). Plots of habitat area and percent of active channel are also provided. In addition, a series of habitat maps for each study site, life-stage, and discharge profile follow the tables and plots. These maps show the relative locations, extents, and patterns for each silvery minnow habitat criteria assessed. Because the imagery used in the maps is dated 2005, approximately two years after the in-channel model was created, the model projections of the channel do not always exactly match the underlying photography. Despite these differences and the age of the modeling, because the study sites were selected as being representative of general reach conditions, the nature of the modeling results and our application of these results remain representative of reach conditions today, except for the San Marcial Reach, which has experienced significant head cutting due to the drawdown of Elephant Butte Reservoir. All geospatial data (source data, GIS layers, and assessment results) are included on the accompanying digital media.

> ***Bernalillo Study Site*** **–** The Bernalillo Study Site is located just south of the Highway 550 bridge in Bernalillo at River Mile (RM) 203.5. The planform of this site includes a substantial bank-attached bar. As a result, available aquatic habitat increased as sufficiently greater flows inundated the bar. Then, with still greater flows, habitat availability is negatively correlated with flow increases. These habitat patterns generally occurred for each of the three life-cycle requirements assessed; however, small gains in Feeding and Rearing Habitat, as well as the Egg/Larval Retention Habitat, appeared at early stages of bar inundation (approximately 1,024 cfs). A larger gain in all categories of habitat occurred at the 2,108 cfs discharge and, among the discharge profiles modeled, is the maximum in-channel habitat available at this study site. This is due to the widespread inundation of the bank-attached bar at this flow profile. At the highest discharge modeled (3,488 cfs) in-channel habitat shows a negative correlation with increasing flow, suggesting maximum possible habitat lies somewhere between 2,108 and 3,488 cfs, although greater habitat area could exist between 1,024 and 2,108 cfs when the bar is inundated with shallower, low velocity water.

Flow profiles considered in the original model, however, do not have model results for intervening discharges between 1,024 and 2,108 cfs.

Figure 5 illustrates the general pattern of progressively decreasing habitat area from Most Commonly Occupied Habitat to Highest Quality Spawning and Egg/Larval Retention Habitat. This pattern exists at all sites and discharge profiles. This is not surprising since the three habitat criteria classifications are categorically nested. That is, Highest Quality Feeding and Rearing Habitat is a subset of Most Commonly Occupied Habitat and Highest Quality Spawning and Egg/Larval Retention Habitat is a subset of Highest Quality Feeding and Rearing Habitat.

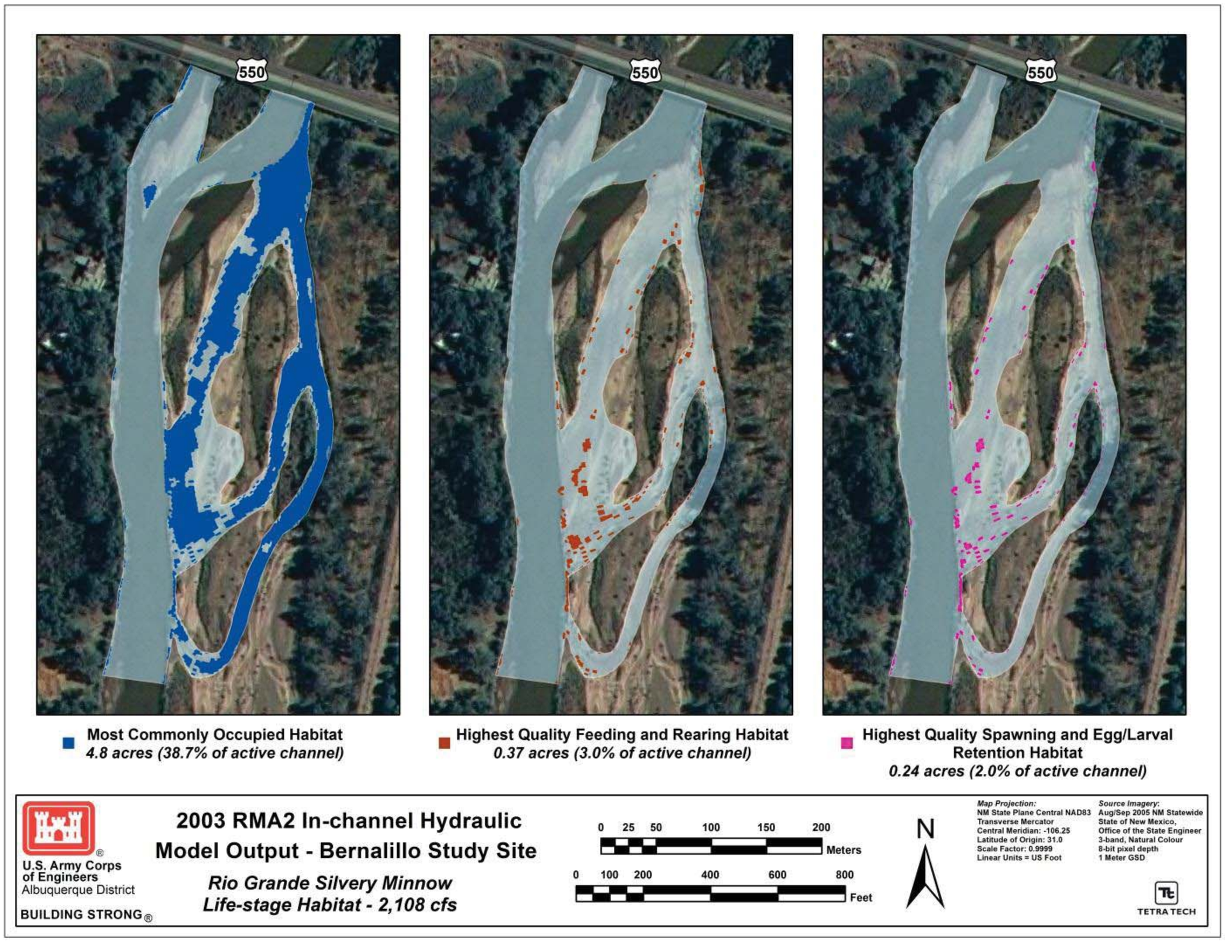


Figure 5. Bernalillo RMA2 in-channel study site showing all three Rio Grande silvery minnow habitat categories; 2,108 cfs.

Central Avenue Study Site – The Central Ave. Study Site is located just south of the Central Avenue bridge at RM 183. The planform at this site includes a slight bend at the upstream end, a small bank-attached bar near the middle of the site on the west bank and a somewhat larger bank-attached bar near the end of the reach on the east bank. Here also, there is a negative relationship between silvery minnow habitat and increasing flows, although there is a slight increase in Highest Quality Feeding and Rearing Habitat and Highest Quality Spawning and Egg/Larval Retention Habitat at the highest modeled discharge profile (3,488 cfs). This increase is largely due to a small bar area on the west side of the study site that experiences inundation at higher flows.

Bernardo Study Site – The Bernardo Study Site is located just south of the Highway 60 bridge at RM 130.5. Like the Bernalillo Study Site, this site also contains a considerable bank-attached bar on the eastern side. This bar represents additional habitat area; however, this only tends to manifest in Most Commonly Occupied Habitat. As with the previous two study sites, Bernardo shows a negative relationship between silvery minnow habitat and increasing flows and, like the Bernalillo site, displays a slight increase over the previous level when additional portions of the bank-attached bar become inundated (from 1,025 to 2,218 cfs). At the highest modeled discharge (3,500 cfs) the negative relationship again occurred.

Bosque del Apache Study Site – The Bosque del Apache Study Site is located just south of the north boundary of Bosque del Apache National Wildlife Refuge at RM 84, and is a generally straight section of river. It is unique in that the habitat-flow relationship shows a roughly normal distribution. That is, peak levels of habitat occurred at the mid flow profiles and lessen toward both the high and low modeled flows. This occurred for all habitat categories. Although the normal distribution of habitat area is quite different from previous study sites, the planform is a similar bank-attached bar. The difference being that the extensive bar inundates throughout the range of modeled flows providing a continuum of aquatic habitats and a greater proportion of -Highest Quality Feeding and Rearing Habitat and Highest Quality Spawning and Egg/Larval Retention Habitat. Interestingly, while habitat area exhibits a normal distribution, the habitat percent of the active channel (for all categories) follows the more familiar negative relationship – as flows increase the relative proportion of silvery minnow habitat within the active channel decreases. Again, this pattern occurred for all habitat categories.

San Marcial Study Site – The San Marcial Study Site is located just south of the San Marcial Railroad Bridge. The site is on a gentle bend with only small areas of bank attached bars or islands. The San Marcial Study Site also shows a pronounced negative relationship between habitat of all categories and increasing flow; however, like the Bosque del Apache Study Site, it possess a greater relative proportion of Highest Quality Feeding and Rearing Habitat and Highest Quality Spawning and Egg/Larval Retention Habitat for the period modeled.

5.1.2. Habitat Trends and Relationships to In-channel Geomorphology

Common to all in-channel study sites is an overarching negative relationship between available quality habitat area and increasing flows; in general, as modeled flows increase the classification of quality habitat area decreases across all categories. Where bank-attached bars are present, however, this dynamic is altered somewhat by conferring additional aquatic habitat as these areas are progressively inundated by increasing flows. Where little or no bar areas are present, Highest Quality Feeding and Rearing Habitat and Highest Quality Spawning and Egg/Larval Retention Habitat become largely limited to the channel margins or to where some kind of inundated channel structure (e.g., an island or emergent backwater area) provides favorable conditions.

Due to the less stringent parameters, Most Commonly Occupied Habitat, which is essentially adult resting habitat, is more widely distributed across discharge profiles and study sites.

Nonetheless, this category of silvery minnow habitat also shows precipitous declines as flows increase – the exception being the Bosque del Apache Study Site where the large bank-attached bar on west side allows for extensive areas of shallow, slow-water habitat.

5.2. Floodplain Habitat

Results for the three modeled floodplain reaches (Angostura Diversion Dam to the north boundary of Isleta Pueblo, South Boundary of Isleta Pueblo to San Acacia Diversion Dam, and San Acacia Diversion Dam to San Marcial Railroad Bridge) are provided in Appendix B. As with the in-channel results, each reach, discharge profile, and life-stage habitat category classified has a table quantifying the area (ft^2), percent of total active channel, mean depth (ft), and mean velocity (ft/s). Plots of habitat area and percent of total inundation are also provided. In addition, a series of maps similar to the in-channel results, provide an example sub-reach showing the pattern of floodplain inundation for each life-stage at the discharge profile where inundation becomes widespread. That is, at flow profiles less than those mapped in Appendix B, inundation is much reduced. All geospatial data is included on the accompanying digital media.

Angostura Diversion Dam to the North Boundary of Isleta Pueblo – This reach extends from the Angostura Diversion Dam (approximately RM 209.7) through Albuquerque to the north boundary of Isleta Pueblo (approximately RM 172.4). The reach is generally incised and does not experience marked overbank inundation until 7,000 cfs. Much of the total floodplain inundation along this reach provides suitable silvery minnow habitat across all three habitat categories above the 7,000 cfs threshold (Exhibit B4). The discharge/quality-habitat area relationship follows a positive relationship from 5,000 to 10,000 cfs; however, the percent of high quality habitat for all three categories in inundated areas decreases as flow increases through this range (Exhibit B1).

South Boundary of Isleta Pueblo to San Acacia Diversion Dam – This reach extends from the south boundary of Isleta Pueblo (approximately RM 166.1) to the San Acacia Diversion Dam (near RM 116.1). This reach is less incised and shows significant overbank inundation at 5,000 cfs (Exhibit B5). A positive discharge-quality habitat area relationship exists from 3,500 to 7,000 cfs with slight declines in area for all but the Most Commonly Occupied Habitat at 10,000 cfs. As with the upstream reach, the percent of high quality habitat for all categories in inundated areas decreases as flow increases from 3,500 to 7,000 cfs, but by 10,000 cfs all high quality habitat categories are half or less of the 3,500 cfs profile (Exhibit B2).

San Acacia Diversion Dam to San Marcial Railroad Bridge – This reach extends from the San Acacia Diversion Dam (near RM 116.1) to the San Marcial Railroad Bridge (near RM 68.6). This reach shows the least degree of incision as floodplain inundation is replete at 3,500 cfs and even considerable at 2,000 cfs (Exhibit B6). Different from the two upstream reaches, the habitat-flow relationship follows a normal distribution with the greatest areas of quality habitat for all categories at the 5,000 cfs profile. Again, the percent of all high quality habitat categories in inundated areas declines with increased flow volumes (Exhibit B3).

5.3. Seasonal Flows Variability: 2010-2012 Drying Probabilities

The three most recent RiverEyes reports available includes sets of figures that present the probability of channel drying by month along the Isleta and San Acacia reaches of the MRG during 2010 through 2012, (Hatch 2010, 2011; Hatch et al. 2013). We summarize these probabilities in Figure 6 using three probability groupings:

- Green - Channel projected as having low likelihood (probability 0.0 to 0.1) of drying (i.e., likely to remain wet or mostly wet) during that month and year
- Yellow - Channel projected as having intermittent likelihood (probability > 0.1 to < 0.25) of drying during that month and year
- Red - Channel projected as having high likelihood (probability ≥ 0.25) of drying for at least one or more weeks for that month and year

5.4. Densities of Silvery Minnow Captured in the MRG

Appendix C presents five figures summarizing the silvery minnow long-term monitoring data collected 1993 through 2012. This information allows for a comparison of how population densities (based on total captures) have varied among and within MRG reaches. It also provides a basis for comparative trend assessments on how silvery minnow population densities, as reflected by the sampling techniques used, may respond to restoration projects in these reaches.

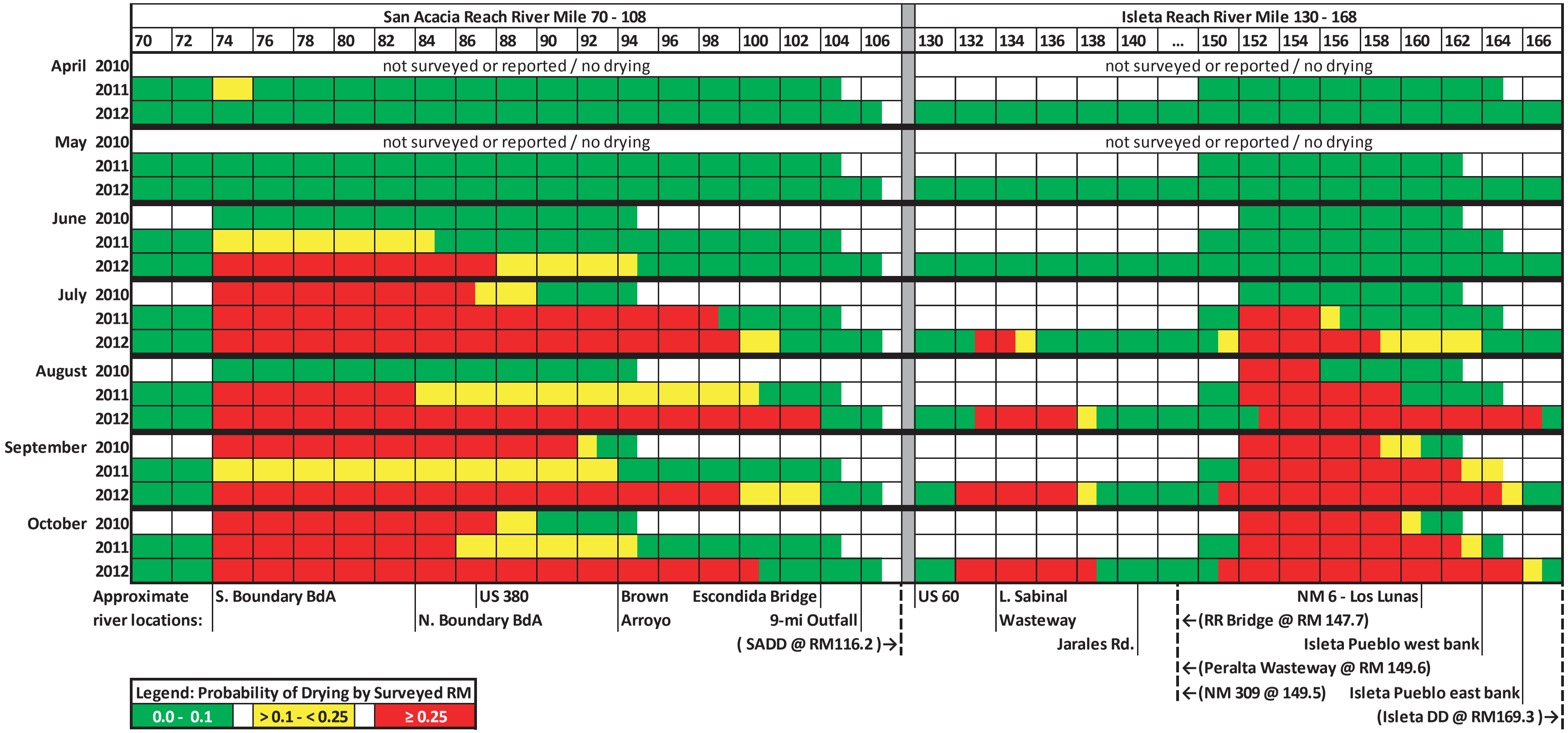
Over the period of this long-term monitoring for the entire MRG, maximum capture densities for silvery minnow occurred in 2005, with relatively high densities occurring in all three reaches (Exhibit C1, Appendix C). In that year, the most captures occurred in the Isleta Reach. The second highest capture densities occurred in the Albuquerque Reach. Minimum silvery minnow captures occurred in 2003 and 2012 (Exhibit C1, Appendix C).

Across the data set, maximum captures by month typically have occurred in July (Exhibit C2, Appendix C). This likely should be expected because, by then, the young of year silvery minnows would begin reaching the necessary size to be retained in the beach seine used for monitoring. Maximum July captures occurred in 2005 followed by 1999 (Exhibit C2, Appendix C). Minimum monthly captures for 1993 through 2012 typically occurred in March, with only slightly greater captures in January (Exhibit C2, Appendix C).

October is the index month for population status assessments under the Recovery Plan. The plot for October captures in the MRG long-term monitoring data shows that maximum captures occurred in 2005 followed by 2007, 2009, and 2008 (Exhibit C3, Appendix C). Minimum October captures occurred in 2002 and 2012, with very low October capture occurring in 1996, 2000, and 2003 (Exhibit C3, Appendix C). Interestingly, periods of very low capture year are regularly followed by marked increases in the silvery minnow population accompanying years with greater water supplies. Whether this pattern of population recovery will again occur following the low water years of 2012-2014 will need to be assessed when these data become available.

In total, over the past five years of record, maximum catches of silvery minnow have occurred at the two monitoring sites downstream from Isleta Diversion Dam (Exhibit C4, Appendix C). Relatively high concentrations also have occurred at scattered locations downstream from these two sites throughout the Isleta and San Acacia reaches (Exhibit C4, Appendix C).

Figure 6. Probability of channel drying by river mile (RM) and month along the Isleta and San Acacia reaches of the MRG for 2010, 2011, and 2012 (data extrapolated from figures in Hatch 2010, 2011; Hatch et al. 2013).



Of note, reaches having moderate to high probabilities of drying, as shown in Figure 6, show relatively consistent site-by-site patterns across years that range from very low to relatively high total captures of silvery minnow annually during the 2008 to 2012 sampling period (Exhibit C4, Appendix C). This trend would offer support to options that focus on restoration projects intending to maintain at least minimum in-stream flows in upper and lower portions of drying segments. Such projects would tend to benefit the overall viability of the silvery minnow population in these reaches.

During 2012, maximum collections of silvery minnows again occurred at two sites downstream of the Isleta Diversion Dam plus immediately downstream of the San Acacia Diversion Dam (Exhibit C5, Appendix C). Minimal collections occurred in the Angostura reach. The relatively high probability that this reach will maintain flows into the future, coupled with the recurring pattern of depressed populations in the Angostura Reach indicates this reach should be a priority for additional habitat restoration projects to improve the overall suitability of the reach for silvery minnow habitat.

6. Discussion

6.1. Additional Consideration of Present-day Risks Linked to Specialized Adaptations by Silvery Minnow to Historic Habitat Extremes

Habitat restoration efforts intended to aid the persistence and recovery of listed endangered or threatened species typically and most simply have the goal of modifying existing habitats to make their conditions better correspond to the oftentimes specialized life-history needs of the species. An early question in designing these projects should be what habitat attributes are needed to meet the unique physiological or behavioral adaptations for the target species. For those traits that likely produced competitive advantages for the species the next question becomes, what attributes of its historical environment likely led to these traits and are those attributes missing in its contemporary environment? Answers to these questions provide the basis for designing key modifications in the species’ existing environment to lessen or eliminate the risk of local extirpation or extinction.

We know that much of the Rio Grande, including the MRG, historically held frequent but contrasting environmental extremes: repeated patterns of widespread flooding caused by spring snowmelt and summer thunderstorms juxtaposed with seasonal drought cycles producing channel drying along many reaches of the river (e.g., Horgan 1984, Paulson et al. 1991, Scurlock 1998). For any fish species to not only persist but to rise to dominance in a river system with such environmental extremes would require the species to incorporate considerable adaptability and physiological hardiness into its biology.

The following subsections review key characteristics silvery minnow would have needed to survive these environmental extremes, which they still retain today. Because their contemporary environment differs in definable ways from their historical environment, these historical adaptations do not yield the same advantages and may even tend to increase the present-day risks and mortality rates for this species. The closer that the present day habitat conditions for the species can match historical conditions, the more likely silvery minnow will persist in the MRG.

6.1.1. Reproductive Adaptations Keyed to Flood Flows and Floodplain Connectivity

Floodplains Provide Key Habitat Values for Fish

Much information exists on the ecological importance of river channel to floodplain connectivity and on the adversity produced within a river system when these environments are disconnected (e.g., see brief review by Bayley 1995). Balcombe et al. (2007) documented key benefits to fish populations that accompany floodplain inundation in arid river systems. These include significant enhancement of growth rates for larval and juvenile fish due to the warmer water temperatures and the shallow, food-rich conditions in the floodplain relative to the adjacent channel environment. Such benefits result in overall increases in fish population productivity and abundance when compared to systems having disconnected floodplains (Balcombe et al. 2007).

Inundated Floodplains Enhance Food Availability for Fish

Shallow, slowly flowing water in floodplain and backwater habitats allows for sediment to settle, enhancing the solar warming rate of the flooded ground and overlaying water column. The clearer, warmed waters then tend to enhance primary productivity and growth rates for diatoms and other components of the benthic community that many fish species, including silvery minnow, tend to favor as a food resource. In addition, the freshly flooded terrestrial areas also provide new sources of organic matter and small invertebrates of terrestrial origin that also can provide added nutrition for many species of adult fish and faster growth rates for the developing young fish. In combination, conditions produced by inundated floodplains tend to increase retention of adult fish in the population and boost recruitment of young fish into the population.

Inundated Floodplains Enhance Upstream Retention and Survival of Young Fish

In floodplain connected river systems, waters in inundated overbank areas have reduced velocities with many complex eddy currents and near zero-velocity areas. Eggs spawned onto the floodplain would have markedly reduced potentials for downstream drift and displacement from their natal reaches for any semi-buoyant fish eggs drifting into or spawned in these areas. This is also true for any newly hatched, developing fish larva occurring there. Of note, Górski et al. (2010) reported that all fish species stimulated to spawn during the spring flood in the Volga River, spawned primarily on the floodplain, whereas no channel spawning fish spawned on the spring flood pulse.

Major Floods in the Rio Grande Significantly Influenced the Development of Fish Life-Cycle Characteristics

Considering that much of the Rio Grande, including the MRG, had a history of major floods, it remains in question what benefits silvery minnow received in keying spawning to such events. In today’s channelized and leveed Rio Grande, where long reaches of the river channel are now also deeply incised, spawned semi-buoyant eggs may be flushed 100 miles or more downstream (Platania 1995, Platania and Altenbach 1998, Dudley and Platania 2011, Medley and Shirey 2013). Such downstream displacement has been characterized to be an adaptation to promote re-colonization by silvery minnow in downstream reaches where populations have been lost due to channel desiccation (Platania and Altenbach 1998). Actual distance of downstream displacement depends on current velocities in habitats where eggs were released, and the opportunities for retention of eggs and larvae in quiet water areas, including backwater eddies, side channels, and floodplains.

However, such high-flow induced events can markedly lower survivorship of larval fish lacking mobility to escape the current. For example, Harvey (1987) found that all larval fish less than 10 mm (0.4 inches) were killed within a few hours when exposed to large flushing events. Freshly spawned silvery minnow eggs, depending on water temperature, require about a day to hatch and about another two days in the early larval stages before they become sufficiently mobile to escape drifting with the current. The newly hatched silvery minnow larvae are about 3.7 mm (0.15 inch) standard length after hatching and grow about 0.15 mm (0.006 inch) per day during their early larval stages (Platania 1995, Platania and Altenbach 1998). Thus, based on the findings of Harvey (1987), when silvery minnow eggs are spawned into flooded channels of the MRG, the young silvery minnow would unlikely survive the two-day post-hatch development period typically needed prior to the larvae becoming sufficiently mobile to escape the current.

When the MRG river channel and its floodplain were well connected, before dams, channelization, and riverside jetty jacks and flood-control levees, spring floodwaters could spread across the Rio Grande floodplain often for two miles or more (Berry and Lewis 1997, Scurlock 1998). This appears to have been prevalent in many reaches downstream of White Rock Canyon through the San Marcial Reach. As a result, large portions of inundated floodplain and backwater habitats during flood events would have near-zero current velocities. Focusing spawning on the inundated floodplains would have minimized possibilities for extensive downstream drift of silvery minnow buoyant eggs and developing larvae. It would also have allowed the developing larvae to take advantage of the warmer water and newly available food supply to enhance their rates of development. Such an adaptive focus on floodplain spawning is generally consistent with observations of spawning habitats used by other silvery minnow species (e.g., Raney 1939, Copes 1975).

Many Studies Link Quality Habitat for Silvery Minnows to the MRG Floodplain

Connected floodplains in the MRG could provide key habitat both for retention of spawned eggs and for providing nursery conditions for newly hatched larvae of silvery minnow (e.g., Massong et al. 2004, Hatch and Gonzales 2008). When floodplains are disconnected, however, the only habitat available for silvery minnow spawning would be within the confines of the channel. This would indicate that silvery minnow spawning could occur in either floodplain or in-channel habitats.

Similar to the findings for fish species in other arid rivers, research along the MRG increasingly points to floodplain habitat as import to silvery minnow (e.g., Medley and Shirey 2013). Rescue efforts to retrieve silvery minnow from drying floodplains during 2005 resulted in collections of high numbers (100,000s) of both adult and young-of-year silvery minnow (USFWS 2006b). Other projects have found that areas in the MRG that have low-rates of water exchange, such as the edges of over-bank areas at greatest distance from the river channel, held relatively high concentration of eggs and young-of-year silvery minnow (M. Porter, USACE, personal communication, 2008; Porter and Massong 2004; Hatch et al. 2008).

Tave and Hutson (2011) reported on findings for silvery minnow inhabiting a naturalized stream habitat developed to aid the recovery of this species. When stimulated by high water velocities to simulate high-flow river conditions, the silvery minnow schools moved from the river channel to off-channel habitat where they then spawned.

Magaña (2012) documented floodplain habitat use by four species of larval fish, including silvery minnow, during a 2005 controlled flood pulse through Cochiti Dam that inundated the Los Lunas Habitat Restoration Project site on the MRG south of Los Lunas, NM. Using light traps, he reported capturing 394 larval fish comprising 4 species, with 46 percent captured on the leeward side of restoration features having the lowest current velocities. A total of 32 percent of the collected fish were silvery minnow; fathead minnow (*Pimephales promelas*) was the dominant species captured (59 percent). Magaña (2012) stated that no light traps were placed in the channel margins because, citing Dudley and Platania (1997), silvery minnow are rarely collected from this habitat. Additional seining of the restoration habitats produced a total of nine fish species. From his data, he concluded that silvery minnow and other fish species clearly use shallow, low velocity constructed floodplain habitat, and that the silvery minnow has evolved a reproductive strategy that “is well adapted for the flashy spring-summer hydrograph” of the MRG, enabling it “to quickly colonize and spawn in recently inundated areas (*sensu* Bayley 1995).”

Hatch and Gonzales (2010) assessed fish populations monthly in the MRG channel near the Los Lunas Habitat Restoration Project from October 2008 through February 2009. They also assessed fish use of the constructed floodplain site during four weeks of the May-2009 spawning period for silvery minnow. Although they assessed environmental conditions in both channel and floodplain habitats during this time, flow in the channel was too dangerous to sample for fish. While they reported that floodplain water temperature only averaged about 1°C (1.8°F) warmer than in channel temperatures, the maximum temperature recorded in the floodplain water was nearly 3°C warmer during the four weeks of the May spawning period (about 25°C on the floodplain and 22°C in the river). Such a temperature difference may enhance biological activity on the floodplain in terms of primary production, egg maturation rates, and growth rates of young fish. Of added interest, the greatest average weekly catch-per-unit effort for silvery minnow in floodplain habitats coincided with the warmest maximum floodplain water temperatures and when average weekly water temperatures differed most from those of the main channel (Hatch and Gonzales 2010). From lab studies, Platania (2002) reported that increasing the incubation temperature from 20 to 25°C decreased the range of time required for silvery minnow eggs to hatch from a maximum of nearly 4 days to just over 2 days.

During spring runoff flows in 2008 and 2009, Gonzales et al. (2013) assessed fish use of constructed floodplain habitats at six locations along the Angostura (aka, Albuquerque) Reach of the MRG, plus one naturally connected floodplain in the Isleta Reach south of Isleta Pueblo. The spring reservoir releases during 2008 simulated a relatively natural spring flow pattern, but a similar dam release in 2009 was abruptly curtailed from 3,800 to 1,350 cfs for three days in late May to aid a search for the body of a missing person, after which higher flows were again resumed. Over this two year study, a total of 14,481 fish were collected from the floodplains, including 15 species. Silvery minnow was the most common species collected in both years, with a total of 9,545 collected in 2008 and 2,057 in 2009. (The interrupted 2009 discharges appeared to disrupt fish behaviors observed during the previous year.) Gravid female silvery minnow were collected from the sites in both years, with the numbers collected increasing from 34 to 44 percent between survey weeks 1 and 2 in 2008, then decreased to 10 percent by survey week 4, whereas the number of post-spawn females increased from 1 percent in week 1 to 43 percent in week 4. Similar, but less pronounced, patterns of increasing percentages of spawned female silvery minnow were observed in 2009 (from 0 to 15 percent during week 1 to 4) at the restoration sites. Similar patterns were also observed for male silvery minnow emitting milt. Silvery minnow eggs and larval fish were collected from the sites both years. Localized turbulent churning of the water surface, as can be produced by spawning fish, was also observed in the floodplain habitat during these studies (E. Gonzales, personal communication, 2013). In combination, these results and observations strongly support the hypothesis that silvery minnow preparing to spawn were actively entering both the restored and natural floodplain habitats prior to spawning and that spawning occurred there. This, however, does not exclude potential that other silvery minnow were also spawning in channel habitats; since these habitats were not assessed during this study.

Concerns about Stranding of Fish on Drying Floodplains

The above discussion and studies point to inundated floodplains as likely the preferred spawning habitats for silvery minnow. However, concern remains on whether floodplain spawning may lead to significant stranding and mortality of silvery minnow in the drying floodplain habitat. Without specific information from the MRG, the work of Moyle et al. (2007) in California provides helpful information. They found that, for fish using the floodplain for spawning, both “adults and YOY [young-of-year] of all native species seemed to have the capacity to find their way off the floodplain before it disconnected ….” They added, however, that “exceptionally rapid, intermittent, and early disconnection” of the floodplain did tend to strand abnormally high numbers of some species. Incidental observations on the MRG indicate that silvery minnow appear to have an innate ability to move in with wetting habitats and out with drying habitats, ahead of other MRG fish species (M. Hatch, personal communication, 2005). From this, it is tempting to suggest that there should be minimal concern about stranding of significant numbers of silvery minnow on the floodplain; particularly, if floodwaters are not rapidly or intermittently drained from floodplains and if floodplains are not disconnected early from the river channel. Recall also from Section 2.7, silvery minnow recue is no longer conducted on the floodplain, instead the USFWS allow young and old fish to find their own way to the river channel. However, studies to verify the validity of this conclusion have not been completed on the MRG. As such, one or more studies similar to Moyle et al. (2007) should be conducted specifically for MRG floodplains.

6.1.2. Physiological Adaptations Key to Low-flow, Drying Channel Habitats

Specialized Adaptations of Silvery Minnows to Water Quality Extremes

Laboratory studies by Buhl (2006a, 2006b) on the effects of low dissolved oxygen concentrations and elevated water temperatures have shown that silvery minnow have a remarkable tolerance to such conditions that would be highly stressful, if not lethal for many other fish species (USEPA 2008). The lab tests included newly hatch, 30-day post-hatch, and 90-day post-hatch juvenile silvery minnow; the oldest group are presumed to have characteristics similar to those for adults. Buhl reported that 50 percent of the exposed silvery minnow could survive a range of 0.5 to 1.1 mg/L dissolved oxygen for up to 96 hours under two different exposure protocols, one allowing the fish to gulp air and one preventing them from doing so. Another of his studies showed similarly low sensitivities to elevated water temperatures nearing 100°F (37°C) (Buhl 2006a, 2006b).

Apparent Developmental Based Adaptations to Drought Conditions

Buhl (2006a, 2006b) suggested that his results have important implications for slivery minnow tolerance to adverse water quality conditions often found in drying pools during flow intermittency. The results also suggest certain adaptations to drought conditions. Specifically, during times of channel drying, the persistence of off-channel or in-channel ephemeral pools can provide important refugia for silvery minnows. Such habitats can develop nighttime dissolved oxygen concentrations approaching 0 mg/L due to net respiration demand by resident biota. Daytime photosynthesis often allows the dissolved oxygen concentrations in the pools to recover. However, markedly elevated daytime waters temperatures can also develop in the pools due to solar heating, which would tend to decrease oxygen saturation in the pools. Riverine fish species that regularly and repeatedly become confined in such environments annually and survive could develop resistance to low dissolved oxygen and high temperature events. The laboratory studies demonstrated that silvery minnow have the capacity to survive in these extreme water quality events. These adaptations may have strongly contributed to their persistence and often dominance among the native Rio Grande fish populations. Indeed, physical and chemical conditions associated with refugia habitats and their formation during drought, have been found to benefit fish populations, their interactions among other species populations, and have reproductive consequences long after the cessation of the drought (Humphries and Baldwin 2003).

