Middle Rio Grande Habitat Suitability Criteria

Plan B Technical Report
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Abstract of Technical Report

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The Rio Grande silvery minnow was once one of the widest ranging and most abundant native fish species in the Rio Grande River. Presently, the remaining population is restricted to 5% of its historical range due to a combination of river fragmentation, habitat decay, stream channelization, and the presence of non-native fish species. Despite a recent increase in research and recovery efforts concerning the Rio Grande silvery minnow, there is no quantifiable connection between the biological opinion of it and the hydraulic environment in which it resides. Through an extensive literature review, three quantitative hydraulic criteria that define suitable habitat in terms of velocity, hydraulic depth, and substrate type for both mature and juvenile Rio Grande silvery minnow were determined. The accuracy of these criteria was verified through a brief comparison of reach-averaged hydraulic parameters of two subreaches of the Middle Rio Grande: the Bernalillo Bridge reach, which maintains low silvery minnow catch rates (441 CPUE), and the Escondida reach, which sustains high silvery minnow catch rates (1020 CPUE). Following verification, criteria were applied to cross sections every 500-ft along the Escondida reach for a length of 17.7 miles in order to map out the areas best fit for Rio Grande silvery minnow survival. Out of 163 total cross sections, only 1.8% met the velocity criterion, 18.4% met the depth criterion, and 100% met the substrate criterion for adults. Even fewer met the juvenile criteria: 0% met the velocity or the substrate criteria and 3.1% met the depth criterion. These results demonstrate the lack of adequate Rio Grande silvery minnow habitat within the main channel and highlight the importance of floodplain connection, where most of the appropriate mesohabitat resides.

Acknowledgements

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1. Introduction

The Middle Rio Grande runs through New Mexico from Cochiti Dam, north of Albuquerque, to Elephant Butte Reservoir, south of Socorro. It has seen a shift both in morphology and in instream habitat due to human influence over the last two centuries. With the construction of floodways, levees, diversion structures, and dams, the Rio Grande has become a highly engineered river. Once braided, sand-bed reaches turned into narrow, single thread channels where levees constrict the main channel. Dams deprive downstream reaches of fine sediment, creating gravel-bed channels in the upstream reaches of the Middle Rio Grande. Flows are controlled so that natural fluctuations are reduced, restricting flooding in the spring and low flows in the winter. Anthropogenic influences have not only changed the morphology and hydraulics of the Middle Rio Grande but also the habitat of native species and their presence in this area.

The Rio Grande silvery minnow, once the widest ranging species native to the Rio Grande, is presently bound to 5% of its historical reach due to the fragmentation of its habitat. The species was listed under the Endangered Species Act in 1994 due mainly to habitat decay and fragmentation. The population has steadily declined over the past decade, with a record low in September of 2003 following two consecutive years of severe drought. These alarming events spurred a growth in research on the Rio Grande silvery minnow to better understand the species and how to recover it. Though the scientific and political communities have an increased understanding of the silvery minnow after this surge, there has not been made a quantifiable connection between the biological opinion of it and the hydraulic environment in which it resides. This technical report aims to fill this gap and create a quantifiable hydraulic measure of suitable Rio Grande silvery minnow habitat.

The objectives of this study include:

- Formulation of a set of habitat suitability criteria that are easily applicable to a stretch of the Rio Grande given knowledge of its geometry and hydraulics
- Validation of these criteria to ensure its accuracy and usability by applying the criteria to two subreaches of the Middle Rio Grande (one with high and one with low Rio Grande silvery minnow population density) and comparing the resulting habitat suitability with silvery minnow catch rates
- Application of criteria to the Escondida subreach of the Middle Rio Grande at cross sections every 500-ft over a 17.7-mile total length

The information presented in this technical report is divided into five chapters. Chapter One includes an introduction to the Middle Rio Grande and Rio Grande silvery minnow as well as the purpose of this study. A comprehensive literature review of the Rio Grande River and the Rio Grande silvery minnow, its behavior, and the state of its current population is included in Chapter Two. Chapter Three details the Rio Grande silvery minnow habitat suitability criteria and includes verification of said criteria. The methods, results, and discussion of the application of the suitability criteria are described in Chapter Four. Chapter Five closes the technical report with a summary, conclusions from the analysis, and suggestions for future application and development of the suitability criteria.

2. Literature Review

2.1. **Rio Grande River History**

The Rio Grande River runs just over 3,000 km from its headwaters in the San Juan Mountains of Southern Colorado to its confluence with the Gulf of Mexico (Kammerer, 1990). Fed by snowmelt in the spring and the occasional storm events seen in the arid and semi-arid environments it transects, the river drains segments of southern Colorado, central and eastern New Mexico, and western Texas. Though not its primary source, tributaries, such as the Pecos River and the Rio Conchos, also contribute to the total discharge within the Rio Grande.

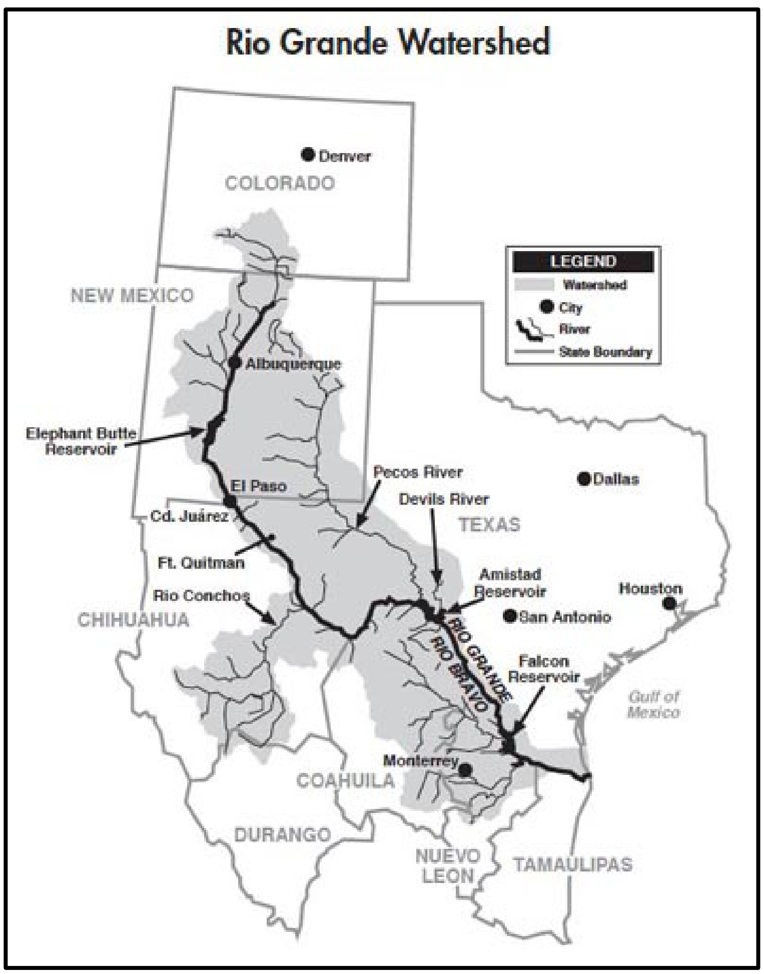

Figure 1. Rio Grande Watershed

Historically, the Rio Grande was a wide, sand-bed river with a dynamic and braided geomorphology reflective of the natural hydraulic and sediment regimes specific to its environment. Even as an aggrading fluvial system, the Rio Grande is thought to have had a broad active floodplain, connecting secondary channels and arroyos to the main channel (U.S. Fish and Wildlife Service, 2007).

Due to its location in an arid climate, the Rio Grande has long been used to support agriculture and ranching in nearby communities (Ward et al., 2006). The irrigation of its floodplains began to support agrarian settlements beginning in the 1600s and grew to large-scale irrigation diversions in the 1700s. Subsequently, the Rio Grande was often dry throughout the lower half of its reach in New Mexico and Texas due to over-appropriation of flow (U.S. Senate, 1898). In an effort to meet irrigation needs in Mexico, the US Mexico Treaty of 1906 ensured a constant 60,000 acre-ft of annual delivery from US to Mexico in absence of severe drought Similarly, the Rio Grande Compact in 1938 mandated water delivery requirements and depletion entitlements from state to state (Ward et al., 2006).

As a river fed by snowmelt and supplemented by sporadic storm events, the Rio Grande historically experienced frequent flooding and drought. Settlements along the floodplain created a demand for constant water supply, an anomaly in an arid environment. In order to mitigate flooding and regulate annual flows, the construction of large-scale dams began in 1916 with the completion of Elephant Butte Dam in New Mexico and La Boquilla in Mexico (Cowley, 2006). Since then, over 50 additional dams have been constructed on the Rio Grande, 70% of which are in the United States. These structures have caused a major change in the hydraulics of the river, creating reservoirs for water storage and regulation and reducing peak spring flows. In addition to the obvious change in the annual hydrograph of the Rio Grande, diversion structures and channel modifications have interrupted fundamental fluvial processes such as sediment and nutrient transport, impeded movement of native fauna, and prompted a change in the flora dominating the riparian corridor.

In an attempt to increase conveyance and contain flow to the main channel, levees were constructed along many reaches of the Rio Grande. This, coupled with the construction of dams and mitigation of frequent floods, prevented the channel from naturally avulsing and reducing the complexity of the river itself (Cowley, 2006). As a result, much of what was once a wide, braided river has become a narrower, single thread channel (Larsen, 2007). Additionally, the impoundment of sediment behind dams has caused incision in many areas, making the channel even deeper and narrower. In some areas, specifically Big Bend, Texas, the establishment of bankside non-native vegetation introduces a positive feedback loop, further contributing to channel narrowing and vertical accretion (Dean and Schmidt, 2010). The combination of these causes resulted in a general shift in geomorphology of the main stem Rio Grande.

Many fish species native to the Rio Grande evolved in an environment with frequent fluctuations in climate and therefore flow regimes as well as the inevitability of a sometimes-hostile riparian environment typified by desert regions. Thus, many species maintain adaptations that allow them to persist through intermittent drought and flooding (Pease et al., 2006). These adaptations are unsuited for the Rio Grande of today. River fragmentation and flow regulation have severely impacted the habitat available both instream and within the riparian corridor. As a result, only half of the original 27 fish species native to the Rio Grande can be found in these reaches (Cowley, 2006).

2.2. **Middle Rio Grande Description**

As a result of extensive fragmentation and habitat deterioration, the once wide-ranging native fish species *Hybognathus amarus*, commonly known as the Rio Grande silvery minnow, can only be found in the Middle Rio Grande (Bestgen and Platania, 1991). The Middle Rio Grande is a 290 km reach contained within New Mexico and bound upstream by Cochiti Dam and downstream by Elephant Butte Reservoir. It is split into a series of four subreaches by five dams: Cochiti reach (bound by Cochiti and Angostura dams), Bernalillo reach (bound by Angostura and Isleta dams), Isleta reach (bound by Isleta and San Acacia dams), and San Acacia reach (bound by San Acacia Dam and Elephant Butte Reservoir). These subreaches range from 37 to 97 km in length and increase in length in a downstream trend (U.S. Fish and Wildlife, 2007). This reach, like most of the Rio Grande, is fed by snowmelt and used primarily for agriculture. The Middle Rio Grande has also seen a change in flow and sediment regimes similar to that of the remainder of the river. It was once a wide, braided river that saw perennial flow in an arid to semi-arid environment (U.S. Fish and Wildlife, 2007). Historically, the Middle Rio Grande was also a dynamic, aggrading channel that commonly migrated across its floodplain. The Middle Rio Grande now exhibits variable hydraulic characteristics. The reach moves from a cooler, narrower channel with gravel to cobble substrate upstream to wider, more braided sand-bed channel downstream with more diverse mesohabitats available (U.S. Fish and Wildlife, 2007).

2.3. **Rio Grande Silvery Minnow**

The Rio Grande silvery minnow, a member of the cyprinid family, is a small, heavy-bodied minnow native to the Rio Grande. It is a species characterized by a round to ovate, fully scaled body that appears yellow-greenish dorsally and cream-white ventrally, as shown in Figure 2. It has a sub-terminal mouth with a snout that overhangs its upper lip (U.S. Fish and Wildlife, 2007). Generally, due to its coiled and elongated gastrointestinal tract, the Rio Grande silvery minnow is thought to be an herbivorous fish; however, algae and macrophytes make up a large part of the larval and juvenile diet due to energy content and gape-size (Pease et al., 2006). Additionally, its sub-terminal mouth suggests that silvery minnow feed directly on benthic substrates with plant material or detritus (Cowley et al., 2006)

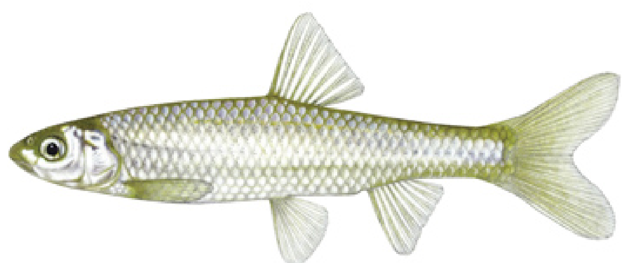

Figure 2. Rio Grande silvery minnow appearance

The Rio Grande silvery minnow begins as a small, non-adhesive egg, about 1mm in diameter, that grows to about 3mm in diameter, becomes semi-buoyant, and enters the water column. The egg drifts downstream and hatches within 24-48 hours, though time to hatch varies inversely with water temperature (Platania, 2000b). Once hatched, proto-larvae remain semi-buoyant by swimming vertically until the development of a gas bladder, absorption of the yolk sac, and start of external feeding (Platania and Altenbach, 1998). This change usually occurs within three to five days and is accompanied by the transition between swimming vertically and horizontally. Larvae begin to actively seek out shallow, low-velocity habitat with high level of productivity that aids in rapid growth. Larvae are just under 4 mm in total length (measured from tip of snout to longest lobe of caudal fin) upon hatching and grow to about 40 mm by late autumn (U.S. Fish and Wildlife Service, 2007). The hasty development and growth of silvery minnow eggs and larvae is an adaptation specific to most fish native to plains and desert environments that ensures a greater chance of survival into the juvenile stage of life.

