BUREAU OF RECLAMATION

Effects of Bosque del Apache South Boundary water pumping on aquatic habitat, fish movement and density

Middle Rio Grande Project, New Mexico
Upper Colorado Basin Region

U.S. Department of the Interior

November 2020

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Upper Colorado Basin Region

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Cover Photo: Aerial view of the Low-Flow Conveyance Channel running parallel to the Rio Grande hydrologically connected by the pumping channel at the South Boundary pump station (Reclamation)

Executive Summary

Streamflow intermittency is a major disturbance for aquatic organisms. Persistence of Rio Grande Silvery Minnow (RGSM) and other fishes may be at risk as intermittency increases in duration, frequency, and spatial extent in the Middle Rio Grande (MRG). Understanding how fishes use refuge habitat during streamflow intermittency can help inform resource managers implement effective conservation actions to mitigate effects from increasing streamflow intermittency. In the MRG, mechanical pumps are used to move water from the low-flow conveyance channel (LFCC) back to the river channel and have variable flow output, allowing for an experimental, controlled flow recession. Here, we intentionally ramp down flow rates from mechanical pumps to observe changes in habitat amount, habitat quality, fish assemblage, and refuge-use strategies including movement. Our primary objectives were:

1. Examine changes in habitat quantity and quality related to decreasing flow.

2. Examine species-specific refuge use through observation of changes in fish densities and movement of marked fishes.

3. Compare the spatial distribution of RGSM collected during fish rescue in 2018 and 2020 to evaluate differences related to rate of pumping recession.

4. Predict impacts to RGSM October catch-per-unit effort (CPUE) and occupancy surveys.

We performed fish and habitat surveys during June and July 2020 at 10 randomly selected locations between the pumping station at the South Boundary of Bosque del Apache National Wildlife Refuge (BdA) at river mile (RM) 74 and the confluence with the LFCC below RM55. Each site was surveyed five times: twice prior to decreasing pumping rate, and three times during weekly flow reductions. Mesohabitats, except for run habitat, changed little in available surface area during flow reductions until all pumping ceased. Run habitat was affected differentially and decreased in surface area with every flow reduction. We found very little change in the spatial distribution of fishes during decreased flows, suggesting movements to refuge patches were at the site scale and not the reach-scale (i.e., no evidence of a large-scale movement to escape drying). Despite flow recession being controlled over three weeks in 2020, the spatial distribution of RGSM collected during fish rescue mirrored that observed in 2018, when flow recession occurred over 4 days. This suggests RGSM are not making large-scale movements to refuge patches. Therefore, under dry conditions and with the absence of pumping, standard fish population monitoring sites will remain dry, which will have implications for October surveys. For these conditions, our analyses show range wide changes in CPUE would be minimal; however, site occupancy would be reduced by as much as 30% under worst case conditions, indicating effects on species distribution. Reductions in local densities may have implications for October CPUE as fewer fish are available to recolonize dried areas once flows return. Ultimately, the absence of pumping eliminates the offset used to mitigate drying for ~21 miles of RGSM habitat below the Bosque del Apache South Boundary pumping station where river intermittency is experienced during very low water years. There are fewer fish below the South Boundary of BdA compared to areas upstream, but the absence of additional wetted refuge during

summer months is likely to decrease the number of minnows available to recolonize when flows return.

Alternative measures to support species distribution in this area should be explored, including potentially increasing flows upstream in higher quality, cooler habitats to enhance recolonization potential and providing flows that maintain connectivity among habitat to support survivorship during irrigation season.