Examples of Competitive Advantages Provide by "Adverse Water-Quality Adaptations"

Other fish species in other systems are also known to possess similar resistance to extremes of dissolved oxygen and temperature that are lethal to many fish species. These species commonly occur in plains streams historically affected by frequent channel drying, this particularly includes a cogeneric species of the silvery minnow, that is the Plains Minnow (Hybognathus placitus) (Matthews and Manes 1979, Matthews 1987). The Topeka shiner (*Notropis topeka*) is another recently well studied example, which provides insight on the competitive advantages due to survival adaptations linked to isolated pools in drying channels.

Topeka shiners are a federally endangered species characterized in their listing as,

> *"…found in small to mid-sized prairie streams of the central prairie regions of the United States with relatively high water quality and cool to moderate temperatures. Many of these streams exhibit perennial flow, although some become intermittent during summer or periods of prolonged drought…. Topeka shiners appear to be well adapted to periodic drought conditions common to prairie streams and are able to endure acute periods of high water temperatures. For example, Kerns (1983) found that even though mortality of several fish species was high in desiccating pools, juvenile Topeka shiners seemed especially drought-resistant."*

During their studies of off-channel habitats in Minnesota, Koehle (2006) reported that Topeka shiners were often found to inhabit oxbow lakes, where harsh environmental conditions, such as high temperatures and low dissolved oxygen occur. She reported,

> *"…overall, temperature and oxygen are probably not responsible for Topeka shiner population declines and are not limiting factors in most off-channel habitats. Judging by the abundance of Topeka shiners in off-channel habitats,*

> *these habitats may be population sources, rather than sinks, and thus may be important to Topeka shiner populations."*

In Kansas, Kerns and Bonneau (2002) found that both off-channel pools and ephemeral main channel pools can be important to Topeka shiner populations during periods of drought. They reported that, since Topeka shiners appeared to be more drought tolerant than many species, they were often the last species alive found in drying pools. Additionally, the largest and deepest pools remained habitable throughout the dry season and served as refugia.

Chris Mammoliti (personal communication, 2006), author of the 2004 state recovery plan for the Topeka shiner in Kansas, described that cycles of drying are known to be critical to Topeka shiner. When stream systems holding such species are augmented with the intent to ensure a perennial wetted condition, the low-dissolved oxygen / high temperature adapted fish lose their competitive advantage; then other native and non-native species lacking such adaptations can persist in the system. He concluded that drying, low-flow refuge pools appeared to be a critical-habitat element helping to ensure the survival, persistence, and dominance of the low-dissolved oxygen and high-temperature adapted fish species.

Field Observations of Silvery Minnows Using the MRG Floodplain during Drought

Reports of silvery minnow rescue efforts along the MRG commonly include examples of abundant silvery minnow dominating captures from the drying pools along the disconnected channel (USFWS 2006b). Like other small-bodied fish species in ephemeral river systems, silvery minnow appear to have evolved a robust ability to survive under challenging conditions of periodic drought. Based on studies like those above for Topeka shiner, such abilities have likely contributed to historical claims of dominance by silvery minnow in the Rio Grande. This relationship would tend to support the hypothesis that a critical habitat for silvery minnow has included persistent pools during periods of channel drying. These pools would have been accessible to silvery minnow during drying and have routes that allowed their return to the channel as it rewetted. The opportunity for such pools to develop has diminished as channel reaches have aggraded and groundwater levels have declined with pumped-water use in the valley. Both trends would limit the persistence of such refuge pools.

To address this altered habitat condition, the Collaborative Program's *Silvery Minnow In-channel Wetted Habitat Workgroup* (2005) proposed to assess the development of a "string-of-pearls" pool systems for the MRG channel, which was to be fed by irrigation return water and/or water from the Low Flow Conveyance Channel, (see Appendix D). If feasible and implemented, such a habitat restoration project could help to address contemporary habitat changes in the MRG and provide silvery minnow habitat that once may have provided a key competitive advantage supporting their frequent dominance in the native Rio Grande fish community.

6.1.3. Key Feeding Habitat for Post-Spawn Silvery Minnow Adults

As discussed in Section 3.2, the relationship between flow, velocity, and the production and availability of food for silvery minnow in sandbed systems naturally leads to questions about where silvery minnow feed when spring and storm flows in the MRG exceed 0.5 ft/s. Of critical importance is, where do silvery minnow feed in the days, weeks, or months of high velocity springtime river flows after their principal period of spawning?

An Inadequate Definition of Silvery Minnow Feeding Habitat

Neither the expired 2003 BO (USFWS 2003) nor the current silvery minnow Recovery Plan (USFWS 2010) provide a definition of critical feeding habitat for silvery minnow. The recovery plan includes, as its third primary constituent element, the need to provide “appropriate silt and sand substrates, which are important in creating and maintaining appropriate habitat and life requisites such as food and cover.” Section 3.2, above, described how the instability of silt and sand substrate provides a very poor substrate for growing or accumulating silvery minnow food. As such, it would seem that such a substrate would most often *not* provide appropriate habitat for food or cover for this fish. The quoted statement from the Recovery Plan likely relates to the fact that the most common bed material in the MRG is silt and sand, therefore silvery minnow are most often found over this substrate, not because it is preferred but because it is what predominates in the MRG. Certainly, a mobile silt and sand substrate is among the most unsuitable habitat for growing the diatoms, algae, and other aquatic microorganism plus for accumulating fine organic material on which silvery minnows predominately depend on for food. It is interesting to note that during the USGS (2014) assessment of silvery minnow habitat in the Big Bend reach of the Rio Grande, “silvery minnow was more commonly collected in seine hauls from mesohabitats dominated by cobble substrates and less frequently collected in mesohabitats with substrates dominated by fine-sized silt and clay particles, gravels, and sands, in that order.”

Inundated Floodplain Habitats can Provide Critical Feeding Areas during Flood Conditions

The historical channel of the MRG during high volume spring and storm flows included dynamic conditions of regular channel avulsions, considerable channel diversity, and extensive inundation of the floodplain during the spring snowmelt (Crawford et al. 1993). The avulsive nature of many Rio Grande floods frequently “re-set” the river’s ecology with newly relocated generally wide, multi-threaded channels along its course that yielded opportunities for re-development of the riparian community along many reaches. The silvery minnow adapted to such conditions, as discussed above. That is, high volume spring flows could persist for days, weeks, and months, in some years, flushing food from the mobile sandbed and from confined channel reaches. (This is particularly true for the present state of the channel in the MRG.) In contrast, inundated floodplains can provide abundant supplies of newly wetted fine particulate organic matter and invertebrates of terrestrial origin as readily available food for fish during the time of flood flows (Pease et al. 2006). As such, inundated floodplains likely have been of critical importance to the survival of post-spawn silvery minnow adults.

Post-spawn Adult Silvery Minnow Critically Need High Quality Feeding Habitat

Appropriate feeding habitat is critical for the survival of adult silvery minnow following spawning in the spring. Production of eggs and sperm along with the activity of spawning are two of the three most energetically demanding activities in the life cycle of a fish. Maintaining water position during periods of high flows is the third. The co-occurrence of these three activities before and during periods of springtime flows in the MRG would tend to maximize stress and energy demands on silvery minnow. The stress produced by these three demands are further intensified in the spring because they occur at the end of the winter during which photosynthesis and food production for silvery minnow have been limited by the cold winter water temperatures. Silvery minnow enter the spring with low energy stores to spawn in the high flow contemporary MRG channel, where most potential food has been scoured away. This lack of available feeding habitat at the critical post-spawn life stage likely correlates directly with the basis for concluding from silvery minnow population monitoring results from the past three decades that relatively few silvery minnow live beyond their first or second spawning, with most mortalities occurring relatively shortly after spawning for either age (e.g., Platania and Dudley 2003).

Assuming that historical populations of silvery minnow moved from the limited confines of the defined channel habitat and onto broadly inundated floodplains to spawn during periods of the high volume spring snowmelt flows, and during other high flow periods, it is then reasonable to hypothesize that extensive silvery minnow feeding would have occurred in these areas having extensively available food resources. Also, with the slowing of channel flows and lowering water levels, food materials and nutrients would drain from the floodplain to enrich the channel habitat. Then, this would help to rapidly stimulate primary productivity and new food resource supplies for silvery minnows within days after sufficient slowing of channel flows, particularly along the shallower, lower-flow, braided channel sections.

The above discussion strongly indicates that the early death of silvery minnow (after their first or second spawn) may not always have been normal and that older (> 2 years old) silvery minnow may once have been common along the MRG when broadly inundated floods were widespread providing abundant food resources for all age classes of silvery minnows. This tends to be supported by the finding that laboratory cultures have documented silvery minnow commonly living much beyond 1 to 2 years (e.g., K. Buhl, USGS, personal communication, 2006).

6.2. Patterns of In-channel and Floodplain Habitat

In-channel Habitat – Our assessment to characterize patterns of in-channel and floodplain aquatic habitat has employed a set of complementary two-dimensional hydraulic models. We have defined in-channel habitat to be the total area available below and including bankfull stage. In the mobile-bed environment of the MRG, this is an ever-changing condition as islands, bank-attached bars, and complex aggradation/degradation patterns continuously reshape the active channel.

The hydraulic models produce an output containing depth and velocity variables for a gridded network of cells. With post-processing of the model outputs, each grid cell contains a value for both depth and velocity and thus the ability to query the network for various depth-velocity combinations. These combinations define habitat characteristics, or flow-ecology relationships, that can be spatially quantified. It must be noted that both the in-channel and floodplain models are somewhat dated (2003 and 2006, respectively). As a result, the location and extent of silvery minnow habitat has undoubtedly changed, but we believe the overall patterns and general interpretations of habitat availability we infer from these models remain valid. What is likely to be more impacted is the stage where floodplain inundation occurs. That is, either aggradation or degradation of the channel has led to locally different overbanking thresholds. Once floodplain inundation occurs, however, the patterns, locations, and extents should be similar as the floodplain is far less likely to undergo widespread structural changes.

The results for the in-channel models show reasonable amounts of Most Commonly Occupied Habitat at lower and some mid-range flows. Where extensive bank-attached bars are present, Most Commonly Occupied Habitat area can be significantly increased at higher flows as these areas are increasingly inundated. It appears, however, that because bank-attached bars are generally not complex in their topography, the expanded area does not necessarily translate into habitat diversity (i.e., a commensurate increase in the area of spawning and rearing habitat categories). In fact, there is a distinct lack of Highest Quality Feeding and Rearing Habitat and Highest Quality Spawning and Egg/Larval Retention Habitat across all sites except at the Bosque del Apache site, which has a more complex topography, including an extensive bank-attached bar along the west floodplain in 2003 that is readily inundated; however, contemporary conditions are very different at this site and inundation of the west floodplain would likely be much reduced. Nonetheless, the pattern of greater habitat availability being related to bar inundation is evident but, again, does not necessarily include the spawning and rearing habitat categories (for example, compare the Bernalillo and Bosque del Apache sites). In addition, another obvious pattern shows a negative relationship between habitat availability and increasing discharge that is common at all sites – although, the relationship manifests at different discharge profiles and can be mitigated to some degree by structural enhancements to the active channel (i.e. bank-attached bars or islands). Habitat area (and percent of active channel) reductions are often precipitous indicating the very limited nature of silvery minnow habitat within the active channel. This notion is further supported by the habitat mapping (see Appendix A). In general, based on the in-channel modeling we can conclude the following:

- Most Commonly Occupied Habitat (basically adult and young-of-year habitat) is fairly replete at lower and mid-range discharge levels.
- Except where appropriate and extensive structural features (bank-attached bars and islands) exist, spawning and rearing habitat categories are very limited and largely discontinuous within the active channel.
- All habitat categories show a negative relationship of availability and increasing discharge. This trend can be improved somewhat by the presence of appropriate structural features.
- Small bank-attached bars and islands, even when numerous, do not provide notable silvery minnow habitat of any kind.
- A complex braided or anastomosing channel, cut through extensive bars, appears to be the best in-channel planform for all habitat categories.

Floodplain Habitat – Here also, we employ a set of spatially adjacent, two-dimensional hydraulic models to characterize aquatic floodplain habitat defined by the area above the bankfull stage inundated at less frequent, larger magnitude discharge. In the highly regulated and channelized setting of the MRG, the floodplain is very stable and not likely to undergo significant structural alterations; although fire is a contemporary driver in the structure of the terrestrial ecosystem and thus a component of the aquatic floodplain habitat dynamic.

The results of the floodplain hydraulic models are also a gridded output, the resolution of which is much courser than the in-channel models. Nonetheless, the results provide a comprehensive view of flow-habitat relationships through identical queries of the combined depth-velocity characteristics of the model output. Like the in-channel models, the floodplain models are also somewhat dated (parameterized in 2006). This is less important here as again the floodplain is far more stable than the active channel. A more meaningful consideration is how changes in the active channel (aggradation/degradation) locally influence the stage at which a given inundation event occurs. There have certainly been changes in this regard during the intervening years but we cannot quantify where and by how much without newly constructed models. Once floodplain inundation occurs, however, the patterns and extent should be similar between the 2006 model predictions and contemporary conditions. The exception is recent habitat restoration efforts completed by the USACE in the Albuquerque subreach.

Although results for the reach-wide floodplain modeling show many similar patterns, some important differences are apparent. The Angostura Diversion Dam to the north boundary of the Isleta Pueblo Reach does not begin to experience significant inundation until 7,000 cfs, with greater amounts of all habitat types at the 10,000 cfs discharge. These levels, however, are at or exceed the functional conveyance capacity of the MRG; as witnessed in 2005, damage to infrastructure (levees and irrigation facilities) begins at approximately 7,000 cfs in many areas. Therefore, the floodplain in this reach is realistically isolated and does not provide meaningful silvery minnow habitat. Despite the conveyance limitations, the pattern of floodplain habitat area, of all categories, shows a positive relationship with increasing discharge; however, the percent of total inundation is negatively correlated with increasing discharge. The south boundary of Isleta Pueblo to the San Acacia Diversion Dam reach shows nearly an identical pattern except significant inundation begins at the lower discharge of 5,000 cfs. In addition, the 10,000 cfs discharge shows a slight decrease in area of the spawning and rearing habitat types. Percent of total inundation shows a progressive decline with increasing flow. Interestingly, and different from the previous reaches, the San Acacia Diversion Dam to San Marcial Railroad Bridge reach shows normal distribution of habitat area and flow with the maximum area of habitat at the 5,000 cfs discharge. The percent of inundation follows a familiar negative relationship with increasing flow, being greatest at the 2,000 cfs discharge.

Based on the results of the floodplain models, we can conclude the following:

- The Most Commonly Occupied Habitat is plentiful at all discharge levels, similar to the in-channel habitat output. This is less meaningful in the floodplain as this area is not frequently inundated and, when it is, the duration is typically short. It is therefore not applicable for sustainable adult (non-breeding) habitat.
- Widespread floodplain inundation within the three reaches occurs at notably different discharges, decreasing from upstream to downstream.
- Notwithstanding the discharge at which inundation occurs within each of the three reaches, there is a positive relationship between increasing discharge and all types of habitat area in the Angostura to north boundary of Isleta Pueblo reach and the south boundary of Isleta Pueblo to the San Acacia Diversion Dam reach whereas the San Acacia Diversion Dam to San Marcial Railroad Bridge reach shows maximum habitat area at 5,000 cfs. This indicates that the maximum habitat area has been attained in the latter while additional habitat may be available in the upstream reaches.
- All reaches show a negative relationship between percent of floodplain inundation and increasing discharge. This suggests there is a trade-off between habitat area and the amount of water used (or discharge attained) for silvery minnow spawning and retention habitat purposes.

Key attributes for successful silvery minnow breeding include adequate shallow water habitat with low overall velocities. Shallow water zones promote primary production and suitable food resources for developing young. Low velocities promote egg and larval retention thus resisting downstream displacement. The in-channel model results show that these conditions are not common and, when they do occur, are not generally continuous. Further, as flows increase and the active channel fills, suitable breeding habitat becomes even scarcer; however, some suitable habitat can be gained where diverse bank-attached bars are present. Although our sample size is limited and not designed to assess relative differences, it appears that a series of small islands and/or bars do not afford the same level of quality breeding habitat types. Where these smaller features occur, silvery minnow breeding habitat tends to be very patchy and discontinuous at best. Even where larger in-channel features are present, silvery minnow breeding habitat can be limited (see Bernalillo vs. the Bosque del Apache in-channel study sites, Appendix A). While, Most Commonly Occupied habitat is fairly widespread in the active channel, it tends to also diminish as flows increase. Conversely, in-channel breeding habitat appears to be functionally limited by the nature of the active channel itself and, while silvery minnow do obviously spawn in the active channel, it does not provide for egg/larval retention at greater flows that would tend to stimulate spawning.

When sufficiently inundated, the floodplain provides extensive habitat of all types. Most importantly, however, are the breeding habitat categories. Thresholds of floodplain inundation differ between reaches in two ways. First, it merely describes the discharge at which floodplain inundation occurs and becomes widespread. Second, as an inflection point where habitat is maximized; that is, where larger flows do not increase habitat area. Again, in the Angostura Diversion Dam to the north boundary of Isleta Pueblo reach widespread inundation is absent below the functional conveyance capacity of 7,000 cfs. Silvery minnow habitat does increase at 10,000 cfs but this consideration is unlikely as, without significant improvements to flood control infrastructure, these flows will not be reached. Thus, in this reach, silvery minnow breeding habitat is confined to the active channel and, as we have seen, is very limited, certainly not optimal, and subject to a downstream displacement of progeny. Thresholds in the south boundary of Isleta Pueblo to the San Acacia Diversion Dam reach show widespread inundation beginning at 5,000 cfs and maximum breeding habitat at 7,000 cfs. Since the 7,000 cfs discharge level is at the functional conveyance capacity, the 5,000 cfs would appear to be the threshold for maximum habitat area. In the San Acacia Diversion Dam to San Marcial Railroad Bridge reach, significant inundation is evident at the 3,500 cfs discharge with some inundation occurring at 2,000 cfs. Maximum habitat area occurs at 5,000 cfs; however, there is a steady decrease in percent of total inundation as flow increases that could be considered an efficiency trade-off between habitat area and volume of water needed to achieve a certain level of inundation.

Taken together, the results from the in-channel and floodplain models strongly suggest that the long-term viability of the silvery minnow is dependent on the extent of the river’s connection to its floodplain. Without this connection, flows once thought to foster a beneficial breeding environment (both spawning and rearing) do not appear to be as supportive. Rather, the floodplain must be inundated to provide the necessary shallow water, low velocity habitat. If the floodplain is not connected, then spawning releases are not an efficient use of water in terms of silvery minnow habitat and recovery efforts as the vast majority of eggs and larvae tend to be displaced downstream and what progeny do remain in upstream reaches do not appear to have adequate rearing habitat.

7. Conclusions, Implications, and Recommendations

7.1. The Habitat Quality Assessment Criteria can be Refined

In Section 3, above, the bases for the *high quality habitat* criteria used during this assessment were defined. As described, all three criteria were developed using available information from the literature. The validity of these criteria, however, has not been confirmed through field investigations for silvery minnow in the MRG. In particular, the water depths used in the criteria for defining highest quality feeding and rearing habitat and for spawning and egg/fry retention habitat are likely excessively deep. Both criteria defaulted to the water depth used for the criteria for *most frequently occupied habitat*, for lack of any clear, defendable bases for defining shallower depths. In reality, primary production, and hence rearing habitat, is minimal in the turbid conditions of the mainstem at depths greater than a few inches. Also, field observations of silvery minnow egg distributions and apparent silvery minnow spawning activity indicates that most may occur in water depths of 3 to 6 inches (M. Porter, USACE, personal communication, 2014). This observation, however, may reflect observational bias as observing or sampling spawning activity in deeper water is difficult at best, due to high in-channel flow velocities with depth during times of spawning, typically making sampling dangerous, and bottom vegetation along the bottom of floodplains that snag nets makes sampling difficult.

Despite indications that the depths used in this assessment for these two criteria are excessively deep, these values were used to provide relatively liberal water depth definitions so that the assessment results would not appear to be artificially constrained in using an excessively conservative criteria to produce artificially low aerial projections of quality habitat. Future field research of the life history / habitat relationships for silvery minnow in the MRG is required to refine the screening criteria that could be used for potentially more accurate future habitat quality assessments.

7.2. The Model Results used Yielded the Best Information Available of High Quality Habitat for Silvery Minnow

Section 5.1.1 stated that the results derived from the RMA2 modeling for in-channel habitat and those from the FLO-2D for floodplain modeling are approximately a decade old, and the river channel and its connectivity to the floodplain have undoubtedly since changed. In addition, in the years since these models were developed, the Collaborative Program and its major members, including individual pueblos, the USACE, NMISC, USBR, and the City of Albuquerque, have installed many acres of both in channel (e.g., island, backwater, and side channel) and off-channel (bankline and floodplain) habitat restoration projects. These have likely improved habitat conditions for both species in the localized areas. It is also important to recognize that both of the assessments of modeled output were completed using information collected and models produced to represent general conditions in the reaches at that time. Therefore, while site-specific environmental conditions have changed since these models were completed, there is currently no clear reason to conclude that these projections are any less representative of the overall average conditions of MRG reaches today (except for the San Marcial Reach, which has had significant head cutting in recent years due to the drawdown of Elephant Butte Reservoir). Assessing the correctness of this conclusion requires updating these earlier modeling assessments, particularly the FLO-2D assessment using the improved, higher resolution model now available. Until such time that funding to update the models becomes available, these two earlier modeling projects provide the best available information to prioritize future MRG habitat restoration projects.

7.3. Options Exist for Future Model Development

Due to the age of the hydraulic models available for use in this habitat assessment, there is a need for the MRG hydraulic modeling to be updated. The most powerful technical choice for such an effort would be to construct an SRH-2D model (Lai 2008). SRH-2D is a fully integrated, two-dimensional hydraulic model that allows both the active channel and overland floodplain flows to be modeled in concert. The SRH-2D also accords the ability to model flows over in-channel structures, such as diversion dams, as well as flows through reservoirs and tributary systems. While a strong technical choice, the construction of large, reach-scale SRH-2D models would require a significant investment in terms of time and money. Such models would provide highly resolved outputs capable of very accurate and precise predictions of habitat conditions. Also, like any other hydraulic model, an SRH-2D model could be updated as physical conditions change. This would allow for the maintenance of the accuracy and precision of the original model at a more moderate cost. Since costs for extensive reach-scale modeling are likely to have programmatic limitation, small site-specific scale models also can be especially useful for individual pre- and post-construction habitat restoration assessments in the MRG.

A less costly but still reasonable alternative for reach-scale assessments would be to develop an updated FLO-2D model based on a finer grid than was available for use during our current assessment. Such a model update also could be supplemented by a number of representative in-channel SRH-2D models. An obvious disadvantage with this alternative would be the discontinuous in-channel component of the SRH-2D modeling framework and the lack of tangible information for all but a few in-channel study sites. In either case, the development of contemporary hydraulic models is strongly recommended. An updated FLO-2D model would provide a basis to produce at least first-order assessments of benefits produced along the MRG by the habitat restoration projects.

7.4. Connected Floodplains are Critical Silvery Minnow Habitats

The Section 5 assessment and the subsequent discussion highlight the importance of floodplain connectivity and channel diversity as critical aspects of the historical habitat for silvery minnow and a continuing critical habitat need for the species. Specifically, in other locations inundated floodplains have been found to be key habitats for fish; this is also likely true in the MRG where inundated floodplains would tend to benefit:

(1) Spawning, egg retention, survivability, and recruitment in to the population of young silvery minnow due to the minimum current velocities in these areas;

(2) Development of eggs and growth of young silvery minnow due to the comparatively shallower and clearer water that aids solar warming of the water benefiting primary production of diatoms, algae, and other microbial food resources, plus provide newly wetted organic matter and invertebrates of terrestrial origins as food for silvery minnow of all ages; and

(3) The potential survivability of post-spawn adult silvery minnow, leading to an increasing number of spawning cycles and thereby increasing the population viability for silvery minnow in the MRG.

Fundamental to this last point, egg production by other female *Hybognathus* species has been reported to increase exponentially with length and age (e.g., Young and Knoops 2012). As such, designing and implementing habitat restoration projects along the MRG that are intended to increase the potential abundance of older, larger silvery minnow in the population would have the likely consequence of increasing recruitment, population viability, and the potential recovery of silvery minnow.

7.5. Elevating MRG Flows above Low Threshold Levels Degrades In-channel Habitat Quality for Silvery Minnow in the MRG

The in-channel habitat assessment, based on the existing RMA2 model interpretation, demonstrates some important patterns. First, there appears to be reasonably abundant *Most Commonly Occupied Habitat* at lower flows. This is essentially adult silvery minnow habitat having the least stringent velocity requirements of the criteria assessed. This is consistent with Bovee et al. (2008) who concluded that optimal habitat at three sites in the Isleta Reach occurred at discharges of less than100 cfs (see Section 2.8.3, above, for a more detailed discussion of that assessment). Second, both categories of breeding/egg and larval retention habitat and feeding/rearing habitat have very limited aerial extents at all discharge rates modeled. Third, the spatial extent of all habitat categories is negatively correlated with discharge – high quality habitat decreases rapidly with increasing discharge. The negative relationship, however, can be mitigated to some degree by the occurrence of extensive bar, island, and/or connected ephemeral side channel features. The value all such features, however, can be enhanced by the increased topographic diversity within the habitat as well as by the development of dense vegetative growth that helps to support the array of silvery minnow habitat needs over a range of increasing discharge volumes (for example, compare Bernardo and Bosque del Apache NWR in-channel results, Appendix A).

The pattern of *in-channel* habitat quality declining with increasing discharge appears to be in direct opposition to reproductive and feeding needs for silvery minnow. That is, with a confined channel under highly regulated flows, floodplain inundation is limited during both nominal runoff and drought conditions. Floodplain inundation is ostensibly the best option for developing extensive areas of habitat for egg/larvae retention and feeding (which the available literature shows to have been a dominant feature along much of the historical Rio Grande). Since in-channel silvery minnow habitat decreases precipitously with increasing discharge, spawning flows that do not inundate the floodplain do not produce favorable recruitment conditions throughout the MRG nor do they appear to be an efficient use of a limited water supply. Thus, when spawning pulses having markedly elevated flow velocities are released, these discharges should be of sufficient magnitude (attenuated for channel seepage losses) to adequately inundate the floodplain in the target reach or reaches. Without floodplain inundation during high discharge volumes, most newly spawned silvery minnow eggs and larvae are destined to be flushed downstream; of considerable concern here, the available literature from experimental channel and natural stream studies indicates that such events produce extremely high mortality rates, if not total mortality of the displaced larvae (Harvey 1987). Again, exceptions to this appear to be when extensive in-channel structures (e.g., bars, backwaters, and vegetated side channels) are present. It must be noted, however, that such features need to be (1) fairly large and (2) sufficiently diverse in topography. Finally, it also must be recognized that the larvae of many fish species can and do successfully drift for considerable distances during periods of low-flow when their survivability is not at significant risk. Such drift is thought, for example, to contribute to population recruitment in larger downstream rivers (Muth and Schmulbach 1984).

7.6. Achieving Marked Floodplain Inundation Requires High-Volume Discharges

Our assessment of the FLO-2 modeling results shows that the 2006 floodplain began to inundate at flows in the range of 7,000 cfs in the Angostura to Isleta Reach, 3,500 cfs in the Isleta Pueblo to San Acacia Diversion Dam reach, and 2,000 cfs between San Acacia Diversion Dam and the San Marcial Railroad Bridge. Significant silvery minnow habitat is not achieved until the floodplain is engaged. Until that occurs, quality silvery minnow habitat tends to be very limited and is primarily located only in bank attached bars and islands. The modeled results indicate that these areas tend to be discontinuous in most reaches and provide minimal areas of quality habitat area, except within the Bosque del Apache NWR.

Successful recruitment of young silvery minnow into the population appears to occur at minimal spring discharges in the range 1,500 to 2,000 cfs, as discussed in Section 2.2. Recruitment success tends to increase, however, with greater flow volumes producing increased floodplain inundation. While the FLO-2D modeling results indicate that discharges of less than 2,000 cfs would produce no measurable floodplain connection in any reach, the assessment cells within the model are too coarse to capture smaller slack-water areas potentially occurring within these cells. Also, this FLO-2 model was developed prior to habitat restoration projects were installed along the MRG. Nevertheless, the overall general lack of significant inundated floodplain habitat along the MRG would tend to minimize annual potentials for silvery minnow recruitment, particularly in the Angostura and Isleta reaches. Spawning that occurs at these lower flows is suspected to most commonly occur along in-channel microhabitats such as channel margins, small backwater pockets, and areas where eddy currents tend to minimize flows. Spawning in such locations and conditions would tend to maximize downstream displacement of eggs and larvae as most would quickly be flushed from these small, relatively quiet-water areas. This would minimize the survivability of the flushed larvae, lowering overall population recruitment, viability, and recovery. The sand beds, feeding habitats, and food resources for silvery minnow in the MRG also mobilize during the high flow events, leaving little in the way of food resources for newly hatched larvae or the post-spawn adult silvery minnow.

7.7. Lower Minimum Activation Flows can Benefit the Persistence and Effectiveness of Restoration Designs for Inundation

Past habitat restoration designs have often used a minimum discharge of 1,500 cfs as the trigger to produce overbank flows and floodplain inundation. This is the discharge that has been commonly associated with successful recruitment of silvery minnow. Such designs would then start producing habitat at the 1,500 cfs trigger flow that is most suitable for spawning, while also minimizing downstream drift of eggs and larva, increasing survivability of larva and post-spawn adults, and increasing population recruitment, viability, and recovery.

Setting habitat restoration designs to trigger floodplain inundation at discharge volumes approximating projected minimum spawning discharge rates can lower initial costs for construction earthmoving. Unfortunately, such designs also can result in increased future maintenance costs. That is, rivers naturally deposit fine sediment along their margins, due to the decrease in flow energy in these areas. These natural levees then form and grow with continued sediment deposition along the shorelines, including along constructed habitat restoration projects. In turn, this leads to ever greater discharge volumes being required before floodplain inundation initiates at the restoration site. To maintain inundation initiation at designed flows that equal minimal spawning flows would tend to require regular mechanical removal of the accumulated material.

In contrast, habitat restoration designs set to initiate overbank flows at markedly lower than minimal in-channel flows for spawning would more frequently scour sediment accumulated along the natural riverside levees before they become armored in place through compaction and vegetative growth. With such designs, post-construction costs have the potential to be much less due to reduced maintenance requirements. Actual flows needed to trigger these designs would depend on the projected river hydrology, the nature of the local bed material and modeled flow hydraulics at the post-construction site. Consistent monitoring of sediment accumulation patterns for both shorelines and interior inundated areas associated with habitat restoration designs would help provide the necessary understanding for defining the best approach to enhance the benefits to species and the persistence of constructed restoration features. This information could lead to developing more cost-effective construction designs.

7.8. In-channel Habitat Restoration to Benefit Silvery Minnow Recruitment Requires Large Contiguous Areas of Inundation

The interpreted RMA2 modeling results show that, even where relatively high-quality in-channel habitats are shown to exist, these areas most commonly include relatively small, separated patches of quality feeding and rearing and egg/larvae retention habitat. Thus, when silvery minnow schools concentrate onto such small patches of in-channel habitat, these areas would not long persist as quality feeding habitat for more than a relatively few silvery minnow. In addition, due to their generally small, discontinuous nature, small habitat patches would also have minimal value for silvery minnow spawning or egg retention. Most developing silvery minnows would not likely remain confined for long within such a limited area before drifting into a faster current where their potential survival rates would markedly decline. This relationship highlights the need, when designing *in-channel* habitat restoration features, to produce the largest feasible areas that meet the habitat quality design criteria for the silvery minnow life stage(s) for which the features are designed to benefit. Due both to their size and location, small in-channel restoration projects of limited size, including small mid-channel bar and island lowering projects, produce the least benefit for habitat quality. These locations also have a relatively short lifespan. Additional research and monitoring is required to define “how large is large enough to maximize habitat benefits and minimize construction and maintenance costs.

7.9. Reaches with Marked Channel Drying Require Special Considerations for Siting Key Habitat Restoration Projects

From a management perspective, reaches of the MRG shown in red and yellow in Figure 6 should have a high priority for management actions to improve water supplies and/or reduce water loss. If reasonable opportunities for the success of such measures are not available, these reaches should have, for example, lower priorities for habitat restoration projects requiring dependable water supply. The affected reaches, based on the three years of monitoring data, would apply to RM 74 through 104 in the San Acacia Reach and RM 132 through 137 and RM 151 through 167 in the Isleta Reach. In the San Acacia Reach, this includes, roughly, the subreach from the south boundary of Bosque del Apache to the Escondida Bridge. In the Isleta Reach this includes approximately 2-miles north of the US 60 crossing of the MRG to 3-miles south of Jarales Road and 1.5-miles north of NM 309 crossing to at least the south boundary of Isleta Pueblo. In contrast, these reaches, particularly their more upper and lower extents, do deserve special consideration for the development of refuge habitat, as discussed in the next subsection.

7.10. Silvery Minnow Need Drought Refuge Habitats

As described in Section 6.1.2, the history of silver minnow throughout the Rio Grande would appear to have led the species to develop a set of specialized tolerances. Such adaptations by this species, as is true for any species in other environmental settings, allow individuals to survive and populations to persist during times of environmental stress, such as periods of drought and channel drying. Specifically, the abilities of silvery minnow to withstand extremely low dissolved oxygen concentrations and very high water temperatures, fatal to many other fish species, would appear to have helped this species to become at times the dominant fish species in the Rio Grande, similar to that documented for other species in other river systems.