The transition from larvae to minnow is generally achieved upon reaching a standard length of 15 mm. During the juvenile stage of life, silvery minnow switch from feeding on plankton and other micro-invertebrates to an herbivorous diet due to increased gape size, strength of jaw muscles, and the availability of prey with a high-energy content (Pease et al., 2006). Finally, Rio Grande silvery minnow reach sexual maturity at the age of one, ranging in standard length from 30 to 90 mm. Presently, roughly 90% of wild silvery minnow die before reaching the age of two though the species is thought to have historically lived up to five years (Cowley et al., 2006). Silvery minnows raised in hatcheries can reach the age of three as a result of life in a controlled environment.

The Rio Grande silvery minnow fulfills an important life history characteristic upon returning to its natal spawning site for reproduction. They achieve upstream redistribution via dispersal, which implies permanent, one-way movement, as opposed to migration, which is associated with movement between two points (Platania et al., 2003). Upon completion of dispersal, Rio Grande silvery lay up to 5000 eggs at a time (Cowley et al., 2006). Females are highly fecund and can produce between 3 and 18 clutches of eggs, with a mean clutch size of 270 eggs per clutch, in a 12-hour period (U.S. Fish and

Wildlife Service, 2007). Biologists believe spawning is stimulated by high flows in late April to early May when snowmelt feeds into the river. This provides spawning microhabitats with moderate to high water velocities that carry eggs over 100 km downstream, though drift distances are highly dependent on flow conditions and riparian habitat each year. Spawning occurs over a relatively short one-month period when water temperatures are about 18-24 degrees Celsius; however, the peak spawning period typically lasts for about three days following the initiation of spring runoff (or an artificial flow release) (Platania and Dudley, 2008a; Platania and Dudley, 2006). The Rio Grande silvery minnow is the only remaining member of a reproductive guide of five small cyprinids native to the Rio Grande (Rio Grande silvery minnow, speckled chub, Rio Grande shiner, phantom shiner, and Rio Grande bluntnose shiner) in the Rio Grande River. Each species is a short-lived minnow with a common reproductive strategy and egg type adapted to recolonize areas previously extirpated after natural droughts (Platania, 1995).

2.4. **Rio Grande Silvery Minnow Habitat Use**

As a small, heavy-bodied fish, usually 8-9 cm in standard length (measured from tip of snout to posterior end last vertebrae) with a mean critical swimming speed of 52 cm/s (Bestgen et al., 2010), the Rio Grande silvery minnow most commonly occupies low-velocity and low to moderate depth habitats with silt or sand substrate (Cowley et al., 2006). The most extensive study on habitat use in the Middle Rio Grande by the Rio Grande silvery minnow to date is one performed by Dudley and Platania in 1997 for the New Mexico Department of Game and Fish and the Bureau of Reclamation. In their study, 86.5% of silvery minnows were caught in areas where velocity stayed below 10 cm/s, 11% were found in areas with velocities between 11 cm/s and 20 cm/s, and only 0.8% were found in areas where water velocity exceeded 40 cm/s. Additionally, 91.3% of individuals were caught over silt substrata and 8.1% were caught over sand. These habitat preferences were reflected in the mesohabitats in which silvery minnows could be found. The most commonly occupied habitats were debris piles (40.5%), pools (35.8%), and backwaters (13.8%). In this particular studies pools were defined as "portions of the river that are deep and with relatively low velocity compared to the rest of the channel" (Dudley and Platania, 1997). Backwaters were described as "bodies of water connected to the main channel with no appreciable flow and often created by a drop in flow, which partially isolates the former channel" (Dudley and Platania, 1997). Given that the silvery minnow shows a strong preference for the shelter provided by debris piles and adjacent pools throughout the winter, restoration efforts could include creation and preservation of these mesohabitats.

While the silvery minnow is almost exclusively found in habitats that maintain a velocity below 40 cm/s, mesohabitat preferences can vary based on stage of life and time of year. When larvae transition from vertical to horizontal swimming and leave the water column in search of food, they typically occupy shallow, very low or zero velocity habitats with silt substrates and warmer temperatures from 20-24 degrees Celsius (U. S. Fish and Wildlife Service, 2007). The smallest size-class, less than 10 mm standard length, utilized depths of 15 cm on average and was never found in water depths greater than 30 cm (Dudley and Platania, 1997). Mesohabitats with these characteristics, like secondary channels and backwaters, require minimal energy expenditure while the individual is small and allow larvae to develop very quickly into juvenile fish (Pease et al., 2006). The presence of habitats with no measurable velocity or flow direction is vital for egg and larvae retention (Porter and Massong, 2003).

As larvae develop into juvenile fish and increase almost tenfold in size, Rio Grande silvery minnow swimming ability greatly increases allowing them to utilize additional habitat. When total body size increases, young-of-year and mature silvery minnows begin to inhabit areas with velocities below 20 cm/s and depths from 11-20 cm. Some minnows can even be found in areas with velocities up to 40 cm/s, as shown in the figure below (Dudley and Platania, 1997). While few rivers maintain velocities and depths as low as these, small secondary channels and inundated floodplains can provide habitat with minimal water velocity and shallow hydraulic depth.

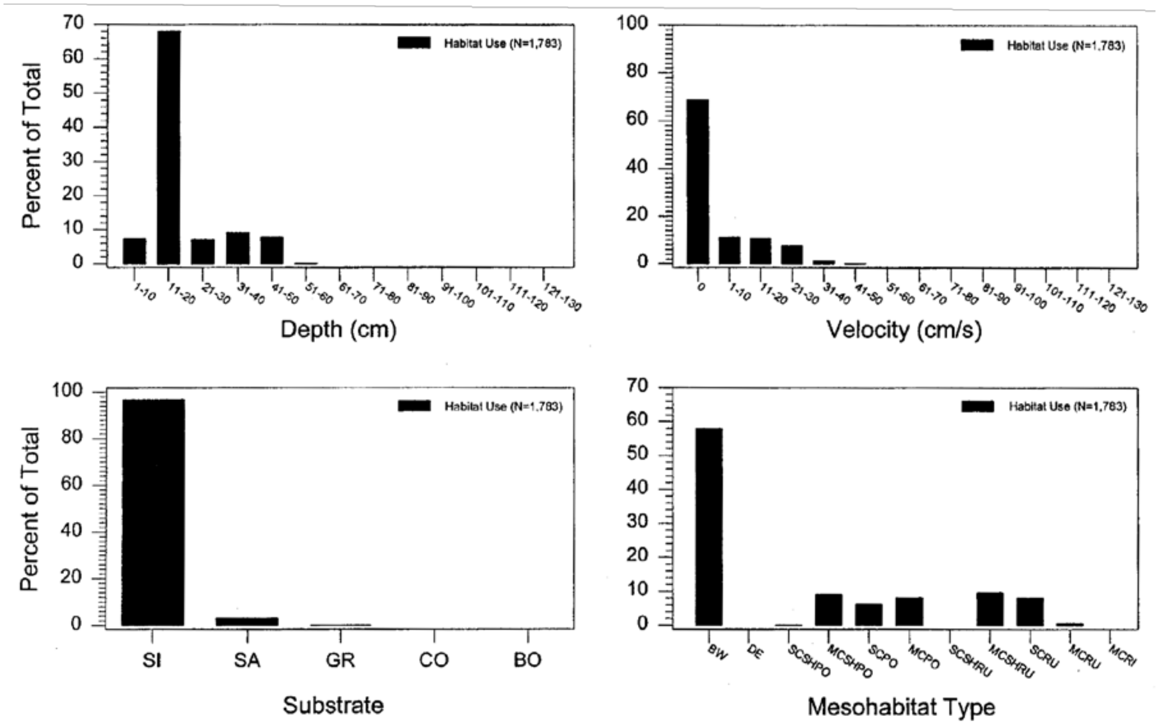

Figure 3. Habitat used by juvenile Rio Grande silvery minnow, Standard Length=21-30 mm (Dudley and Platania, 1997)

Table 1. Mesohabitat type codes and definitions used in Figure 3 above (Dudley and Platania, 1997)

Primary	
MC	Main channel- the section of the river which carries the majority of the flow; there can be only one main channel.
SC	Secondary channel- all channels not designated as the main channel; there can be zero or several secondary channels at a site.
Secondary	
BW	Back water- a body of water, connected to the main channel, with no appreciable flow; often created by a drop in flow which partially isolates a former channel.
ED	Eddy- a pool with current moving opposite to that in the channel.
FL	Flats- a region of uniform shallow depth, moderate velocity, and sand substrate.
IP	Isolated pool- a pool which is not connected to the main or secondary channel; frequently a former backwater which is no longer connected to the main or secondary channel.
PO	Pool- the portion of the river that is deep and with relatively little velocity compared to the rest of the channel.
RI	Riffle- a shallow and high velocity habitat where the water surface is irregular and broken by waves; generally indicates gravel-cobble substrate.
RU	Run- a reach of relatively fast velocity water with laminar flow and a non-turbulent surface.
SH	Shoreline- usually a shallower, lower velocity area that is adjacent to shore. This designation precedes other mesohabitat types (i.e. SHRU=shoreline run)

There was a noticeable ontogenetic shift in water velocities inhabited by silvery minnows at 60 mm standard length. Fish below 60 mm standard length were caught in slight lower velocities, average range between 4 - 4.6 cm/s, than fish greater than 60 mm standard length, average range between 7.6 – 8.4 cm/s (Dudley and Platania, 1997). Similarly, juvenile and mature silvery minnows no longer exclusively occupy habitat with predominantly silt substrata. Though silvery minnows are almost always found over silt and sand substrates, individuals were observed in the 1997 habitat use study in mesohabitats like pools and shoreline runs with sand and gravel, and, in extreme cases, cobbles in less than 1% of samples (Dudley and Platania, 1997). Therefore, the mesohabitats occupied by larger size-classes extends to main and side channel runs, though the majority of all silvery minnows were taken from low-velocity habitats. These observations are shown in Figures 4 and 5 below.

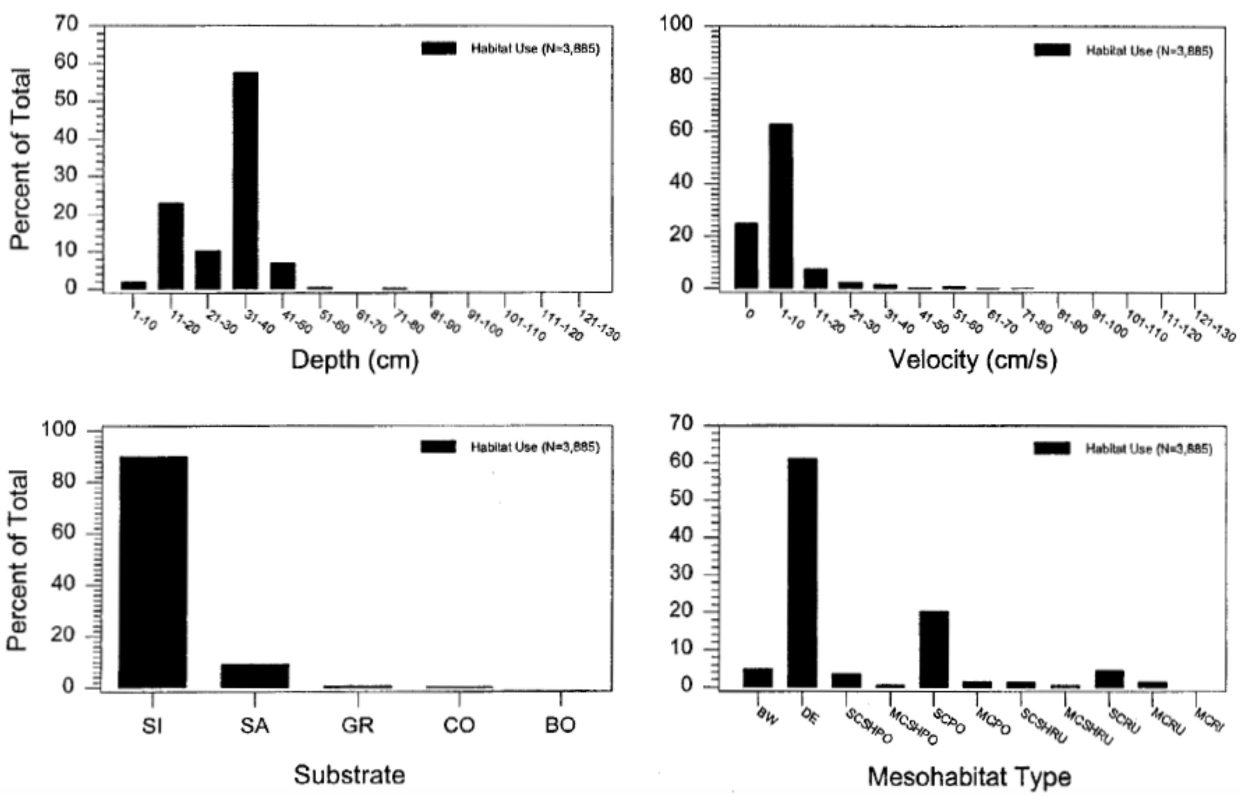

Figure 4. Habitat used by adult Rio Grande silvery minnow, Standard Length=41-50 mm (Dudley and Platania, 1997)