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Acronyms

°C	degrees Celsius
AF	acre-feet
BACI	before-after-control-impact
BdA	Bosque del Apache National Wildlife Refuge
BO	2016 Biological Opinion
cfs	cubic feet per second
COVID-19	Coronavirus disease 2019
CPUE	catch-per-unit effort
DOI	U.S. Department of Interior
GRTS	Generalized Random-Tessellation Stratified
hrs	hours
IA	interagency agreement
LC50	lethal concentration limit 50%
LFCC	Low-Flow Conveyance Channel
km	kilometer
m	meter
m s-1, m/s	meter per second
m^2	square meter
MRG	Middle Rio Grande
MRGCD	Middle Rio Grande Conservancy District
R^2	proportion of variance
Reclamation	Bureau of Reclamation
RGSM	Rio Grande Silvery Minnow
RM	river mile
SADD	San Acacia Diversion Dam
Service	U.S. Fish and Wildlife Service
SL	standard length
spsurvey	Spatial Survey Design and Analysis
USGS	U.S. Geological Survey
VIE	visible implant elastomeric
YOY	young-of-year

1.0 Introduction

1.1 Background on Low-Flow Conveyance Channel pumping

The LFCC is an unlined canal that was originally excavated to expedite delivery of Rio Grande Compact water to Elephant Butte Reservoir during low flow conditions (Cowley 2006). It begins at the San Acacia Diversion Dam (SADD), the upstream boundary of the San Acacia Reach, and parallels the river for ~75 miles before it converges again with the Rio Grande. From 1959 to 1985, water was diverted from the Rio Grande at SADD to the LFCC. The San Acacia Reach of the Middle Rio Grande is both hydrologically and geomorphically complicated. In some locations the LFCC is at a lower elevation than the riverbed, which results in more groundwater flow from the river to the LFCC, which accounts for a loss of surface flows in the river channel. Due to sedimentation problems at the LFCC's outfall into Elephant Butte Reservoir, water has not been intentionally diverted into the LFCC since 1985.

In 2000, a program to pump water from the LFCC back to the main channel of the Middle Rio Grande was initiated to manage river recession and support the Rio Grande Silvery Minnow (Hybognathus amarus) and the Southwestern Willow Flycatcher (Empidonax traillii extimus). Initially the pumping program had a total of three pump stations in the San Acacia Reach. These pump stations augmented flows throughout the reach. This program reduced the intermittency of the reach in 2000 and 2001. In 2002, pumping was expanded to five stations with the goal of maintaining approximately 20 continuous miles of river from the middle of BdA to Elephant Butte Reservoir, from about 3 miles upstream of US 380 (~RM90) to near Old Fort Craig (~RM 64). The pump stations at the southern boundary of BdA and Fort Craig created approximately 16 miles of flowing water. Approximately four miles north of the South Boundary Pump Station, the Mid-Bosque Pump Station was installed to provide an additional four miles of flowing water. However, this station was only operated twice (in 2002 and 2003).

With the U.S. Fish and Wildlife Service (Service) issuance of the 2003 Biological Opinion to Reclamation, Army Corps of Engineers and non-Federal Partners on the Middle Rio Grande provided strict guidance on maintaining in-channel surface flows, and pumping became mandatory from 2003 through 2016. In December 2016, the Service issued a new Biological Opinion with more flexible water management guidelines based on adaptive management. To date, individuals hired to monitor river drying under the River Eyes contract begin conducting daily reconnaissance when flows at the Bosque Farms gage (USGS gage 08331160) reach 80 cubic feet per second (cfs) or the San Acacia gage (USGS gage 08354900) drops to 300 cfs. Pumping was typically initiated when contractors physically observed the interruption of surface flows or if the San Marcial gage (USGS gage 08358400) reaches 50 cfs. Weather conditions were also evaluated, and the pumps at South Boundary were activated (Carolyn Donnelly and Dustin Armstrong, Reclamation, personal communication).

From 2000 to 2019, pumping at varied capacity occurred at the Neil Cupp Hub (RM 90), North Boundary Pump Station (RM 84), Mid-Bosque (RM 78), South Boundary Pump Station (RM 74), or the Fort Craig Pump Station (RM 64). However, precise records of how much water was pumped from which location were not always available. Table 1 provides the available pumping records and Figure 1 depicts the total volume of water pumped between 2000 and 2019, including records of the maximum river miles that dried in the San Acacia Reach each year.