Unfortunately, the kind of historically persistent ephemeral pools, maintained by groundwater, do not currently develop or persist along most of the present-day MRG. Such pools have been documented as key in other river systems, for native fish species having similarly high tolerances to low dissolved oxygen concentrations and high water temperatures, as reported for silvery minnow, to survive and dominate the fish fauna. Aggrading channels, particularly over large portions of the Isleta and San Acacia reaches and the overall lowering of groundwater elevations along the MRG largely prevents the development of such refugial pools.

In 2005 the members of the, then called, Science, Habitat Restoration, and Water Acquisition and Management subcommittees worked together in developing a conceptual approach for restoring reaches of perennial in-channel wetted habitat along the MRG. The Collaborative Program Steering Committee approved funding to continue assessment of this approach; Appendix D, below, includes the document supplied to the Steering Committee for this approval. This document presents the collective knowledge of this group at this time and, perhaps, more importantly, remaining questions the group hoped to answer. The viability and effectiveness of the approach remains to be evaluated.

At the time that document was developed, the primary focus was on considerations related the development of in-channel wetted habitats, where a series of in-channel pools would be regularly watered by, for example, irrigation returns, irrigation wasteways, or pumping from the LFCC.

That group also gave limited considerations to options for off-channel refugia pools maintained by similar water sources. During that same period, the Collaborative Program and MRGCD also supported a project that installed cottonwood snags in the MRG channel with the intent to create and maintain high-flow scour pools in the riverbed (Wesche et al. 2006). The efficacy of this approach to benefit silvery minnow in this sandbed system remained inconclusive due largely to the lack of high-flow events during the period of the study and during subsequent years of monitoring. High-flow events are key to developing and maintaining such in-channel pools. Indeed, a problem with any in-channel refugia pool system within the MRG would be their tendency to infill during periods of lower flows.

USACE researchers reported that small floodplain pools (less than 2 m deep, less than 500 m^2) along large river systems are commonly inhabited by species morphologically and physiologically adapted to shallow, periodically hypoxic water with wide temperature regimes, inhospitable to most except a few fish species (Hoover and Killgore 2002). In some such pools during long periods of drought which causes pools to remain isolated, individuals of some fish species have been found to survive for 27 to 34 months. As such, Hoover and Killgore (2002) concluded that, considering the importance of floodplain pools to some key species and the ease with which these pools can be created, such habitats are attractive candidates for mitigation or for habitat enhancement. Unfortunately, as they also point out, appropriate models to evaluate habitat quality or for developing construction guidelines for floodplain pools do not exist. Therefore, a future priority for the MRG would appear to assess the feasibility and options for developing off-channel refugial pools to benefit silvery minnow survival and recovery during periods of both short-term drought and long-term climate change.

7.11. MRG Water Management involves Trades Offs and Thresholds

Due to the low snowpacks during the winters of 2012-2014, the MRG has witnessed a period of extreme drought, at times relieved by major monsoonal storm flow events. It is unknown whether limited water supplies to the MRG will continue as the new reality for the system, or whether the pattern is just a temporary transitory climatic cycle. If predictions hold, water supply under the current climate change predictions will continue to decline in the range of nearly 10 to more than 50 percent (Section 2.6, Bui 2011, Gutzler 2013). If so, then the water supply available to aid the recovery of silvery minnow will clearly become even more limited. Such forecasts point to a supportable conclusion that water management RPAs presented in the now expired 2003 BO (USFWS 2003) are not realistically obtainable goals, as described in Section 7.11.1. It remains unknown whether the pending new BO for water operations along the MRG will include alternative goals under alternative projections of future climatic change effects.

It is beyond the purview of this project to define appropriate water operations and management practices to optimize the MRG habitat for silvery minnow. Our assessment, however, does point to several concerns that should be incorporated into the development of obtainable water operation alternatives intended to benefit silvery minnow persistence and recovery during times of limited water supply. These alternatives include what could be considered tradeoffs between water needed to induce spawning and upstream retention of silvery minnow eggs and larvae versus maintenance of water in the channel during the irrigation season. The following provides a set of considerations that could, with minimal water supply needs, help to ensure the potential persistence of silvery minnow in the MRG.

7.11.1. Adequacy of MRG Flows to Meet Historical 2003 BO Requirements

In 2005 hydrologists representing member participants of the Collaborative Program computed estimated MRG water volumes that would be required to meet the wet, average, and dry year RPAs included in the 2003 BO. Using historical gage records (1940-1999) they computed the sufficiency of unregulated Rio Grande flows to meet these RPA flow targets in the BO. Results from these analyses indicated that the average historical flows along the MRG, as assessed, would be inadequate to meet the water management RPAs defined in the 2003 BO during 26 percent of the years (WAMS 2005).

In short, these analyses indicated that as much as 97,000 acre-feet of water would be required to meet the BO's RPAs under Article VII years[1] with poor snowmelt runoff and a dry monsoon season, 84,000 acre-feet for an average monsoon year, and 72,000 acre-feet in a wet monsoon year. In contrast, in a wet year lacking the constraints of Article VII and having an average to above snowmelt and monsoon season would require 21,000 acre-feet to meet the BO.

The analyses indicated that an average of 50,000 acre-feet would be required to meet the BO RPAs over time. Also, on average, there would be insufficient flows to meet Article VII and BO-defined Dry Year flow targets during approximately half of the years, particularly in the months of July through September, with September being the month in which flows would be most commonly lacking (Table 7).

Table 7. Probabilities that mean daily flows in the MRG would have been insufficient to meet BO flow targets over the period of record 1940-1999 analyzed (WAMS 2005).

Month	**March**	**April**	**May**	**June (1st half)**	**June (2nd half)**	**July**	**August**	**September**	**October**
Probability that mean daily flow would be equal or less than RPA flow	0.05	0.13	0.08	0.16	0.06	0.24	0.26	0.29	0.17

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[1] Under Article VII, as defined in the Rio Grande Compact, "Neither Colorado nor New Mexico shall increase the amount of water in storage in reservoirs constructed after 1929 whenever there is less than 400,000 acre feet of usable water in project storage; provided, that if the actual releases of usable water from the beginning of the calendar year following the effective date of this Compact, or from the beginning of the calendar year following actual spill, have aggregated more than an average of 790,000 acre feet per annum, the time at which such minimum stage is reached shall be adjusted to compensate for the difference between the total actual release and releases at such average rate; provided, further, that Colorado, or New Mexico, or both, may relinquish accrued credits at any time, and Texas may accept such relinquished water, and in such event the state, or states, so relinquishing shall be entitled to store water in the amount of the water so relinquished." Note that all upstream NM reservoirs in the Rio Grande drainage were constructed after 1929. An overriding consequence for Article VII years is that the MRGCD has no storage available for supplemental irrigation releases during the year and that its operations throughout the year will consist solely of run-of-river plus the storage and release of Prior and Paramount water for the six Middle Rio Grande Pueblos.

7.11.2. Spring Spawning Flows

Based on laboratory studies, flow durations of 7 days at 20°C appear to be the minimum necessary to produce successful recruitment of silvery minnows into the population (Platania 2000). Flow spikes of 100-200 cfs over ambient flow conditions can sometimes produce silvery minnow spawning (M. Porter, USACE, personal communication, 2014). Flows above 1,500 cfs at the Central Gage provide some inundated habitat in the Albuquerque reach and appear to be correlated with years with successful recruitment of silvery minnow young into the population (M. Porter, USACE, personal communication 2014). Without the availability of appropriate egg and larvae retention habitat and rearing habitat, detectable recruitment at lesser flows typically does not occur. Additional monitoring is needed during spawning to better understand spawning cues and dynamics.

Calculated using on a flow of 1,500-2,000 cfs for 7 days, approximately 21,000 to 28,000 acre-feet of water would be the minimum needed for producing a successful spring spawn with population recruitment in the Albuquerque Reach; likely more if seepage losses accompanying channel conveyance are considered. Again, additional spawning period monitoring is required to assess the adequacy of this estimate and to refine the actual water volume necessary.

7.1.2 Summer and Fall Flows

Channel drying during the summer and fall irrigation season appears to be the major cause of fish mortality in the MRG. The current climatic trend of decreasing snowpack with lessening spring water supply storage, which is projected to worsen in the long-term due to climate change, indicates the potential for worsening summer habitat conditions for fish in the MRG. As such, an effective strategy is needed to minimize potential impacts on fish, and particularly silvery minnow, during the duration of low seasonal flows in the channel.

Following consecutive dry years in 2011 and 2012 and with a third dry year again having low spring runoff in 2013, the Collaborative Program’s Executive Committee (EC) formed the Minnow Action Team (MAT 2013). This ad hoc interdisciplinary team was comprised of hydrologists and biologists from member agencies of the Collaborative Program. Their mission was to identify the best use of limited supplemental water resources to meet the current needs of the silvery minnow and, to a limited extent, the flycatcher. Their analyses and approaches evolved with changes in snowpack and runoff projections (MAT 2013). The MAT estimated that 86,800 acre-feet of supplemental water would be required to meet the BO’s RPA target in 2013, while it appeared likely that only about 46,000 acre-feet of available supplemental water would be in storage to start the year. The MAT estimated that if the available supplemental water were applied to meet the 2012 BO water supply RPAs, that supply would be consumed by June 25, 2013.

Building from additional model runs and apparently from considerations initiated by the 2005 Silvery Minnow In-channel Wetted Habitat Workgroup (Appendix D), the MAT recommended and the Collaborative Program’s Executive Committee approved a set of recommendations, which included the following.

1) Reduce supplemental water releases as soon as possible to conserve water to maintain species habitat in all three MRG reaches, with managed recession and drying of selected subreach within the Isleta and San Acacia reaches beginning in late May to early June;

2) Attempt to provide continuous flow in the Angostura reach with available water supplies;
3) Employ monitoring and adaptive management approaches to optimize use of the available water as conditions may change;
4) Attempt to maintain suitable silvery minnow habitat below Isleta and San Acacia diversion dams with 2,000 to 5,000 acre-feet of supplemental water, enhance and maintain habitat areas near four drain outfalls in the Isleta Reach, and below the South Boundary pumps;
5) Provide and monitor emergency silvery minnow rearing locations at the Albuquerque BioPark, Los Lunas Silvery Minnow Refugia, and Atrisco Habitat Project; and
6) Increase spawning propagation facilities to allow for increased stocking in the MRG and Big Bend National Park.

While the USFWS acknowledged that some sort of alternative water management actions were needed during 2013, they did not act to approve these actions as appropriate alternatives to the 2003 BO. Fortunately, a wet 2013 monsoon season ameliorated in the situation by reducing the potential river drying along the MRG to somewhat less than had been observed in previous low snowpack years (see Figures 2 and 3, above).

Previously, a preliminary estimate produced by the Silvery Minnow In-channel Wetted Habitat Workgroup (2005) of the water volume required to maintain approximately 41 miles of flow-connected channel and in-channel pool habitat between Isleta Diversion Dam and Bernardo for 100 days in any given year, was that approximately 54 cfs and 11,000 acre feet of water would be required (Appendix D).

In considering water management tradeoffs, in addition to the above water quantity estimates to meet the BO RPAs and other goals that benefit habitat for silvery minnow, it is of interest to have a first-order approximation on the water volume needed to maintain flow through the Isleta Reach, an often heard goal, since this reach can be critical to the goal of silvery minnow recovery. For the purposes of such an estimate, a flow target of 100 cfs through the reach was selected, which equals nearly 200 acre feet per day. This volume is based on Bovee et al. (2008), as reported in Section 2.8.3. As a reminder, their study results indicated that flows of less than 100 cfs produced optimal habitat for adult and juvenile silvery minnow, while flows as low as 25 to 50 cfs still can provide a reasonable degree of quality habitat for the species.

In addition to supplying 100 cfs as a delivery goal for the Isleta Reach, additional water is required to account for open water evaporative losses and other conveyance losses due to riparian evapotranspiration and seepage losses to groundwater. Over the 53.1 miles of the Isleta reach, a consistent flow of 200 cfs would produce a channel of averaging approximately 200 feet in width through the reach (Tetra Tech, Inc., unpublished draft model for the upper Isleta Reach, 2009). Summer and early fall pan evaporation rates at the Los Lunas monitoring station averages approximately 10.5 inches in June to 6.6 inches in September. Over the entire reach, using a standard surface water adjustment factor of 0.7 to estimate evaporation from native surface water and damp soils, the average daily water volume lost from such a channel would range approximately from 26 acre feet per day in June to 16 acre feet per day in September.

Seepage runs were completed on a dozen subreaches of the Isleta Reach during 2001 (SSPA 2002). The investigators detailed a number of problems encountered during this assessment.

Despite these problems, this is the best information available. Therefore, we totaled the high and the low conveyance losses across all subreaches; this indicated that the potential water lost due to riparian ET and seepage losses along the reach ranged between 129 and 430 cfs, with an average near 280 cfs acres. To simplify, we applied 300 cfs as the average conveyance loss for the reach, which translates to approximately 600 acre-feet per day.

Therefore, in total, maintaining a minimum 100 cfs flow through the Isleta reach would require approximately 200 acre-feet per day plus 600 acre-feet to address conveyance losses and surface evaporation, totaling approximately 800 acre-feet per day. The total volume of water necessary to augment flows to a minimum of 100 cfs in the Isleta Reach in any one year would depend on the previous winter's snowpack in the upper watershed and the magnitude of flowing summer/fall drought. The over-winter snowpack provides a major basis for defining flows in the Rio Grande through New Mexico, and the potential start date and length of the period over which flows would require supplementing.

The relatively high water demand to maintain a connected flow in the Isleta reach points to the necessity of implementing alternative management approaches, instead of maintaining a reach-long flowing channel. Alternatives could include keeping only a longer portion of the upper reach flowing during periods of channel drying. Overall, considering the water requirement, maintaining a perennial channel throughout the Isleta Reach, during periods of prolonged drought and channel drying would appear to be an unrealistic goal. Indeed, historical evidence indicates that the subreaches of the MRG were not perennial (Scurlock 1998). Also, as discussed in Section 6.1.2, silvery minnow would appear to have evolved an ecologically competitive advantage in the Rio Grande system that is based on their apparent abilities to be better able to survive seasonal periods of drought and channel drying by inhabiting isolated, slowly drying pools, that would later reconnect with the channel when river flows resumed.

Additional consideration of water requirements and options for water management to address habitat requirements for silvery minnows are beyond the scope this project. Certainly, a diversity of options exists. For example, considerable analysis and information on water supply and management alternatives were prepared and compiled by the Program's Water Acquisitions and Management Plan (WAMS 2005). Alternatives considered and described in the group's final report to the Collaborative Program included estimates of supplemental water demands that would be required to meet the various water management scenarios included the BO's RPAs and an analysis of available Rio Grande flow records to assess the likelihood that the range of annual water supply in the Rio Grande is sufficient to meet the wet, average, and dry year RPAs. Their report also included other assessments, including alternatives for reservoir management to reduce evaporative water loss, potential off-channel water storage alternatives, and routing alternatives to maximize MRG flows to benefit the endangered species. Also, considered were various limitations that are placed on such alternatives by the Rio Grande Compact and the diverse set of water sources and additional water management alternatives that might increase the volume of supplemental water available and delivery efficiencies. Table 8 lists the selection of assessed topics included in that document. That report can provide a useful starting point for continued analysis and assessment to develop long-term water management to benefit habitat quality and silvery minnow recovery in the MRG.

Table 8. Topics assessed in the 2005 the Collaborative Program's Water Acquisitions and Management Plan (WAMS 2005).

- Collaborative Program Water Demand Assessment
- Analysis of Sufficiency of Unregulated Rio Grande Flows to Meet ESA Flow Targets in the Middle Valley
- Preliminary Reservoir Storage Modeling Analysis
- New Mexico Rio Grande Compact Delivery and Credit Water
- Rio Grande Project Usable Water
- Colorado Water
- Collaborative Program Water Acquisition
- Municipal and Industrial Conjunctive Use Strategies
- Supplementing MRG Flows Through Irrigation Efficiency Improvements (Draft)
- Voluntary Irrigation Forbearance in the MRGCD Service Area
- Native American Water
- New Mexico Acequia Water
- Weather Modification – Cloud Seeding Water
- Supplementing MRG Flows Through Active Watershed Management
- Storage And Management of Collaborative Program Water
- Cochiti Lake Water Issues
- Reservoir Evaporation Water
- Evapotranspiration and Water Salvage
- Floodplain Lakes And Flood Flow Retention Basins
- Supplementing MRG Flows through Groundwater Pumping
- Supplementing Middle Rio Grande Flows through Pumping from the Low Flow Conveyance Channel (LFCC)
- Study Of Reconfiguration for the San Acacia Reach

8. References Cited

Andrewartha, H. G., and L. C. Birch. 1982. The Distribution and Abundance of Animals. University of Chicago Press.

Archdeacon, T.P., and W.J. Remshardt. 2012. Rio Grande Silvery Minnow Rescue and Salvage – 2012. U.S. Fish and Wildlife Service report prepared for Middle Rio Grande Endangered Species Act Collaborative Program, Submitted to U.S. Bureau of Reclamation, Albuquerque, NM.

Balcombe, S.R., S.E. Bunn, A.H. Arthington, J.H. Fawcett, F.J. McKenzie-Smith, and A. Wright. 2007. Fish larvae, growth and biomass relationships in an Australian arid zone river: links between floodplains and waterholes. Freshwater Biology 52(12):2385-2398.

Bayley, P.B. 1995. Understanding large river-floodplain ecosystems. BioScience 45(3):153-158.

Berry, K.L., and D.K. Lewis. 1997. Historical Documentation of Middle Rio Grande Flood Protection Projects - Corrales to San Marcial. OCA/UNM Report No. 185-555, Office of Contract Archeology, The University of New Mexico. Report under contract No. DACW47-94-D-0019, Delivery Order No. 0006 prepared for U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM. 61 pages.

Bovee, K.D. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. U.S. Fish and Wildlife Service FWS/OBS-82/26. 248pp.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. U.S. Geological Survey, Biological Resources Division Information and Technology Report USGS/BRD-1998-0004. viii + 131 pp.

Bovee, K.D., T.J. Waddle, and J.M. Spears. 2008. Streamflow and endangered species habitat in the lower Isleta reach of the Middle Rio Grande. US Geological Survey Open-File Report 2008-1323, 177pages.

Buhl, K.J. 2006a. Toxicity of adverse water quality conditions on Rio Grande silvery minnow, Presentation to the Middle Rio Grande Endangered Species Collaborative Program: First Annual Symposium, Albuquerque, NM.

Buhl, K.J. 2006b. Toxicity of adverse water quality conditions of low dissolved oxygen, high temperatures, and pulses of high ammonia concentrations to different life stages of the Rio Grande silvery minnow. Abstract P342, 27th annual meeting Society of Environmental Toxicology and Chemistry (SETAC), Montreal, Quebec.

Bui, C.N. 2011. Application of HEC-HMS 3.4 in Estimating Streamflow of the Rio Grande under Impacts of Climate Change. M.S. Thesis. Civil Engineering. The University of New Mexico, Albuquerque, NM. 126 pages.

Bunn, S.E., and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492-507.

Buntjer, M. and J. Remshardt. 2005. Fish Surveys and Habitat Assessment in the Rio Chama and Rio Grande Upstream of Cochiti Lake. Final Report. New Mexico Ecological Services Field

Office and New Mexico Fishery Resources Office, U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 16p.

Copes, F. A. 1975. Ecology of the brassy minnow, *Hybognathus hankinsoni* (Cyprinidae). University of Wisconsin Stevens Point Museum of Natural History reports on the fauna and flora of Wisconsin 10. Contributions to Ichthyology: 47–72.

Cowley, D. E., J.C. Alleman, R. Sallenave, R.R. McShane, and P.D. Shirey. 2009. Effects of salinity on specific gravity and viability of eggs of a North American minnow (Cyprinidae). Pages 47–58 in C. Clemmesen, A.M. Malzahn, M.A. Peck, and D. Schnack (eds.). Advances in early life history study of fish, Scientia Marina 73S1, October 2009, 47-58, Barcelona (Spain). ISSN: 0214-8358.

Crawford, C.S., A.C. Cully, R. Leutheuser, M.S. Sifuentes, L.H. White, and J.P. Wilbur. 1993. Middle Rio Grande ecosystem: bosque biological management plan. Middle Rio Grande Biological Interagency Team, Albuquerque, NM.

Dudley, R. K. and S. P. Platania. 1997. Habitat use of Rio Grande silvery minnow. Final Report submitted to New Mexico Department of Game and Fish, Santa Fe, New Mexico, and U.S. Bureau of Reclamation, Albuquerque, New Mexico. 87p.

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

Dudley R.K., and S.P. Platania. 2010. spatial spawning periodicity of Rio Grande silvery minnow during 2010. American Southwest Ichthyological Researchers, LLC to the Middle Rio Grande Endangered Species Act Collaborative Program and U. S. Bureau of Reclamation, Upper Colorado Regional Office, Salt Lake City, UT.

ESRI. 2013. ArcGIS 10.1 for Desktop®.

Fisher, J.S., J. Pickral, and W. E. Odum. 1979. Organic detritus particles: Initiation of motion criteria. Limnol. Oceanogr. 24(3):529-532

FLO-2D. 2006. FLO-2D Software, Inc., Nutrioso, AZ. http://www.flo-2d.com.

Gonzales, E.J., D. Tava, and G.M. Haggerty. 2013. Endangered Rio Grande silvery minnow use constructed floodplain habitat. Ecohydrology http://onlinelibrary.wiley.com/doi/10.1002/eco.1438/abstract

Górski, K., H.V. Winter, J.J. De Leeuw, A.E. Minin And L.A.J. Nagelkerke. 2010. Fish spawning in a large temperate floodplain: the role of flooding and temperature. Freshwater Biology 55, 1509–1519.

Gutzler, D. S. 2013. Regional climatic considerations for borderlands sustainability. Ecosphere 4(1):7. http://dx.doi.org/10.1890/ES12-00283.1.

Harvey, B.C. 1987. Susceptibility of Young-of-the-Year Fishes to Downstream Displacement by Flooding. Transactions of the American Fisheries Society 116:851-855.

Hatch, M.D. 2010. RiverEyes Observations for 2010. SWCA Project No. 16697. Report prepared for U.S. Bureau of Reclamation, Albuquerque Area Office, Albuquerque, NM. 60 pages.

Hatch, M.D. 2011. RiverEyes Observations for 2011. SWCA Project No. 16697. Report prepared for U.S. Bureau of Reclamation, Albuquerque Area Office, Albuquerque, NM. 132 pages.

Hatch, M., P. Dodge, and G. Pargas. 2013. RiverEyes Observations in the Middle Rio Grande for the 2012 Irrigation Season. SWCA Project No. 17402. Report prepared for U.S. Bureau of Reclamation, Albuquerque Area Office, Albuquerque, NM. 251 pages.

Hatch, M.D., and E. Gonzales. 2010. Los Lunas Habitat Restoration Fisheries Monitoring – 2009. SWCA Project No. 15009. Report prepared for U.S. Bureau of Reclamation, Albuquerque Area Office, Albuquerque, NM. 103 pages.

Hoover, J. J., and Killgore, J. 2002. Small floodplain pools as habitat for fishes and amphibians: Methods for evaluation. EMRRP Technical Notes Collection (ERDC TN-EMRRP-EM-03), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Horgan, P. 1982. Great River, the Rio Grande in North American History. Wesleyan University Press, Hanover, NH. 1020 pages.

Horner, M.W. 2007. Spring 2005 inundation mapping of the Middle Rio Grande. U.S. Army Corps of Engineers, Albuquerque District.

Humphries, P. and D. S. Baldwin. 2003. Drought and aquatic ecosystems: an introduction. Freshwater Biology 48:1141–1146.

Kerns, H.A., and J.L. Bonneau. 2002. Aspects of the Life History and Feeding Habits of the Topeka shiner *Notropis topeka* in Kansas. Transactions of the Kansas Academy of Science 105(3/4):125-142.

Koehle, J.J. 2006. The Effects of High Temperature, Low Dissolved Oxygen, and Asian Tapeworm Infection on Growth and Survival of the Topeka shiner, *Notropis Topeka.* A Masters of Science Thesis Submitted to the University Of Minnesota, Minneapolis, MN.

Lai, Y. 2008. SRH-2D version 2: Theory and User's Manual. U.S. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group. Denver, Co. November 2008.

Magaña, H.A. 2012. Habitat use of the Rio Grande silvery minnow (Hybognathus amarus) during a long-term flood pulse in the Middle Rio Grande, New Mexico. Envion. Biol. Fish. 95:201-212.

Massong, T., M. Porter, and T. Bauer. 2004. Design improvements for constructed Rio Grande Silvery Minnow Nursery Habitat. Technical Report, U.S. Bureau of Reclamation, Science and Technology Program, Albuquerque, NM.

Marcus, M.D., S. Covington, B. Liu, and N.R. Smith. 2010. Use of existing water, sediment, and tissue data to screen ecological risks to the endangered Rio Grande silvery minnow. Science of the Total Environment 409: 83–94.

Marcus M.D., Covington S., Smith N. Using existing data from the Middle Rio Grande to screen water quality risks to Rio Grande silvery minnow. 2005. Volume 1—final report and Volume 2—appendix data. Prepared for the NM Interstate Stream Commission and the Middle Rio

Grande Endangered Species Act Collaborative Program, US Department of Interior Bureau of Reclamation. Albuquerque, NM.

Matthews, W. J. 1987. Physicochemical tolerance and selectivity of stream fishes as related to their geographic ranges and local distributions. Pp. 111-120, in: W.J. Matthews and D.C. Heins (eds.). Community and evolutionary ecology of North American stream fishes. University of Oklahoma Press, Norman, OK

Matthews, W.J., and J.D. Maness. 1979. Critical Thermal Maxima, Oxygen Tolerances and Success of Cyprinid Fishes in Southwestern River. American Midland Naturalist, Vol. 102, No. 2:374-377.

Medley, C.N., and P.D. Shirey. 2013. Review and reinterpretation of Rio Grande silvery minnow reproductive ecology using egg biology, life history, hydrology, and geomorphology information. Ecohydrol. 6(3):491-505.

Moyle, P.B., P.K. Crain, and K. Whitener. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. San Francisco Estuary and Watershed Science 5(3). http://www.escholarship.org/uc/item/6fq2f838

Muth, R.T., and J.C. Schmulbach. 1984. Downstream Transport of fish larvae in a shallow prairie river. Trans. Am. Fish. Soc. 113:224-230.

New Mexico Department of Game and Fish. 1988. Handbook of species endangered in New Mexico. Santa Fe, New Mexico.

New Mexico Environment Department (NMED). 2009. Water Quality Monitoring of the Middle Rio Grande, Annual Baseline Condition and Trends of Key Water Quality Parameters, October 2006–July 2008, Final Report. New Mexico Environment Department, Santa Fe, NM.

Paulson, R.W., E.B. Chase, R.S. Roberts, and D.W. Moody (Compilers). 1991. National Water Summary 1988-89-- Hydrologic Events and Floods and Droughts. U.S. Geological Survey Water-Supply Paper 2375. 591 p.

Pease, A.A., J.J. Davis, M.S. Edwards, and T.F. Turner. 2006. Habitat and resource use by larval and juvenile fishes in an arid-land river (Rio Grande, New Mexico). Freshwater Biology 51:475-486.

Platania, S.P. 1995. Reproductive biology and early life-history of Rio Grande silvery minnow, *Hybognathus amarus.* Report under Purchase Order DACW47-94-P-0462, prepared for U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM. 30 pages.

Platania, S.P. 2000. Effects of four water temperature treatments on survival, growth, and developmental rates of Rio Grande silvery minnow (Hybognathus amarus) eggs and larvae. Report to U.S. Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, NM. 35 pp.

Platania, S. P. and C. S. Altenbach. 1998. Reproductive strategies and egg types of seven Rio Grande basin cyprinids. Copeia 1998 (3): 559-569.

Platania, S. P. and R. K. Dudley. 2003. Summary of Biology of Rio Grande Silvery Minnow, an Endangered Species in the Middle Rio Grande, New Mexico. Prepared by American Southwest

Ichthyological Research Foundation, Albuquerque, New Mexico and submitted to the Office of the Governor, State of New Mexico, Santa Fe, New Mexico.42p.

Poff, N.L., J.D. Olden, D.M. Merritt, and D.M. Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences 104(14):5732-5737.

Porter, M.D., and T.M. Massong. 2004. Contributions to delisting Rio Grande silvery minnow: egg habitat identification. Technical Report to US Bureau of Reclamation, Science and Technology Program, Environment Division; Interstate Stream Commission; Middle Rio Grande ESA Collaborative Program; and US Forest Service. Albuquerque, NM.

Raney, E. C. 1939. The breeding habits of the silvery minnow, *Hybognathus regius.* American Midland Naturalist 21:674–680.

Remshardt, W.J. 2008. Rio Grande Silvery Minnow Rescue and Salvage – 2007. Interagency Agreement 06-AA-40-2491. U.S. Fish and Wildlife Service report prepared for Middle Rio Grande Endangered Species Act Collaborative Program, Submitted to U.S. Bureau of Reclamation, Albuquerque, NM.

Remshardt, W.J. 2010. Rio Grande Silvery Minnow Rescue and Salvage – 2009. Interagency Agreement 06-AA-40-2491. U.S. Fish and Wildlife Service report prepared for Middle Rio Grande Endangered Species Act Collaborative Program, Submitted to U.S. Bureau of Reclamation, Albuquerque, NM.

Remshardt, W.J. and T.P. Archdeacon. 2011a. Rio Grande Silvery Minnow Rescue and Salvage – 2010. U.S. Fish and Wildlife Service report prepared for Middle Rio Grande Endangered Species Act Collaborative Program, Submitted to U.S. Bureau of Reclamation, Albuquerque, NM.

Remshardt, W.J., and T.P. Archdeacon. 2011 b. Rio Grande Silvery Minnow Rescue and Salvage – 2011. U.S. Fish and Wildlife Service report prepared for Middle Rio Grande Endangered Species Act Collaborative Program, Submitted to U.S. Bureau of Reclamation, Albuquerque, NM.

Reznick, D, M.J., Bryant and F. Bashey. 2002. r-and K-selection revisited: the role of population regulation in life-history evolution. Ecology 83(6):1509–1520.

Ricklefs, R.E. 1973, Ecology, 2nd edition. Nelson, London, UK.

RMA2. 2003. U.S. Army Corps of Engineers Engineering Resource Development Center, Vicksburg, MS. http://chl.erdc.usace.army.mil/rma2

Scurlock, D. 1998. From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin. General Technical Report RMRS-GTR-5. Rocky Mountain Research Station, United States Department of Agriculture Forest Service, Fort Collins, Colorado, 454 pages.

SEMP – Society for Sediment Geology.. 1984. S.E.P.M. Short Course No. 3. 2nd Edition, Eastern Section SEMP, Providence, RI.

SSPA (S.S. Papadopulos & Associates, Inc.). 2002. Assessment of Flow Conditions and Seepage on the Rio Grande and Adjacent Channels, Isleta to San Marcial, Summer 2001. Report pprepared for the New Mexico Interstate Stream Commission, Santa Fe, NM.

Statzner, B., J.A. Gore, and V.H. Resh. 1988. Hydraulic stream ecology: observed patterns and potential applications. Journal of the North American Benthological Society 7(4):307-360.

Sublette, J.E., M.D. Hatch, and M. Sublette. 1990. The fishes of New Mexico. University of New Mexico Press, Albuquerque, NM.

Tave, D., and A.M. Hutson. 2012. 2012 Annual Report USFWS TE Permit 1699770-5. Los Lunas Silvery Minnow Refugium, Lao Lunas, NM. 70 pages.

Tetra Tech. 2005. Cross section surveys. Data files.

Tetra Tech. 2009. Cross section surveys for the Rivermile 83 Habitat Restoration Project. Data Files.

Tetra Tech, Inc. 2012. Middle Rio Grande, San Acacia Reach Habitat Restoration Analysis - Mapping of Completed Restoration Projects, Contemporary Vegetation, Modeled Floodplain Inundation, and Historic Fluvial Geomorphology. Completed Under Delivery Order 20, Dated 23 September 2011, Contract No. W912PP-08-D-0009. Prepared for U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

Tetra Tech, Inc. 2013a. Middle Rio Grande, Isleta Reach Habitat Restoration Analysis - Mapping of Completed Restoration Projects, Contemporary Vegetation, Modeled Floodplain Inundation, and Historic Fluvial Geomorphology. Completed Under Delivery Order 20, Dated 23 September 2011, Contract No. W912PP-08-D-0009. Prepared for U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

Tetra Tech, Inc. 2013b. Middle Rio Grande, Albuquerque Reach Habitat Restoration Analysis - Mapping of Completed Restoration Projects, Contemporary Vegetation, Modeled Floodplain Inundation, and Historic Fluvial Geomorphology. Completed Under Delivery Order 20, Dated 23 September 2011, Contract No. W912PP-08-D-0009. Prepared for U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

TPWD (Texas Parks and Wildlife Department). 2003. List of state threatened and endangered species. http://www.tpwd.state.tx.us/publications/pwdpubs/media/pwd_lf_w7000_0017.pdf

Tockner, K. and J.A. Stanford. 2002. Riverine floodplains: present state and future trends. Environmental Conservation 29(3): 308-330.

Torres, L.T., W.J. Remshardt, and D.C. Kitcheyan. 2008. Habitat Assessment for Rio Grande Silvery Minnow (Hybognathus amarus) in the Cochiti Reach, at Pefla Blanca, New Mexico. Final Report. New Mexico Fish and Wildlife Conservation Office, U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 46p.

USACE (U.S. Army Corps of Engineers). 2010. 4-band natural color orthophotography of the Middle Rio Grande; 8-bit pixel depth, 0.6 meter GSD, file format is enhanced compression wavelet (ECW); project also included LiDAR data collection.

USACE (U.S. Army Corps of Engineers), U.S. Bureau of Reclamation (USBR), New Mexico Interstate Stream Commission (NMISC). 2007. Upper Rio Grande Water Operations Review and Environmental Impact Statement. FES-07-05.

USBR (U.S. Bureau of Reclamation). 2006. Supplement to the Rio Grande Supplemental Water Programmatic Environmental Assessment and Finding of No Significant Impact. Albuquerque Area Office, USBR, Albuquerque, NM.

USBR (U.S. Bureau of Reclamation). 2013. Supplemental Water 2012 Program Report. Albuquerque Area Office, USBR, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 1994. Final Rule To List the Rio Grande Silvery Minnow as an Endangered Species. Federal Register. Vol. 59: 36988-36995.