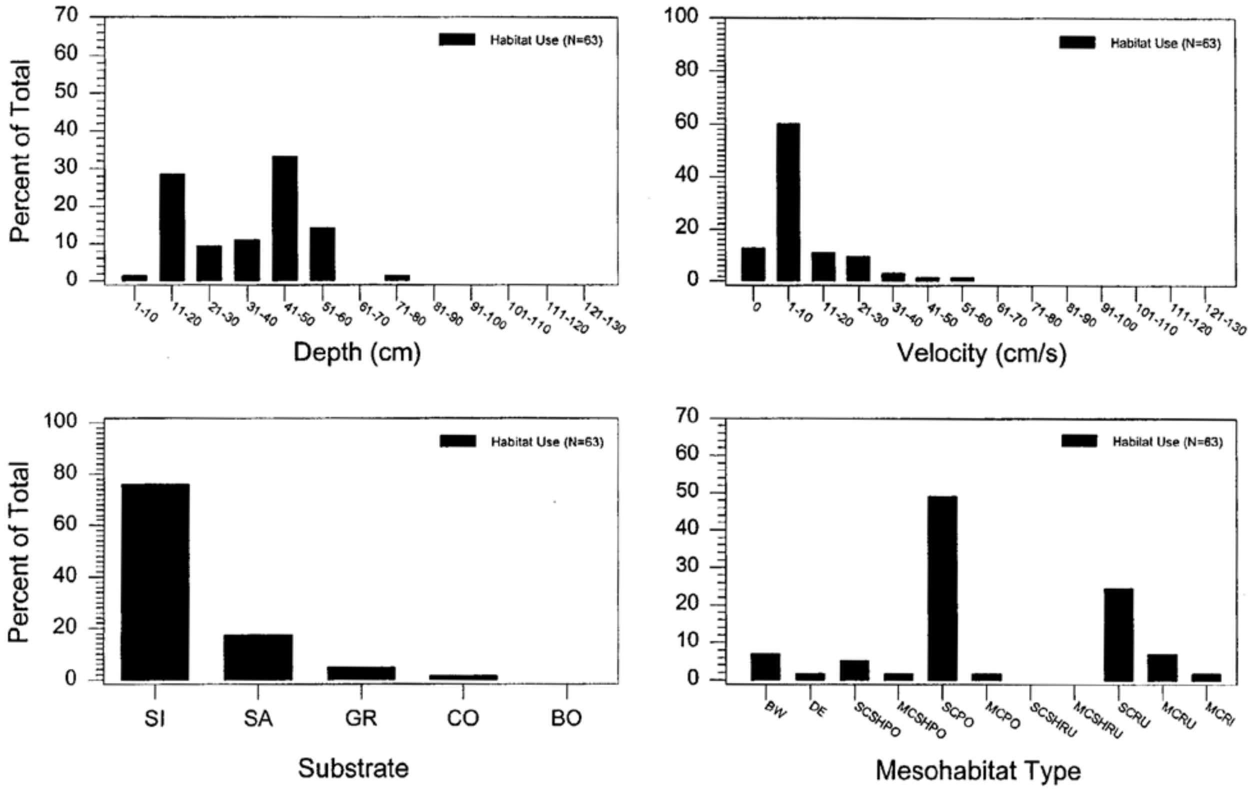

Figure 5. Habitat used by adult Rio Grande silvery minnow, Standard Length=71-80 mm (Dudley and Platania, 1997)

The Rio Grande silvery minnow consistently occupies mesohabitats characteristic of low-velocity, low to moderate depth, warm temperatures, and silt and sand substrata. However, at the time of spawning, silvery minnows can be observed in higher velocity areas commonly associated with main channel mesohabitats so that their semi-buoyant, non-adhesive eggs are carried downstream (Platania and Altenbach, 1998). This allows the species to maintain the characteristic life history trait of downstream dispersal via high-flow recruitment and release (Platania et al., 2003).

Not only do the habitat preferences of the Rio Grande silvery minnow change over the course of their lifespan, they vary seasonally as well. Spring and early summer flows typically connect secondary channels and inundate the floodplain creating low and zero velocity habitats for silvery minnows in addition to pools and shoreline runs. Usable silvery minnow habitat shifts in the cooler months to debris piles that create low velocity niches and provide protection from predators (U.S. Fish and Wildlife Service, 2007). These debris piles are essential throughout the winter season because they create areas where fish can minimize fright responses and energy expenditure while temperatures are cool and food is scarce. Though a higher number of individuals utilized deeper habitats during the winter, lower velocities generally accompanied these areas. A higher percentage of silvery minnows were caught in velocities less than 10 cm/s in winter than in summer as a means to conserve energy (Dudley and Platania, 1997). This seasonal shift is shown in Figure 6 below.

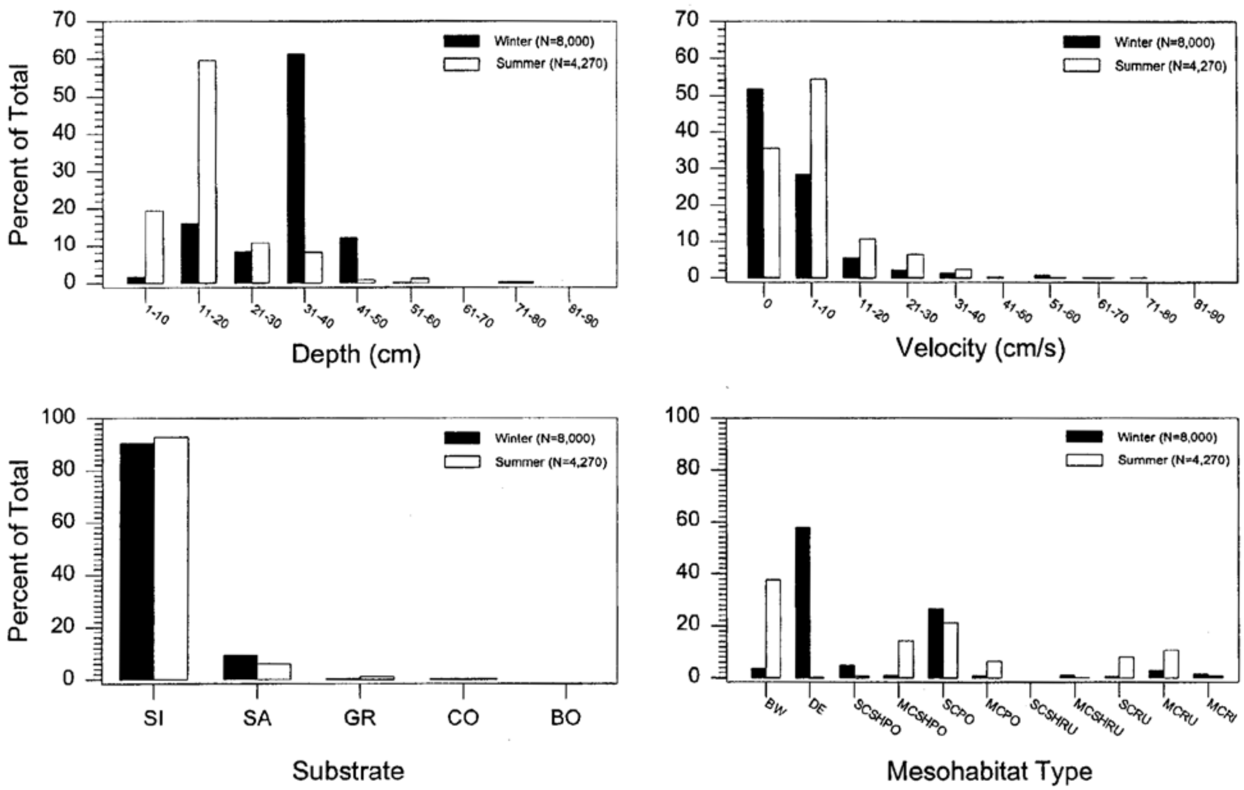

Figure 6. Summer vs winter mesohabitat use by Rio Grande silvery minnow (Dudley and Platania, 1997)

2.5. **Rio Grande Silvery Minnow Decline**

2.5.1. **Endangered Species Act Listing**

Threats to the long term persistence of the Rio Grande silvery minnow, including river fragmentation, intraspecific and interspecific species competition and predation, poor water quality during low flows, and limited genetic diversity, culminated in its listing on the Endangered Species Act in 1994 (U.S. Department of the Interior, 1994). By this time, the species had been bound to 5% of its historical range in the Rio Grande, New Mexico by two major reservoirs and extirpated from the Pecos River entirely (Bestgen and Platania, 1991).

2.5.2. **Catch Rate Studies**

As a result of the rapid decline in silvery minnow population over the past fifty years, the U. S. Bureau of Reclamation, U. S. Fish and Wildlife Service, New Mexico Department of Game and Fish, and U. S. Army Corps of Engineers have united to fund a series of studies monitoring the distribution and abundance of the Middle Rio Grande ichthyofaunal community from 1992 to present day. Though these studies monitored the general fish population, the primary focus of this research was observation of the Rio Grande silvery minnow population within the Middle Rio Grande, New Mexico.

The Middle Rio Grande is described as the reach bound upstream by Velarde, New Mexico and downstream by Elephant Butte Reservoir. This stretch of river changes in geomorphology from a narrow, cold-water river upstream dominated by a salmonid fish community to a wide, sandy river that sustains a warm-water ichthyofaunal population. These catch rate studies focused on the current range of the remaining Rio Grande silvery minnow populations. There are twenty sample sites between Angostura

Diversion Dam and Elephant Butte Reservoir: five in the Angostura Reach, six in the Isleta Reach, and nine in the San Acacia Reach. Samples were not taken from the Cochiti Reach (between Cochiti and Angostura dams) because it is under the jurisdiction of the Native American Pueblos and access is restricted; however, the last fish surveys in this reach done by Platania in 1995 recorded a low density of silvery minnows present. In the years catch rate studies were performed, samples were taken on a monthly basis in order to assess the temporal and spatial changes in species abundance.

Though the Rio Grande silvery minnow population has fluctuated throughout the first decade of sampling efforts, monitoring efforts show a sharp decline. Catch rates have dropped by almost three orders of magnitude from 1993 to 2003. The relative abundance of the silvery minnow has gone from 50% of the total ichthyofaunal population to less than 0.5% (Dudley et al., 2004). Catch rates were the lowest ever recorded by September 2003, making it an important year for understanding the threats to Rio Grande silvery minnows. Distribution of silvery minnows transitioned from being most prominent in the San Acacia reach to most prominent in the Angostura reach due to extremely low flows and dry periods within the San Acacia reach in the summer of 2003 (Dudley et al., 2004). In order to encourage spawning, river flows were artificially elevated via dam release for a short period in the spring of 2003. As a result, a large number of silvery minnow eggs were released. However, the number of young of year minnows declined rapidly following low flows and river drying during the autumn of 2003. The comparison of catch-rates and hydraulic parameters measured during 2003 showed that prolonged, high flows and catch rates were strongly positively correlated. Similarly, low flows and catch rates were strongly negatively correlated (Dudley et al., 2004). This suggests that prolonged, elevated flows resulting in immersed habitats and overbank flooding are important for the successful propagation of wild silvery minnow. Sampling of *H. amarus* between Angostura and Elephant Butte dams also showed a strong correlation between catch rate and locale. Most fish were found in the upstream portion of each reach near the outlet of Angostura, Isleta, and San Acacia diversion dams (Dudley et al., 2004). These dams allow downstream movement of eggs and drifting larvae but block upstream migration of juvenile and adult fish, illustrating the effects of fragmented habitat.

Despite the precipitous decline of silvery minnows in 2002 and 2003, catch rates were markedly higher in 2004. Though catch rates in 2004 were still lower than those seen in 1996, another year with extensive river drying, they were significant in that catch rates between 2003 and 2004 saw the single highest increase (over an order of magnitude) over the duration of these studies (Dudley et al., 2005). The most population monitoring study occurred from September of 2009 to October of 2010. The highest numbers were found in the San Acacia reach while the lowest numbers were found in the Angostura reach, illustrating that the highest density of Rio Grande silvery minnows has shifted to the downstream end of the study reach. Silvery minnows were collected in low numbers in October of 2010 (3.5% of total catch and only present in 21.1% of total hauls) (Dudley and Platania, 2011). However, the 2010 population was still high compared to the 2002 and 2003 catches. Silvery minnow density peaked in summer then slowly declined until September, as do most other species in the area. This study found that a high mean silvery minnow density is positively correlated with the number of days with flow greater than 2000 cfs and greater than 3000cfs (Dudley and Platania, 2011). The relationship between high spring flows and Rio Grande silvery minnow population density is clearly show in Figure 7 below. Notice that years with low spring flows, such as 2002 and 2003, are associated with low autumn catch rates. Conversely, years with high spring flows, like 2005 and 2008, yield high fall catch rates.

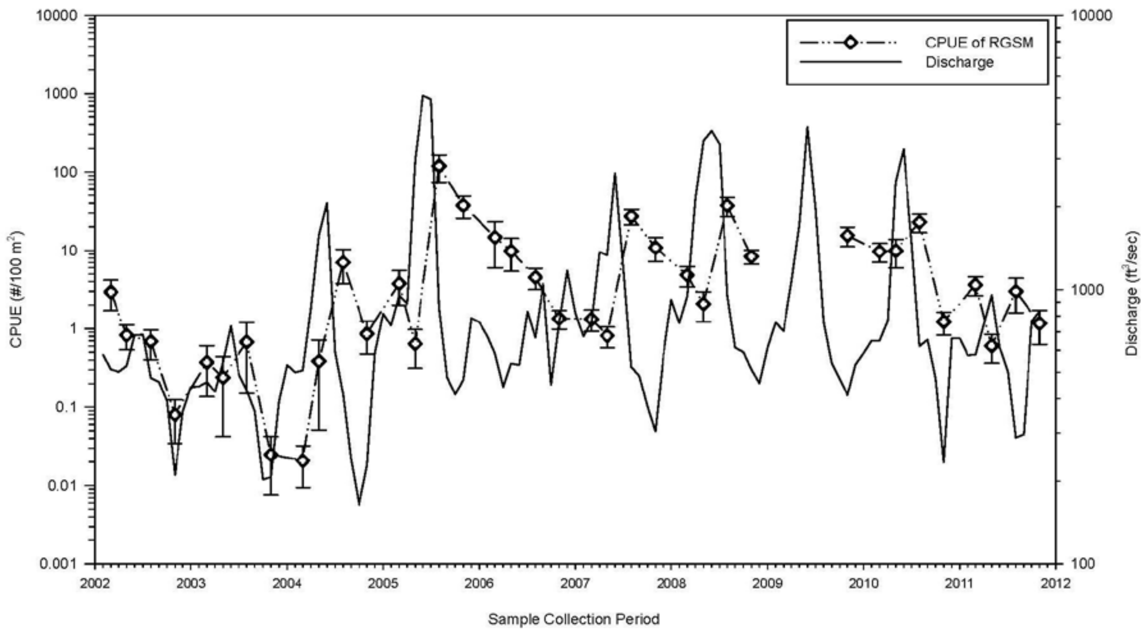

Figure 7. Quarterly RGSM population densities vs. mean monthly discharge at Albuquerque USGS gauge (Dudley & Platania, 2011)

Similarly, October densities increase with the delayed onset of low flows. The authors also observed a strong negative relationship between silvery minnow density and number of days with discharge lower than a given threshold value, <200 and <100 cfs (Dudley and Platania, 2011). These population-monitoring studies demonstrate that fluctuations in Rio Grande silvery minnow abundance are closely related to timing, magnitude, and duration of flows during the spring and summer. High flows and delayed low flows ensure connection with secondary channels and floodplains that provide warm, productive, low velocity habitats needed for larval minnows to complete early life history (Dudley and Platania, 2011).

