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WATER REQUIREMENTS FOR ENDANGERED SPECIES - RIO GRANDE SILVERY MINNOW (*HYBOGNATHUS AMARUS*)

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ABSTRACT

The biology of many endangered species is poorly known. This is well illustrated by the critically endangered Rio Grande silvery minnow. Clear understanding is lacking of its food habits, cover requirements, where and how it reproduces, river channel features that improve juvenile recruitment, and if the species retains sufficient genetic diversity to continue its evolutionary sojourn. It is well known that the Rio Grande silvery minnow's eggs and larvae can be transported downstream. Downstream transport in one phase of the life history must be offset by upstream passage, otherwise extinction is inevitable. Prior to 1975, the species was sustained in the middle Rio Grande by having an upstream source population in the perennially wetted reach from Algodones to Española and Abiquiu. Recurring dry riverbeds during this time did not have a large negative effect on the Rio Grande silvery minnow because it was often found to be an abundant species in the middle Rio Grande. Closure of Cochiti Dam in 1975 led to the loss of the upstream source population and to greater

modification of the river flows. The species currently has a high vulnerability to extinction because it is forced to live in reaches that have often gone dry in the past. Recovery of the species would be enhanced by (1) restoring the species upstream from Cochiti, (2) removal or re-engineering of Cochiti Dam to provide fish passage, (3) providing upstream passage at downstream diversions in the lower river reaches, and (4) developing naturalized refugial habitats in the lower desiccation-prone reaches. The parsimony here is that the Rio Grande silvery minnow and the valley's farmers coexisted for many years prior to Cochiti Dam without supplemental water for the minnow.

INTRODUCTION

Population growth in New Mexico has long been concentrated in the Rio Grande valley. Pueblo settlements arose in the valley, followed by Spanish settlements such as Las Cruces, Albuquerque, Bernalillo, Santa Fe, Española, and Taos. The settlement pattern under Spanish rule was the issuance of small land grants, first up the larger Rio Grande and Rio Chama, and then into mountain valleys with smaller tributary water sources (Scurlock 1986). Throughout the history of human occupation of New Mexico, population growth has been concentrated proximally to surface and groundwater supplies.

As towns grew into cities along the Rio Grande valley, demand for water elevated the depletions from surface and groundwaters from the river basin. Increased depletions elevated the stress on water supplies that contributed along with many other factors to the decline of native aquatic species. Today, long-standing human settlements across the American West, with their agricultural and urban uses of land and water, have begun to face the possibility of giving up water to save an endangered species (Adams and Cho 1998; Parker 2002).

Within the middle Rio Grande valley the fight for "water for the river" versus "water for traditional uses" is centered on water from the San Juan-Chama Project, an interbasin transfer of water across the Continental Divide. Since project completion in the 1970s, a number of cities and agencies contracted for depletion of the water transferred by the project. The availability of additional water encouraged populations of Santa Fe and Albuquerque to grow beyond their supplies of native Rio Grande basin water.

Agricultural interests in the middle Rio Grande valley have also used water from the San Juan-Chama Project. These supplies have provided a reserve in times of drought but they have not fueled growth in agriculture in the way that project water has aided urban population growth.

Demands and shortfalls of water in the middle Rio Grande valley have increased with population growth. Whereas agriculture and the Rio Grande silvery minnow survived together for many decades, burgeoning city limits have begun to convert historical farms into subdivisions and shopping malls. Increasing urban growth seems likely to further exacerbate stress on water supplies and the cascading negative effects on aquatic biota (Jackson et al. 2001).

This paper will address four topics related to water requirements for the Rio Grande silvery minnow and other pelagic-spawning fishes whose eggs and larvae drift passively downstream. First, the biology of the Rio Grande silvery minnow will be reviewed. Second, information from historical data will be used to develop a perspective for the water requirements for the endangered Rio Grande silvery minnow. Third, the water requirements for the Rio Grande silvery minnow will be deduced from biological information and contemporary records. Finally, recommendations will be made to facilitate short-term survival of the Rio Grande silvery minnow through extended shortfalls of water.

BIOLOGY OF THE RIO GRANDE SILVERY MINNOW

The Rio Grande silvery minnow [*Hybognathus amarus* (Girard 1856; Bestgen and Propst 1996)] is native to the Rio Grande basin. Its historical range on the Rio Grande was from near Española, New Mexico to the Gulf of Mexico (Figure 1) and on the Pecos River from near Santa Rosa, New Mexico to its confluence with the Rio Grande. The species appears to have been lost from the Pecos River by the late 1970s (Cowley 1979; Cowley and Sublette 1987). Currently the Rio Grande silvery minnow is restricted to the middle Rio Grande valley between Cochiti Dam and the headwaters of Elephant Butte Lake.[1] The species was listed as federally endangered in 1994 (U.S. Dept. of Interior 1994).