USFWS (U.S. Fish and Wildlife Service). 2001. Programmatic Biological Opinion on the Effects of Actions Associated with the U.S. Bureau of Reclamation's, U.S. Army Corps of Engineers', and Non-Federal Entities' Discretionary Actions Related to Water Management on the Middle Rio Grande, New Mexico. Region 2, U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2002. Final recovery plan; southwestern willow flycatcher (*Empidonax traillii extimus*). Prepared by Southwestern Willow Flycatcher Recovery Team Technical Subgroup. USFWS, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2003a. Biological and conference opinions on the effects of actions associated with the programmatic biological assessment of the Bureau of Reclamation’s Water and River Maintenance Operations, Army Corps of Engineer’s Flood Control Operation, and Related Non-Federal Actions on the Middle Rio Grande. Region 2, U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2003b. Endangered and threatened wildlife and plants; designation of critical habitat for the Rio Grande silvery minnow; Final Rule. 50 CFR Part 17. U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2003c. Designation of Critical Habitat for the Rio Grande Silvery Minnow - Final Environmental Impact Statement. Region 2, U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2005. Endangered and threatened wildlife and plants; designation of critical habitat for the southwestern willow flycatcher (*Empidonax traillii extimus*). Final rule. 50 CFR Part 17. Federal Register/ Vol. 70(20), U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2006a. Amendment to the U.S. Fish and Wildlife Service's March 17, 2003, Biological and conference opinions on the effects of actions associated with the programmatic biological assessment of the Bureau of Reclamation’s Water and River Maintenance Operations, Army Corps of Engineer’s Flood Control Operation, and Related Non-Federal Actions on the Middle Rio Grande. Region 2, U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2006b. Rio Grande silvery minnow rescue and salvage – 2005 Interagency Agreement 02-AA-40-8190. U.S. Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2007a. Rio Grande silvery minnow (*Hybognathus amarus*) draft revised recovery plan. Southwest Region U.S. Fish and Wildlife Service, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2007b. U.S. Fish and Wildlife Service Rio Grande Silvery Minnow Salvage Protocol. U.S. Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, NM.

U.S. Fish and Wildlife Service. 2010. Rio Grande Silvery Minnow (Hybognathus amarus) Recovery Plan, First Revision. Albuquerque, NM. viii + 210 pp.

Valdez, R.A., and S.E. Beck. 2007. Documentation and quantification of food types available to the Middle Rio Grande fish community, New Mexico (2005-2006). SWCA Project No. 11458. Report to New Mexico Interstate Stream Commission and MRG ESA Collaborative Program, Albuquerque, NM.

Valdez, R.A., S.E. Beck, C.N. Medley, R. Schmidt-Peterson, and L. Zeiler. 2008. Abundance and variability of the macroinvertebrate, aufwuchs, and chlorophyll *a* in the Middle Rio Grande, New Mexico. Presentation to the Middle Rio Grande ESA Collaborative Program, Science Subcommittee, November 11, 2008.

WAMS (Water Acquisitions and Management Subcommittee). 2005. Water Acquisitions and Management Plan, Final Report, including 15 December 2005 update. Middle Rio Grande Endangered Species Act Collaborative Program, Albuquerque, NM. 216 pages.

Wesche, T.A., L.B. Wesche, D.E. Cowley, Y. Najmi, and S. Grogan. 2006. Development of Perennial Pools for Rio Grande Silvery Minnow in the Middle Rio Grande using Cottonwood Snags. Final Project Report with Revised Monitoring Results. Grant Agreement No. 03-FG-40-2109-85. Submitted to Middle Rio Grande ESA Collaborative Program, U.S. Bureau of Reclamation. Albuquerque NM.

Young, J.A.M. and Koops, M.A. 2013. Recovery potential modelling of Western Silvery minnow (*Hybognathus argyritis*) in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/084. iv + 18 p.

Appendix A

In-channel Habitat under Example Flow Regimes

Exhibit A1. Differences in habitat quality over five example flows at the Bernalillo RMA2 Study Site.

Exhibit A2. Differences in habitat quality over four example flows at the Central Avenue RMA2 Study Site.

Exhibit A3. Differences in habitat quality over five example flows at the Bernardo RMA2 Study Site.

Exhibit A4. Differences in habitat quality over five example flows at the Bosque del Apache RMA2 Study Site.

Exhibit A5. Differences in habitat quality for five example flows at the San Marcial RMA2 Study Site

Exhibit A6. 2003 RMA2 in-channel hydraulic model output for the Bernalillo Study Site showing most commonly occupied habitat at example flows of 247 to 3,488 cfs in blue highlight.

Exhibit A7. 2003 RMA2 in-channel hydraulic model output for the Bernalillo Study Site showing highest quality feeding and rearing habitat at example flows of 247 to 3,488 cfs in brown highlight.

Exhibit A8. 2003 RMA2 in-channel hydraulic model output for the Bernalillo Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 247 to 3,488 cfs in pink highlight.

Exhibit A9. 2003 RMA2 in-channel hydraulic model output for the Central Avenue Study Site showing most commonly occupied habitat at example flows of 197 to 3,488 cfs in blue highlight.

Exhibit A10. 2003 RMA2 in-channel hydraulic model output for the Central Avenue Study Site showing highest quality feeding and rearing habitat at example flows of 197 to 3,488 cfs in brown highlight.

Exhibit A11. 2003 RMA2 in-channel hydraulic model output for the Central Avenue Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 197 to 3,488 cfs in pink highlight.

Exhibit A12. 2003 RMA2 in-channel hydraulic model output for the Bernardo Study Site showing most commonly occupied habitat at example flows of 334 to 3,500 cfs in blue highlight.

Exhibit A13. 2003 RMA2 in-channel hydraulic model output for the Bernardo Study Site showing highest quality feeding and rearing habitat at example flows of 334 to 3,500 cfs in brown highlight.

Exhibit A14. 2003 RMA2 in-channel hydraulic model output for the Bernardo Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 334 to 3,500 cfs in pink highlight.

Exhibit A15. 2003 RMA2 in-channel hydraulic model output for the Bosque del Apache Study Site showing most commonly occupied habitat at example flows of 256 to 3,097 cfs in blue highlight.

Exhibit A16. 2003 RMA2 in-channel hydraulic model output for the Bosque del Apache Study Site showing highest quality feeding and rearing habitat at example flows of 256 to 3,097 cfs in brown highlight.

Exhibit A17. 2003 RMA2 in-channel hydraulic model output for the Bosque del Apache Study Site showing highest spawning and egg/larval retention habitat at example flows of 256 to 3,097 cfs in pink highlight.

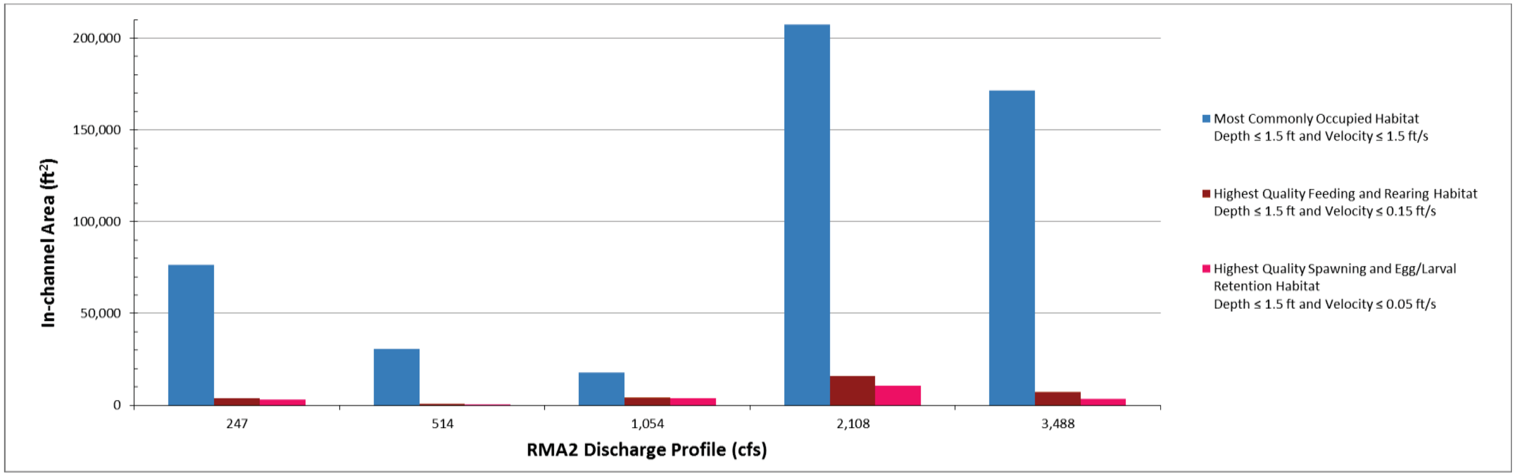
Exhibit A18. 2003 RMA2 in-channel hydraulic model output for San Marcial Study Site showing most commonly occupied habitat at example flows of 225 to 2,753 cfs in blue highlight.

Exhibit A19. 2003 RMA2 in-channel hydraulic model output for San Marcial Study Site showing highest quality feeding and rearing habitat at example flows of 225 to 2,753 cfs in brown highlight.

Exhibit A20. 2003 RMA2 in-channel hydraulic model output for San Marcial Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 225 to 2,753 cfs in pink highlight.

Exhibit A1. Differences in habitat quality over five example flows at the Bernalillo RMA2 Study Site

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s				Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s			
RMA2 Discharge Profile (cfs)	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*
247 (total active channel 220,154.68 ft^2)	76,501.78	34.7%	0.80; SD 0.43	0.88; SD 0.44	3,775.75	1.7%	0.23; SD 0.27	0.02; SD 0.04	2,976.87	1.4%	0.23; SD 0.27	0.02; SD 0.04
514 (total active channel 242,002.59 ft^2)	30,805.64	12.7%	0.71; SD 0.38	1.0; SD 0.43	774.84	0.3%	0.31; SD 0.24	0.05; SD 0.05	362.54	0.1%	0.31; SD 0.24	0.05; SD 0.05
1,054 (total active channel 297,774.66 ft^2)	17,817.24	6.0%	0.51; SD 0.42	0.82; SD 0.52	4,232.31	1.4%	0.23; SD 0.21	0.01; 0.03	3,779.90	1.3%	0.23; SD 0.21	0.01; SD 0.03
2,108 (total active channel 535,939.98 ft^2)	207,338.45	38.7%	0.70; SD 0.37	0.62; SD 0.36	16,074.94	3.0%	0.27; SD 0.29	0.03; SD 0.05	10,530.60	2.0%	0.27; SD 0.29	0.03; SD 0.05
3,488 (total active channel 673,669.06 ft^2)	171,556.54	25.5%	0.78; SD 0.40	0.91; SD 0.40	7,311.08	1.1%	0.28; SD 0.30	0.05; SD 0.05	3,427.33	0.5%	0.28; SD 0.30	0.05; SD 0.05



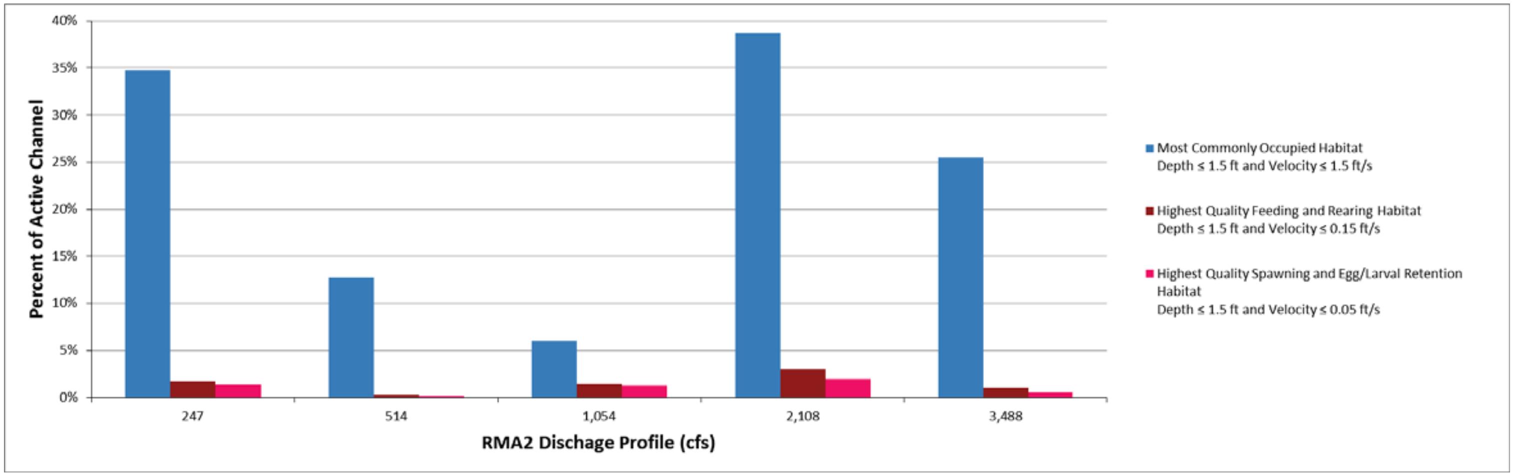
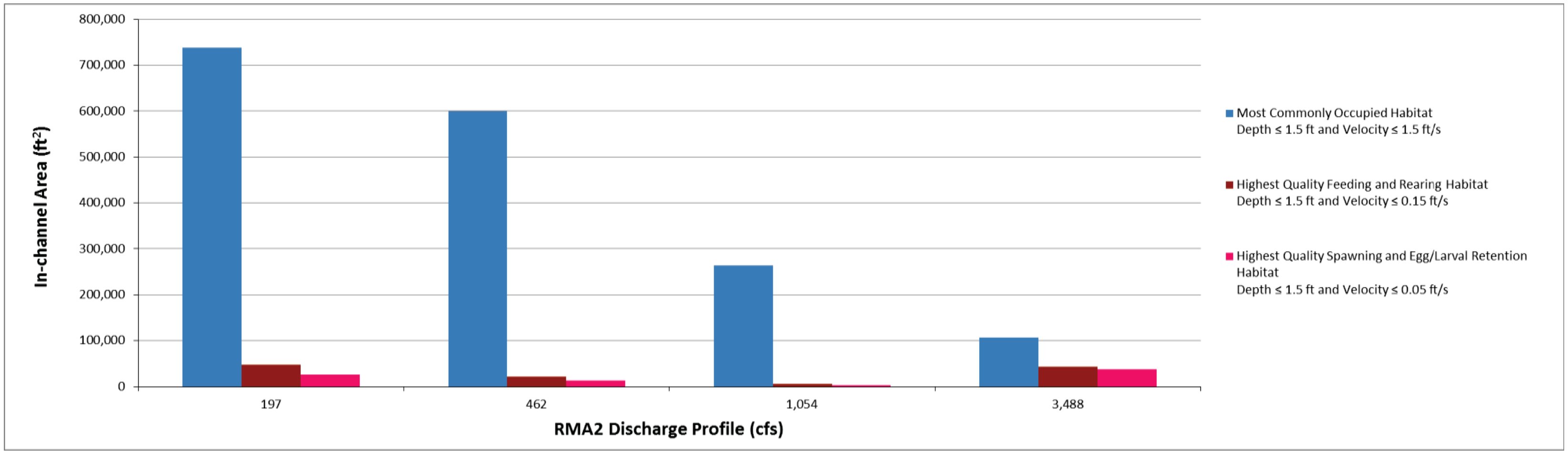


Exhibit A2. Differences in habitat quality over four example flows at the Central Ave. RMA2 Study Site

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s				Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s			
RMA2 Discharge Profile (cfs)	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*
197 (total active channel 874,663.70 ft^2)	738,191.29	84.4%	0.83; SD 0.41	0.54; SD 0.27	48,347.88	5.5%	0.40; SD 0.26	0.05; SD 0.05	25,380.09	2.9%	0.37; SD 0.27	0.02; SD 0.02
462 (total active channel 980,134.15 ft^2)	600,321.59	61%	0.81; SD 0.39	0.81; SD 0.33	21,507.43	2.2%	0.27; SD 0.23	0.04; SD 0.05	12,981.68	1.3%	0.22; SD 0.20	0.01; SD 0.02
1,054 (total active channel 1,032,487.59 ft^2)	263,310.91	25.5%	1.03; SD 0.36	1.01; SD 0.37	5,312.23	0.5%	0.41; SD 0.37	0.04; SD 0.05	3,353.16	0.3%	0.36; SD 0.38	0.01; SD 0.02
3,488 (total active channel 1,173,296.66 ft^2)	106,789.25	9.1%	0.67; SD 0.39	0.44; SD 0.46	42,675.13	3.6%	0.62; SD 0.41	0.01; SD 0.03	37,979.60	3.2%	0.61; SD 0.41	0.00; SD 0.01



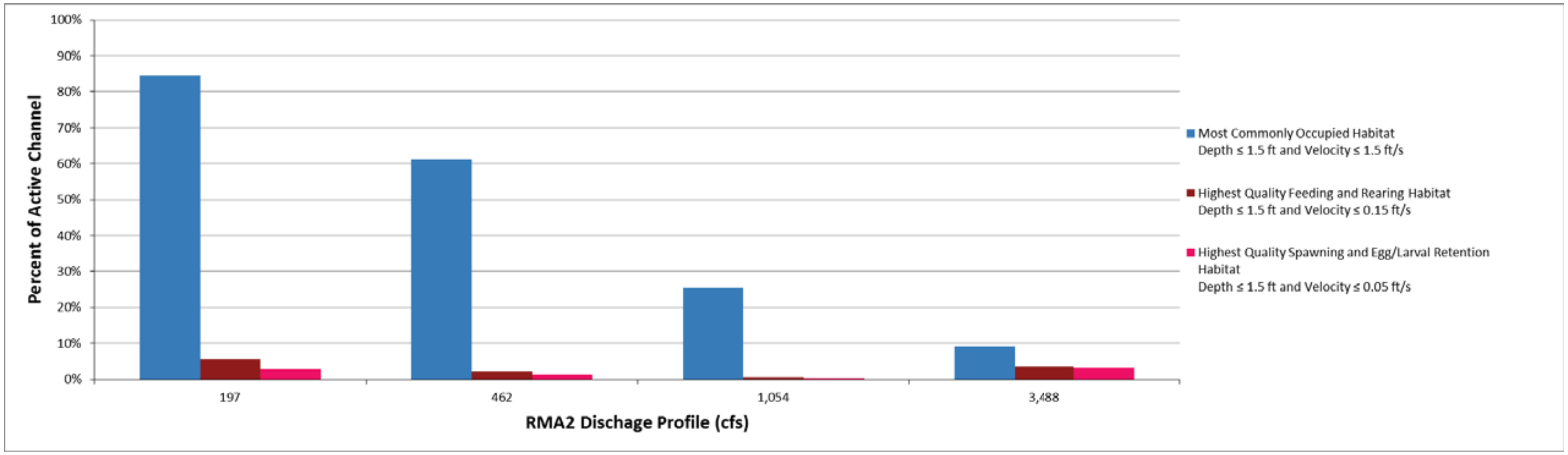
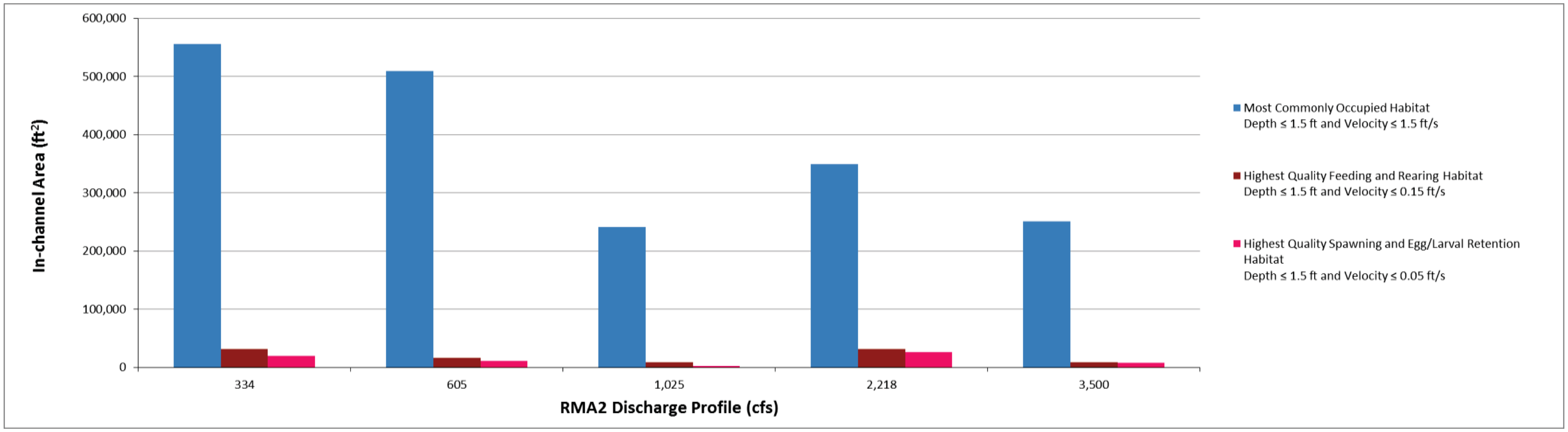


Exhibit A3. Differences in habitat quality over five example flows at the Bernardo RMA2 Study Site

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				**Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s**				**Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s**			
RMA2 Discharge Profile (cfs)	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*
334 (total active channel 751,723.50 ft^2)	555,520.58	73.9%	0.81; SD 0.36	0.88; SD 0.36	31,307.50	4.2%	0.52; SD 0.33	0.04; SD 0.05	19,597.99	2.6%	0.45; SD 0.28	0.01; SD 0.02
605 (total active channel 901,625.35 ft^2)	509,213.77	56.5%	0.86; SD 0.34	0.94; SD 0.40	16,272.95	1.8%	0.52; SD 0.36	0.04; SD 0.05	11,391.06	1.3%	0.37; SD 0.29	0.01; SD 0.01
1,025 (total active channel 997,908.35 ft^2)	240,995.66	24.2%	0.90; SD 0.35	1.1; SD 0.37	8,548.90	0.9%	0.42;SD 0.32	0.08; SD 0.05	2,371.75	0.2%	0.28; SD 0.30	0.02; SD 0.02
2,218 (total active channel 1,367,706.12 ft^2)	349,636.60	25.6%	0.76; SD 0.37	0.88; SD 0.37	31,265.87	2.3%	0.27; SD 0.29	0.04; SD 0.05	25,994.56	1.9%	0.13; SD 0.14	0.003; SD 0.01
3,500 (total active channel 1,393,312.91 ft^2)	250,733.63	18.0%	0.90; SD 0.33	1.04; SD 0.36	8,986.57	0.6%	0.71; SD 0.33	0.02; SD 0.04	7,755.29	0.6%	0.67; SD 0.31	0.003; SD 0.01



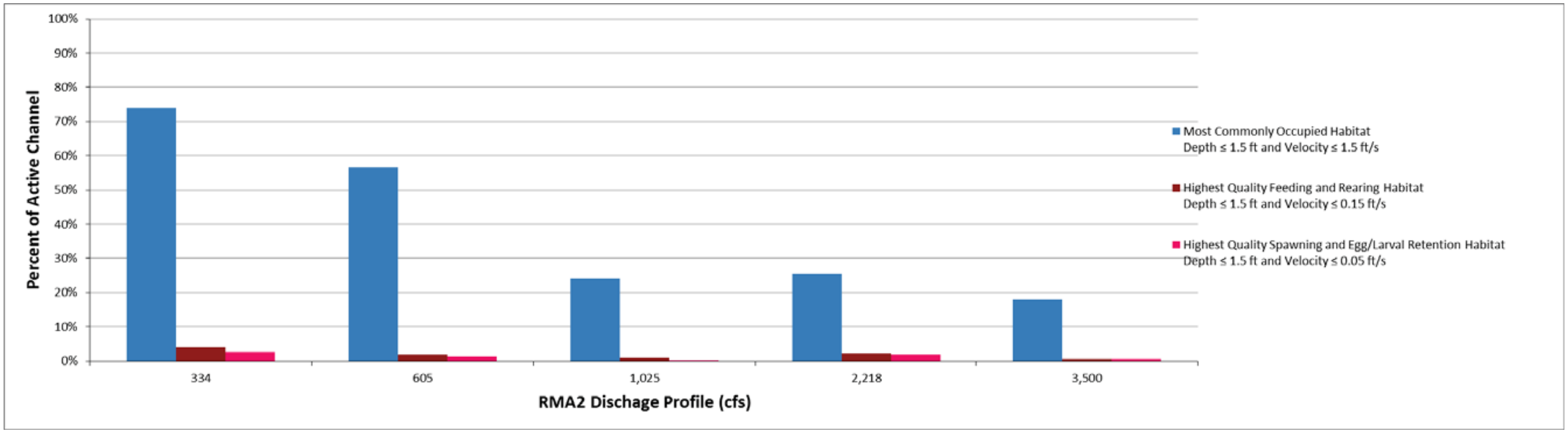
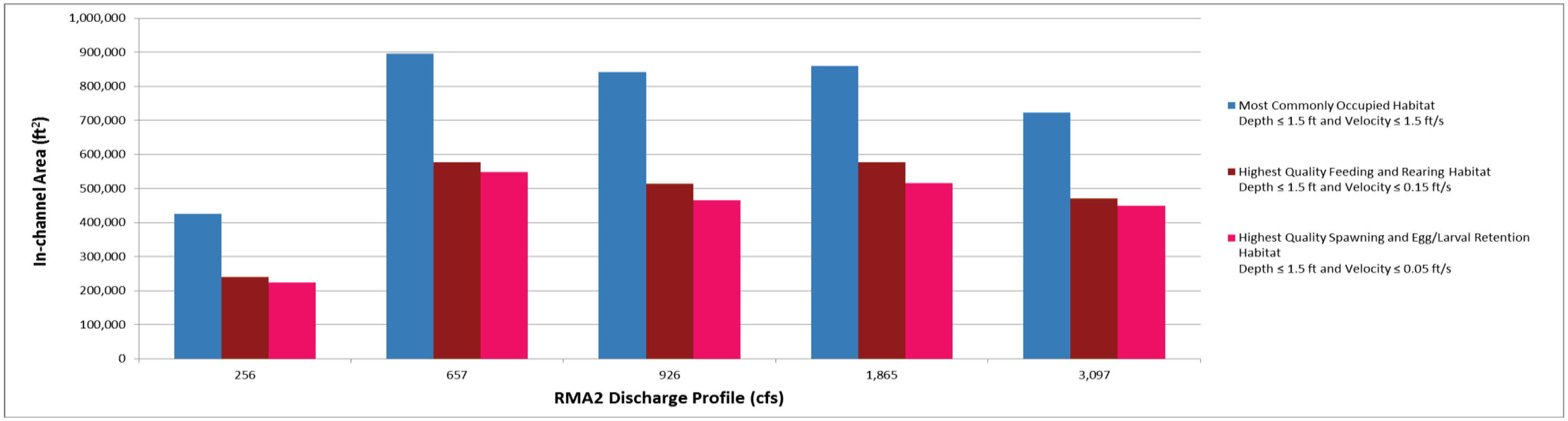


Exhibit A4. Differences in habitat quality over five example flows at the Bosque del Apache RMA2 Study Site

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				**Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s**				**Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s**			
RMA2 Discharge Profile (cfs)	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*
256 (total active channel 553,651.25 ft^2)	425,883.68	76.9%	0.85; SD 0.41	0.43; SD 0.47	239,919.64	43.3%	0.53; SD 0.36	0.01; SD 0.03	224,427.88	40.5%	0.48; SD 0.34	0.003; SD 0.01
657 (total active channel 1,342,681.06 ft^2)	895,161.48	66.7%	0.62; SD 0.35	0.32; SD 0.42	576,689.53	43.0%	0.50; SD 0.34	0.01; SD 0.03	547,450.85	40.8%	0.49; SD 0.34	0.003; SD 0.01
926 (total active channel 1,354,441.53 ft^2)	841,319.64	62.1%	0.65; SD 0.34	0.38; SD 0.46	513,669.19	37.9%	0.53; SD 0.35	0.02; SD 0.04	465,256.08	34.4%	0.49; SD 0.35	0.003; SD 0.01
1,865 (total active channel 1,510,105.95 ft^2)	859,378.84	56.9%	0.78; SD 0.39	0.38; SD 0.48	576,366.65	38.2%	0.60; SD 0.39	0.02; SD 0.04	514,847.68	34.1%	0.53; SD 0.37	0.003; SD 0.01
3,097 (total active channel 1,639,546.77 ft^2)	723,601.46	44.1%	0.74; SD 0.39	0.32; SD 0.43	471,257.38	28.7%	0.57; SD 0.35	0.01; SD 0.03	448,980.44	27.4%	0.55; SD 0.34	0.002; SD 0.01



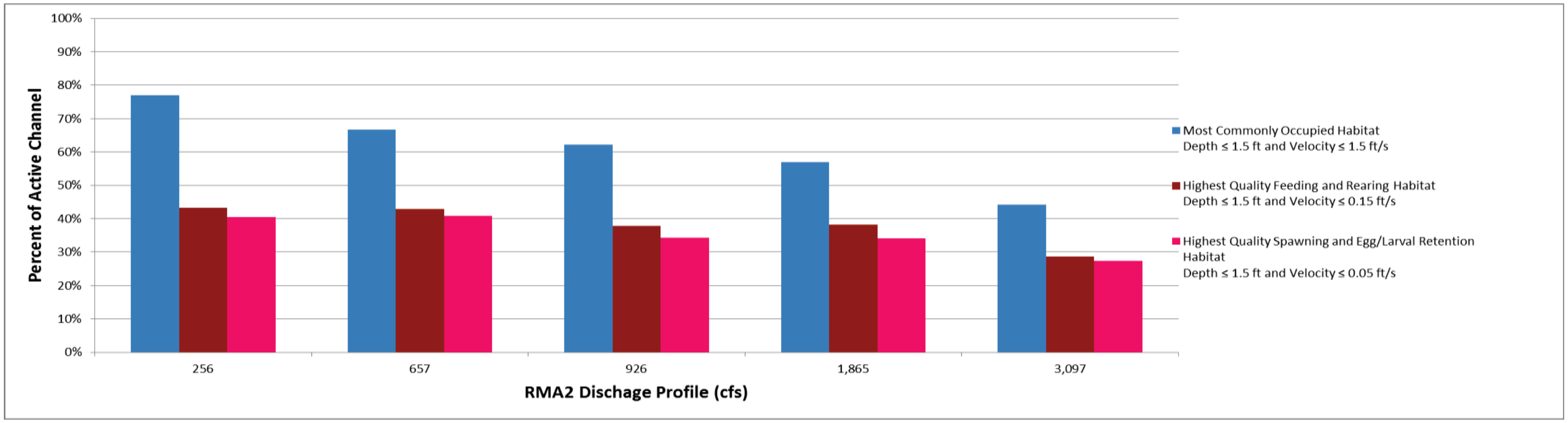
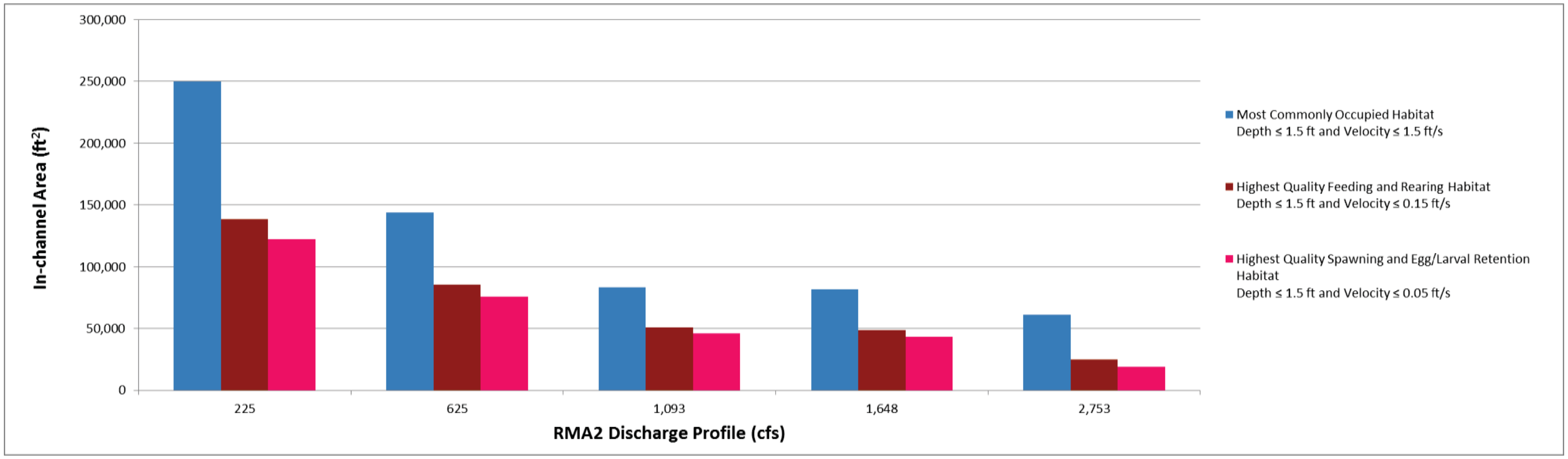
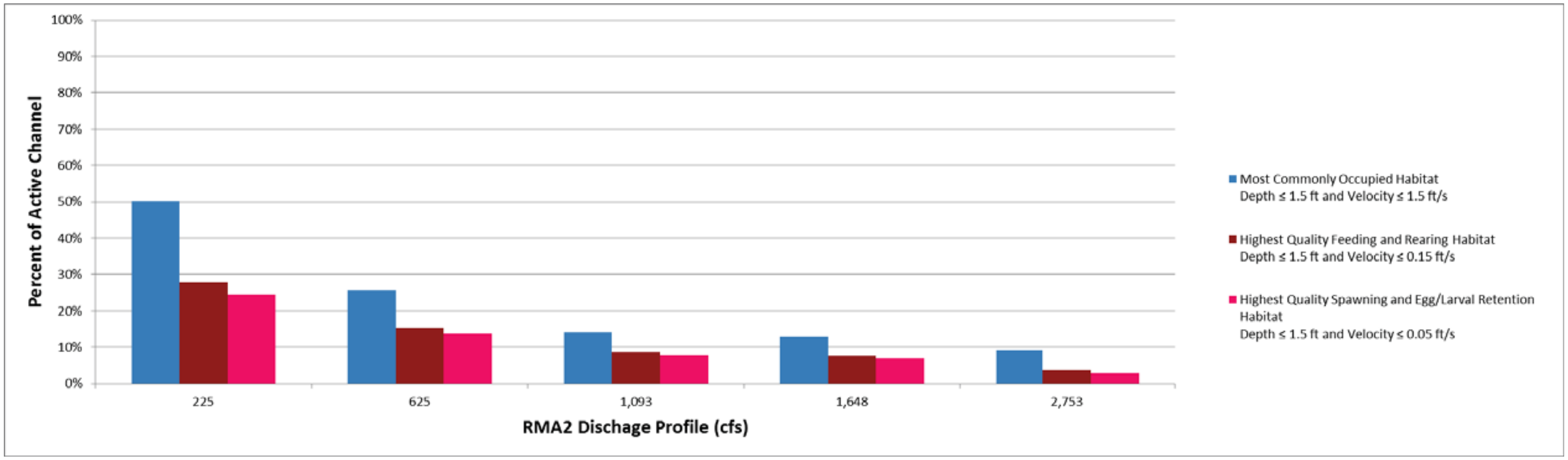


Exhibit A5. Differences in habitat quality over five example flows at the San Marcial RMA2 Study Site.