The 2010 native ichthyofaunal community was dominated by cyprinids. Native species recorded in the study include: red shiner, Rio Grande silvery minnow, fathead minnow, flathead chub, longnose dace, river carpsucker, smallmouth buffalo, blue catfish, flathead catfish, and bluegill. The most abundant, in descending order, were the red shiner (*Cyprinella lutrensis*) (23,683), Rio Grande silvery minnow (*Hybognathus amarus*) (13,856), flathead chub (*Platygobio gracilis*) (2,628), and river carpsucker (*Carpiodes carpio*) (685). The most common introduced species were western mosquitofish (*Gambusia affinis*) (3,726), channel catfish (*Ictalurus punctatus*) (1,703), white sucker (*Catostomus commersonii*) (1,237), and common carp (*Cyprinus carpio*) (450). The Rio Grande silvery minnow dropped from second most common focal species from 2007 to 2009 to fifth in 2010, though higher than 10th in 2002 and 2003.

2.5.3. **Genetic Effective Size**

One of the more subtle contributions to the tenuous state of the Rio Grande silvery minnow is the reduction in genetic effective size that has occurred in recent years. The long-term survival of a species is dictated in part by the amount of genetic diversity maintained within the species. Species decline is almost always accompanied by reduced genetic variation and the loss of allelic diversity and heterozygoticity (U. S. Fish and Wildlife Service, 2007). Genetic testing published in 2005 yielded a present effective size of 78 and historical effective size ranging from 10^5 to 10^6 (Alo and Turner, 2005). The ratio of genetically effective population size to adult census size, represented as N_e/N, for an idealized population is one; however this number is typically lower, from 0.25 to 0.5, for a variety of life histories, mating systems, and demographic circumstances. The ratio of N_e/N for the silvery minnow population in the San Acacia reach ranged from 0.003 to 0.0530 due to fluctuations in adult census size over time and population structure (Alo and Turner, 2005). These results suggest that the Rio Grande silvery minnow population will undergo a loss of genetic diversity in future generations due to the low effective population size. A predicted increase in mean relatedness will lead directly to inbreeding and reduced fecundity in subsequent generations (Alo and Turner, 2005).

The results of this study show that the genetically effective size of Rio Grande silvery minnows is small enough to potentially lead to extinction due to genetic factors in the long term. The ecological factors responsible for the reduction in effective population size most likely occurred recently and are linked to demographic effects caused by severe river fragmentation (Alo and Turner, 2005). Loss of genetic variation could lead to inbreeding, affect a species ability to adapt to environmental changes, and exacerbate the risk of extinction (U.S. Fish and Wildlife Service, 2007). If the fragmentation of the Rio Grande silvery minnow's habitat remains unchanged, large numbers of adult fishes should be provided (most likely through hatchery supplies) in the wild in order to meet acceptable levels of genetic diversity.

While there have been efforts to maintain genetic diversity within the remaining Rio Grande silvery minnow population through hatchery supplementation, this may actually compound the existing problem rather than remedy it. The goal of maintaining genetic variability through preservation of composition and distribution of variation in captively reared Rio Grande silvery minnows is not being realized. While the heterozygosity, a key indicator of genetic variability, of hatchery populations in 2001 was similar to that seen in wild populations, the allelic diversity of the captively spawned population was much lower probably as a function of the "genetic bottleneck" effect (Osborne et al., 2006). However, wild-caught eggs reared in propagation facilities actually had a higher allelic richness than wild populations most likely due to the reduction in mortality rates in hatchery stocks (Osborne et al., 2006).

The genetic effective size of wild Rio Grand silvery minnows is already very small and theory dictates that hatchery supplementation may only compound this effect. As the declining genetic effective size of the silvery minnow population continues to be augmented by hatchery stocks, one can expect a shift in allele frequencies towards those seen in hatchery fish, perpetuating less fit hatchery-raised specimens with potentially maladaptive traits in the wild (Osborne et al., 2006). Reliance on hatchery supplementation will only decrease the probability of long-term persistence of silvery minnows in the wild. The endangered status of the Rio Grande silvery minnow will likely stay unresolved unless the dominant reasons for population decline are mitigated.

2.5.4. **Channelization and Fragmentation**

The morphology of the Rio Grande has effectively changed from a wide, braided river to a narrower, single-thread channel with limited floodplain connectivity and migration in many reaches bound by man-made levees and floodways, as can be seen in the photos compared in Figure 8 below. This change resulted in a deeper, faster flowing river in affected sections (U.S. Fish and Wildlife Service, 2007). The associated increase in main channel mesohabitat effectively eliminates much of the secondary channel and backwater habitats utilized by small-bodied fish, such as the Rio Grande silvery minnow. Additionally, the increased water velocity transports fish eggs drifting in the water column downstream faster than the original river morphology would, sometimes carrying silvery minnow eggs into unsuitable nursery habitat (Dudley and Platania, 2007).

Figure 8. Comparison of Indian Hills Farm, TX, before (1905) and after (2014) floodway construction (McDonald, 2015)

Fragmentation of the Middle Rio Grande without proper fish access to upstream reaches obstructs the return passage of mature Rio Grande silvery minnows to natal sites for spawning. When silvery minnow eggs are transported past dams and diversion structures to downstream reaches of the Middle Rio Grande, those that survive to adulthood fail to recruit to breeding populations upstream (Alo and Turner, 2005). In this same manner, the Rio Grande silvery minnow is prevented from repopulating previously extirpated sites upstream of dams; roughly 40 years after dam completion, silvery minnows are known to be extirpated upstream of the new structure (Cowley, 2006). As a result, higher densities of the silvery minnow are present in the downstream reaches

(Isleta and San Acacia) of the Middle Rio Grande than upstream (Cochiti and Bernalillo) (Dudley and Platania, 1991).

Dams on the Middle Rio Grande do not have adequate fish passage structures for the Rio Grande silvery minnow. A study done in 2010 found that silvery minnow swimming endurance increased inversely with water velocity. Additionally, distance traveled increased with variable flow, meaning the presence of rest points enabled silvery minnows to swim longer distances (Bestgen et al., 2010). The author concluded that the ideal fish passage structure for the Rio Grande silvery minnow is a rock structure with a gradient less than 1% and variable velocity created by alternating obstructions (Bestgen et al., 2010). In the absence of such structures, they cannot redistribute upstream past the existing dams, an important life history characteristic of the Rio Grande silvery minnow.

2.5.5. **Water Quality**

Though poor water quality is not one of the foremost contributors to the decline of the Rio Grande silvery minnow, it is a stressor worth considering given the reduced size and vulnerability of the remaining population. A study on water quality in the Middle Rio Grande done in 2009 identified few water quality issues that exceeded levels known to negatively impact fish health. Only *E. coli*, some samples of elevated metal concentrations, and dissolved oxygen exceeded or did not meet water quality standards (Stringer et al., 2009). However, these issues did not cause fish kills even when expected. This implies that fish were able to avoid areas of poor water quality. Additional water quality issues, while not lethal, have been recorded at levels where Rio Grande silvery minnow reproduction and respiration may be impacted, further contributing to areas of unsuitable habitat and that must be avoided (Stringer et al., 2009). This causes additional stress to the species and decreases likelihood of recovery.

A second study, done in 2012, observed that the condition of Rio Grande silvery minnows deteriorated from upstream to downstream within the study reach (Davis and Lusk, 2012). Fish in severely polluted areas exhibited more frequent lesions or anomalies than in less polluted areas. Chronic stress is causing anomalies such as shortened opercula and liver and gill anomalies in silvery minnows observed within the study area (Davis and Lusk, 2012). Thus, water quality, while not the main cause of Rio Grande silvery minnow decline, is adding stress to the current population within the Middle Rio Grande.

3. Rio Grande Silvery Minnow Habitat Suitability Criteria

3.1. Criteria Description

The formulation of a set of comprehensive, quantitative hydraulic criteria that define the level of suitability for Rio Grande silvery minnow habitat required the extensive literature review outlined above. Previous research has been done on the anatomy, physiology, and behavior (including reproduction, feeding, movement, and habitat use) of the Rio Grande silvery minnow as well as its populations over time. However, this information has not been combined in a manner that describes the exact environmental requirements for silvery minnow survival. Therefore, I propose a set of habitat suitability criteria for the Rio Grande silvery minnow, both juvenile and adult, in the following paragraphs. The purpose of the criteria is to identify and define the critical aspects of silvery minnow habitat using simple, discrete limits. The criteria should be easily applicable to long reaches of the Rio Grande for use in Rio Grande silvery minnow recovery efforts. The criteria will be used to evaluate cross section averaged hydraulic depth, water velocity, and grain size. Water quality was not taken into account because it is a minor issue compared to mesohabitat degradation and is considered by the author to be more of an environmental or ecological characteristic rather than a hydraulic one. Similarly, water temperature was not included in the criteria because it lies outside the realm of hydraulic attributes. The criteria I have determined for adult Rio Grande silvery minnows are as follows:

1. Water velocity less than 40 cm/s
2. Hydraulic depth less than 50 cm
3. Medium sand substrate (D_{50} less than 0.50 mm)

The criteria I have determined for juvenile Rio Grande silvery minnows are as follows:

1. Water velocity less than 20 cm/s
2. Hydraulic depth less than 40 cm
3. Silt substrate (D_{50} less than 0.0625 mm)

The number of criteria fulfilled indicates the suitability of an area or cross-section of habitat, to be indicated visually on a map of the reach of interest. The satisfaction of all three criteria indicates excellent silvery minnow habitat, represented by the color green on a suitability map. The fulfillment of two criteria indicates good to moderate silvery minnow habitat, represented by the color yellow on a suitability map. The satisfaction of one criterion indicates moderate to poor habitat, represented by the color orange on a suitability map. In the case that no criteria are met, the area is deemed as unsuitable Rio Grande silvery minnow habitat, represented by the color red on a suitability map.

3.2. **Criteria Validation**

In order to validate the accuracy of these three suitability criteria, a cursory application of the adult silvery minnow criteria and comparison of two reaches of the Middle Rio Grande, one with a low silvery minnow population density and one with a high silvery minnow population density, was performed. The juvenile silvery minnow criteria were not verified because there is no catch rate data for juvenile Rio Grande silvery minnow available in order to support the results of such an analysis. A subreach of the Bernalillo reach, coined the Bernalillo Bridge reach, was chosen due to the low catch rates of Rio Grande silvery minnow in this area. Similarly, a subreach of the San Acacia reach, named the Escondida subreach, was chosen due to the relatively high catch rates of Rio Grande silvery minnow in this region.

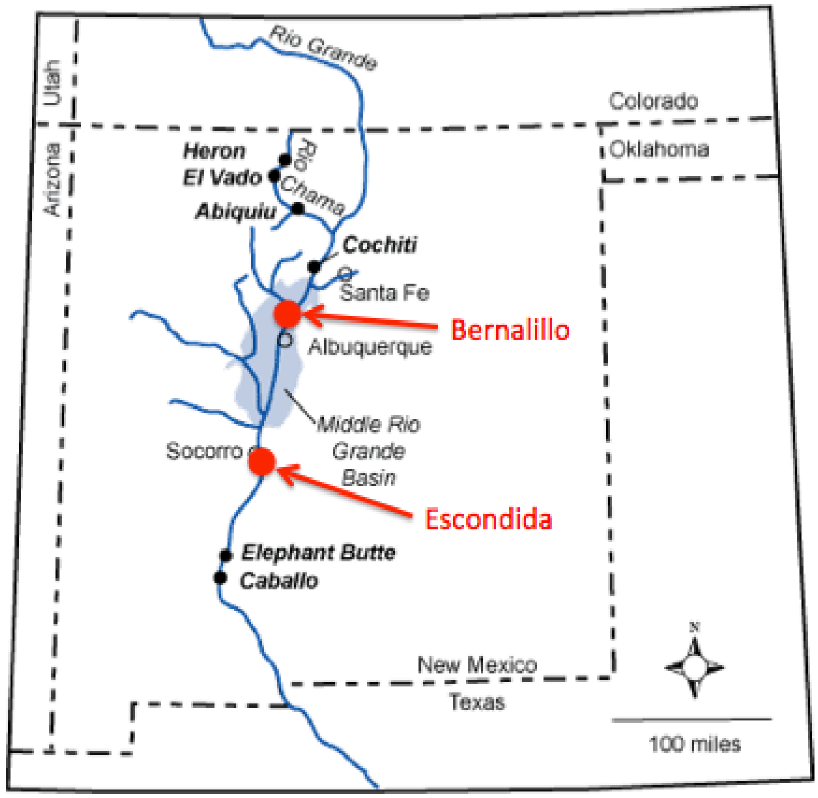

Figure 9. Location of Bernalillo Bridge and Escondida reaches

3.2.1. **Reach Descriptions**

The Bernalillo Bridge reach is just over 5 miles in length, spanning from NM Highway 44 upstream to cross section CO-33 downstream. Historically, this area was a fairly straight, braided sand-bed channel with a general trend of aggradation of the riverbed. Presently, this reach is narrower due to confinement by floodways, even single thread in one subreach, and has a coarser median substrate due to impoundment of sediment upstream by Cochiti Dam (Sixta et al., 2003). It can be divided into three subreaches. The first is made up of the first 1.79 miles of the reach and is bound by Agg/Deg lines 298 and 316. The second is comprised of the middle 1.93 miles of the reach and is bound by Agg/Deg lines 316 and 337. The third and final subreach spans the last 1.38 miles of the reach and is bound by Agg/Deg lines 337 and 351 (Sixta et al., 2003). The criteria will consider all three subreaches shown in Figure 10.