In 2018, much of the lower MRG dried during extremely dry conditions. By July 3, 2018, not enough water was available in the LFCC to continue pumping. Pumps at the South Boundary were turned off, ceasing all pumping. Two days later, several miles of river south of the railroad bridge dried (Figure 2). Between 7 – 10 July, the drying expanded to areas between the railroad bridge and South Boundary as well as above the confluence with the LFCC (Figure 2).

Table 1 - Annual pumping records from 2000 to 2019 for the Middle Rio Grande pumping stations in the San Acacia Reach, New Mexico. Pumped water volume measured in acre-feet (AF).

Year	Neil Cup (AF)	North Boundary (AF)	Middle Bosque (AF)	South Boundary (AF)	Ft. Craig (AF)	Total Volume Pumped (AF)
2000						9,024*
2001	6,000	4,000		10,000	5,000	25,000
2002	7,260	3,850	30	17,210	4,120	32,470
2003	3,192	2,695	358	13,581	1,104	20,930
2004	1,961	460		10,627	122	13,170
2005	2,940	495		373	953	4,761
2006	5,431	1,900		9,413	40	16,784
2007						6,439
2008				30		30
2009	950	802		6,323		8,075
2010	129	78		6,749		6,956
2011						14,477
2012	439	1,384		10,455		12,278
2013		4,425		10,501		14,926
2014		3,476		9,465		12,941
2015		2,887		2,903		5,790
2016		1,363		5,836		7,199
2017				4,478		4,478
2018				19,989		19,989
2019				1,817		1,817
			TOTAL AF PUMPED 2000-2019			**228,510**
Source: Supplemental Water Program Reports 2000 - 2019						
* Estimated based on description (target of 50 cfs for 91 days)						