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s				Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s			
RMA2 Discharge Profile (cfs)	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (ft^2)*	*Percent of total active channel*	*Mean depth (ft)*	*Mean velocity (ft/s)*
225 (total active channel 497,593.74 ft^2)	249,861.37	50.2%	0.86; SD 0.40	0.36; SD 0.40	138,680.40	27.9%	0.63; SD 0.40	0.02; SD 0.04	122,460.30	24.6%	0.55; SD 0.38	0.003; SD 0.01
625 (total active channel 558,581.08 ft^2)	143,602.08	25.7%	0.86; SD 0.42	0.35; SD 0.46	85,326.94	15.3%	0.66; SD 0.42	0.02; SD 0.03	75,902.45	13.6%	0.57; SD 0.39	0.003; SD 0.01
1,093 (total active channel 588,751.05 ft^2)	83,123.73	14.1%	0.78; SD 0.39	0.31; SD 0.45	50,593.63	8.6%	0.62; SD 0.37	0.01; SD 0.03	46,212.71	7.8%	0.58; SD 0.37	0.002; SD 0.01
1,648 (total active channel 629,051.09 ft^2)	81,810.63	13.0%	0.88; SD 0.42	0.23; SD 0.32	48,848.30	7.8%	0.70; SD 0.43	0.02; SD 0.04	43,093.25	6.9%	0.62; SD 0.43	0.006; SD 0.01
2,753 (total active channel 662,773.26 ft^2)	61,101.66	9.2%	0.98; SD 0.32	0.44; SD 0.40	25,064.58	3.8%	0.79; SD 0.36	0.04; SD 0.04	19,188.64	2.9%	0.71; SD 0.38	0.01; SD 0.01





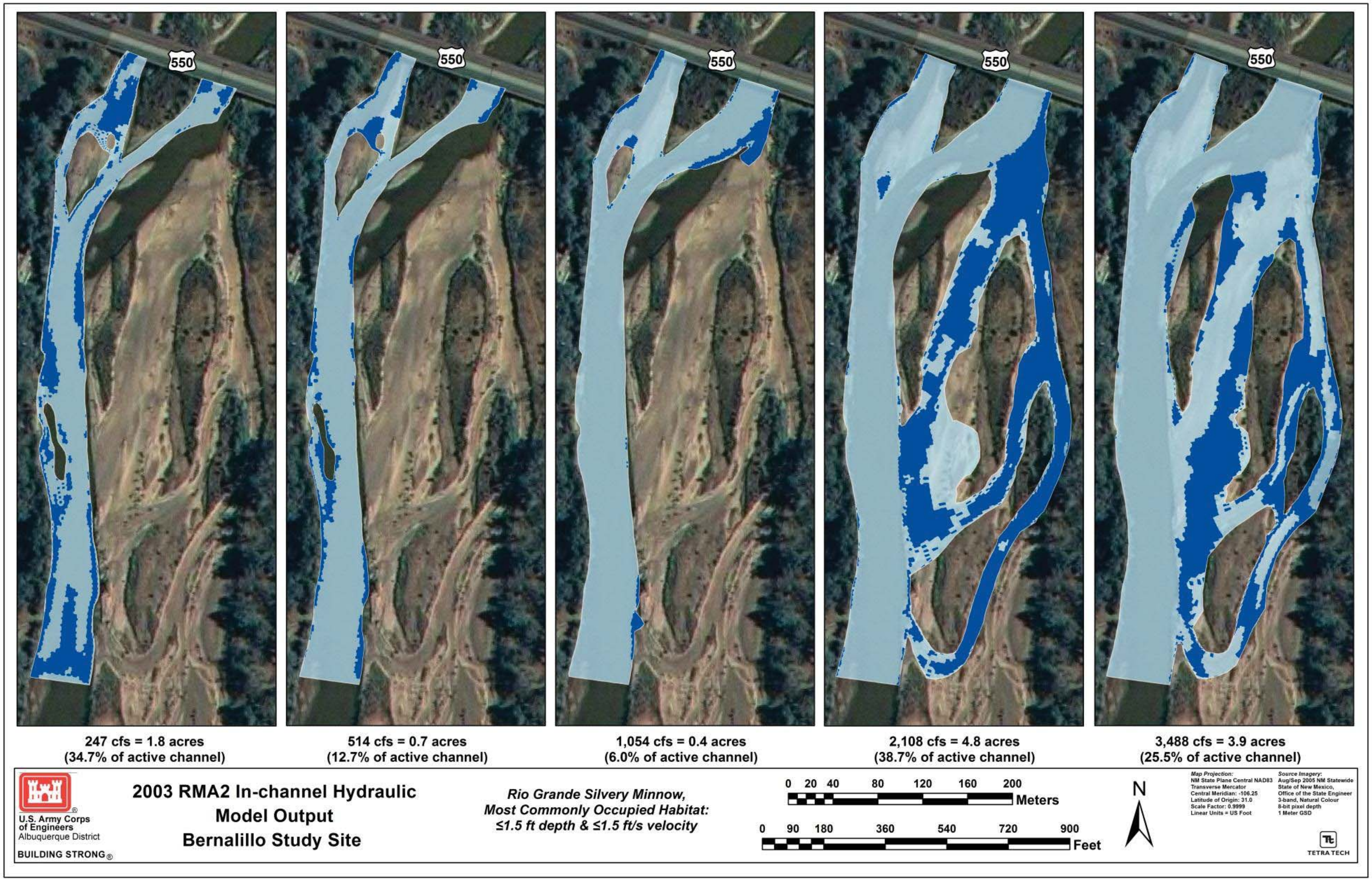


Exhibit A6. 2003 RMA2 in-channel hydraulic model output for the Bernalillo Study Site showing most commonly occupied habitat at example flows of 247 to 3,488 cfs in blue highlight.

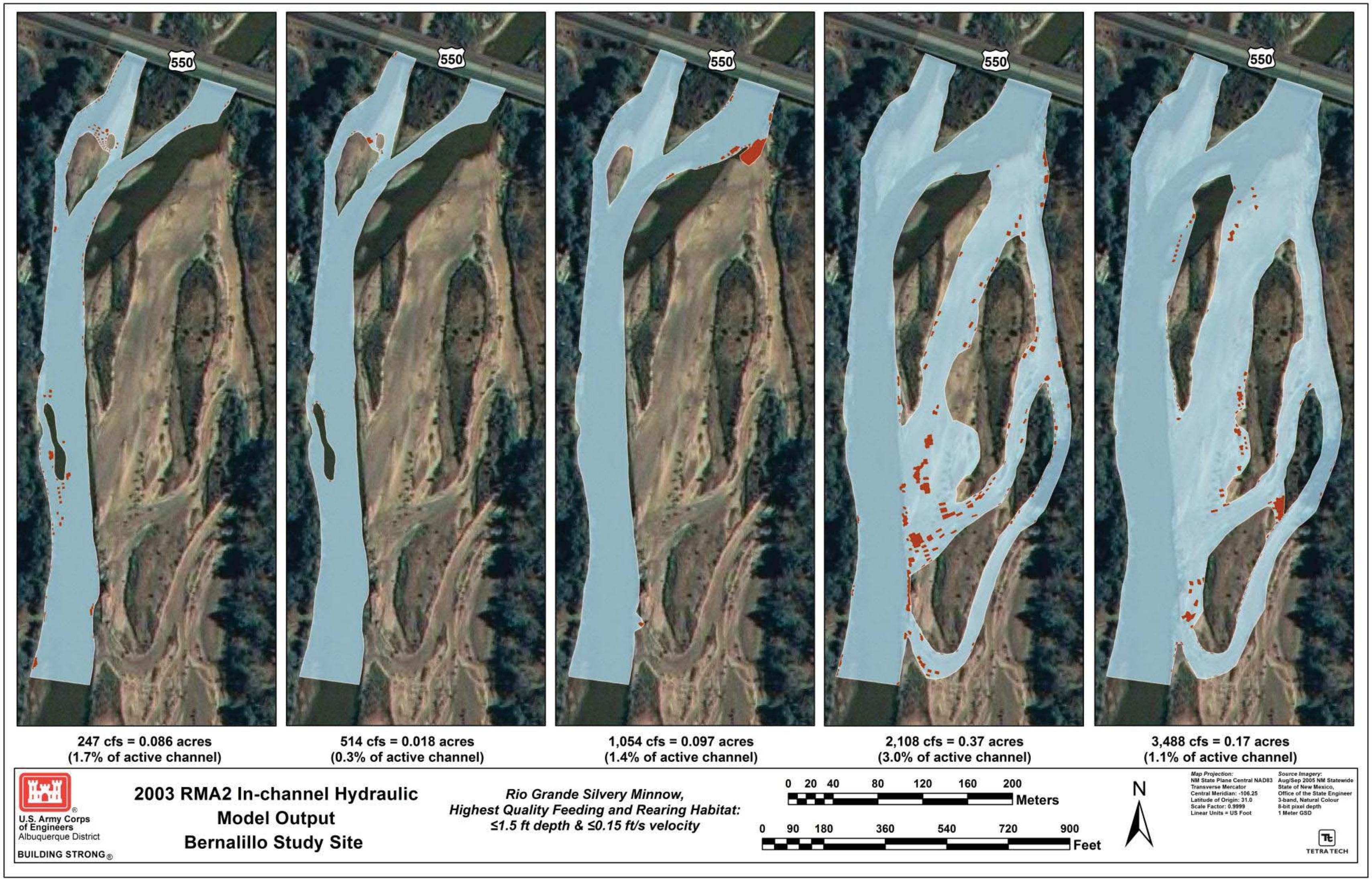


Exhibit A7. 2003 RMA2 in-channel hydraulic model output for the Bernalillo Study Site showing highest quality feeding and rearing habitat at example flows of 247 to 3,488 cfs in brown highlight.

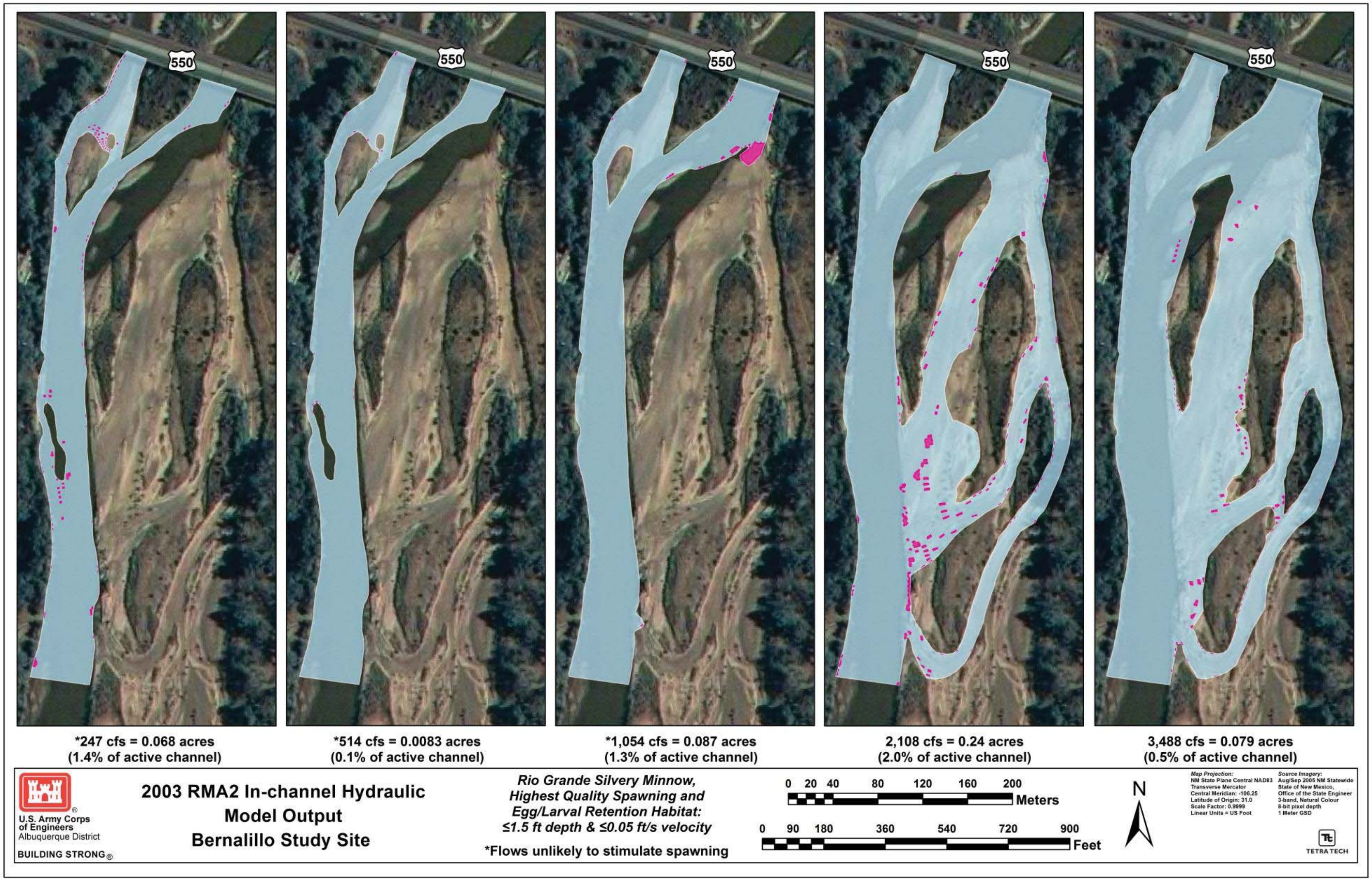


Exhibit A8. 2003 RMA2 in-channel hydraulic model output for the Bernalillo Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 247 to 3,488 cfs in pink highlight.

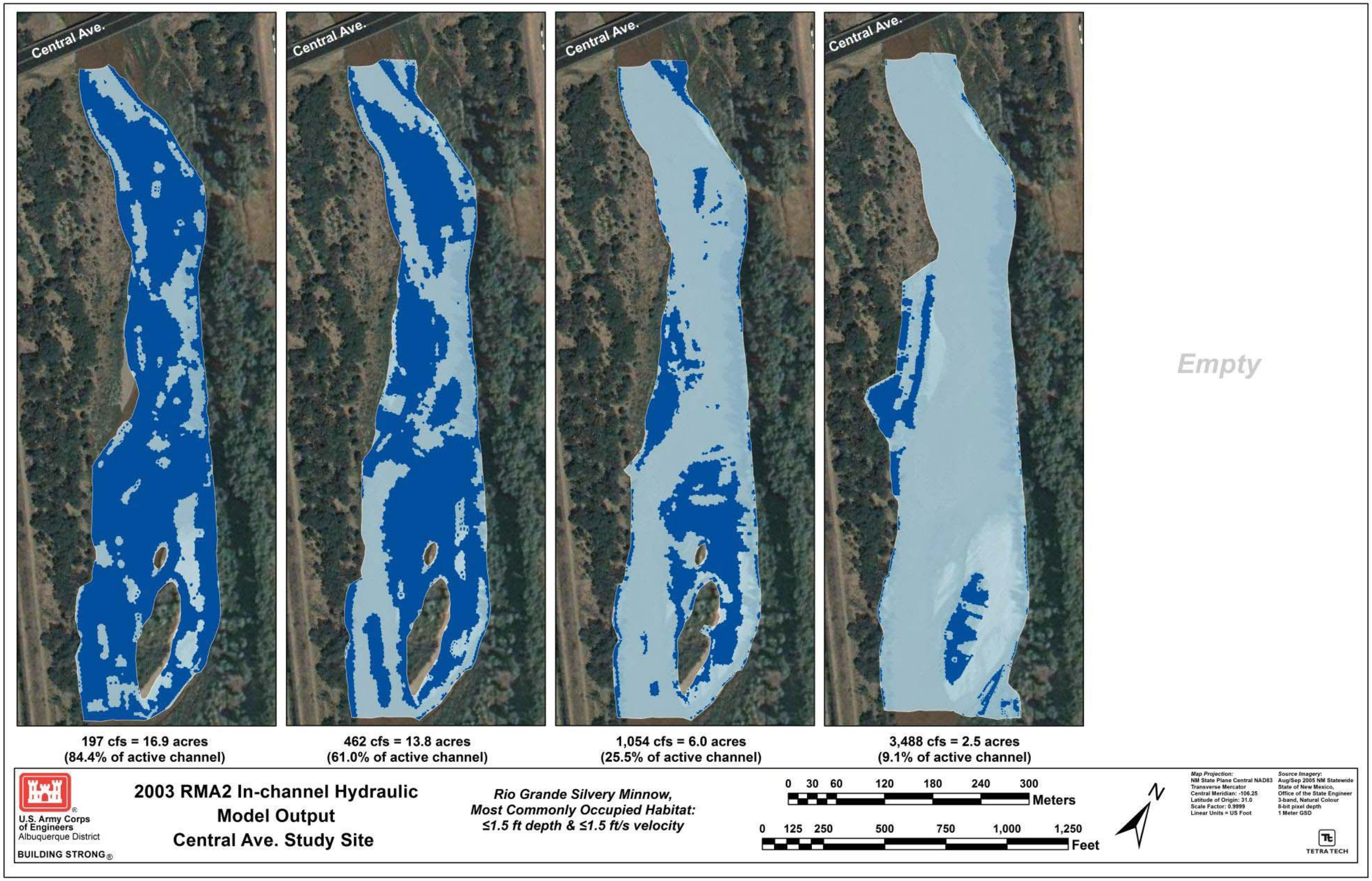


Exhibit A9. 2003 RMA2 in-channel hydraulic model output for the Central Avenue Study Site showing most commonly occupied habitat at example flows of 197 to 3,488 cfs in blue highlight.

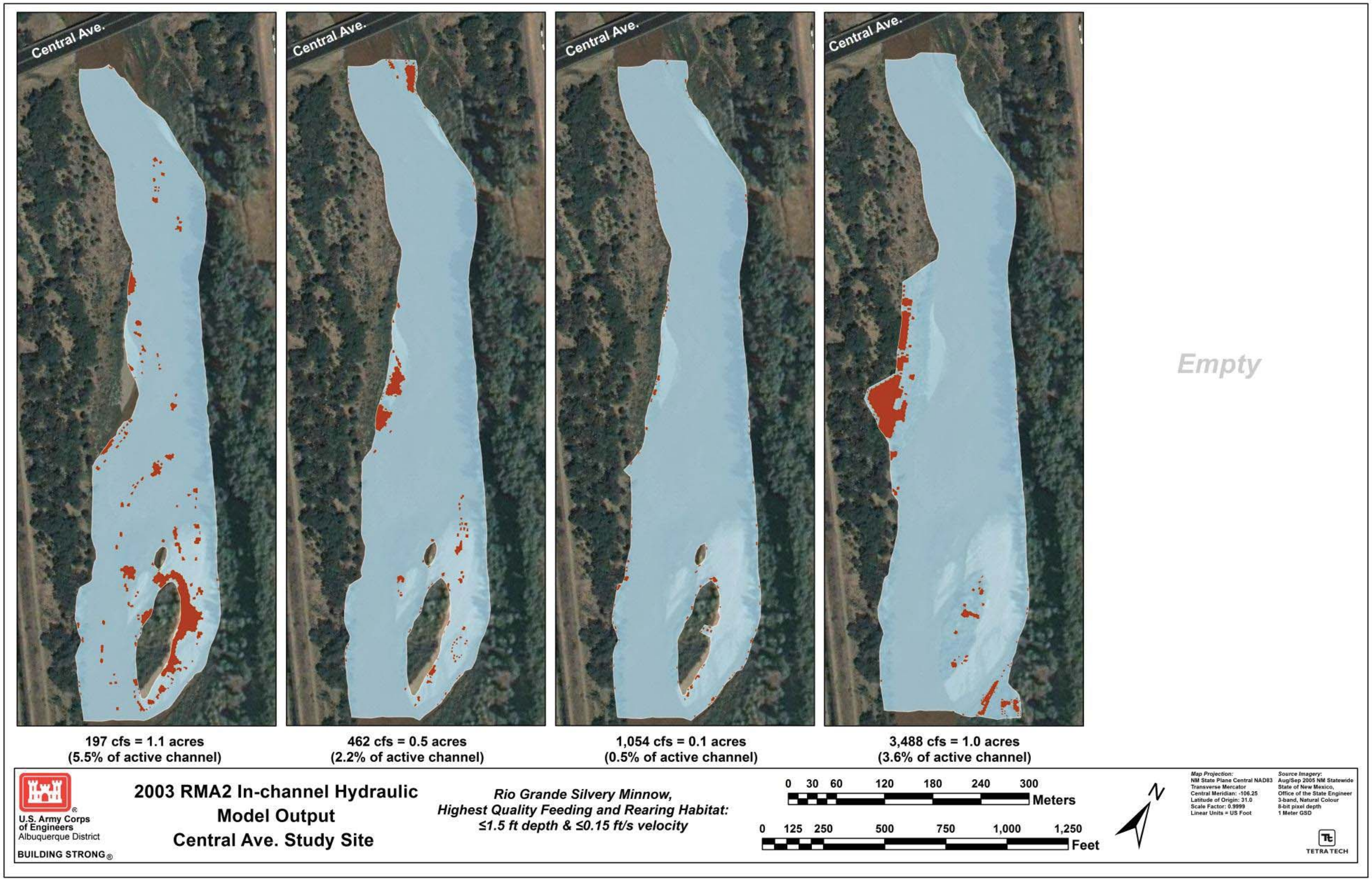


Exhibit A10. 2003 RMA2 in-channel hydraulic model output for the Central Avenue Study Site showing highest quality feeding and rearing habitat at example flows of 197 to 3,488 cfs in brown highlight.

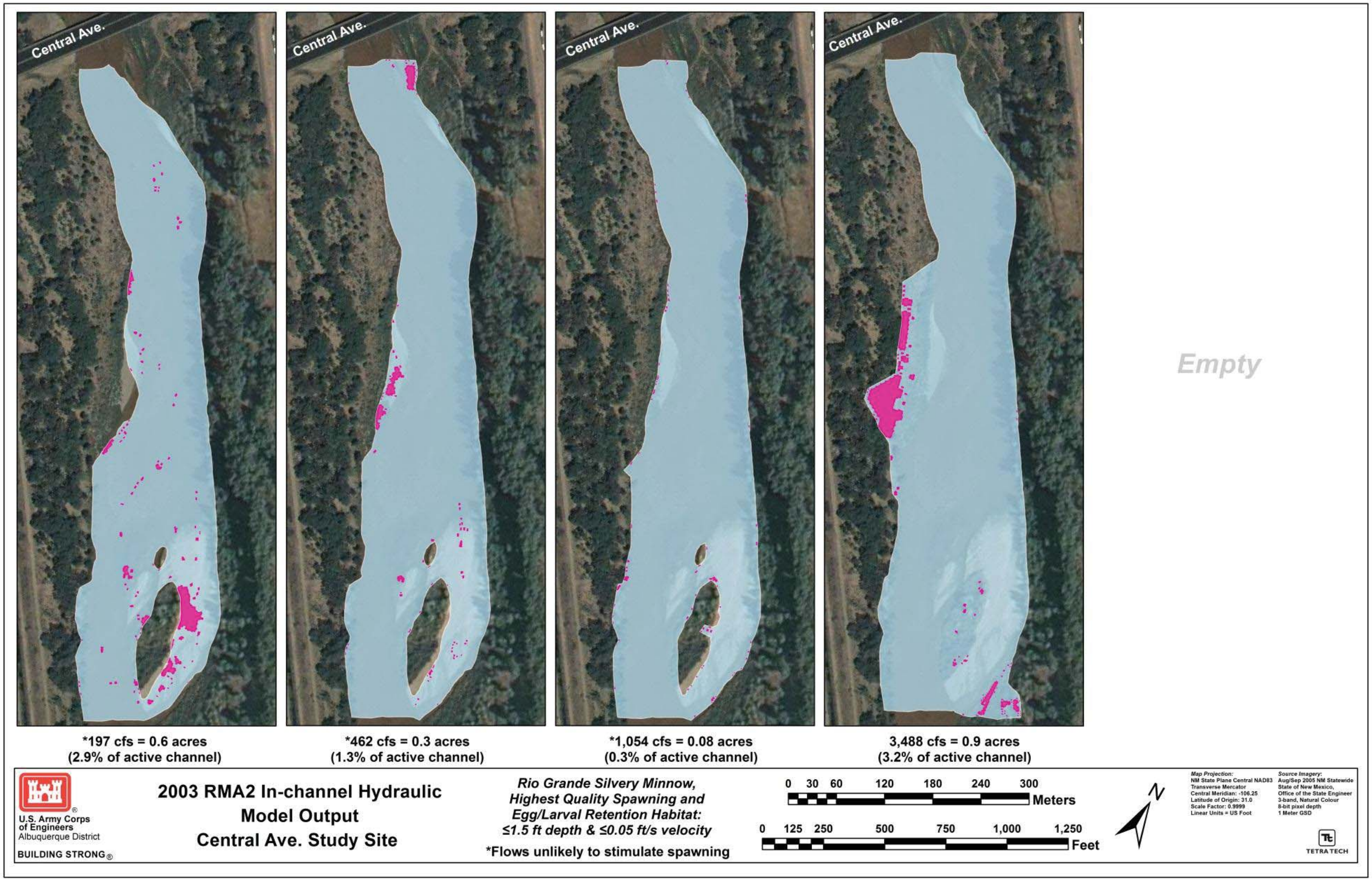


Exhibit A11. 2003 RMA2 in-channel hydraulic model output for the Central Avenue Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 197 to 3,488 cfs in pink highlight.

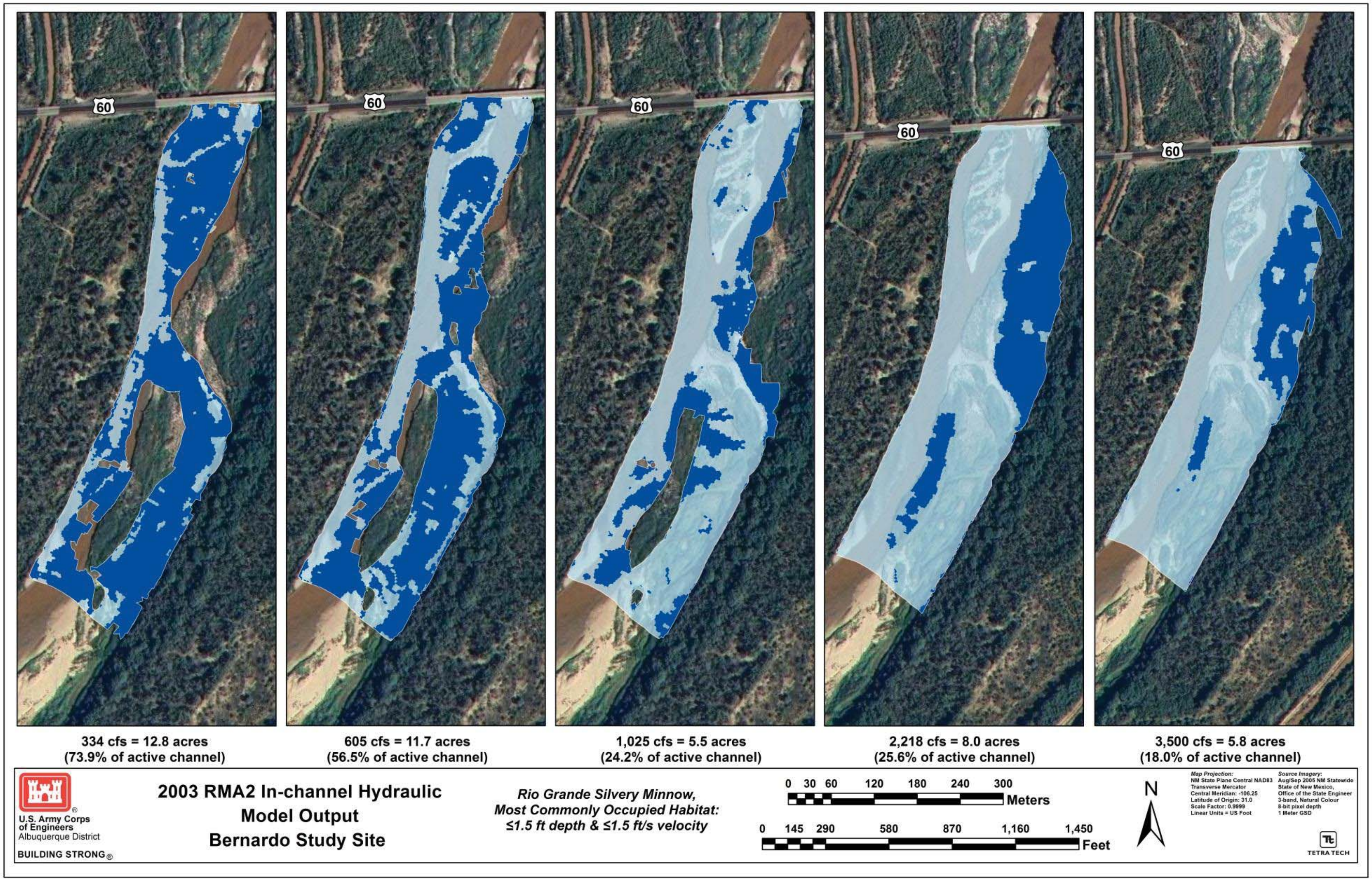


Exhibit A12. 2003 RMA2 in-channel hydraulic model output for the Bernardo Study Site showing most commonly occupied habitat at example flows of 334 to 3,500 cfs in blue highlight.

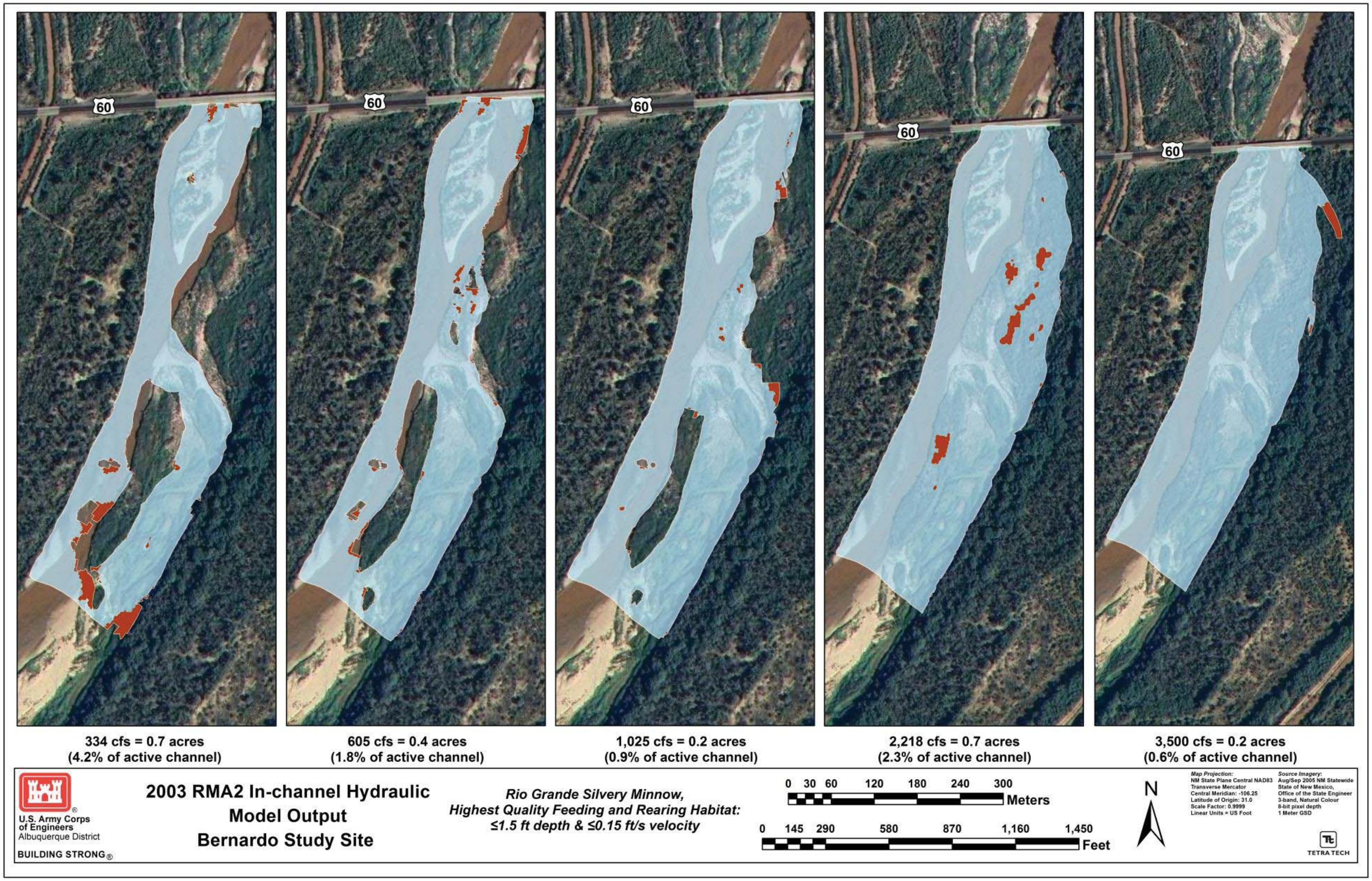


Exhibit A13. 2003 RMA2 in-channel hydraulic model output for the Bernardo Study Site showing highest quality feeding and rearing habitat at example flows of 334 to 3,500 cfs in brown highlight.