The Rio Grande silvery minnow is a member of a reproductive guild of fishes called pelagophils (Balon 1975). Pelagophilic spawners reproduce in open water and produce nonadhesive semi-buoyant pelagic eggs

(Moore 1944) that float downstream as they develop (Platania and Altenbach 1998). Concentrated saline or turbid, sediment-laden water can cause the eggs to float and modest current velocities can transport the eggs downstream. These species typically have a rapid mode of embryonic development and hatching can occur within 24-48 hours depending on water temperature (Moore 1944; Bottrell et al. 1964; Platania and Altenbach 1998). Thus, the life cycle of the Rio Grande silvery minnow consists of downstream displacement of eggs and larvae followed by upstream passage of juveniles and adults.

Other aspects of their biology are poorly known. It is assumed that Rio Grande silvery minnows are herbivorous since they possess a long coiled gut typical of other herbivorous minnows (Sublette et al. 1990). Unfortunately, their food habits have never been documented. This deficit in basic biology makes it difficult to assess if their food base in the river has changed from earlier times when the minnow was more widespread. Likewise, it is not possible to determine if the presence of nonnative salt cedar or the lack of large woody debris in the river limits food availability.

Biologists have devised ways to learn the habitat requirements for a species. However, it is difficult or impossible to deduce preferred environmental conditions for an endangered species when its habitats have been highly modified. As a result, we lack understanding of what channel features provide the best cover for Rio Grande silvery minnows. We do not know how sediment transport and deposition affects cover availability nor can we assess if the conversion of the middle Rio Grande into a floodway adversely affected the availability of cover.

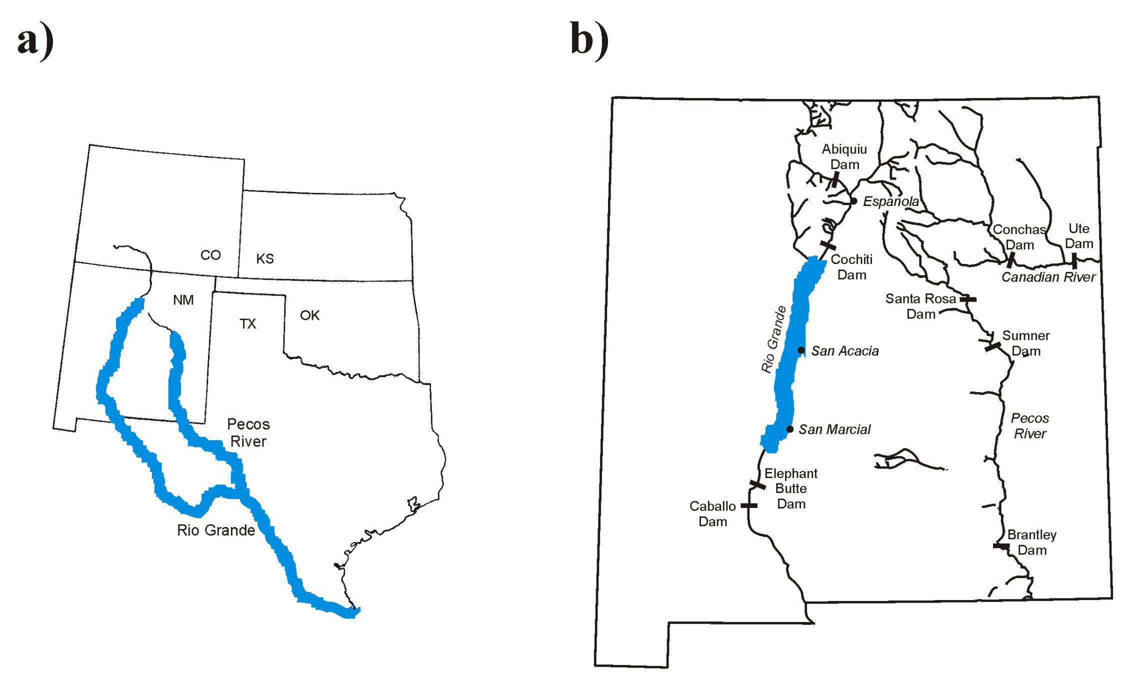

Figure 1. Historical (a) and contemporary (b) distributions of the Rio Grande silvery minnow are shown as thickened lines.