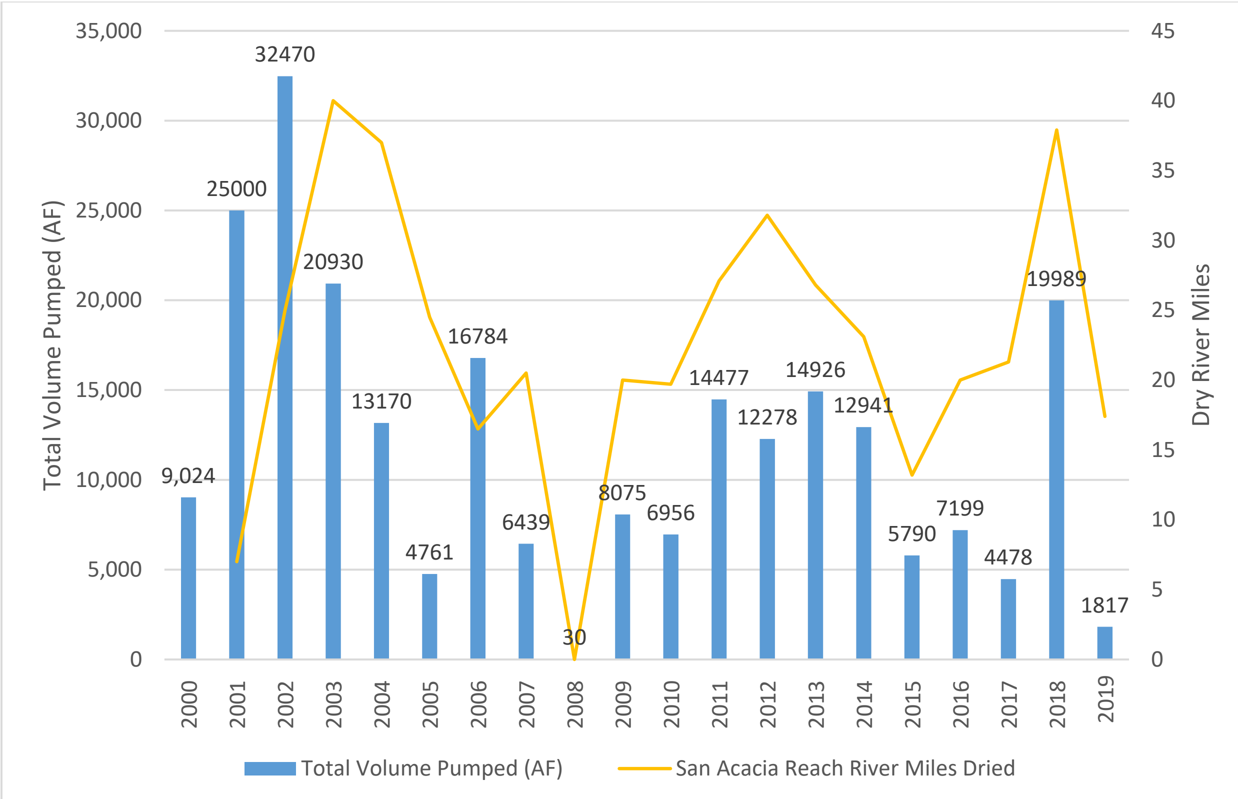

Figure 1 - Total volume of water pumped (AF) from the Low-Flow Conveyance Channel to the Middle Rio Grande, New Mexico, between 2000 and 2019 displayed with records of maximum river miles that dried in the San Acacia Reach during each year.