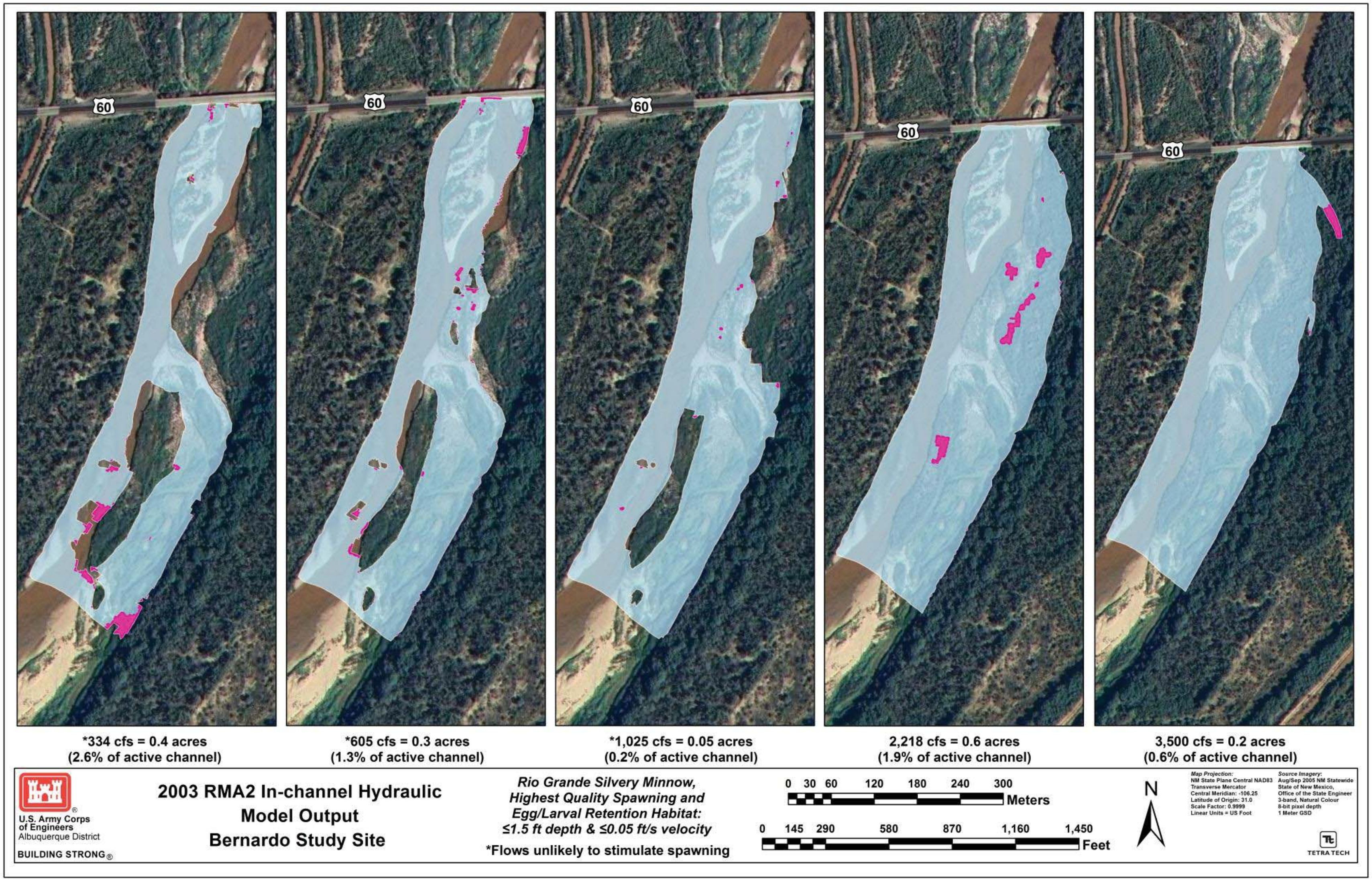


Exhibit A14. 2003 RMA2 in-channel hydraulic model output for the Bernardo Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 334 to 3,500 cfs in pink highlight.

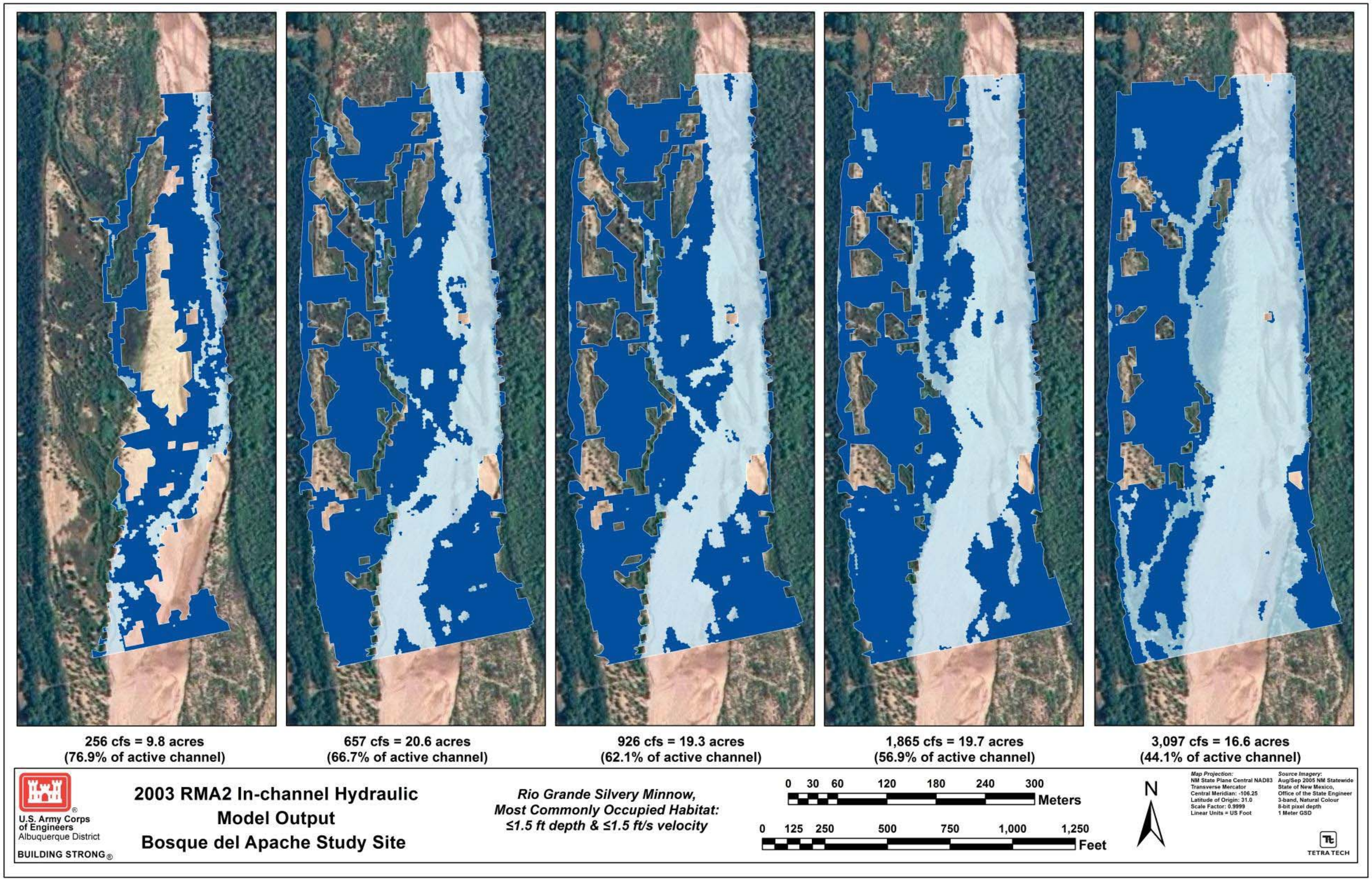


Exhibit A15. 2003 RMA2 in-channel hydraulic model output for the Bosque del Apache Study Site showing most commonly occupied habitat at example flows of 256 to 3,097 cfs in blue highlight.

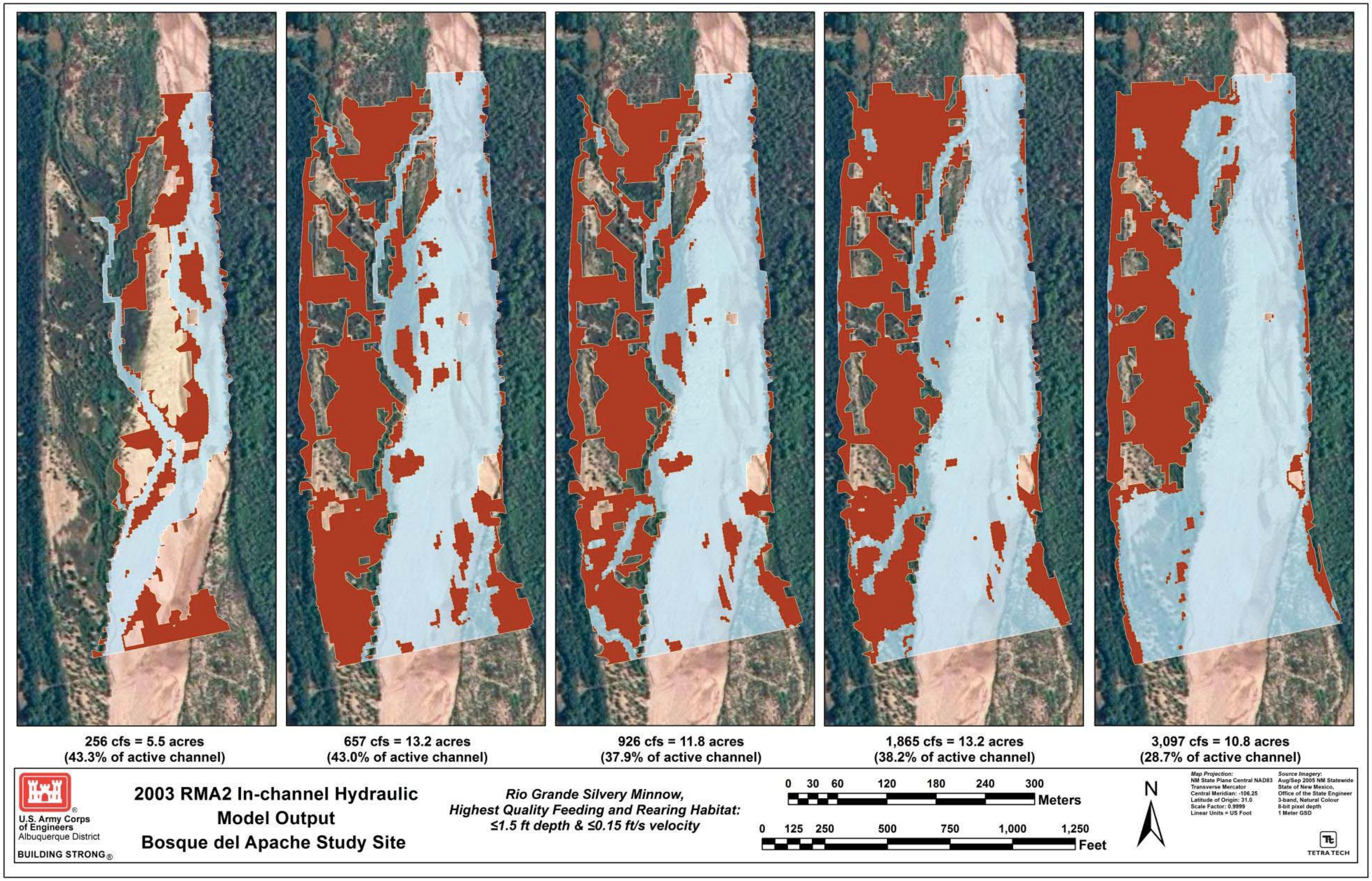


Exhibit A16. 2003 RMA2 in-channel hydraulic model output for the Bosque del Apache Study Site showing highest quality feeding and rearing habitat at example flows of 256 to 3,097 cfs in brown highlight.

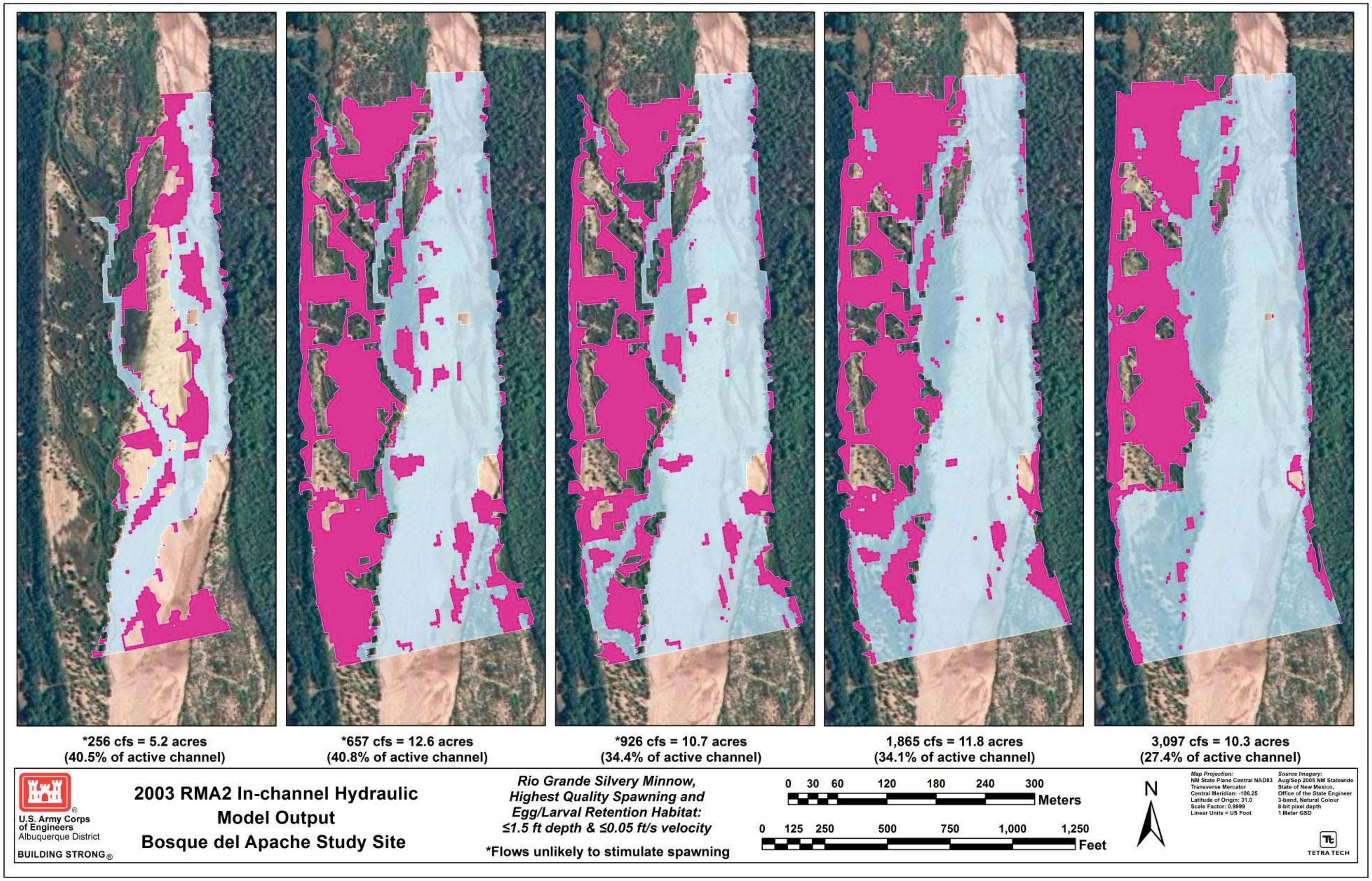


Exhibit A17. 2003 RMA2 in-channel hydraulic model output for the Bosque del Apache Study Site showing highest spawning and egg/larval retention habitat at example flows of 256 to 3,097 cfs in pink highlight.

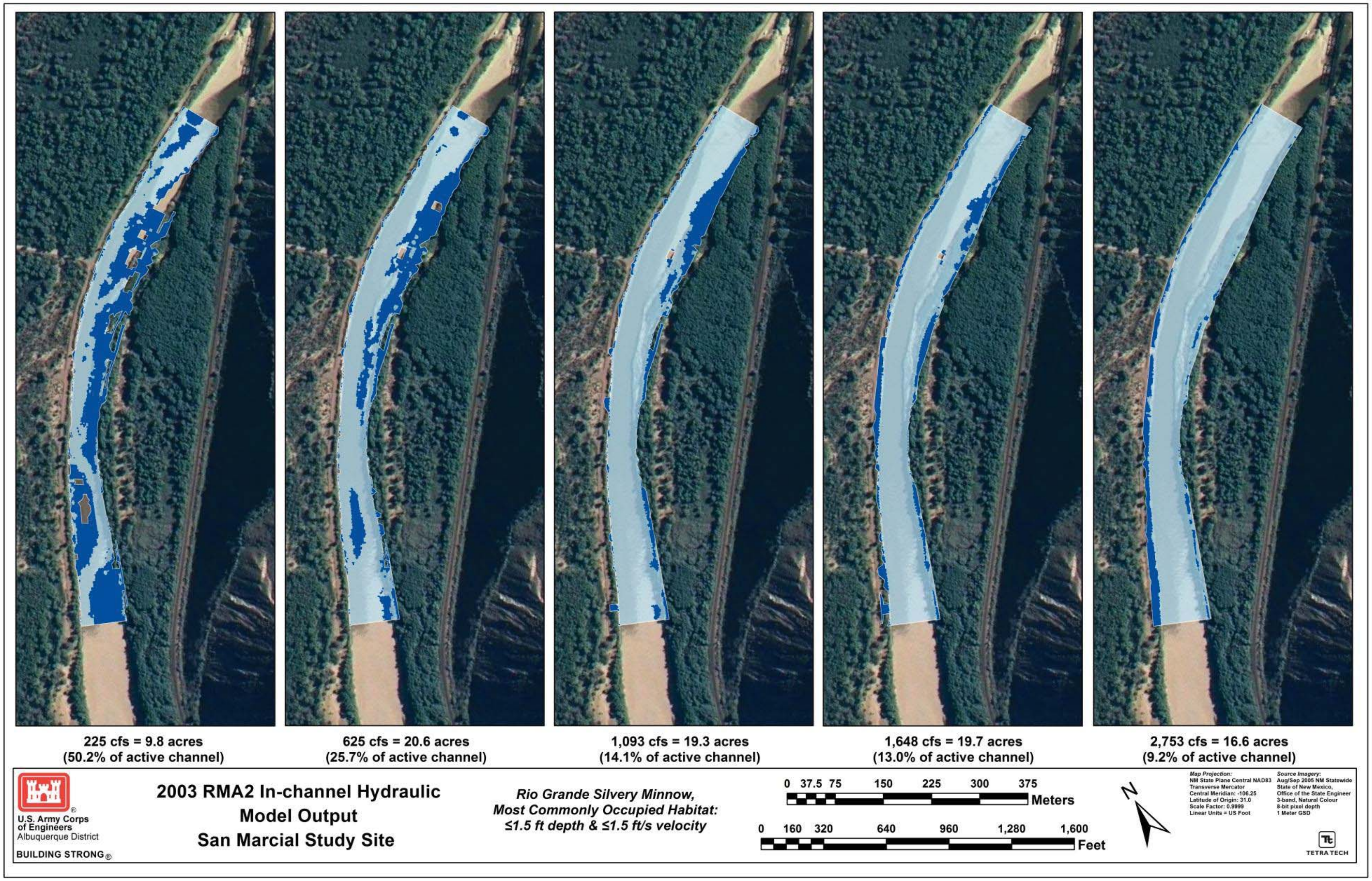


Exhibit A18. 2003 RMA2 in-channel hydraulic model output for San Marcial Study Site showing most commonly occupied habitat at example flows of 225 to 2,753 cfs in blue highlight.

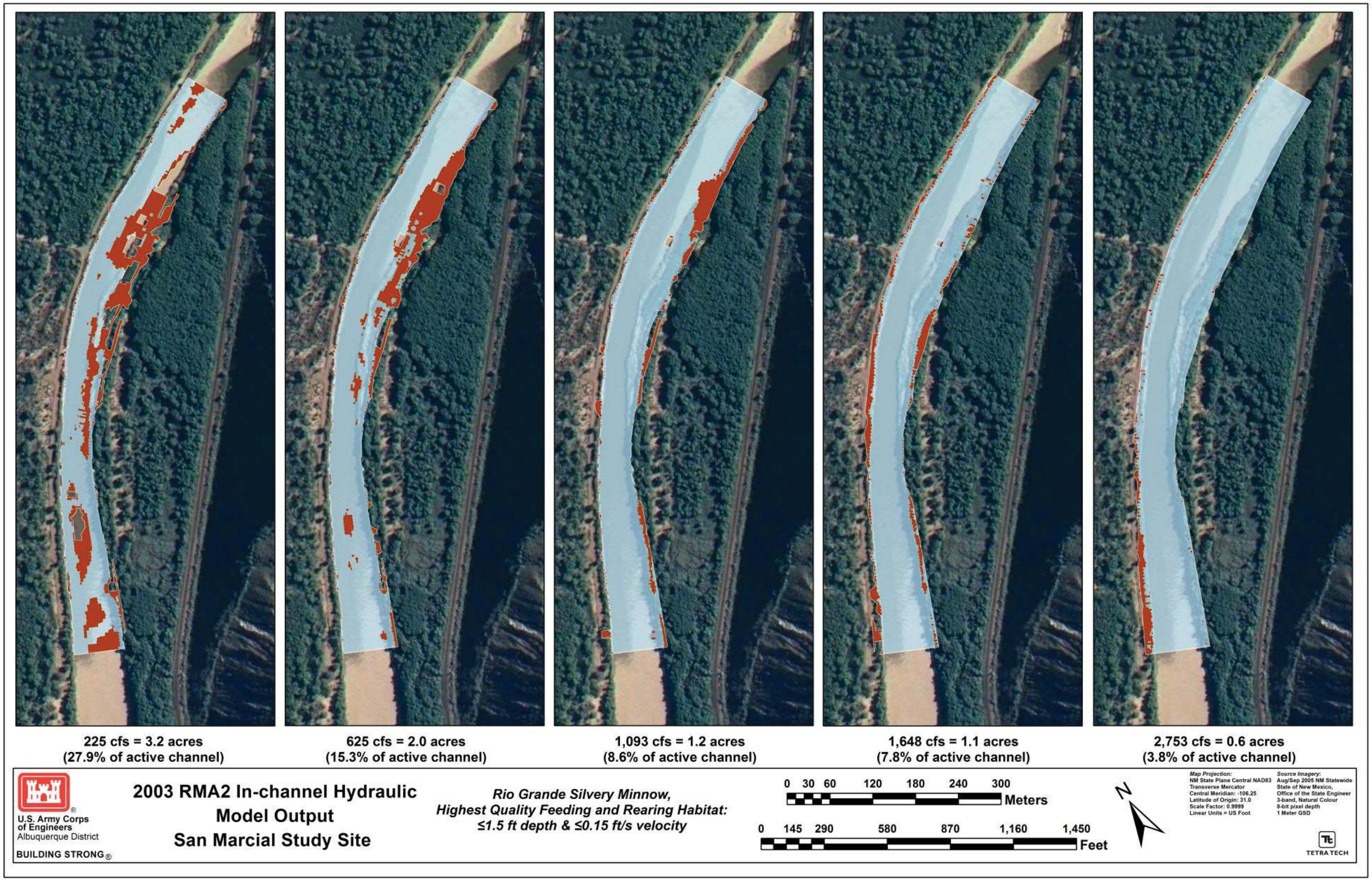


Exhibit A19. 2003 RMA2 in-channel hydraulic model output for San Marcial Study Site showing highest quality feeding and rearing habitat at example flows of 225 to 2,753 cfs in brown highlight.

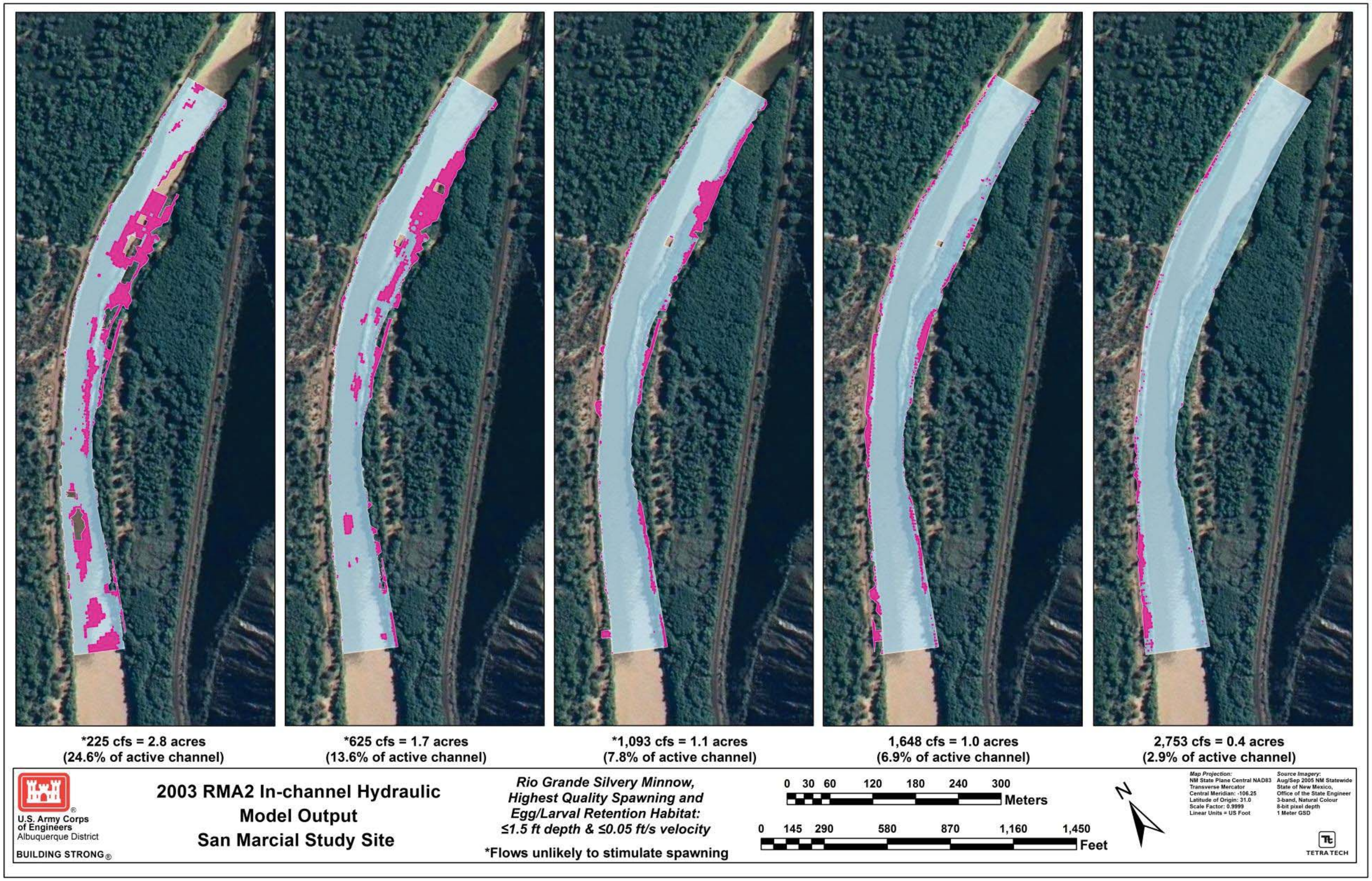


Exhibit A20. 2003 RMA2 in-channel hydraulic model output for San Marcial Study Site showing highest quality spawning and egg/larval retention habitat at example flows of 225 to 2,753 cfs in pink highlight.

Appendix B

Floodplain Habitat under Example Flow Regimes

Exhibit B1. Differences in habitat quality over five modeled example flows based on the Angostura to Isleta Reach FLO-2D.

Exhibit B2. Differences in habitat quality over five modeled example flows based on the Isleta Reach to San Acacia FLO-2D

Exhibit B3. Differences in habitat quality over five modeled example flows based on the San Acacia to San Marcial RR Bridge FLO-2D

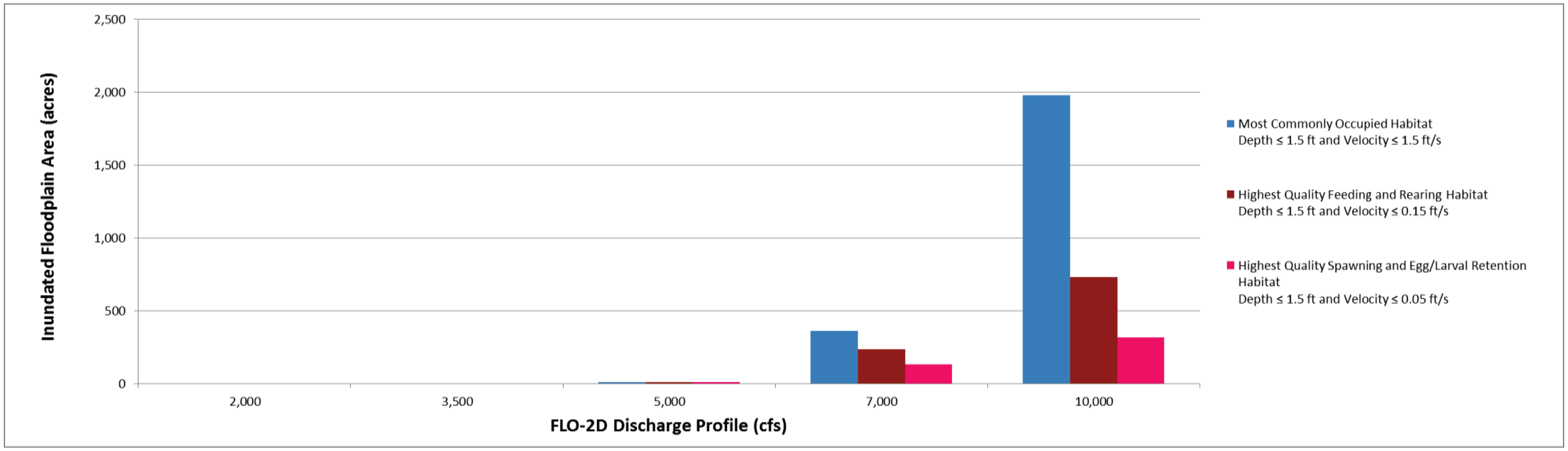
Exhibit B4. 2006 FLO-2D floodplain inundation hydraulic model for Angostura Diversion Dam to Isleta Pueblo showing examples of three indices of habitat quality at 7,000 cfs.

Exhibit B5. 2006 FLO-2D floodplain inundation hydraulic model for Isleta Pueblo to San Acacia Diversion Dam showing examples of three indices of habitat quality at 5,000 cfs.

Exhibit B6. 2006 FLO-2D floodplain inundation hydraulic model for San Acacia Diversion Dam to San Marcial Railroad Bridge showing examples of three indices of habitat quality at 3,500 cfs.

Exhibit B1. Differences in habitat quality over five modeled example flows based on the Angostura to Isleta Reach FLO-2D.