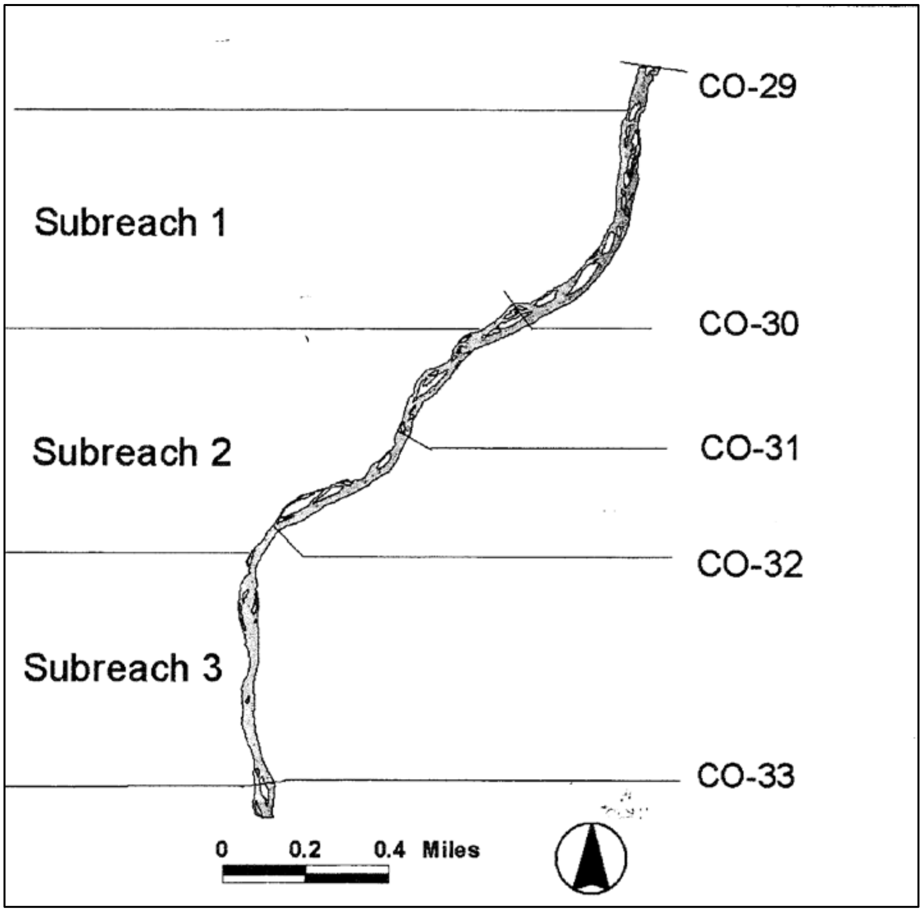

Figure 10. Bernalillo Bridge subreach definition (Sixta et al., 2003)

The Escondida reach spans a 17.7-mile length of the Rio Grande from the Escondida Bridge upstream to the US Highway 380 Bridge downstream. Historically, this reach was a braided, sand-bed channel characterized by an aggradational trend. Like the Bernalillo Bridge reach, the Escondida reach has narrowed and become slightly coarser-grained in recent years due to human influences (Larsen et al., 2007). This reach can also be divided into three subreaches, illustrated in Figure 11. The first subreach runs from the Escondida Bridge to Agg/Deg line 1346, the second from Agg/Deg line 1364 to line 1455, and the third from Agg/Deg line 1455 to the US Highway 380 Bridge.

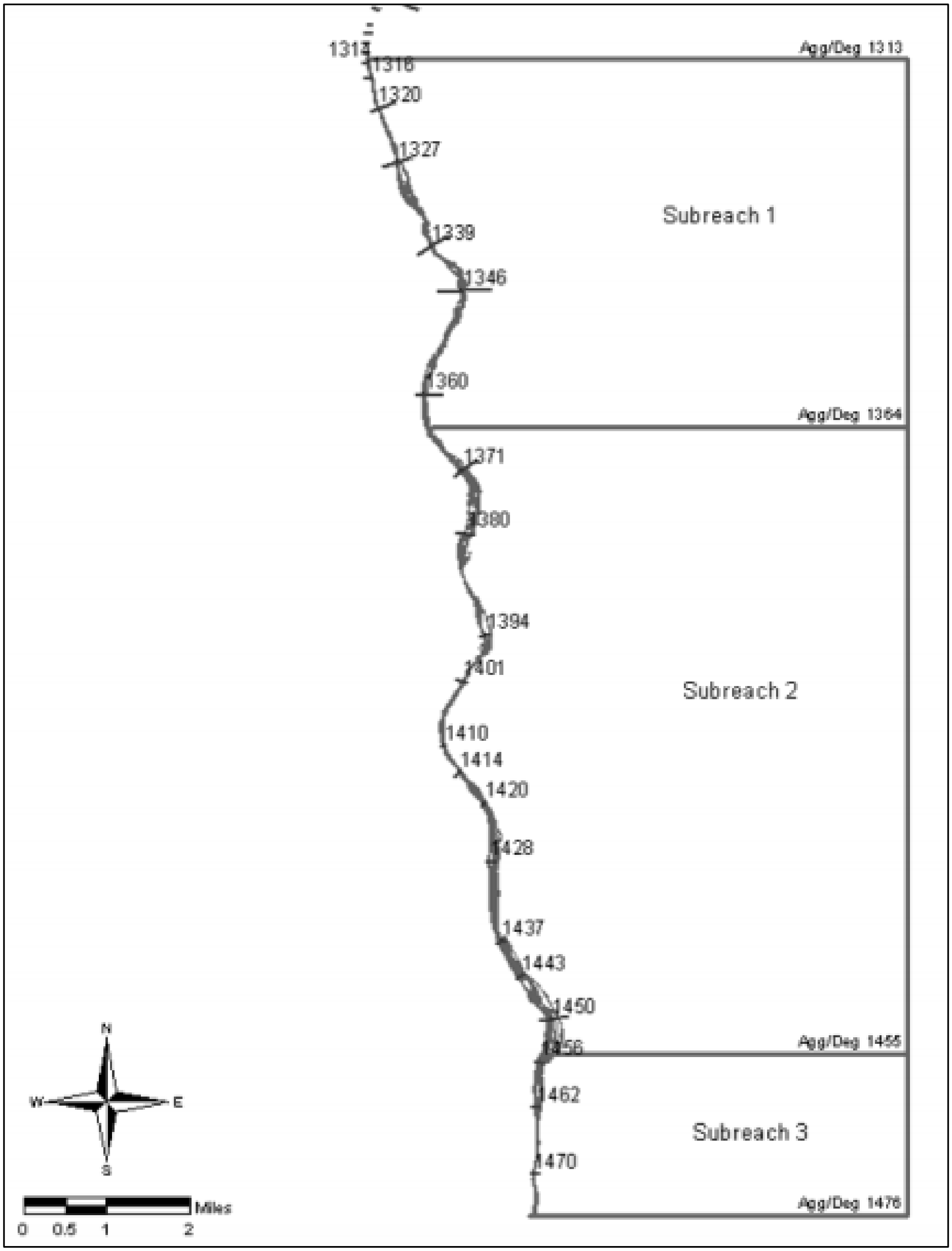

Figure 11. Escondida subreach definition (Larsen et al., 2007)

3.2.2. **Validation Results**

The Rio Grande silvery minnow habitat suitability criteria were applied to the reach-averaged water velocity, hydraulic depth, and substrate for both reaches described above. Table 1 summarizes the results of this evaluation.

Table 2. Criteria satisfaction for Bernalillo vs Escondida reach

Reach	**Velocity<40 cm/s**	**Depth<50cm/s**	**Substrate D_{50}<0.50mm**	**Total Catch Rate (Sept. 2009-Oct. 2010)**
Bernalillo	☒ (all 3 subreaches had a mean velocity ≈90 cm/s)	☒ (all 3 subreaches had average depth ≈97 cm)	☒ (subreaches 1 and 2 do not meet criterion)	441
Escondida	☒ (all 3 subreaches had a mean velocity > 105 cm/s)	☒ (all 3 subreaches had average depth >60 cm)	☑ (all 3 subreaches met criterion)	1020

As seen above, the Bernalillo Bridge reach did not meet any of the criteria while the Escondida reach met one of the three criteria. Though this does not qualify the in-channel habitat as excellent or even good, it does signify that the habitat within the Escondida reach is higher quality than that in the Bernalillo Bridge reach. This is corroborated by the most recent Rio Grande silvery minnow catch rates in each reach. More than twice the number of silvery minnows caught in the Bernalillo Bridge reach was caught in the Escondida reach. The high density of Rio Grande silvery minnows in the Escondida reach reflects the more suitable instream habitat in the downstream portion of the Middle Rio Grande.

4. Application of Criteria

It is most prudent to apply the habitat suitability criteria described above to an area that the highest percentage of the existing Rio Grande silvery minnow population is currently utilizing. According to the most recent available catch rate studies, the highest density of silvery minnows reside within the San Acacia reach (Dudley and Platania, 2011). Therefore, the Escondida reach was selected for this study due to its location within the San Acacia reach of the Middle Rio Grande. A description of the Escondida reach is provided in section 3.2.1 above. Additionally, Figure 12 shows a detailed illustration of the Escondida reach.

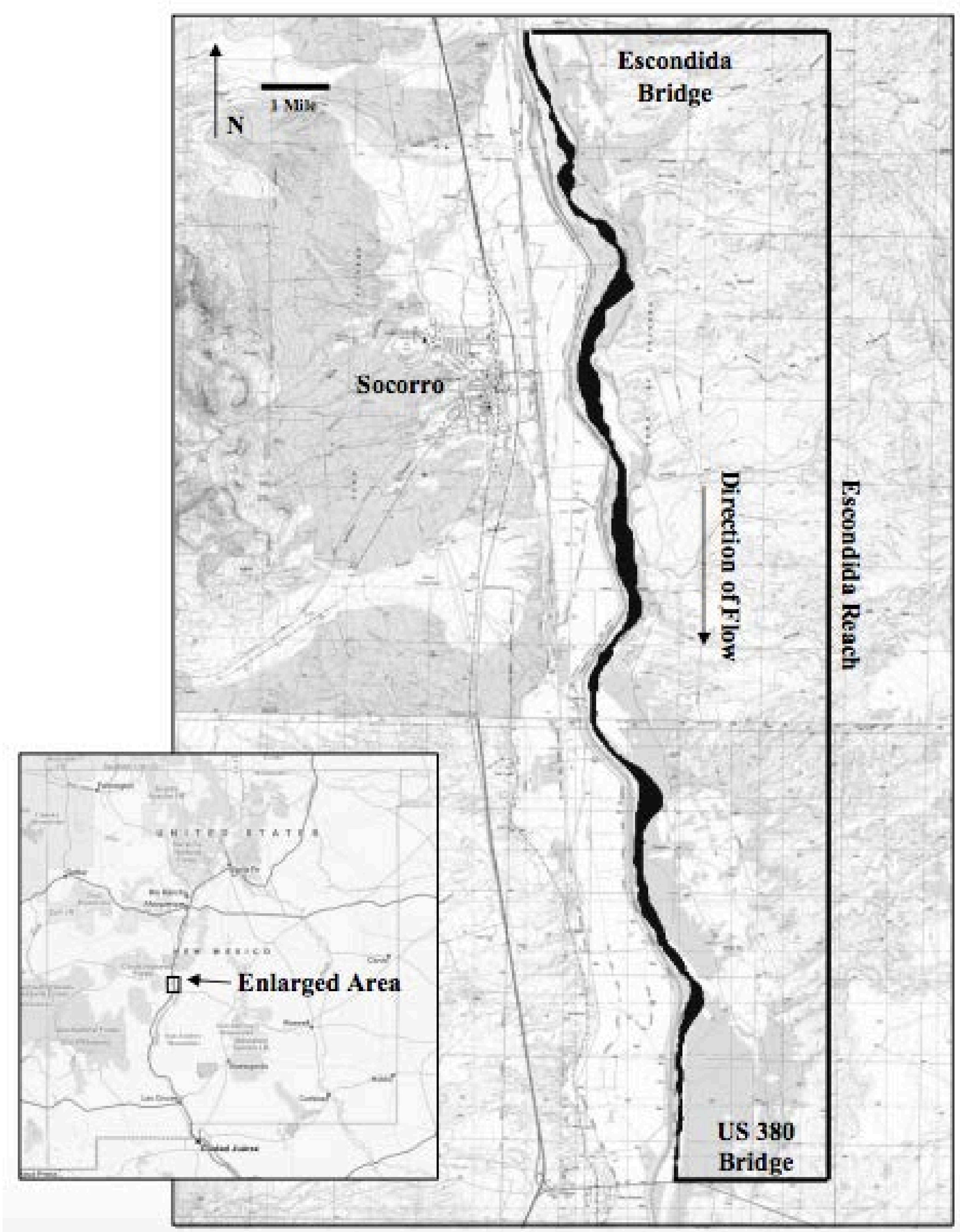

Figure 12. Escondida reach detail (Larsen et al., 2007)

4.1. **Methods**

In order to apply the habitat suitability criteria at each cross section within the Escondida reach, velocity, hydraulic depth, and substrate data was needed for each Agg/Deg cross section, rather than reach-averaged data. A previous study, done by Amanda K. Larsen in 2007 as her Master's thesis, gathered the necessary data to run a HEC-RAS model of the Escondida reach at bankfull discharge, 5000 cfs. The data used in her analysis included daily discharge data from 1949 to 2007, sporadic bed material data from USGS gauging stations as well as Bureau of Reclamation collections as recent as 2005, and survey lines and dates ranging from 1987 to 2005. The HEC-RAS model output data describing the thalweg, water surface elevation, average hydraulic depth, hydraulic radius, mean channel velocity, Froude number, and friction slope at each Agg/Deg line shown in Figure 11. These HEC-RAS results were used to apply the habitat suitability criteria at all 163 available cross sections for both juvenile and adult Rio Grande silvery minnows. The results were compiled in maps, see Figures 16 and 20, that illustrate the linear change in habitat suitability traveling downstream of the reach.