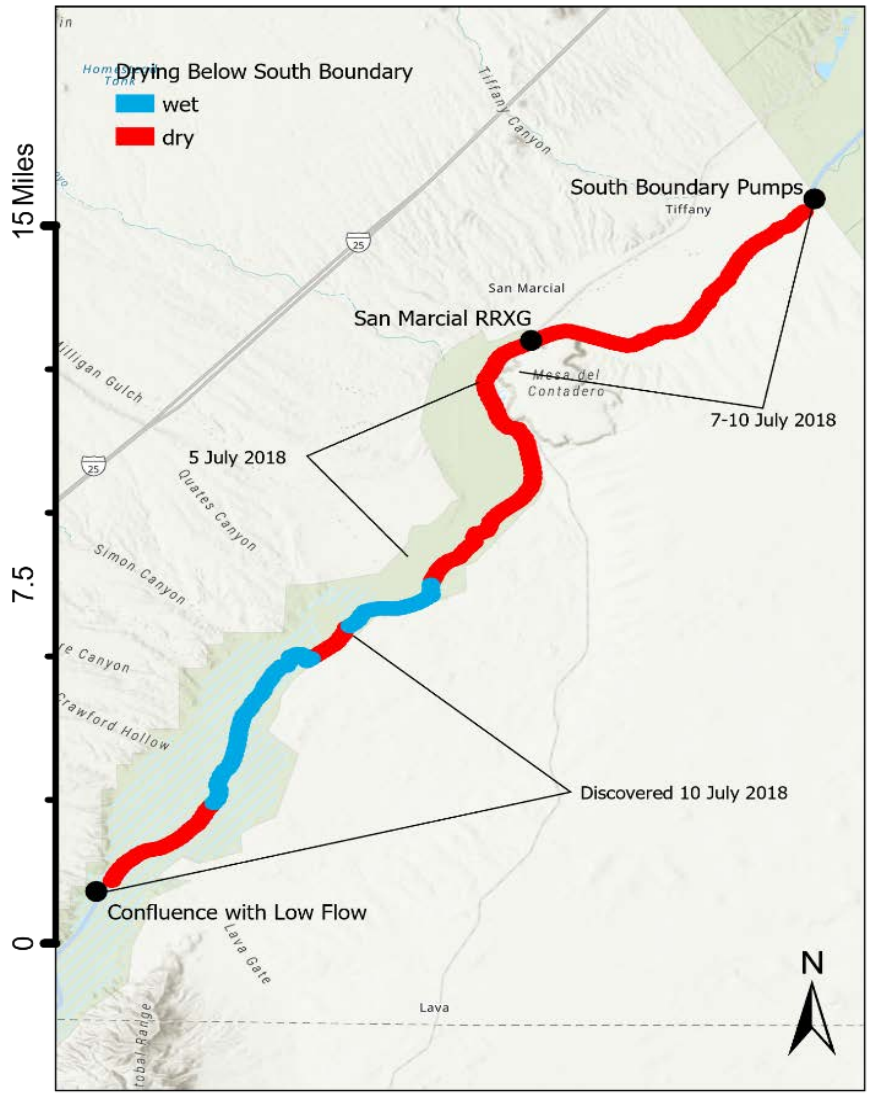

Figure 2 - Map of 2018 drying in the Middle Rio Grande, New Mexico as a result of ceased pumping from the South Boundary Pump Station.

1.2 Current River Conditions in the San Acacia Reach

As discussed, pumping in the lower portion of the MRG has occurred in some capacity over the past 20 years. However, recent adjustments to river alignment, pumping infrastructure, and the costs associated with operating the pump station at the South Boundary have exposed the need to evaluate the effectiveness of pumping. This study will inform a cost-benefit analysis related to pumping given new river conditions while Reclamation and its Partners examine management options in the San Acacia Reach as part of commitments made in the 2016 Biological Opinion (BO). The first major adjustment in upstream conditions began in 2019 with the construction of the Bosque del Apache River Realignment Pilot Study. This effort moved the river channel to the east within the current floodway between RM 82 and RM 79, north of where a sediment plug continually formed causing water conveyance issues, as well as threatening the structural integrity of the levee. The pilot realignment moved the river channel to a lower elevation with room to form its own channel. The effect of this effort on downstream flows is being monitored and will likely change over time as the river carves a new path. However, it is expected to improve downstream surface flows beyond the previous experience with a sediment plug that continually developed within the former river channel.

Another adjustment to upstream conditions occurred in 2019 when the Middle Rio Grande Conservancy District (MRGCD) upgraded the Neil Cupp pump station. The pump station now has the capacity to divert water to both the Socorro Main canal with the purpose of delivering irrigation water to MRGCD farmers or sending water to the river at RM 90 (Figure 3). In 2020, the Socorro Main Hub began operating, and while operating procedures are still being established, the capability of MRGCD to supplement river flows at RM 90 now exists. Additionally, a management decision was made to decommission the pumps at North