Aside from the basic knowledge of its life history, we know little about how Rio Grande silvery minnows reproduce. We do not know where they spawn in the river channel, what current velocity or channel depth they seek out, or how they find each other in a turbid river. Studies have not assessed the effects of hormones and their derivatives in sewage effluent on the minnow's reproduction. From a population dynamics perspective, it is unknown if there is a quasi-extinction threshold for the Rio Grande silvery minnow beneath which the minnows would have a very low probability of finding a mate.

Additional aspects of their biology are also unknown. For example, what channel features retain eggs and larval silvery minnows and stop their downstream drift? Are backwaters essential to recruitment? Is recruitment affected by predation from mosquitofish, carp, or nonnative game fish like white bass? Answers to these questions are critically important considerations for habitat restoration.

Questions remain regarding the genetic integrity of the Rio Grande silvery minnow. Does the species retain sufficient genetic diversity to continue its evolutionary sojourn? Should we expect deleterious effects from inbreeding to accrue in captive stocks or in the wild? Will propagation in captivity further erode their genetic diversity and continue the trend toward extinction? Is there evidence that Rio Grande silvery minnows in the Rio Grande have hybridized with Plains minnows as was found in the Pecos River (Cook et al. 1992)?

In spite of the vague and poorly known biology of the Rio Grande silvery minnow, it is possible to deduce approximations to their water requirements. In the following sections, historical and contemporary sources of information are evaluated to elucidate the water requirements of the Rio Grande silvery minnow.

RIVER MODIFICATIONS

In order to discuss water requirements for an endangered species of fish like the Rio Grande silvery minnow, it is informative to consider the history of river modification in the Rio Grande valley and the effect of drought conditions on the flows of the river. Three significant activities are relevant: irrigation diversions in the upper regions of the Rio Grande basin, construction of dams, and canalization of the middle Rio Grande.

Irrigation has a long history in the Rio Grande valley of New Mexico that extends back to the 1400s (Scurlock 1998). The first small-scale irrigation networks were constructed by Native Americans and led to a sizeable acreage under cultivation; perhaps as much as 30,000 acres were irrigated by pueblo residents by the late 1500s (Scurlock 1998). The Spanish introduced ditch irrigation to New Mexico in the early 1600s and it has been estimated that 125,000 acres of farmland were being irrigated in the middle Rio Grande valley by 1848. Presently there are about 57,000 acres under irrigation in the middle Rio Grande valley (Clark 1987; Wozniak 1987; DuMars and Nunn 1993).

Large-scale irrigation diversions on the upper Rio Grande began in Colorado during the late 1870s and early 1880s.[2] These diversions reduced river flows in the Rio Grande of New Mexico and when combined with significant soil erosion from heavily used rangelands, aggradation[3] of the river channel began in the vicinity of Albuquerque and areas downstream. As the river bed increased in elevation, flooding became more prevalent and soils formerly irrigated for crop production became waterlogged. The engineering solution to the flooding problem in the middle Rio Grande valley was two-fold. Dams were constructed to capture sediment and drains were excavated to alleviate soil saturation. Four sediment control dams were constructed: Jemez Canyon Dam (1954), Abiquiu Dam (1963), Galisteo Dam (1970), and Cochiti Dam (1975). Over four hundred miles of drains were excavated between Cochiti and Elephant Butte Lake.

The engineers were successful in capturing sediment and degradation[4] of the riverbed began from Albuquerque to past Socorro. As riverbed elevation dropped[4], irrigation diversions became barriers to upstream movement of fish (Figure 2) including the Rio Grande silvery minnow. Controlling sediment transport and regulating flows with dams fragmented the formerly connected habitat of Rio Grande silvery minnow into shorter segments. Recent population trends suggest that these shorter reaches of river may be insufficient to sustain a population of pelagic-spawning minnows (M. Hatch, personal communication).

Additional modifications to the Rio Grande occurred that were detrimental to the native fishes. Following the drought of the 1950s, the engineers set

Figure 2. San Acacia diversion weir, viewed from a downstream perspective, is currently a barrier to upstream fish passage. *(photo by D. Cowley, Nov. 23, 2002*)

out solve another problem. How could more water be delivered to Elephant Butte Lake?[5] The solution was to construct the Low Flow Conveyance Channel (LFCC) from San Acacia downstream to Elephant Butte Lake. The LFCC was excavated in the bottom of the valley roughly following the river channel at the time. It acted as a levee confining the present-day river channel to the higher, eastern side of the valley.