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s				Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s			
FLO-2D Discharge Profile (cfs)	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*
2,000 (total floodplain inundation 0.0 acres)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3,500 (total floodplain inundation 0.0 acres)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5,000 (total floodplain inundation 10.04 acres)	10.04	100.0%	0.07; SD 0.04	0.003; SD 0.005	10.04	100.0%	0.07; SD 0.04	0.003; SD 0.005	10.04	100.0%	0.07; SD 0.04	0.003; SD 0.005
7,000 (total floodplain inundation 374.43 acres)	359.43	96.0%	0.47; SD 0.40	0.13; SD 0.13	235.83	63.0%	0.35; SD 0.36	0.05; SD 0.05	131.79	35.2%	0.25; SD 0.31	0.01; SD 0.01
10,000 (total floodplain inundation 2,401.70 acres)	1,977.45	82.3%	0.60; SD 0.41	0.21; SD 0.15	728.85	30.3%	0.39; SD 0.37	0.07; SD 0.05	315.46	13.1%	0.30; SD 0.35	0.01; SD 0.02



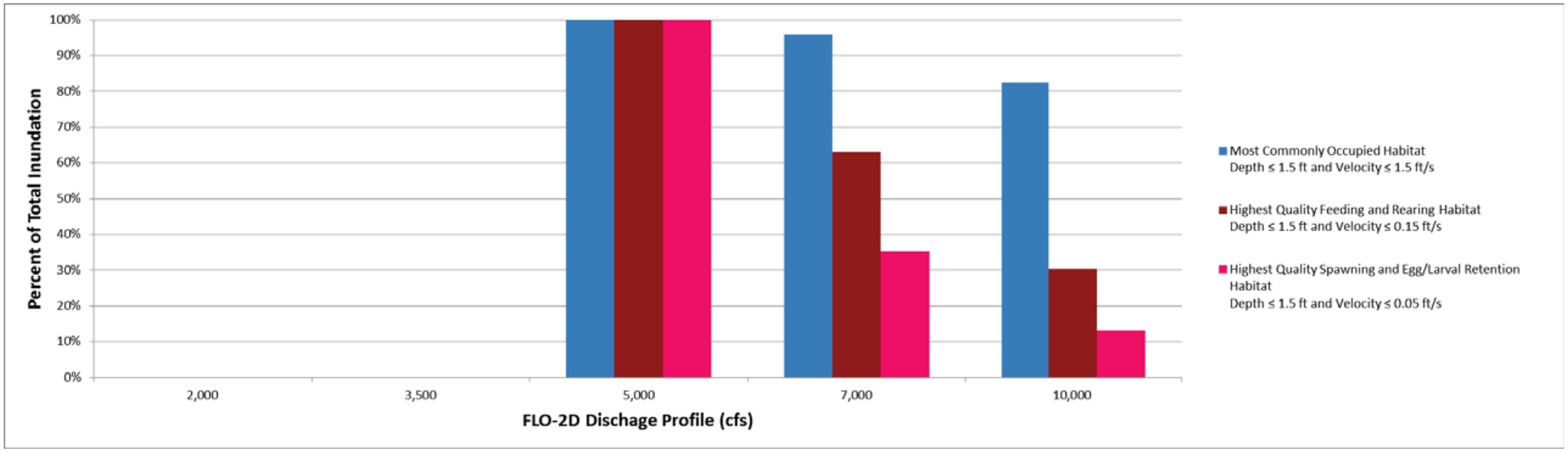
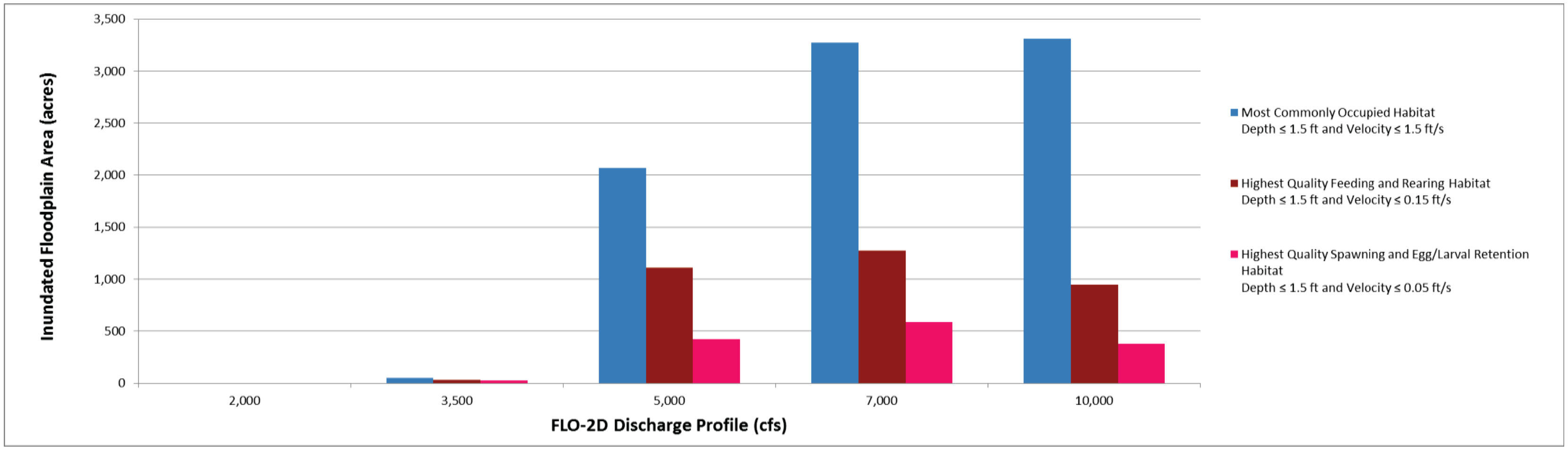


Exhibit B2. Differences in habitat quality over five modeled example flows based on the Isleta Reach to San Acacia FLO-2D

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s				Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s			
FLO-2D Discharge Profile (cfs)	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*
2,000 (total floodplain inundation 0.0 acres)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3,500 (total floodplain inundation 47.98 acres)	47.98	100%	0.40; 0.25 SD	0.08; SD 0.09	35.08	73.1%	0.36; SD 0.27	0.03; SD 0.05	25.04	52.2%	0.41; SD 0.30	0.004; SD 0.008
5,000 (total floodplain inundation 2,110.79 acres)	2,068.21	98.0%	0.52; SD 0.33	0.15; SD 0.1	1,112.40	52.7%	0.41; SD 0.34	0.07; SD 0.05	425.90	20.2%	0.27; SD 0.29	0.02; SD 0.02
7,000 (total floodplain inundation 4,017.33 acres)	3,274.74	81.5%	0.70; SD 0.45	0.19; SD 0.12	1,274.73	31.7%	0.39; SD 0.39	0.06; SD 0.05	585.33	14.6%	0.23; SD 0.28	0.01; SD 0.02
10,000 (total floodplain inundation 6,059.96 acres)	3,313.95	54.7%	0.74; SD 0.44	0.24; SD 0.15	948.92	15.7%	0.42; SD 0.38	0.07; SD 0.05	377.78	6.2%	0.25; SD 0.32	0.02; SD 0.02



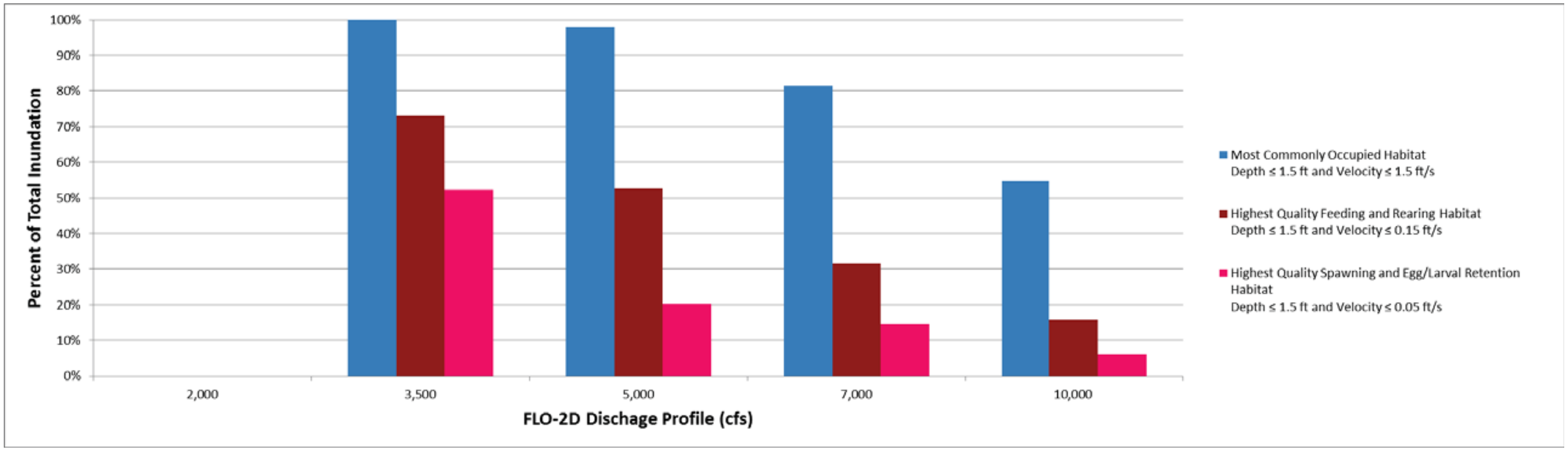
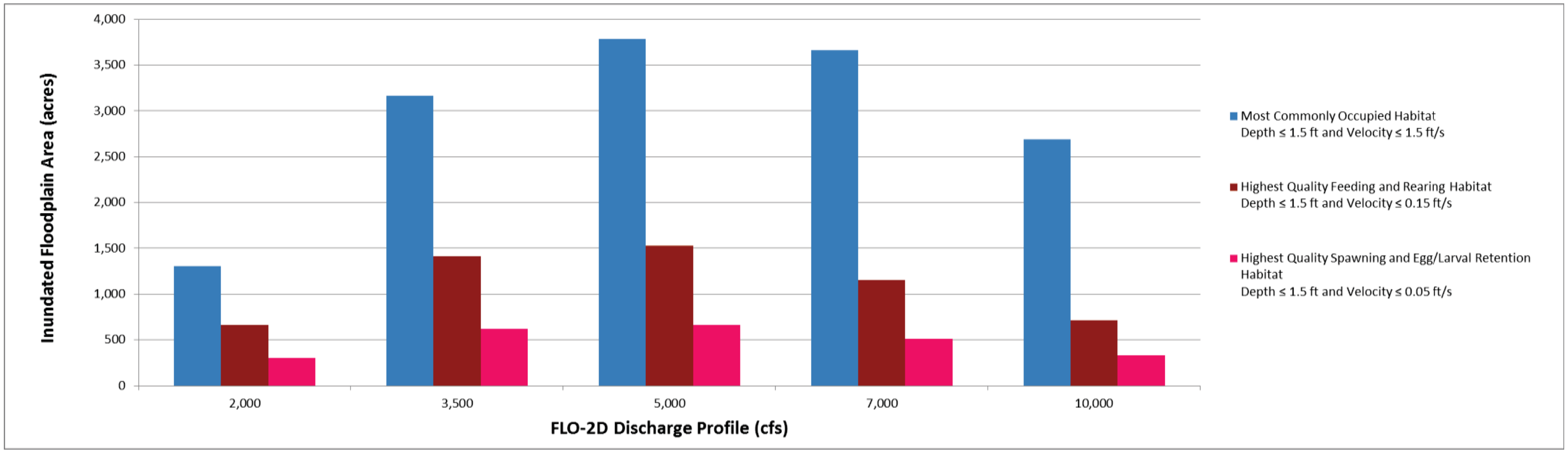
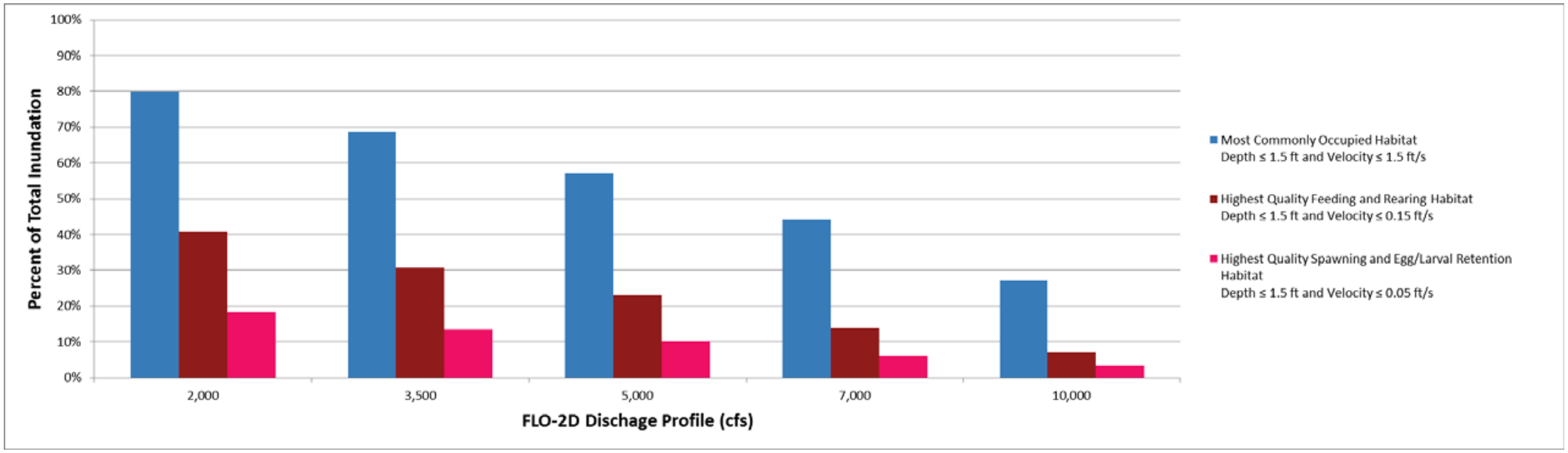


Exhibit B3. Differences in habitat quality over five modeled example flows based on the San Acacia to San Marcial RR Bridge FLO-2D

	Most Commonly Occupied Habitat Depth ≤ 1.5 ft and Velocity ≤ 1.5 ft/s				Highest Quality Feeding and Rearing Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.15 ft/s				Highest Quality Spawning and Egg/Larval Retention Habitat Depth ≤ 1.5 ft and Velocity ≤ 0.05 ft/s			
FLO-2D Discharge Profile (cfs)	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*	*Area (acres)*	*Percent of total inundation*	*Mean depth (ft)*	*Mean velocity (ft/s)*
2,000 (total floodplain inundation 1,630.67 acres)	1,303.26	79.9%	0.51; SD 0.40	0.18; SD 0.16	665.06	40.8%	0.33; SD 0.33	0.06; SD 0.05	299.87	18.4%	0.21; SD 0.27	0.01; SD 0.02
3,500 (total floodplain inundation 4,611.45 acres)	3,165.93	68.7%	0.63; SD 0.43	0.20; SD 0.16	1,414.29	30.7%	0.43; SD 0.39	0.07; SD 0.05	620.66	13.5%	0.23; SD 0.26	0.02; SD 0.02
5,000 (total floodplain inundation 6,625.31 acres)	3,787.13	57.2%	0.68; SD 0.44	0.22; SD 0.17	1,528.56	23.1%	0.43; SD 0.41	0.06; SD 0.05	665.89	10.1%	0.29; SD 0.34	0.01; SD 0.02
7,000 (total floodplain inundation 8,270.59 acres)	3,663.17	44.3%	0.71; SD 0.45	0.26; SD 0.19	1,150.86	13.9%	0.39; SD 0.40	0.06; SD 0.05	509.63	6.2%	0.23; SD 0.31	0.01; SD 0.02
10,000 (total floodplain inundation 9,891.77 acres)	2,687.47	27.2%	0.79; SD 0.44	0.31; SD 0.22	713.06	7.2%	0.41; SD 0.40	0.07; SD 0.05	332.68	3.4%	0.28; SD 0.36	0.01; SD 0.02





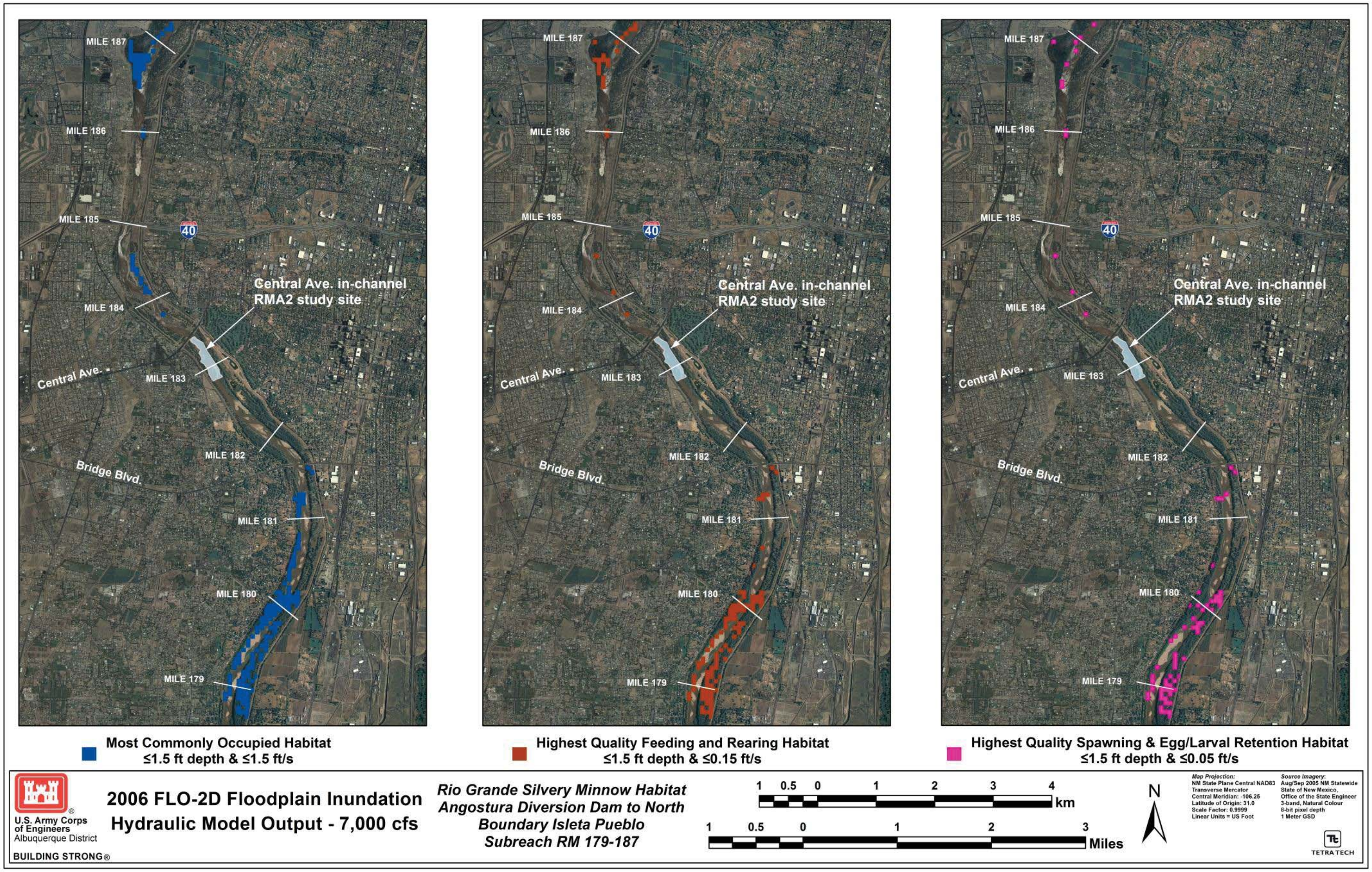


Exhibit B4. 2006 FLO-2D floodplain inundation hydraulic model for Angostura Diversion Dam to Isleta Pueblo showing examples of three indices of habitat quality at 7,000 cfs.

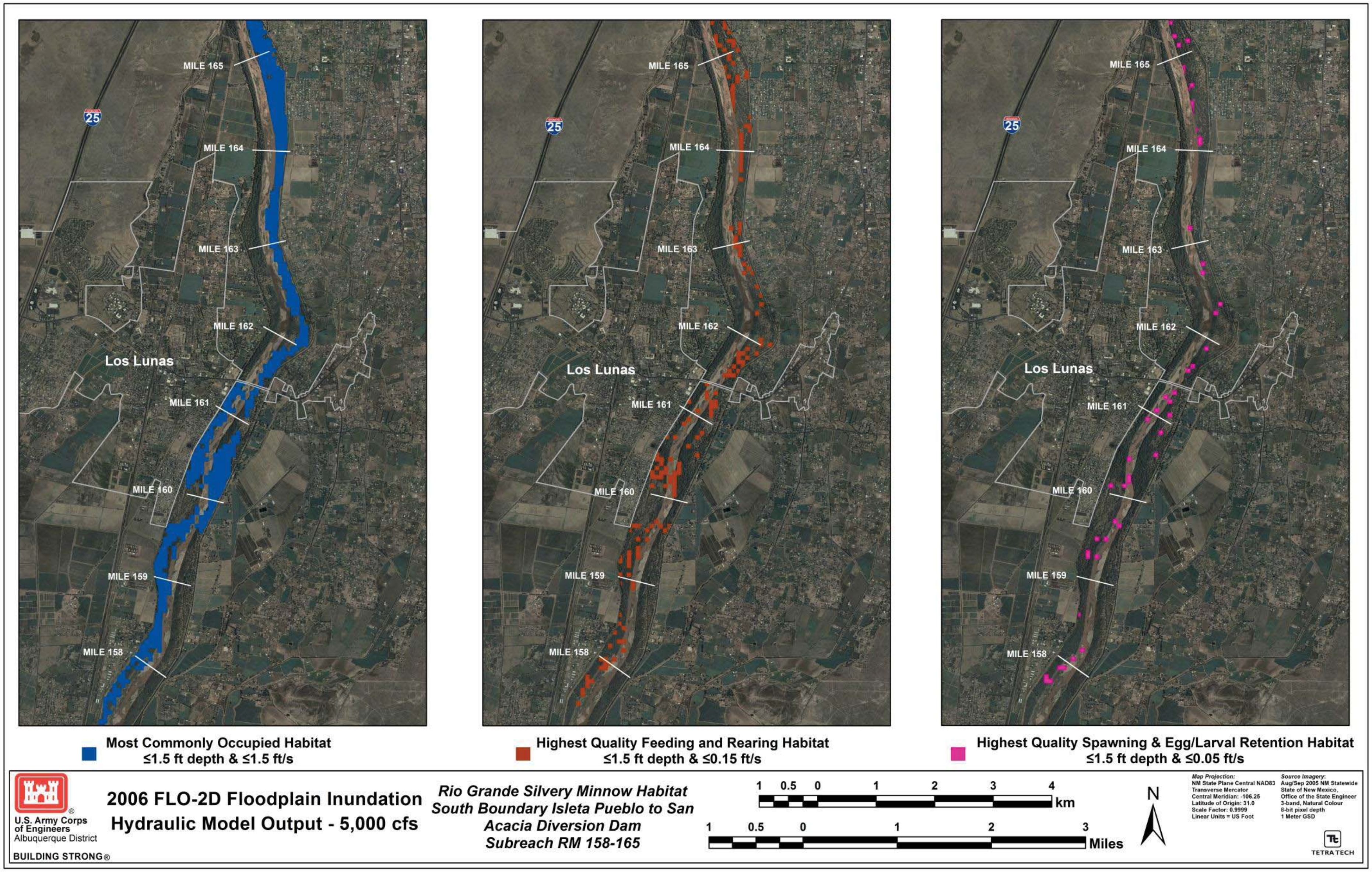


Exhibit B5. 2006 FLO-2D floodplain inundation hydraulic model for Isleta Pueblo to San Acacia Diversion Dam showing examples of three indices of habitat quality at 5,000 cfs.

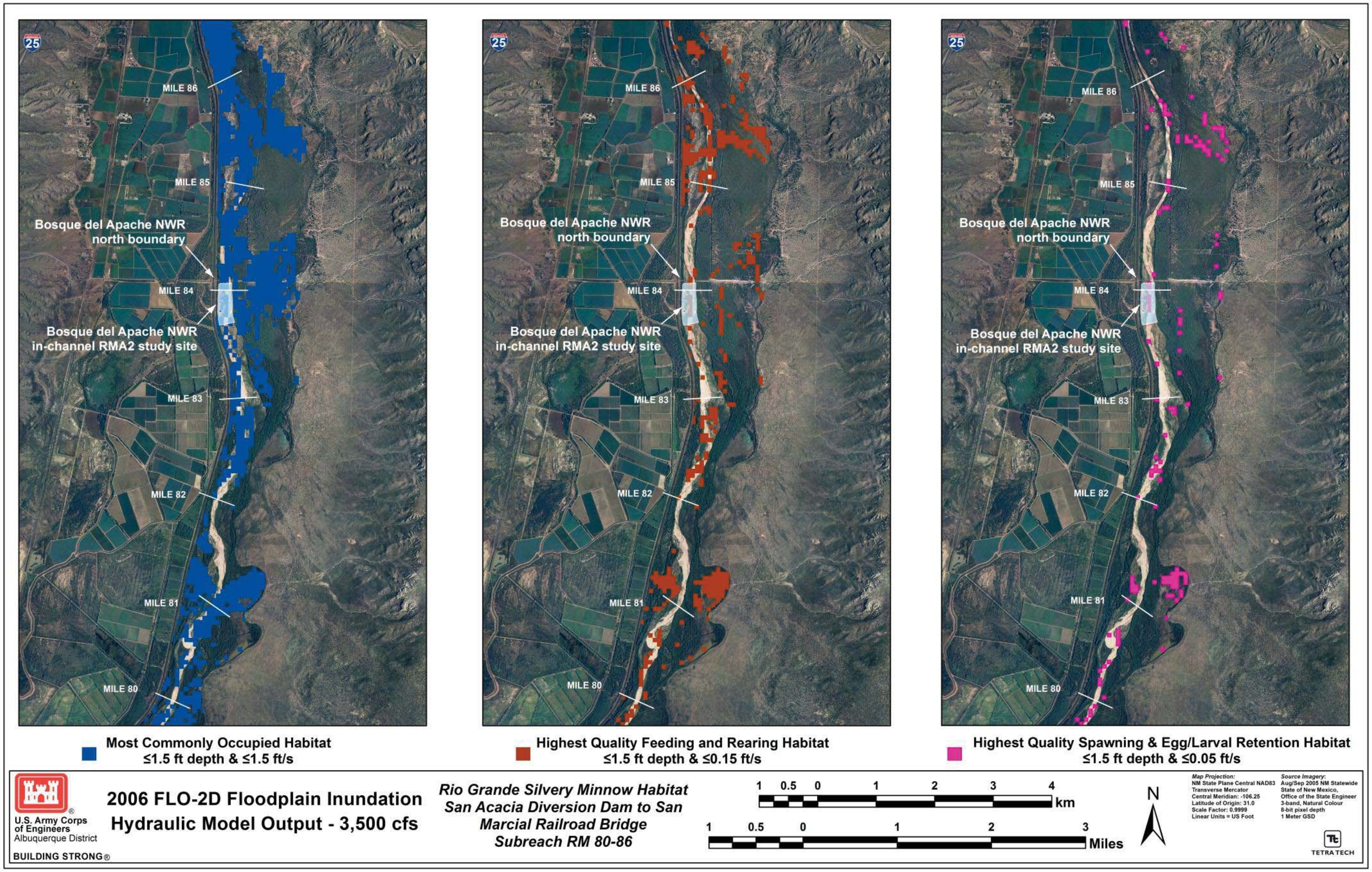


Exhibit B6. 2006 FLO-2D floodplain inundation hydraulic model for San Acacia Diversion Dam to San Marcial Railroad Bridge showing examples of three indices of habitat quality at 3,500 cfs.

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Appendix C

Densities of Rio Grande silvery minnow captured in the MRG

Exhibit C1. MRG Long-Term Monitoring Program total capture of Rio Grande silvery minnow by year and reach, 1993-2012.

Exhibit C2. Total capture of Rio Grande silvery minnow in the MRG by month and year, 1993-2012.

Exhibit C3. MRG Long-Term Monitoring Program total capture of Rio Grande silvery minnow during October index sampling by year and reach, 1993-2012.

Exhibit C4. MRG Long-Term Monitoring Program total capture of Rio Grande silvery minnow by year and reach, 2008-2012.

Exhibit C5. MRG Long-Term Monitoring Program total capture of Rio Grande Silvery minnow by reach in 2012.

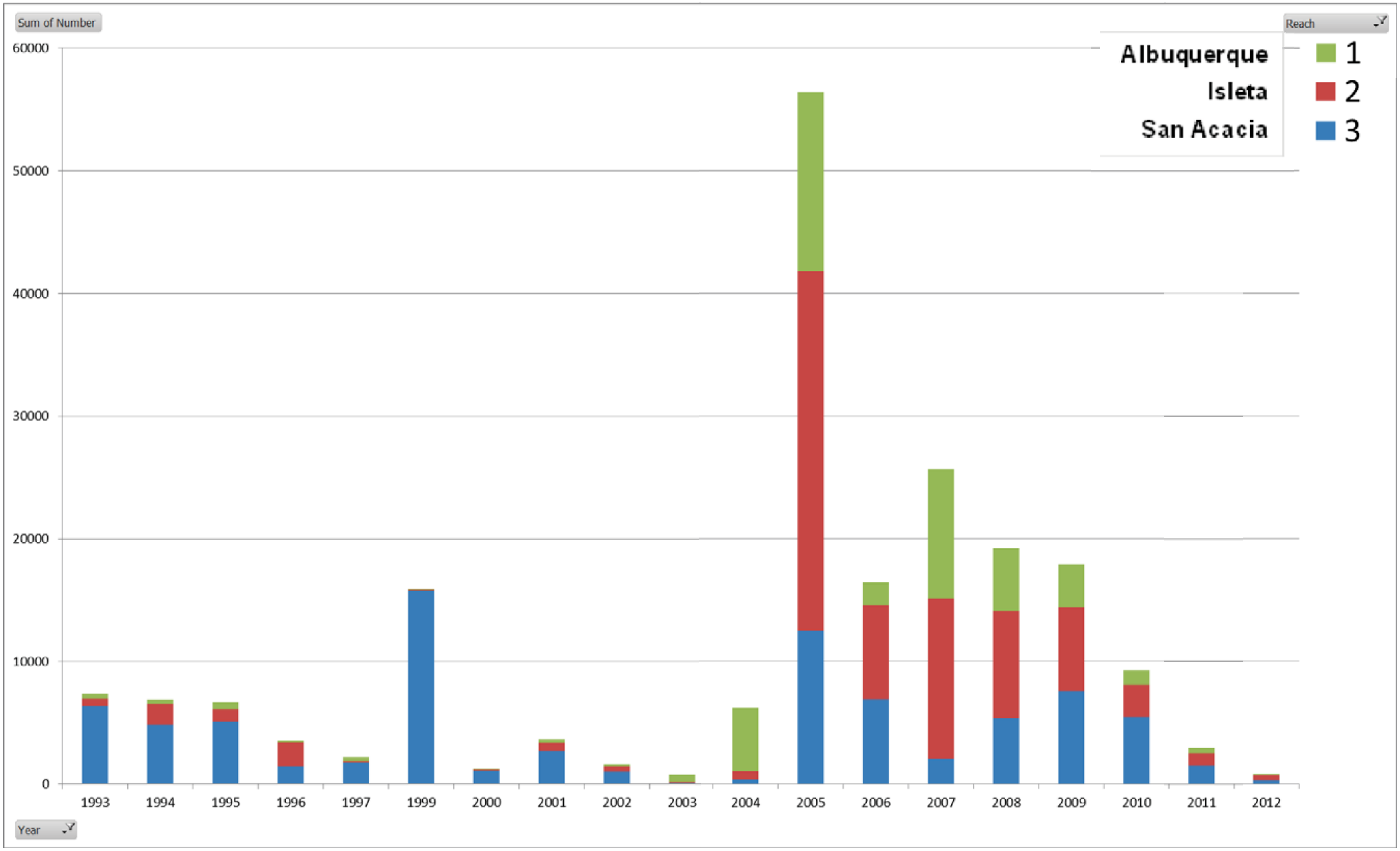

Exhibit C1. MRG Long-Term Monitoring Program total capture of Rio Grande silvery minnow by year and reach, 1993-2012.

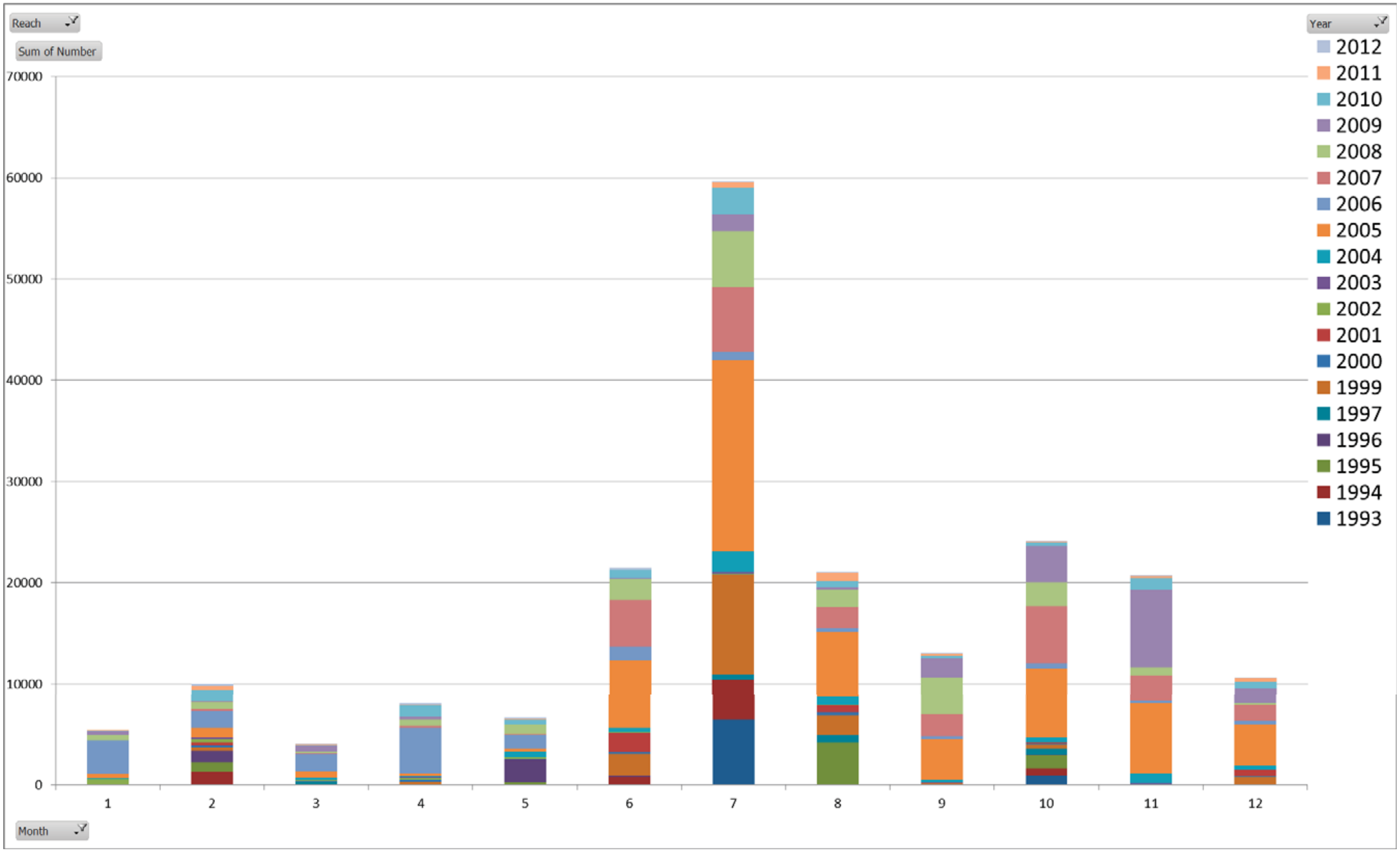

Exhibit C2. Total capture of Rio Grande silvery minnow in the MRG by month and year, 1993-2012.