Boundary, assuming the Neil Cupp Hub operations could cover anticipated streamflow losses. In 2019, Reclamation determined that the South Boundary Pump Station (Figure 3), which resides on private land south of the refuge, would be removed in 2020. In 2020, Reclamation and Service staff proposed to evaluate the effects of the pumping program to downstream aquatic habitats. The effort to quantify the effects of pumping under new river conditions will assist with water management decisions in the San Acacia Reach. Primarily it will help determine if a new pump station location must be sited, whether significant costs for pumping should be prioritized over other habitat and conservation measures, and whether an alternative to pumping can be identified.

Evaluating the effects of pumping on RGSM and other fish habitat and densities will help inform any cost-benefit analyses and support management decisions. Fish sampling has been conducted in the reach downstream of BdA since at least 1993. RGSM have been commonly collected throughout this reach with catches as high as 300 fish per site. Generally, the abundance in this reach follows the overall species abundance and distribution pattern throughout the MRG. Because pumping has provided additional water to the river downstream of BdA during dry conditions over the past 20 years, this section of the Rio Grande has infrequently dried and may provide a source of colonizers for upstream reaches as water returns to the river channel. However, based on analyses of fish rescue data and RGSM use of available refuges/pools during drying, there does not appear to be directed RGSM movement within the San Acacia Reach in advance of drying (Archdeacon and Reale 2020). Additionally, recent tag-recapture fish movement studies (Ben Stout, Utah State University, May 2020 presentation at Reclamation's Albuquerque Area Office) indicate substantial potential for recolonization as tagged RGSM showed movement preferentially downstream. This suggests that focusing surface flows to support higher quality habitat in upstream areas of the San Acacia Reach may benefit RGSM more than providing surface flows below BdA during times of river intermittency.