The LFCC was designed so that at low flow conditions, all of the river's flow could be diverted at San Acacia and moved downstream through a channel shorter than the river channel. It has not been fully operated since 1985 because of outfall problems at Elephant Butte Reservoir. Presently the LFCC functions as a large drain that grows in discharge with proximity to Elephant Butte Reservoir. The draining action of the LFCC and the confinement of the river channel to the higher eastern side of the river valley has made it even more difficult to maintain water in the river when drought occurs. The Biological Opinion for Rio Grande silvery minnow (U.S. Fish and Wildlife Service 2001) promotes pumping water out of the LFCC to help maintain a wet river channel lower in the valley. This has proven to be an expensive struggle against gravity.[6]

HISTORICAL RECORDS OF CHANNEL DESICCATION

A review of historical records indicates clearly that channel drying was a frequent event. Observations of channel desiccation during the 19th century are recorded in a Senate document (U.S. Senate 1898, see Table 1). The observations in 1851, 1861, and 1879 predate the over-appropriations of Rio Grande flows that occurred in the San Luis Valley of Colorado. Considerable angst was expressed in 2002 regarding the possibility of the Rio Grande drying in the Albuquerque area. In spite of extensive and prolonged periods of channel desiccation in the 1890s that dried the river channel in the Albuquerque area for nearly three months in 1896, the Rio Grande silvery minnow persisted handsomely into the 1900s. It was often found to be extremely abundant in the middle Rio Grande.

Table 1. Historical records of channel desiccation in the middle Rio Grande valley during the 19th century (U.S. Senate 1898).

Year	Reach with Dry Riverbed	Notes
1851	Las Cruces	river dry for about 1 month
1861	Socorro to El Paso	
1879	Los Lunas to El Paso	dry 2 weeks at Los Lunas, 6 weeks at Socorro to Palomas, and 3 months at Las Cruces
1889	Socorro to El Paso	dry at El Paso for 5 months
1892	Los Lunas to El Paso	dry July 1-September 20 at Los Lunas
1894	Albuquerque to El Paso	dry 4 weeks at Albuquerque, 6 weeks at Los Lunas
1895	Socorro to La Mesilla	dry 2 weeks at Socorro, 6 weeks at La Mesilla
1896	Albuquerque to El Paso	dry June 22-September 19 at Albuquerque

Flow records on the middle Rio Grande during the 1900s were examined from gage station data (U.S. Geological Survey). The San Acacia and San Marcial gage data were of special interest because the Biological Opinion for Rio Grande silvery minnow established base flow requirements at these sites (U.S. Fish and Wildlife Service 2001).

During the 63-year period of record examined (May 1, 1936 through September 30, 1999), the Rio Grande had no flow 49 times at San Acacia and 225 times at San Marcial. Total days of no river flow were 347 at San Acacia and 6998 at San Marcial. The longest dry period was 60 days at San Acacia and 608 days at San Marcial. From these gage data, it is clear that the frequency of riverbed drying increased with distance downstream from San Acacia.

Another way to view the frequency of drought in the middle Rio Grande valley is to consider gage data at a site just upstream from the valley. The longest running period of record for gage data on the Rio Grande in New Mexico, 103 years, is at the Embudo gage. These data are used to study the probability of successive years of drought.[7]

Gage data (personal communication, Michael Hatch and Viola Sanchez, U.S. Bureau of Reclamation) indicate that two successive years of below average annual discharge occurred 25 times during the period of record for the Embudo gage; hence, the probability of two successive years of drought as deduced from historical data is about 24% (25/102). Three successive drought years occurred about 13% of the time. Four consecutive years of drought flows occurred five times at the Embudo gage.

It is clear that drought conditions are common in the Rio Grande basin. Rio Grande silvery minnow survived repeated droughts that dried lengthy reaches of riverbed in New Mexico for significant periods of time yet the species rebounded many times to become very abundant in downstream reaches.

It was a significant accomplishment for the Rio Grande silvery minnow to survive at least 125 years of recurring channel desiccation in the middle Rio Grande valley. The species biology and life history features facilitated its persistence. Prior to the closure of Cochiti Dam in 1975, the Rio Grande silvery minnow occurred up through the Cochiti reach all the way to at least Española and up the Chama River to near Abiquiu Dam. This upstream reach, thought to have been wet perennially (U.S. Fish and Wildlife Service 2001), supported a core population of the Rio Grande silvery minnow that enabled the species to survive extended drought conditions that dried the river as far northward as Albuquerque. During wetter years in the upper and middle Rio Grande, the pelagic spawning life history of the minnow enabled it to rapidly recolonize downstream reaches from which it was probably extirpated during extended drought.