4.2. **Results**

4.2.1. Adult Rio Grande Silvery Minnow Criteria

In the year 2002, only 1.8% of cross sections had a mean velocity of 40 cm/s, shown in Figure 14 below. Average velocity in the channel is generally much higher than what the Rio Grande silvery minnow utilize, at about 105 cm/s. As seen in Figure 13, 18.4% of cross sections had an average hydraulic depth less than 50 cm. Again, the average hydraulic depth, about 65 cm, is greater than the depths most commonly inhabited by the silvery minnow. Most notably, all cross sections had a D_{50} less than 0.50 mm, meaning the substrate was primarily composed of sand (see Figure 15).

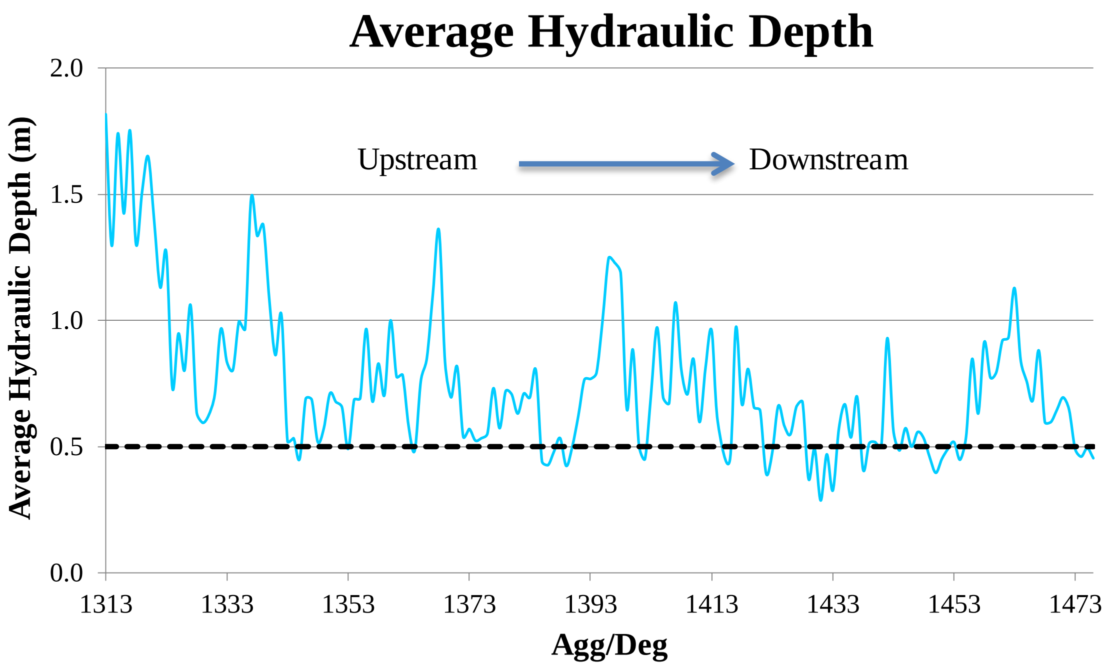

Figure 13. Adult depth criteria compared to average hydraulic depth in 2002 at each cross section in the Escondida reach

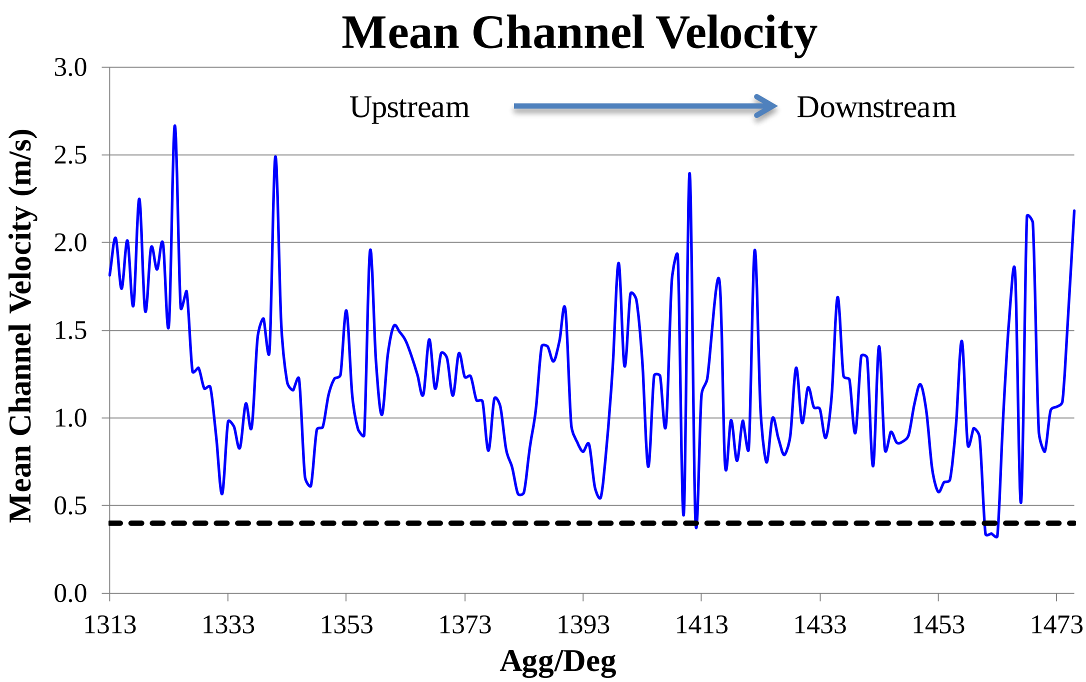

Figure 14. Adult velocity criteria compared to mean channel velocity in 2002 at each cross section in the Escondida reach

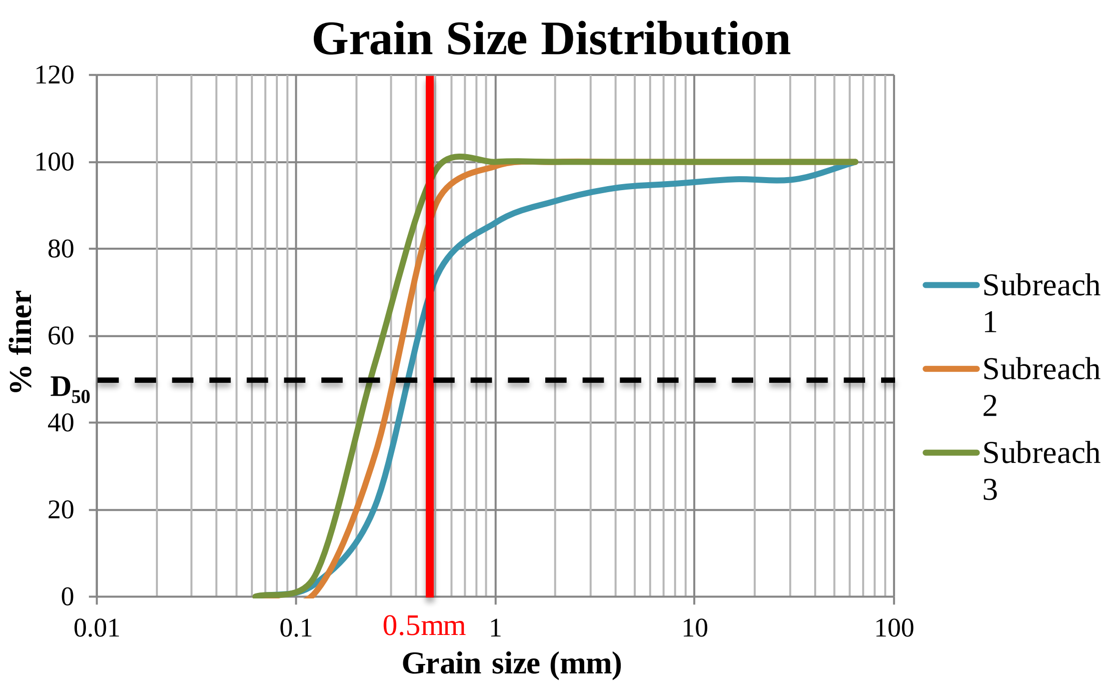

Figure 15. Adult substrate criteria compared to grain size distribution in 2002 for each subreach of the Escondida reach

Given the variability of hydraulic depth and velocity throughout the reach, not a single cross section fulfilled all three criteria and only a fifth of the cross sections fulfilled two criteria. Table 2 quantifies the habitat suitability of cross sections within the Escondida reach.

Table 3. Percentage of cross sections that meet all three, two, one, or no adult criteria.

# of criteria met	% cross-sections that meet # of criteria
0	0%
1	100%
2	20.2%
3	0%

Figure 16 is the resulting suitability map that illustrates the change in adult Rio Grande silvery minnow habitat suitability in one dimension traveling downstream of the reach. The satisfaction of all three criteria indicates excellent silvery minnow habitat, represented by the color green on a suitability map. The fulfillment of two criteria indicates good-moderate silvery minnow habitat, represented by the color yellow on a suitability map. The satisfaction of one criterion indicates moderate-poor habitat, represented by the color orange on a suitability map. In the case that no criteria are met, the area is deemed as bad Rio Grande silvery minnow habitat, represented by the color red on a suitability map.

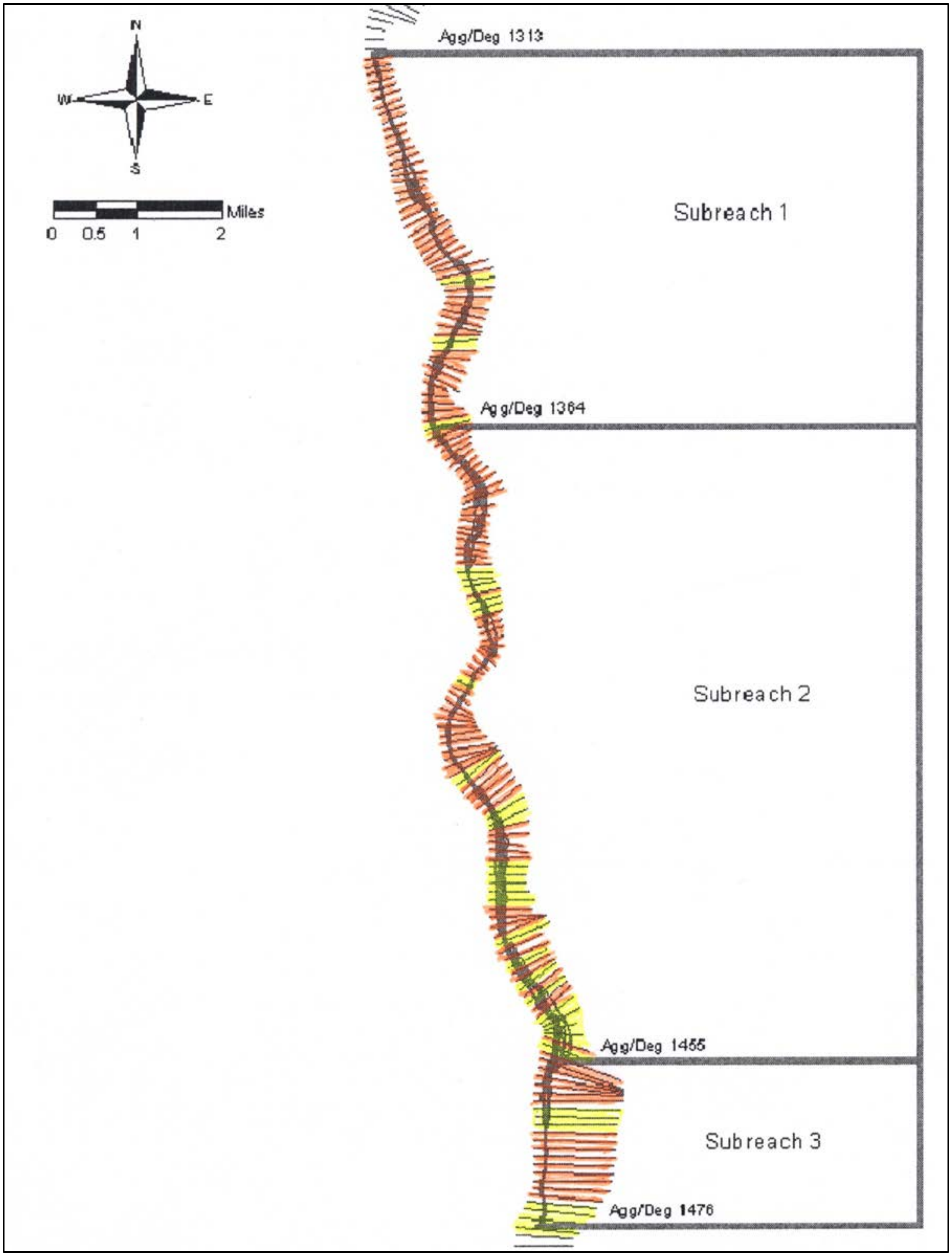

Figure 16. Map of adult suitability criteria applied to Escondida reach

4.2.2. Juvenile Rio Grande Silvery Minnow Criteria

In 2002, none of the cross sections had an average water velocity less than 20 cm/s or a D_{50} less than 0.0625mm, shown in Figures 18 and 19. This is unsurprising, given that the reach-average water velocity in the channel is 105 cm/s and the substrate is primarily sand. Only 3.1% of cross sections had an average hydraulic depth less than 40 cm/s (see Figure 17)