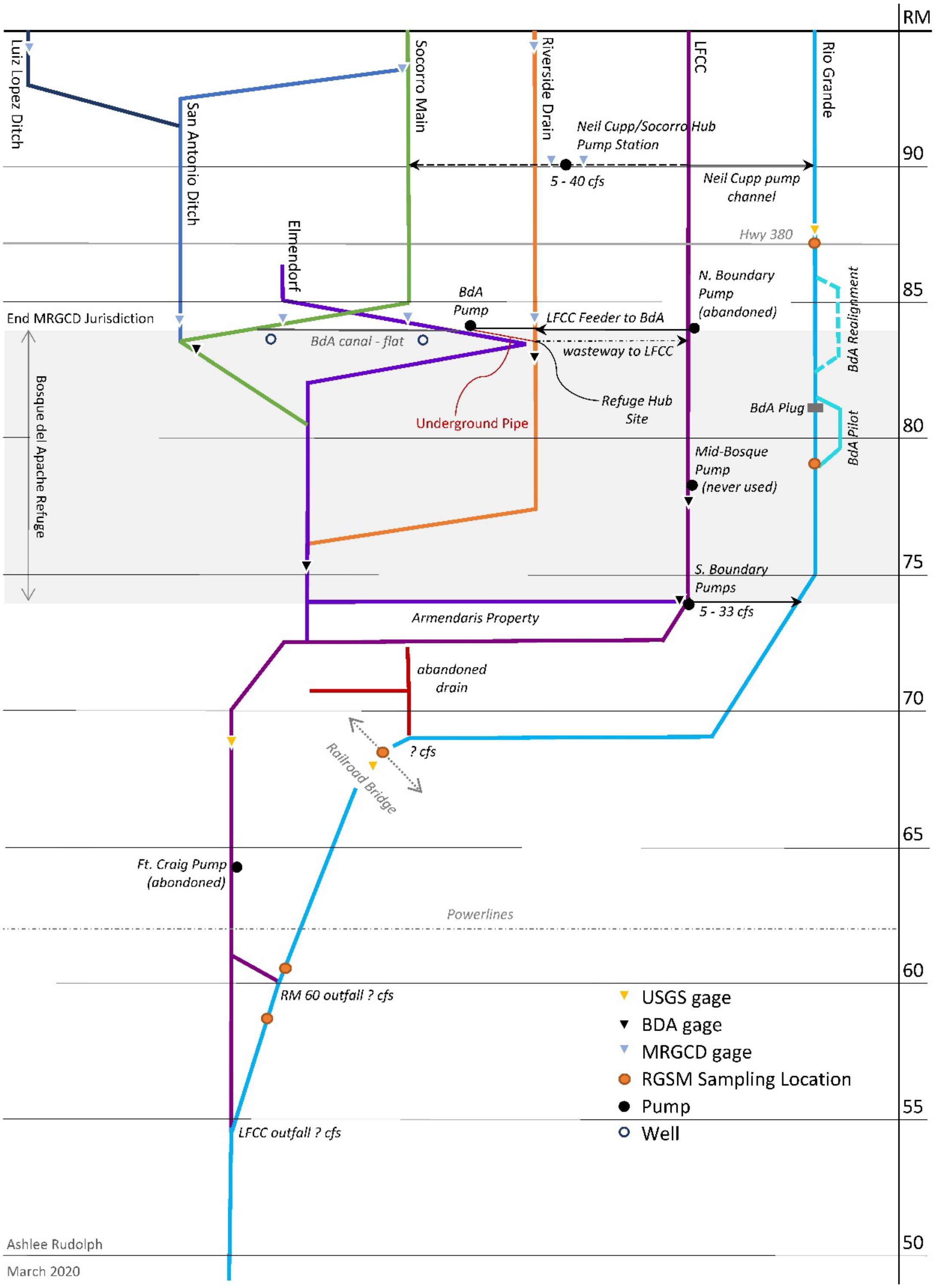

Figure 3 - Schematic drawing of the MRG and canal system between River Miles 95 and 50 with the locations of the pump stations, gages and RGSM sampling sites.

1.3 Objectives

Understanding how fish respond to drought is critical for their long-term persistence in the face of climate change (Lennox et al. 2019). It was anticipated that pumping water to maintain flow in the reach downstream of BdA would cease after 2020. This study sought to understand some of the consequences of river drying to fish and aquatic habitat in this section of the river system affected by pumping. This will provide information that allows for adaptive management strategies to be developed and implemented to improve outcomes for the MRG fish community, the RGSM, and improve Reclamation's ability to meet October RGSM density as described by the 2016 BO. Thus, our objectives included: (a) examining how reductions and the cessation of pumping at South Boundary changes the overall extent of drying and impacts the quantity and quality of fish habitat; (b) examining species-specific refuge use through observed changes in fish densities and movement of marked fishes; (c) comparing the distribution of RGSM collected during fish rescue in 2018 and 2020 to evaluate differences related to the rate of pumping recession; and, (d) to predict impacts to RGSM October CPUE and occupancy surveys. Given the potential effects on RGSM and habitat, we performed repeat fish and habitat surveys at randomly selected sites in the affected area to quantify changes in flow, temperature, amounts of mesohabitat, and temporal and spatial changes in the fish assemblage.

2.0 Methods

Monitoring at 10 sites occurred weekly from 15 June – 16 July, 2020. Monitoring included fish sampling, flow (discharge) measurements, and mesohabitat characterization at each site. Water temperature was also monitored at six of the ten sampling sites, at the pump channel and river confluence, and at two locations within the LFCC (Figures 4 & 5). We completed baseline surveys twice (15 – 17 June and 22 – 24 June) to capture spatial and temporal variability prior to reducing the pumping rate by one pump each week, in a before-after design. While not as powerful as a before-after-control-impact (BACI) design (Smith et al. 1992; Smokorowski and Randall 2017), it was not feasible to sample control sites given the short time frame and distance to an upstream control. Thus, two before-impact surveys were completed as temporal controls in the absence of spatial controls. Because multiple surveys were performed prior to pumped flow reductions, and occurred concurrently with pumped flow reductions, the design is robust for determining the effects of the disturbance (Rytwinski et al. 2019). Each week we performed fish rescue as necessary, then repeated fish and habitat surveys at each site. During the 15 – 17 June surveys, fishes >30 mm standard length (SL) were marked with visible implant elastomer (VIE) tags to allow us to track fish recaptures and movement between sites.