Following closure of Cochiti Dam, the core upstream population of the Rio Grande silvery minnow was lost and a downward trend began in the remainder of the silvery minnow population. Whereas the minnow had endured significant, repeated channel desiccation events prior to Cochiti Dam, Cochiti Dam appears to have been the trigger toward extinction.

WATER REQUIREMENTS OF THE RIO GRANDE SILVERY MINNOW

In spite of the deep deficits in biological knowledge for Rio Grande silvery minnow, one can deduce general aspects about the water requirements for pelagic-spawning minnows. Recovery of the Rio Grande silvery minnow requires at least three things to occur with respect to wetted habitat requirements: (1) a sufficient number of miles of connected river habitat must be made available for the species to complete its life cycle, (2) at least some portion of the upstream end of that habitat needs to remain wet even during deep drought, and (3) individuals displaced downstream need the ability to reach upstream spawning places. All of these factors are critical for survival of the Rio Grande silvery minnow because its life history embraces downstream transport. It is a fundamental fact known as the "Drift Paradox" (Hershey et al. 1993) that extinction is inevitable if downstream drift is the only transport process (Speirs and Gurney 2001).

To estimate the length of connected habitat necessary to support pelagic-spawning minnows, data are examined for contemporary river reaches between reservoirs. River reaches that support one or more species of pelagic-spawning minnows are informative if some of those species have viable populations. Summaries of the distances between dams are shown on Figure 3.

Approximately 220 miles of connected habitat on the Pecos River (Figure 3) between Sumner Dam and Brantley Lake support five pelagic-spawning minnow species. The three native species include Rio Grande shiner (*Notropis jemezanus*), Pecos bluntnose shiner [*Notropis simus pecosensis*, federally threatened (U.S. Department of Interior 1987)], and speckled chub (*Macrhypobsis aestivalis*). Two of the species are nonnative: Arkansas river shiner (*Notropis girardi*) and plains minnow (*Hybognathus placitus*). No native or nonnative pelagic-spawning minnows remain in the 47 miles between Santa Rosa Dam and Sumner Reservoir.

About 148 miles (Figure 3) between Ute Dam in eastern New Mexico and Meredith Lake in the Texas panhandle support three native pelagic-spawning cyprinids. These include Arkansas River shiner, plains minnow, and four-barbled chub (*Macryhybopsis tetranemus*). Native pelagophils have been lost in the 58 mile reach between Conchas Dam and Ute Reservoir and no native pelagophils occupy the 130 miles of the Canadian River upstream from Conchas Reservoir.

Historically, the middle Rio Grande supported five pelagic-spawning minnow species (Sublette et al. 1990): Rio Grande shiner, Rio Grande bluntnose shiner (*Notropis simus simus*), speckled chub, and Rio Grande silvery minnow. The Rio Grande subspecies of bluntnose shiner went extinct in the 1960s and the speckled chub and Rio Grande shiner were extirpated from the Rio Grande about the same time (Sublette et al. 1990). Whereas the other pelagophils in the middle Rio Grande valley were extirpated before the closure of Cochiti Dam in 1975,[8] the Rio Grande silvery minnow became critically endangered after 1975.

Given that Rio Grande bluntnose shiner, speckled chub, and Rio Grande shiner survived in the middle Rio Grande valley for about 50 years after closure of Elephant Butte Dam (1916), it seems reasonable to conclude that the 205 miles of river between Española and Elephant Butte Reservoir were sufficient to support the four native pelagic-spawning minnows. There were several notable events prior to their extirpation in the 1960s: (1) an enduring drought occurred through most of the 1950s, (2) Jemez Canyon Dam was closed in 1954, and (3) Abiquiu Dam was closed in 1963.

The short distances shown on the Rio Grande (Figure 3) are between irrigation diversions. From north to south, areas not supporting a viable population of Rio Grande silvery minnows include 42 miles upstream of Cochiti Lake, 22 miles between Cochiti Dam and Angostura diversion, 40 miles between the Angostura and Isleta diversions, 53 miles between the Isleta and San Acacia diversions, and 56 miles from San Acacia diversion to Elephant Butte Reservoir. None of these distances appear to be sufficient in length to support a viable population of Rio Grande silvery minnow.

Other factors besides the miles of connected habitat may determine if pelagic-spawning minnows can survive over the long term. The length of connected habitat needed for a self-sustaining population is affected by biological features such as the specific gravity (buoyancy) of the eggs, the swimming ability of the species, and its life expectancy. Physical features of the channel like discharge, current velocity, channel complexity, and perhaps also sediment load and salinity may also affect habitat length. The conversion of the middle Rio Grande to a floodway following the closure of Cochiti

Dam probably reduced channel complexity to the point that the Rio Grande silvery minnow is no longer able to sustain its populations.