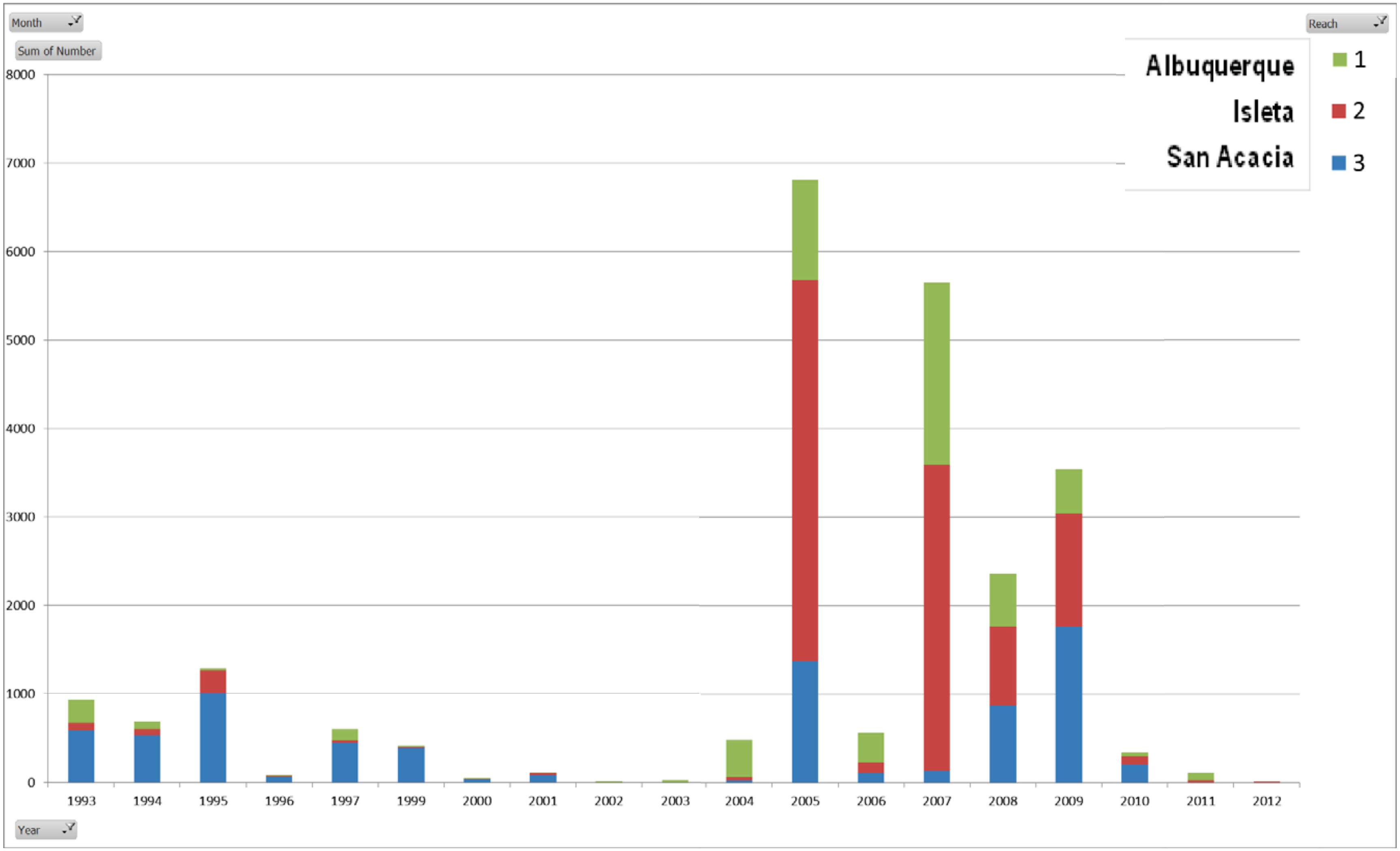

Exhibit C3. MRG Long-Term Monitoring Program total capture of Rio Grande silvery minnow during October index sampling by year and reach, 1993-2012.

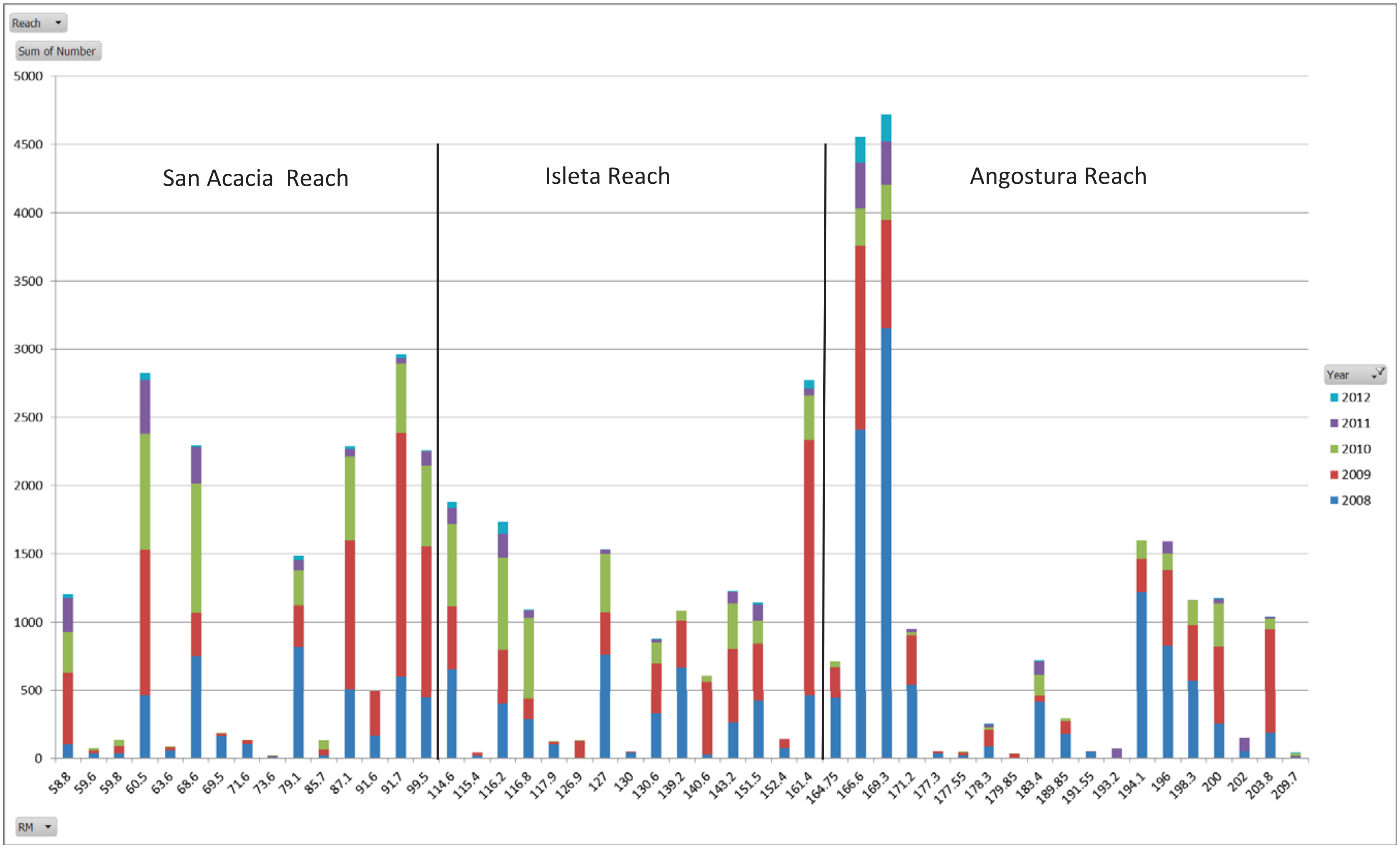

Exhibit C4. MRG Long-Term Monitoring Program total capture of Rio Grande silvery minnow by year and reach, 2008-2012.

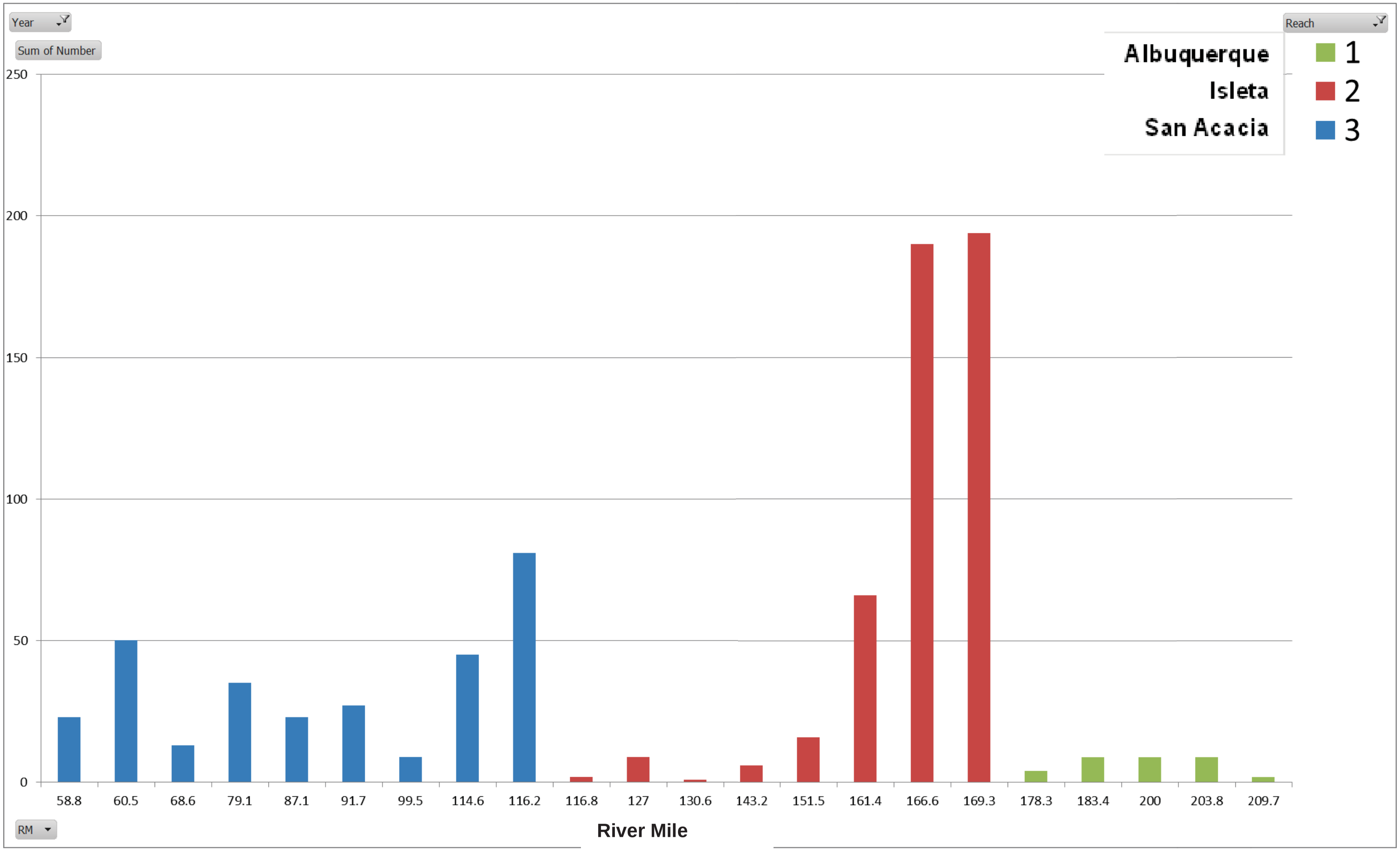

Exhibit C5. MRG Long-Term Monitoring Program total capture of Rio Grande Silvery minnow by reach in 2012.

Appendix D

Restoring Perennial In-Channel Wetted Habitat as a Collaborative Program Priority to Enhance Survival and Recovery of Rio Grande Silvery Minnow

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Middle Rio Grande Endangered Species Act Collaborative Program
Silvery Minnow In-channel Wetted Habitat Workgroup
Concepts Paper

20 June 2005

I. INTRODUCTION

Extensive and prolonged channel desiccation in the Isleta and San Acacia reaches of the Middle Rio Grande (MRG) during low precipitation years can adversely impact the potential recovery of Rio Grande silvery minnow (RGSM, *Hybognathus amarus*). These impacts continue under the March 2003 Biological Opinion (BO, USFWS 2003). To address this problem, the Middle Rio Grande Endangered Species Act Collaborative Program's (Collaborative Program's) Science Subcommittee initiated discussions on a concept intended to reduce this risk by developing and implementing multiple areas of in-channel wetted habitat in the Isleta and San Acacia reaches. Following joint meetings with and input from other Collaborative Program technical subcommittees, the Science Subcommittee formed a workgroup to define habitat restoration and water management issues associated with this concept. In this paper, *perennial in-channel wetted habitat* refers to portions of the channel kept continually watered by shallow ground water or dependable surface water supplies, including directly managed water, to produce and maintain sufficient water depths, areas, and water qualities for the persistence of RGSM and other entrained aquatic life.

Establishing such wetted habitats during periods of channel drying are viewed by the Collaborative Program's technical sub-committees as viable habitat enhancements that have high potential for decreasing the threat of RGSM extinction and increasing their recovery in the MRG. This is consistent with the Collaborative Program Advisory Panel (PAP) recommendation to "investigate options for increasing the temporal duration and spatial extent of wetted river in summer across all reaches in below average years, including the San Acacia and Isleta reaches."

Under this concept, water management techniques would be identified that are projected to help minimize both short- and long-term conservation water demands and maximize the area and persistence of in-channel wetted habitat in the critical reaches during times they would otherwise be desiccated by channel drying. In developing such habitats, however, a key design constraint is recognition that repeated cycles of channel wetting and drying is stressful to resident RGSM and all other aquatic populations. Therefore, it is better alternative to maintain some portions of the channel wet, while allowing other reaches to dry. This habitat restoration concept has been developed to improve the status of the listed species while improving the likely regulatory compliance for Collaborative Program signatories.

II. OBJECTIVE

The objective in this paper is to provide background information and to request approval from the Collaborative Program's Interim Steering Committee to form a Workgroup to develop monitoring protocols and a series of focused Request for Proposals (RFPs) that will focus on designing, implementing, and evaluating appropriate water management and habitat restoration practices. This work will allow the Collaborative Program to determine how best to enhance the value of this innovative restoration concept.

III. JUSTIFICATION

A. Channel Drying in the MRG

Historical periods of extensive and prolonged channel drying have occurred along the MRG, with marked affects on the native fish community (USFWS 2003). Recent analysis by the Collaborative Program's Water Acquisition and Management Subcommittee shows that native water supplies can frequently be inadequate to meet the water supply requirements defined in the 2003 BO (WAMS 2005). Therefore, there is a high probability there will continue to be many years with insufficient water to keep the MRG continuously wet to Elephant Butte Reservoir, a situation exacerbated at times by Article VII requirements of the Rio Grande Compact.

B. RGSM Response to Channel Drying

RGSM have evolved and are relatively well-adapted behaviorally to surviving in rivers with periodic and sometimes extended periods of extensive channel drying (HRS 2004). As such, RGSM appear to have natural tendencies to cope with drying river conditions. For example:

- Collaborative Program rescue and salvage personnel have observed RGSM to be among the first to leave a drying reach as well as the first to enter a re-wetted reach (M. Hatch, USFWS, pers. comm.).
- 2004 salvage efforts found many RGSM in deeper pools and wasteway discharges during times of river drying, with RGSM often rescued from shallow water habitats when these habitats began as deep pools (M. Hatch, USFWS, pers. comm.).
- Collaborative Program monitoring data suggest the number of RGSM tend to increase in an upstream direction within major MRG reaches, with the upper portions of each reach where continuous water supplies tend to be most dependable (Dudley et al. 2005; M. Hatch, USFWS, pers. comm.).

These RGSM behavioral and habitat use observations, when coupled with the current low population numbers and high variability in their longitudinal abundance along the MRG, strongly suggest that persistence of RGSM in the MRG depend on increasing suitable in-channel and near-channel wetted habitat during periods of channel drying. While deep pools persist during channel drying periods at a few locations along the Isleta and San Acacia reaches, both the number and size of these pools declines in the absence of re-wetting events. Developing additional in-channel wetted habitats, especially in the upper portions of these reaches, can be expected to markedly benefit recovery of the RGSM.

C. Maintaining RGSM Genetic Diversity

Studies supported by the Collaborative Program indicate that genetic variability has existed among the three major reaches of the MRG (Turner and Osborne 2004); as such, genetic variability may still exist or additional diversity may again develop. However, the complete drying of any of the MRG reaches results in the temporary extirpation of the resident silvery minnow, contributes to the loss of any of their genetic uniqueness, possibly producing a decline in the overall genetic diversity in the remaining population. Such declines in genetic diversity reduce the ability of the species to cope with natural variability in their environment and increase the likelihood of their eventual extinction. Development of in-channel wetted habitat will help to protect as much habitat as possible in a variety of locations, maintain RGSM genetic diversity, and increase independent survival probabilities for groups of RGSM along the three MRG reaches.

D. Improving Silvery Minnow Population Structure

Few RGSM in the MRG are found to survive past age 1 in the lower reaches (Dudley et al. 2005), although older fish are common in hatchery and artificial wetted environments. One apparent contributor for this limited age structure is the stress of frequent drying and re-wetting events, as discussed above. Hatchery raised RGSM have been documented to live at least two years following augmentation in the Albuquerque reach where more permanent water has existed (USFWS 2005). Increasing life expectancy for even a small portion of the RGSM population in the lower reaches would not only contribute to increasing their densities, but would also be expected to enhance their fecundity and the likelihood of reproductive success during favorable spawning conditions. Therefore, development of in-channel wetted habitat in the Isleta and San Acacia reaches should lead to improved RGSM population structure and viability.

IV. RECOMMENDATION

Based upon this background and justification, this concept paper recommends:

1. The Collaborative Program establish a near-term priority to maintain and expand this Workgroup to develop monitoring protocols and a series of focused Request for Proposals (RFPs) to design, implement, and evaluate appropriate water management and habitat restoration practices thereby allowing the scientific assessment of the value and enhance the success of this innovative restoration concept. (The Collaborative Program management will have the opportunity to review, modify and/or approve any resulting RFPs prior to their release.)
2. The Collaborative Program should establish a near-term priority to fund one or more projects to define design and operation requirements intended to produce the best method to couple habitat restoration and local water management efforts to develop and maintain suitable in-channel habitat that persists in a wetted condition along locations having dependable water supplies.
3. Management of Collaborative Program water and other conservation water supplies obtained to support RGSM survival and recovery should include a high priority to keep these restored habitats wet.

V. IMPLEMENTATION CONSIDERATIONS

To provide the Collaborative Program with a better understanding of the proposed in-channel wetted habitat concept, we have developed a hypothetical example for the MRG reach between Isleta and San Acacia diversion dams (Figure 1). Eight wasteways are identified within this reach, some that regularly carry water to the river and some that could be rehabilitated to allow for regular discharge to the river. An estimate of the flow needed in each wasteway at its confluence with the MRG is provided in Figure 1. These flows, working in conjunction with habitat restoration measures implemented at each of these confluences, would create the in-channel wetted habitats. Also shown in Figure 1 are example flow releases over (or around) each diversion dam to maintain additional wetted habitats in the river downstream of the dams. In total, these estimated flow requirements equal 54 cfs, which if required for 100 days in a given dry year, would be about 11,000 acre-ft. Again, this is a hypothetical example that assumes the capability of providing continuous flow and that the given flow volumes are what will be required. The research and pilot demonstration project(s) we request would answer questions such as these.

The requested RFP could also address the feasibility of pulse or discontinuous flows (i.e. “little squirts”) and the minimum flows required through the wetted habitats to maintain water quality and pool volume, as well as opportunities for habitat development elsewhere in the system (e.g., Low Flow Conveyance Channel outflows).

Considerations on the morphology of restored in-channel wetted habitats should include:

- Deeper pools offer greater protection from avian predators;
- Water flow should be maintained into and through pools to lessen the likelihood of severe water quality impacts such as low dissolved oxygen, high ammonia , and excessive water temperatures;
- For maximum effectiveness, developed pools should include pathways for natural ingress and egress during higher flow conditions;
- Consideration of local conditions such as water management activities and groundwater depths should be considered in the design, placement and operation of wetted habitats.

Finally, it is critically important to point out that the development and maintenance of any such wetted habitat systems is not specifically defined in the 2003 BO. Therefore, water used to maintain such in-channel wetted networks would be viewed as a water demand, at least in part, on-top of water supply requirements resulting from the current BO. While we have provided some hypothetical estimates of what these maintenance flows may be, it is also important recognize that these demands could vary over wet to dry years and it is impossible to quantify these water requirements accurately without operational experience from implementing pilot or demonstration projects.

VI. LITERATURE CITED

Dudley, R.K., S.P. Platania, and S.J. Gottlieb. 2005. Rio Grande Silvery Minnow Population Monitoring Program Results from 2004. Final report to the Middle Rio Grande Endangered Species Act Collaborative Program, Albuquerque, NM.

Habitat Restoration Subcommittee (HRS). 2004. Habitat Restoration Plan for the Middle Rio Grande. A report prepared for the Middle Rio Grande Endangered Species Act Collaborative Program, Albuquerque, NM.

Turner, T.F., and M. J. Osborne. 2004. Genetic consequences of supportive breeding in the endangered Rio Grande silvery minnow (Hybognathus amarus): genetic evaluation of wild and captively reared and propagated stocks, 1999-2004. An Annual report for FY 2003 to the US Bureau of Reclamation and Middle Rio Grande Endangered Species Collaborative Workgroup, Albuquerque, NM

USFWS (U.S. Fish and Wildlife Service). 2003. Biological and Conference Opinion on the Effects of Actions Associated with the Programmatic biological Assessment of the Bureau of Reclamation’s Water and River Maintenance Operations, Army Corps of Engineers’ Flood Control Operation, and Related Non-Federal Action on the Middle Rio Grande, New Mexico. Memorandum to the Area Manager, Area Office, Bureau of Reclamation, from Regional Director, Region 2, USFWS, Albuquerque, NM.

USFWS (U.S. Fish and Wildlife Service). 2005. Experimental Augmentation and Monitoring of Rio Grande Silvery Minnow in the Middle Rio Grande, New Mexico. Annual Report June 2003- May 2004 submitted to the Middle Rio Grande Endangered Species Act Collaborative Program, Albuquerque, NM.

Water Acquisition and Management Subcommittee (WAMS). 2005. Analysis of Sufficiency of Unregulated Rio Grande Flows to Meet ESA Flow Targets in the Middle Valley. Report to the Middle Rio Grande Endangered Species Act Collaborative Program, Albuquerque, NM.

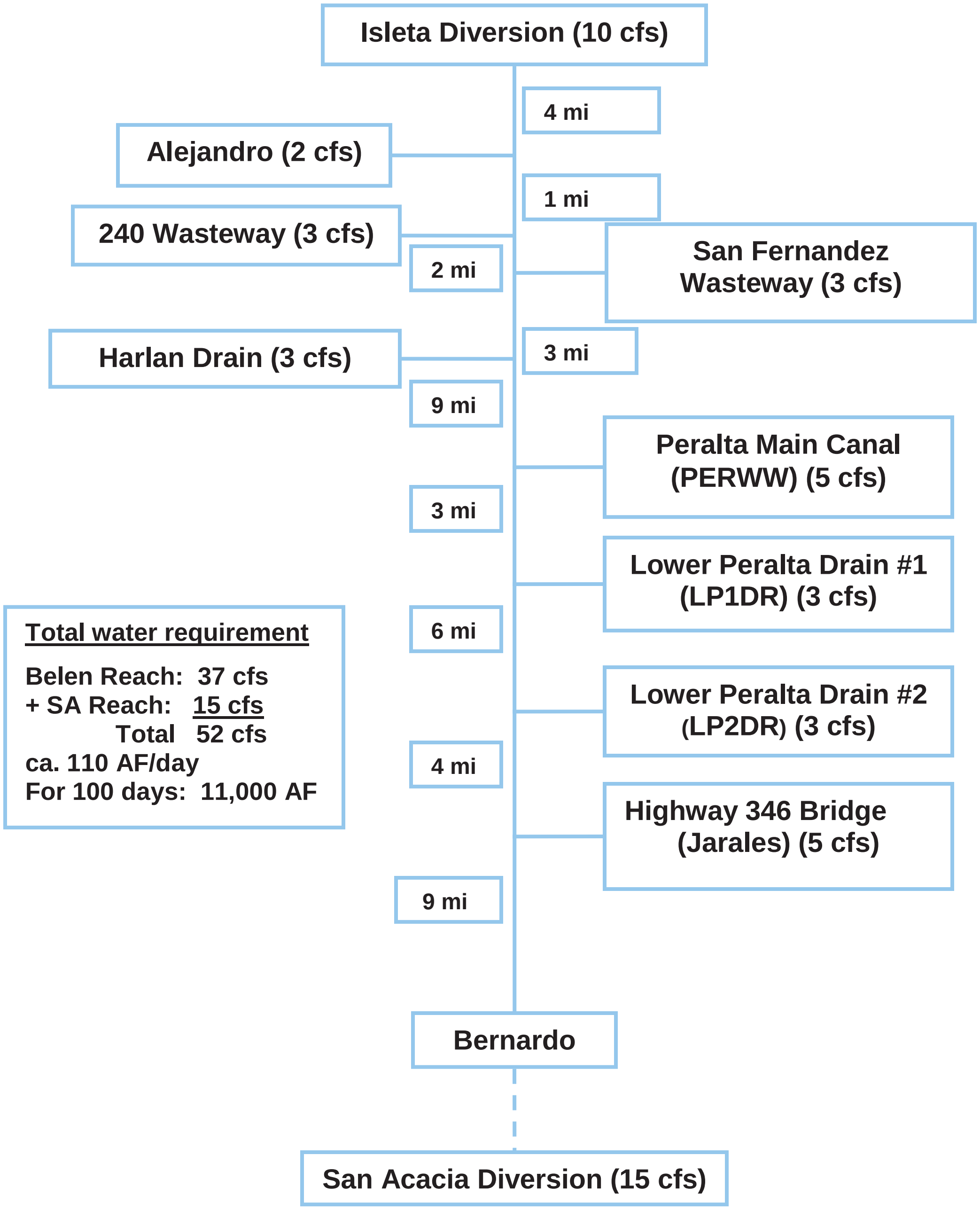

Figure 1. Projected locations and supplemental water requirements for the development of perennial pools downstream of wasteway and drain discharges into the MRG.

Additional Issues and Questions for Consideration by the Workgroup

1. Predation by larger fish on small fish in pools during periods of extensive drying and long-term mutual confinement has not been assessed. (Page: 106
If water quality adequate, predation might become a problem, but if water quality eroding, doubtful predators interested in eating.)
2. Neither GIS nor other data are available for locations or site-specific characteristics of the pools where silvery minnow have been rescued. Overall, caution is needed to not overburden rescue crews with data collection requirements. Their most important role is rescue; data collection can significantly slow the crews' progress, leading to increased take.
3. To what extent is there a need for spatial data analysis identifying the distribution of RGSM in proximity to existing and/or newly constructed refuge habitats and drain outfalls? Can the USFWS 2004 rescue report provide maps at the appropriate detail to evaluate distances and minnow densities in relations to such locations? Since a major refuge area occurs on Isleta Pueblo, can the USFWS work with the Pueblo in developing appropriate maps?
4. The locations and persistence of long-term wetted habitat along the MRG during drought should be mapped and recorded to allow a better opportunity to take advantage of persisting water features in the development and enhancement of those habitat areas that have persisted wetted.
5. What volume of species conservation water is typically delivered to Isleta Dam during the summer? How can this information be best incorporated into this planning and decision process?
6. What qualitative or quantitative information supports the above statement on page 2 regarding RGSM being "the first to leave a drying reach"?
7. Some wetted habitats could be developed via strategic placement of instream log-deflection structures, coupled with, e.g., 3000 cfs scour flows to create deep holes. But, peak-flow and high-flow conditions are required to produce full benefits from the use of log-structures in the development of scour pools.
8. While log structures may be a viable approach to producing refuge habitats, questions remain on whether it is possible to build a sufficiently large structure using only logs. Additional assessment is required, for example, of the root wad structures installed by MRGCD near the Hispanic Center. Other construction options to build large structures include rock and untreated wooden piling, which would eventually rot away. Such structures also could be used where there is a need to limit bank migration, e.g., for protection of levees or other structures.
9. Pool habitats are commonly observed to form in the MRG along sharp bends or corners in the bank; helical currents caused by the change in flow direction appear to scour these holes. Similar conditions may be artificially produced by building groins or hard point structures along the bank. Modeling studies might help to optimize appropriate designs.

10. MRG is a sand bedded river. Therefore, keeping any such holes scoured out may require periodic high discharge volumes. Modeling studies could be used to help configure designs to minimize scour flow requirements.
11. Experience is required to determine the long-term persistent of scour pools, i.e., how long does it take for refuge pools to refill with sediment?
12. When/how could mechanical excavation or other structural activities benefit development of refuge habitat developments?
13. Why do some pools along drying reaches of the MRG maintain their water level after river flow in the immediate area has stopped? Assessment of this question could involve assessing at least two probable hypotheses: (1) The pool substrate has high clay content, minimizing leakage; and/or (2) The pool is located where there is a continuous water supply, e.g., a subsurface recharge. Is the resolution of these relationships a key requirement prior to developing pilot wetted refugia habitats? Or, could needed water supplies for each such development just require definition and calibration through operational experience to maintain water against leakage and evaporation. Where groundwater is providing a reliable water supply, pools could be created without requiring additional conservation water. In areas with good substrate composition, pools could be dug so they fill with water from the receding river. (But, how quickly would such pools fill with sediment?)
14. Dependable water management strategies that include the cooperation of MRGCD, the involved Pueblos, and other affected parties are necessary to maintain flows over the diversion structures and through the targeted wasteways.
15. Sometimes, when excess irrigation water is present in the irrigation system, this water could be used to help keep the refuge habitat wet. At other times, when such water is not available, Collaborative Program water would be needed to maintain a wetted condition. Any water pay-back requirements will need to be negotiated between the Collaborative Program, MRGCD, involved Pueblos, and other involved parties.
16. Would it be possible to deliver at Angostura Diversion all the water needed to maintain perennial pools in the downstream reaches?
17. Alternatives exist to pump from the Low Flow Conveyance Channel (LFCC) to irrigate an adjacent series of in-channel pools in the river. For example, one pump operating every 3 days could irrigate approximately 2.5 miles of refuge habitat, including 10-15 pools. These pumps should operate only long enough to fill the area of the refuge. They should not rewet the channel downstream of the target length of the refuge habitat. Under this strategy, multiple pump and habitat series could be developed.
18. What evidence exists that pumping from the LFCC has benefited RGSM populations downstream of Bosque del Apache? Prior to the March 2003 BO? Following drying of the river channel under the March 2003 BO? Is the approximate $400K/yr cost for pumping the best investment for these funds? Does this information support the implementation of the refuge habitat concept?
19. In the assessment of impacts accompanying storm-flow diversions, consideration should be given to whether the significance of any such impacts changes with the size of the

storm flows; should a threshold flow be defined, above which storm flows would not be diverted? Should such impacts be projected as insignificant, options could also be considered to mount the existing LFCC pumps on trailers to allow pumping to channel wherever analyses project habitat needs and benefits to be most critical.

20. Could bubble curtains be used as effective aids to reduce entrainment of minnows in storm-flow diversions, should significant entrainment of silvery minnows occur with such diversions?
21. Is it essential, from a biological view, to keep the MRG wet from Central to Isleta (considering this is the end of the reach where relatively fewer silvery minnows apparently are expected to occur, as also apparently supported by existing data), or could that water requirement be better used to help maintain flows to downstream enhanced perennial pool habitats? (Note that the SSc has emphasized that flows through the Central-to-Isleta Reach should be maintained to meet the existing and any BO requirements. Any future alterations of those requirements should occur only as supported by appropriate new scientific evidence that such flows are not essential to the persistence and recovery of the silvery minnow population.)
22. Additional sampling and analysis is required to verify that silvery minnows consistently trend to develop greater population densities in the upper portions of the reaches; specifically, additional assessment needs to evaluate the relative populations densities along the Central to the Isleta Dam reach.
23. Should additional analysis confirm that silvery minnow populations tend to maintain significantly smaller population densities in the lower ends of reaches, additional research should focus on the possible causes and whether these relationships originate from natural or induced causes?
24. Similarly, additional analysis is required to evaluate whether the elevated densities of silvery minnows, as observed in association with the Rio Rancho treated wastewater discharges during June 2004, recur in subsequent years and why this density persists.
25. Should wasteway-associated refuge developments include both in-channel and off-channel habitats, relative to the river? Are there times or locations that off-channel habitats could provide additional or superior refuge conditions?
26. Additional data are needed to improve abilities to project pool design characteristics (e.g., pool size, flow through rates) to effectively limit possible water quality impacts in wetted refuge habitats. Who should collect data from rescued pools that could help address these data needs? Should individuals be added to rescue crews, or should separate crews come behind the rescue crews? Likely, only a small subset of the total number of ponds rescued can be sampled for such characterization data. How would the subset be selected? Would each pool be sampled once or multiple times during the day? Could continuous monitoring probes be used at some sites?
27. Refuge habitat developed in the Socorro area would require additional measures to control cattle access and associated water quality problems.

28. How would increases in irrigation efficiency affect abilities to maintain refuge habitat? Less water leaking into the groundwater could increase the local surface-water demand to keep the refuge habitat wetted.
29. Groundwater pumping could aid maintaining wetted conditions in the refuge habitat at some locations, but this option should be considered to be “an action of last resort.” When and where could/should it be used?
30. Local geological conditions can enhance opportunities for maintaining water for some refuge locations. Additional assessment is necessary to identify such locations.
31. Should larger fish predators prove to be a significant risk to silvery minnows, selected refuge pools could be “gill netted” during drying periods to remove the larger fish. No information is available to assess whether insect predators may be a problem to silvery minnows seeking refuge in these pools. What priority should be placed on developing studies to assess this problem?
32. How would success of any refuge habitats would be measured? Is monitoring of minnows in the pools using seining appropriate? Would it produce excess stress on the minnows?