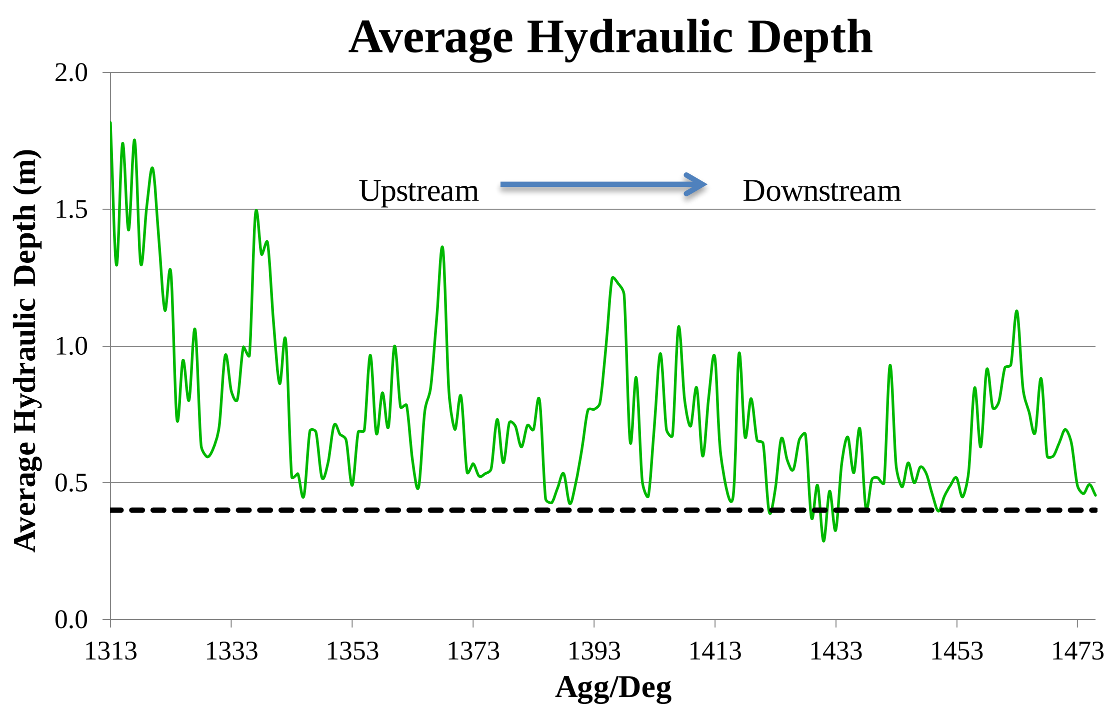

Figure 17. Juvenile depth criteria compared to average hydraulic depth in 2002 at each cross section in the Escondida reach

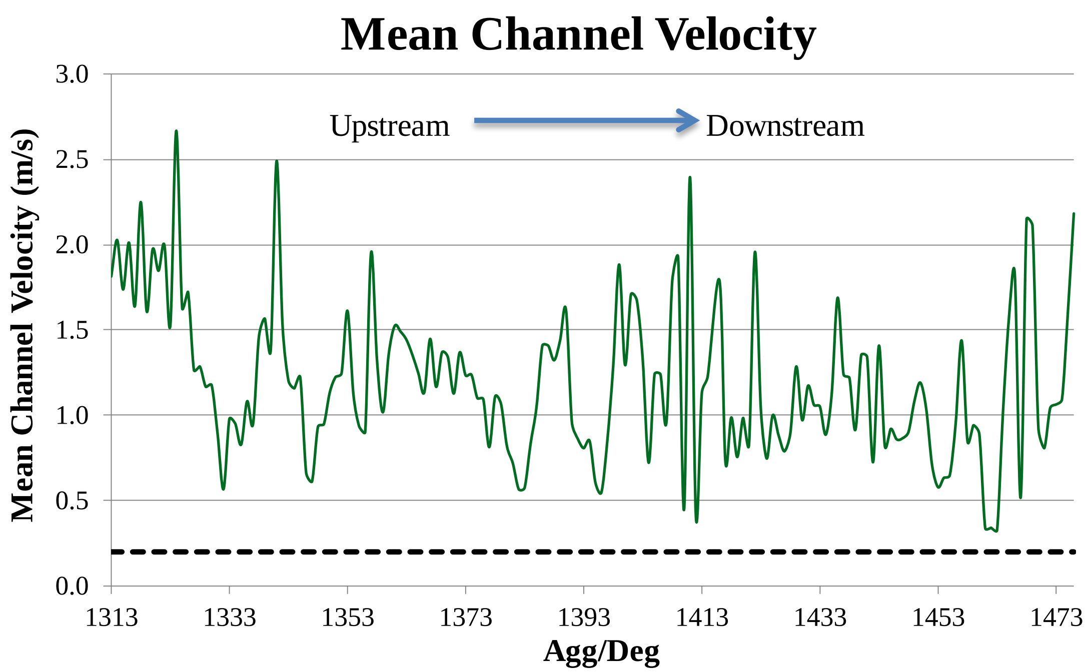

Figure 18. Juvenile velocity criteria compared to mean channel velocity in 2002 at each cross section in the Escondida reach

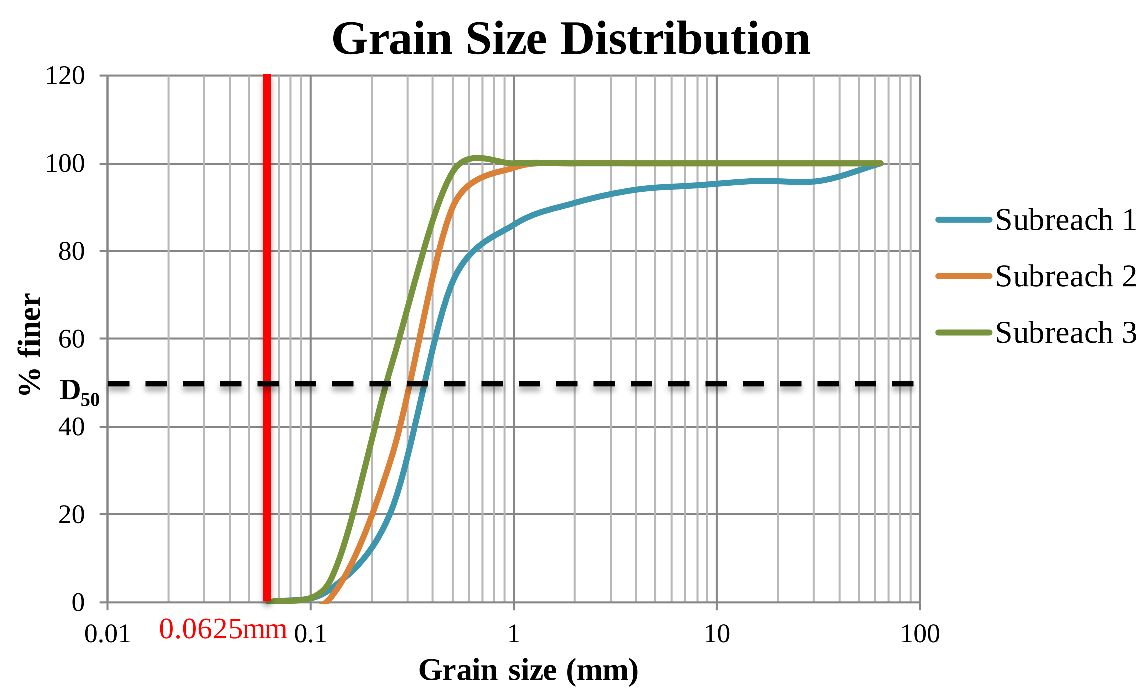

Figure 19. Juvenile substrate criteria compared to grain size distribution in 2002 for each subreach of the Escondida reach

Given that none of the cross sections fulfilled the juvenile velocity and substrate criteria, it is unsurprising that the juvenile habitat suitability of the Escondida reach is poor, as seen in Table 3 below.

Table 4. Percentage of cross sections that meet all three, two, one, or no juvenile criteria.

# of criteria met	**% cross-sections that meet # of criteria**
0	96.9%
1	3.1%
2	0%
3	0%

Figure 20 is the resulting suitability map that illustrates the change in juvenile Rio Grande silvery minnow habitat suitability in one dimension traveling downstream of the reach. The satisfaction of all three criteria indicates excellent silvery minnow habitat, represented by the color green on a suitability map. The fulfillment of two criteria indicates good-moderate silvery minnow habitat, represented by the color yellow on a suitability map. The satisfaction of one criterion indicates moderate-poor habitat, represented by the color orange on a suitability map. In the case that no criteria are met, the area is deemed as bad Rio Grande silvery minnow habitat, represented by the color red on a suitability map.

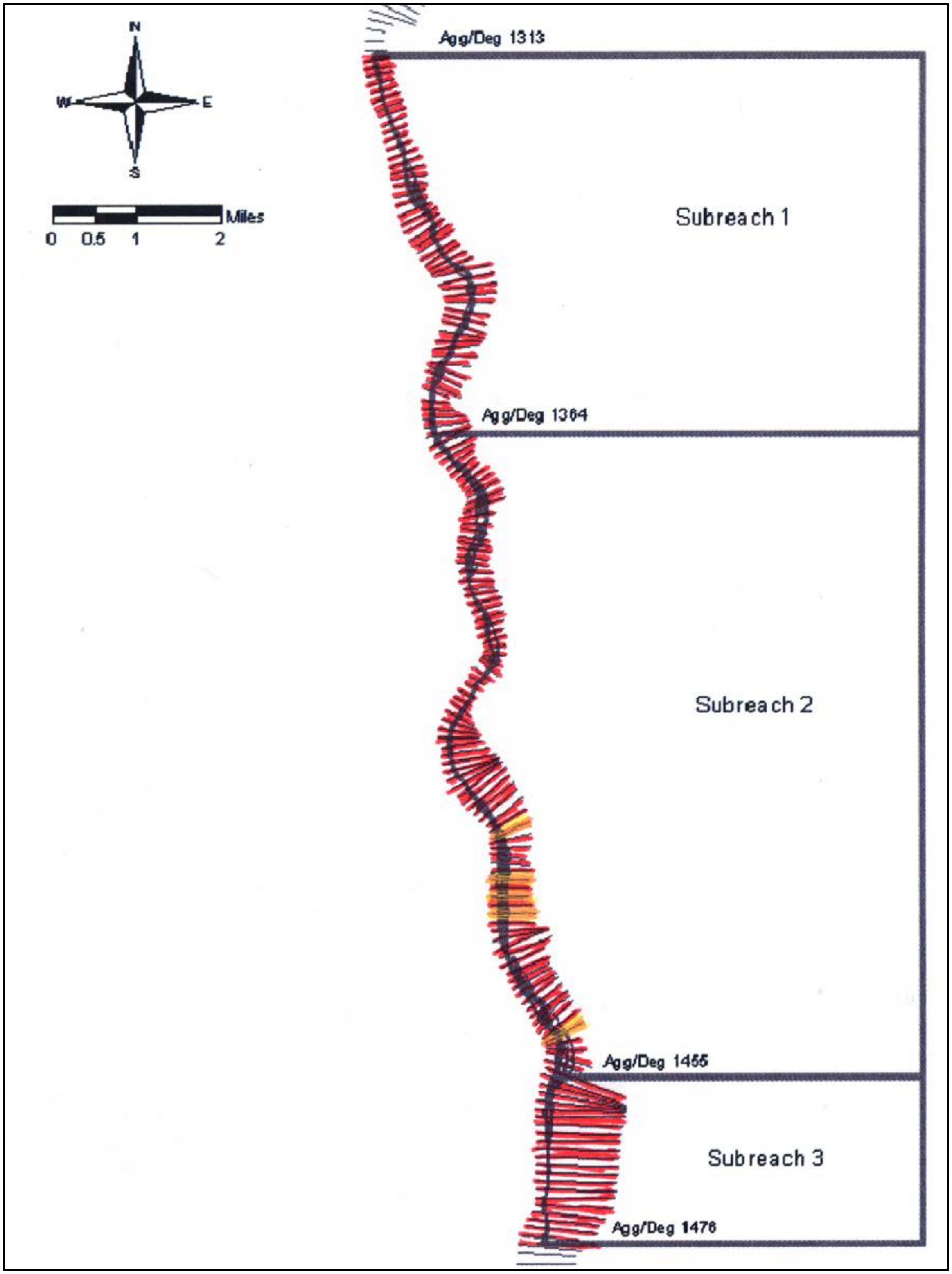

Figure 20. Map of juvenile suitability criteria applied to Escondida reach

4.3. **Discussion**

The results of the application of both adult and juvenile Rio Grande silvery minnow habitat suitability criteria show that, despite the concentration of the species in the San Acacia reach, the Escondida reach has little instream habitat that is considered "good" on the scale of suitability. Only 20% of 163 total cross sections within the study area fulfilled two of the three criteria for adults, and a disappointing 3.1% fulfilled one of the three criteria for juveniles. This indicates that the main channel of the Escondida reach contains none of the mesohabitats described for silvery minnow survival.

Some insight can be gained by comparing the current hydraulic characteristics of the Escondida reach to those of the past. Compared to 18.4% in 2002, 22.7% of cross sections met the depth criteria for adult minnows in 1962; compared to 0% in 2002, 4.3% of cross sections met the depth criteria for adults in 1962, shown in Figure 21.