In summary, the contemporary river reaches on the Rio Grande, Pecos, and Canadian rivers suggest the following: (1) the Rio Grande silvery minnow survived historical droughts that shortened its occupied habitat in the middle Rio Grande valley to 75-80 miles (Albuquerque to Española); (2) different species may require different lengths of connected habitat (Rio Grande silvery minnow, Rio Grande shiner-speckled chub-bluntnose shiner); (3) flow regulations may have greater effects on Rio Grande bluntnose shiner, speckled chub, and Rio Grande shiner than on Rio Grande silvery minnow; and (4) short reaches of connected habitat less than about 60 miles appear to be insufficient to support pelagic-spawning minnows, especially in modified river channels.

In the author's opinion, several things need to happen to ensure the long-term survival of Rio Grande silvery minnow. First, barriers to upstream movement must be alleviated. Second, restoring the upstream source population in a permanently wetted reach of river will improve the chance that the Rio Grande silvery minnow will not go extinct. In order to provide an upstream source population like was once present, one that persisted through repeated channel drying events, the population upstream of Cochiti Dam needs to be restored. Restoration of the source population will require modifying Cochiti Dam to reconnect upstream and downstream reaches. Such an approach might forego the impoundment of water in Cochiti Lake while minimizing destructive flooding downstream and encouraging beneficial flooding.

Modifying Cochiti Dam as suggested above could provide two benefits. First, it may yield a better chance at avoiding extinction of the Rio Grande silvery minnow by restoring the species to permanently wetted habitat. Second, it would require far less water be taken from human use for recovery of Rio Grande silvery minnow, which is focused according to the recovery plan, in the desiccation-prone reach of river between Albuquerque and Elephant Butte Reservoir. A clear disadvantage of these recommendations is that implementing them will require a significant amount of study, public debate, and time. The Rio Grande silvery minnow is likely too vulnerable to extinction to discontinue on-going recovery activities. One could argue that additional recovery efforts are needed in downstream reaches of the middle Rio Grande valley to help the minnow avoid extinction caused by drought-related channel drying.

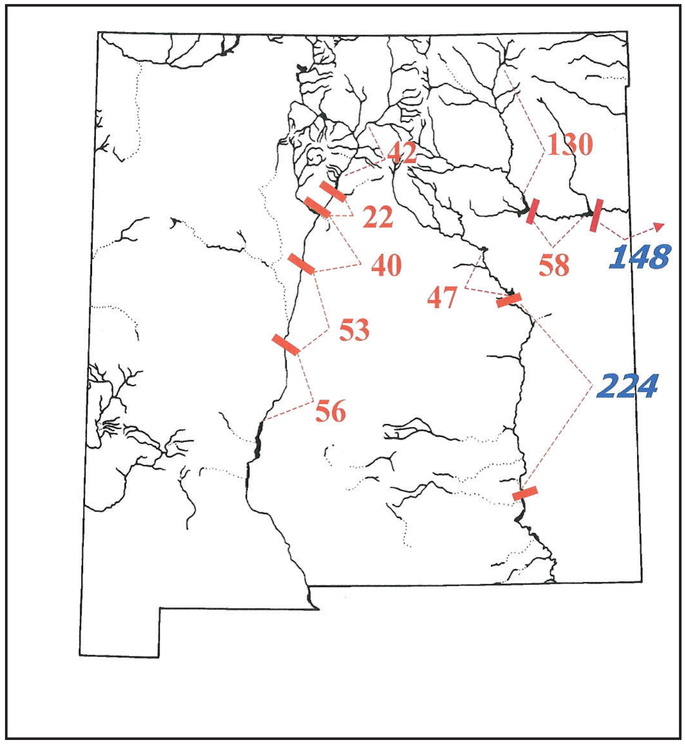

Figure 3. Miles of connected habitat between dams are shown for the Rio Grande, Pecos, and Canadian rivers.

REFUGES FOR RIO GRANDE SILVERY MINNOW

Refugial habitats are needed to promote short-term survival of the Rio Grande silvery minnow during periods of drought. Refugia on irrigation structures could address two problems, (1) provision of wetted habitats when the main river channel dries during extended drought and (2) entrainment of eggs, larvae and minnows into irrigation ditches. This paper concludes with some ideas on using existing agricultural irrigation ditches and drains to facilitate short term survival of the Rio Grande silvery minnow.

Concept for Refugial Habitats: Figure 4 shows a hypothetical deployment of conservation structures on an irrigation district. ***Propagaria***, or propagation aquaria, are installed as small diversions off a main irrigation delivery ditch very near its origin, close to a diversion dam. Depending on the distance back to the river, more than one propagarium could be installed on a single diversion. The diversions off the main ditch that contain propagaria provide a way to recover fertilized eggs, larvae, or minnows that become entrained into the irrigation ditch. A link back to the river ecosystem is shown in Figure 4.

Propagaria could also be constructed along the river channel to provide propagation and nursery areas. If the inlet to propagaria could be designed to capture eggs or larvae drifting downstream in the river, they might significantly shorten the distance that the silvery minnow offspring drift downstream.

Refugia are installed on a drain (Figure 4). The concept with refugial habitats on drains is to provide safe haven for minnows, especially those stranded in isolated river pools during droughts. Multiple refugia could be installed on a single drain.

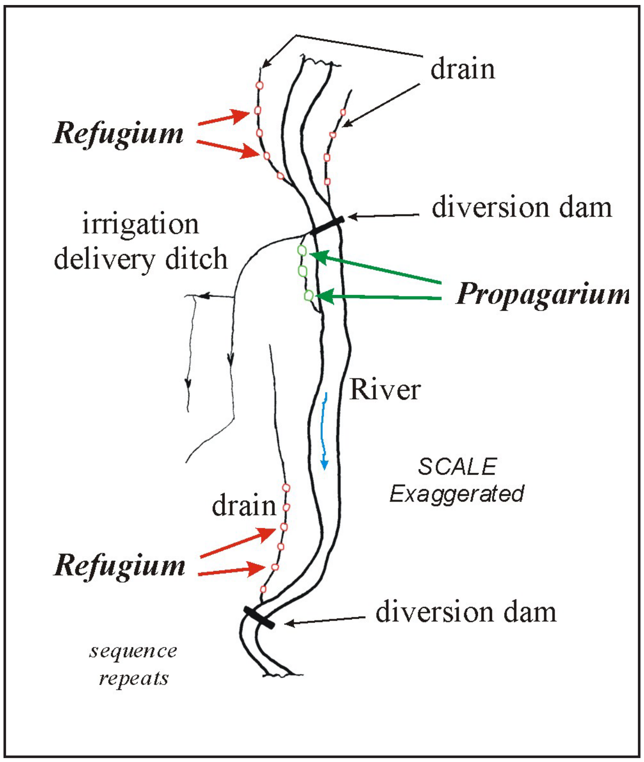

Figure 4. A deployment of refugia and propagaria is shown on a hypothetical irrigation system.

Naturalized Habitats: The ideas presented here for naturalized refugial habitats on irrigation conveyances were stimulated by a visit to the Armendaris Ranch south of Bosque del Apache National Wildlife Refuge and a short distance upstream from the headwaters of Elephant Butte Reservoir. After construction of the Low Flow Conveyance Channel, significant reaches of the Rio Grande were relocated to the eastern side of the valley. Evidence of the former braided and sinuous river channel was apparent from aerial photographs such as the one shown in Figure 5 and on the ground at the Armendaris Ranch.

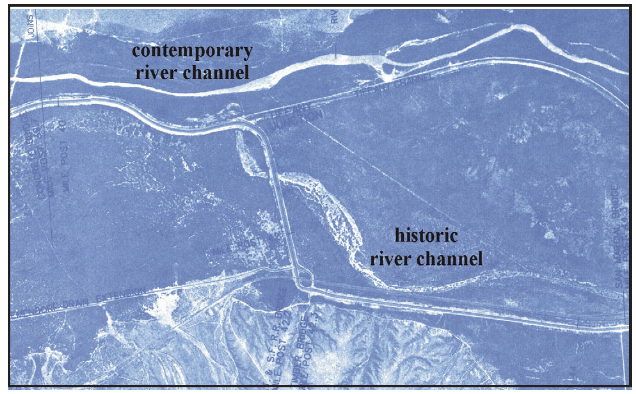

Figure 5. High altitude aerial photographs show historic and contemporary channels of the Rio Grande. [Image was provided by the U.S. Bureau of Reclamation (U.S. Department of Interior, Bureau of Reclamation 1997)].

At ground level, the historic river channel was composed of numerous relatively narrow diverging and converging channels that formed a highly complex, braided river channel. The high degree of channel complexity would have greatly increased the number of river miles of available minnow habitat per linear mile of valley. Many of the former channel braids were found to lie in remnants of the cottonwood bosque on the Armendaris Ranch just south of Bosque del Apache National Wildlife Refuge. Some of the abandoned channels were narrow and deep while others were wider and shallower.