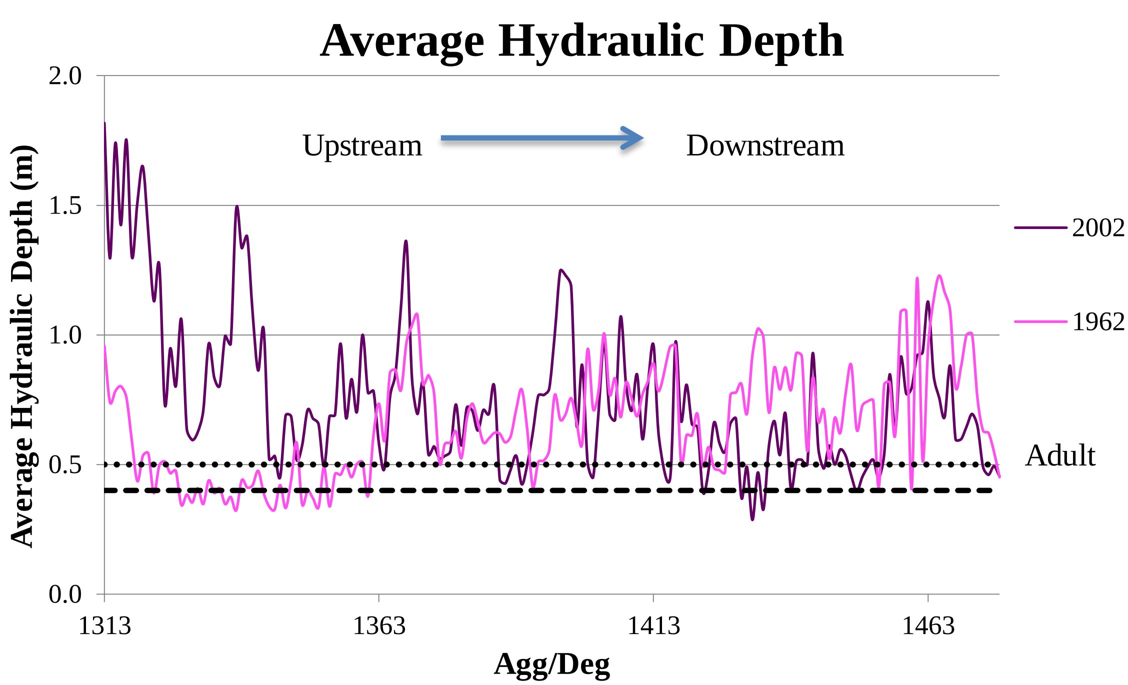

Figure 21. Adult and juvenile depth criteria compared to average hydraulic depth in 2002 and 1962

A slightly higher percentage of cross sections met the velocity criteria for both juvenile and adult silvery minnows in 1962 than in 2002. In 1962, 7.4% of cross sections met the adult velocity criteria, as opposed to 1.8% in 2002. Similarly, 4.3% of cross sections met the juvenile velocity criteria in 1962, as opposed to 0% in 2002, as demonstrated in Figure 22.

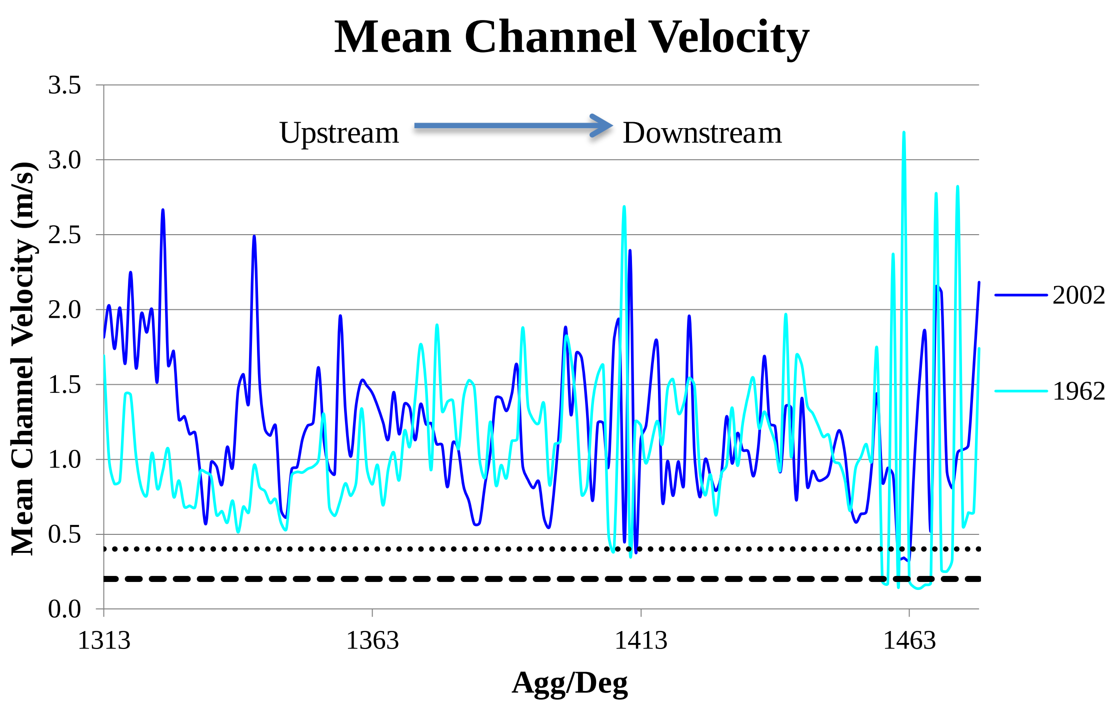

Figure 22. Adult and juvenile velocity criteria compared to average hydraulic depth in 2002 and 1962

A similar trend can be found in the grain size distribution for the reach, found in Figure 23 below. Throughout the last several decades, the median grain size has shifted from as low as 0.1 mm to 0.27 mm in 2002. This, however, shows that even at its lowest in 1972, the median grain size of the Escondida reach did not meet the juvenile substrate criteria. Conversely, it has always met the adult substrate criteria.

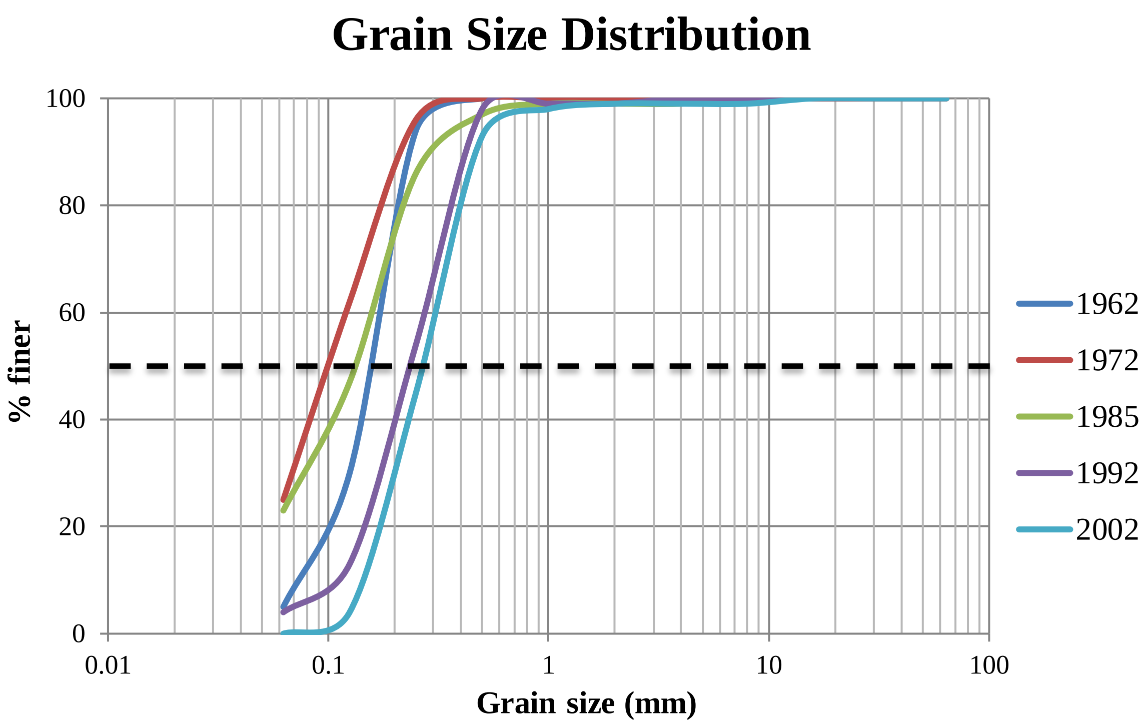

Figure 23. Evolution of grain size distribution over past five decades

Despite the slight increase in number of cross sections that meet either the velocity or depth criteria in 1962 compared to 2002, the overall number of cross sections that meet two criteria for adult criteria or one criteria for juvenile criteria is still relatively low, shown in Tables 4 and 5.

Table 5. Percentage of cross sections that meet all three, two, one, or none of the adult habitat criteria

# of criteria met	% cross-sections that meet # of criteria	
	1962	2002
0	0%	0%
1	100%	100%
2	35%	20.2%
3	0%	0%

Table 6. Percentage of cross sections that meet all three, two, one, or none of the juvenile habitat criteria

# of criteria met	% cross-sections that meet # of criteria	
	1962	2002
0	84.0%	96.9%
1	16.0%	3.1%
2	0%	0%
3	0%	0%

This suggests that even historically, the main channel of the Middle Rio Grande did not maintain habitat that is deemed appropriate for Rio Grande silvery minnow use. Thus, the criteria created in this report may be more applicable to riparian areas outside the main channel. Given that secondary channels and backwaters are characterized by low velocities and shallow depths, extending the boundaries over which the criteria are applied would likely yield areas within the floodplain categorized as excellent Rio Grande silvery minnow habitat for both juveniles and adults. Possible future steps for this application of the criteria using this idea will be outlined in the next section.

In addition to adding insight to the optimal application of the suitability criteria, the change over time in the mean channel velocity, average hydraulic depth, and grain size distribution within the Escondida reach are a microcosm of the changes that have occurred in the Middle Rio Grande in the past century. As explained earlier, the shift in channel morphology has created deeper, faster flowing, and coarser-grained channels in what were historically wide, braided sand-bed channels. This analysis highlights this shift on a reach-scale and demonstrates how that change can affect local fauna, specifically the Rio Grande silvery minnow.

5. Summary and Conclusions

The two sets of criteria set forth in this paper, for adult Rio Grande silvery minnows and juvenile Rio Grande silvery minnows, are a reflection of a host of previous biological, behavioral, and population-monitoring studies on this endangered species. The adult criteria I proposed in this report are as follows: water velocity less than 40 cm/s, hydraulic depth less than 50 cm, and medium sand substrate (D_{50} less than 0.50 mm). Similarly, the juvenile criteria include: water velocity less than 20 cm/s, hydraulic depth less than 40 cm, and silt substrate (D_{50} less than 0.0625 mm).

The adult criteria have been validated using recent catch rate information and can be applied with relative confidence. The Bernalillo Bridge reach met none of the adult criteria while the Escondida reach met one out of three adult criteria, demonstrating higher habitat suitability for Rio Grande silvery minnow. The difference in adequate habitat is corroborated by the silvery minnow catch rates in both reaches. The Bernalillo Bridge reach had a catch rate (CPUE) less than half that of the Escondida reach. Unfortunately, verification of the juvenile criteria was not possible at present and should be used with this in mind.

The application of these criteria exhibited the unsuitability of main channel mesohabitats for Rio Grande silvery minnow endurance. Out of 163 total cross sections, only 1.8% met the velocity criterion, 18.4% met the depth criterion, and 100% met the substrate criterion for adults. The resulting overall habitat suitability for adult silvery minnows is as follows: 0% excellent (3 criteria met), 20.2% good to moderate (2 criteria met), 100% moderate to poor (1 criteria met), and 0% bad habitat (no criteria met). Even fewer met the juvenile criteria: 0% met the velocity or the substrate criteria and 3.1% met the depth criterion. The resulting overall habitat suitability for adult silvery minnows is as follows: 0% excellent, 0% good to moderate, 3.1% moderate to poor, and 96.9% bad habitat.

The habitat needs of the Rio Grande silvery minnow are well understood at each stage of life for the species. Drifting eggs and larvae settle in shallow, zero-velocity areas with silt substrate. As individuals develop, they branch out into mesohabitats with higher velocity and depth due to increased swimming ability, though silvery minnows are rarely found outside of velocities less than 40 cm/s and depths less than 50 cm. Their mesohabitat preference for backwaters, secondary channels, pools, and debris piles, as defined in Table 1, reflects these hydraulic parameters. Given this information and the results of the analysis described above, the main channel of the Middle Rio Grande does not provide proper Rio Grande silvery minnow habitat. Typically, the main channel maintains velocities and depths much larger than silvery minnow can withstand. Additionally, the main channel is typically coarser-grained than the areas where silvery minnows thrive. Secondary channels and backwaters can only be accessed via overbank flows, providing low-velocity habitat for silvery minnows and the productivity required for development and growth of larval and juvenile minnows. Therefore, connection with the floodplain and frequent inundation are crucial for Rio Grande silvery minnow success. Although this report did not include analysis of the floodplain, it is recommended that the floodplain is included in future research.

While its population has rebounded from the historic low in September 2003, shown in Figure 7, and since stabilized, the Rio Grande silvery minnow is still in a far more tenuous position than its historical presence. Recovery efforts have begun to see positive results in the face of fragmentation and habitat degradation but the push to ensure the success of this native Rio Grande species is not over. The aim of these habitat suitability criteria is to identify and focus on the areas of habitat that could aid in cultivating the remaining population. This analysis could be refined and built upon to make this possible.

5.1. **Future Research**

The criteria set forth in this paper, while robust in their ability to measure habitat suitability, could be applied differently to produce more specific and even more meaningful results. Before another analysis is done, up to date discharge, grain size, and cross sectional data would need to be obtained for the desired study area so that the criteria judge the current reach. Cross-sectional data should reflect the entirety of the active channel, not just the channel bounded by bankfull. An ideal application would include analysis of the floodplain, given that the best habitat for Rio Grande silvery minnow resides here. This would best highlight the mesohabitats silvery minnows prefer and yield a much higher percentage of excellent habitat. It would also provide a far more advanced analysis if the model used to simulate flow in the channel produced velocity and depth data at intervals along each cross section so that the criteria can evaluate the channel at each point. This would produce a two-dimensional map that could pinpoint entire areas of satisfactory habitat rather than a figure that shows suitability for an average cross section.

Additionally, the criteria defined in this report could help to illuminate the problems created by low flows. By modeling flow regimes of both dry and wet years, one could estimate the percentage of suitable Rio Grande silvery minnow decay during unseasonably dry years. This would be useful when preparing and planning recovery efforts for such events, identifying areas crucial for continued success.

In addition to changing the method of application of criteria, the criteria themselves could be expanded to produce specific results. For example, the criteria could be altered to describe the habitat suitability based on season. Given that the primary shift in Rio Grande silvery minnow mesohabitats throughout the winter is toward greater depths and sometimes lower velocities provided by shelter of debris piles, the criteria could easily accommodate this change.

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