The naturalized features envisioned for the ***Propagarium*** and the ***Refugium*** (Figure 6) are intended to mimic in a general way the abandoned channels of the Rio Grande. Features include a widened channel providing a slow-flowing pool habitat bisected by an island. Lateral shallow benches provide abundant substrate for periphyton colonization. Deep water provides cover from herons and other predators. Islands and borders of inflow and outflow channels provide native riparian vegetation and organic inputs to support a food web. A conceptual plan view of the pool-island feature common to both the ***Refugium*** and the ***Propagarium*** is shown in Figure 6.

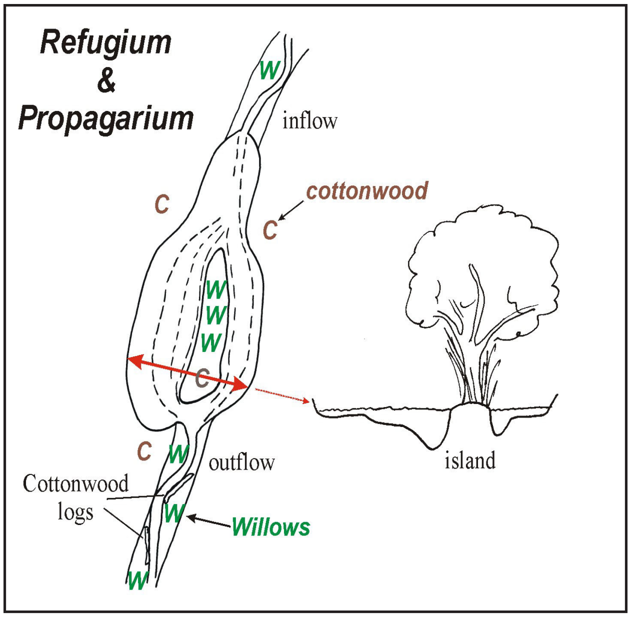

Figure 6. Plan and cross-section views show the naturalized habitats provided by the propagarium and the refugium.

The ***Propagarium*** and ***Refugium*** mimic a 0.15 acre pool on a historic river channel (Figure 6) approximately 120 ft in length and about 60 feet wide. Deep, low-velocity habitats are provided on each side of an island. Riparian vegetation is composed of native willows, cottonwoods, and grasses. Native vegetation proximal to the structure provides organic matter (leaves and twigs) that can support periphyton production, a potential food source for grazer minnows such as *H. amarus*. The riparian vegetation also provides habitat for the endangered Southwestern willow flycatcher.

The new strategy proposed here would provide wetted habitats during drought and it would enable fish eggs, larvae, or adults to be returned to the river after they have become entrained into an irrigation delivery system. Deployment of the proposed structures into irrigation ditches and drains, would provide significant additions of habitat along the river, which should improve retention of minnows in wetted habitats. Refuges on the middle Rio Grande should facilitate short-term survival of the Rio Grande silvery minnow. However, long-term recovery should seek to incorporate recovery actions that complement the minnow's biology. Restoring the upstream core population and re-engineering Cochiti Dam would help recovery of the Rio Grande silvery minnow.

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ENDNOTES

[1] Presently the Rio Grande silvery minnow is not known to occur upstream of Angostura.

[2] These diversions in the upper portion of the basin eventually led to adoption in 1938 of the Rio Grande Compact, an international treaty between the United States and Mexico.

[3] Aggradation is the deposition of sediment. Degradation is erosion of sediment.

[4] Degradation of the riverbed downstream of San Acacia diversion weir was probably accelerated by several causes including: (1) the very high river flows of the mid- to late 1980s associated with a series of El Nino Southern Oscillation events in the Pacific Ocean; (2) invasion of salt cedar and Russian olive that have contributed to stabilization of river banks; (3) the discontinued use of the LFCC beginning in 1985-86; and (4) delivery of nonnative water via the San Juan-Chama Project that elevated flows in the middle Rio Grande.

[5] Elephant Butte Lake is the point of reference for delivery of water to Texas under the Rio Grande Compact.

[6] In FY2001, about 82,700 gallons of diesel fuel was consumed to drive pumps. The estimated FY2002 budget for pumping was $2,037,695 (personal communication, M. Hatch).

[7] A drought year was defined as a year of below average river flow at the Embudo gage, where average flow was calculated over the entire 103 year period of record.

[8] This suggests that different species of pelagic-spawning minnows have different requirements for water.