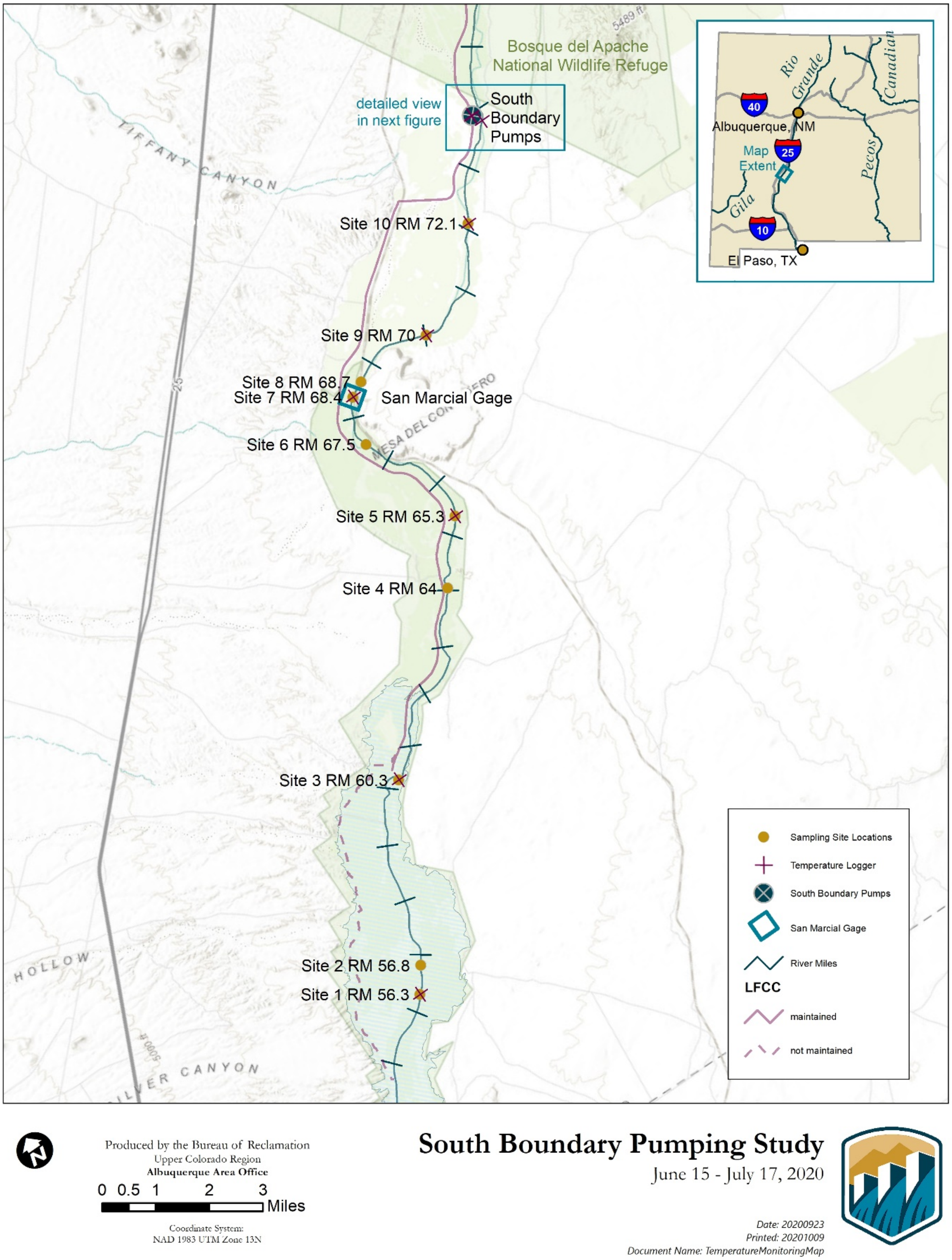

Figure 4 - Study map showing location of the South Boundary Pumps, sampling locations, and the San Marcial gage in the Middle Rio Grande, New Mexico.

Figure 5 - Detailed view of temperature loggers in the Low-Flow Conveyance Channel and at the confluence of the pumping channel and mainstem of the Rio Grande.

2.1 Study Area and Site Selection

The study area resides in the sub-reach of the Rio Grande between the South Boundary Pumps upstream and the confluence of the LFCC and MRG downstream (Figure 4), encompassing approximately 21 miles. We used a Generalized Random-Tessellation Stratified (GRTS) sampling scheme to select 10 sampling sites between the South Boundary Pumps and the LFCC confluence (Figure 4). GRTS sampling is a spatially balanced probability sampling design that allows inferences of the entire sampling area (Stevens and Olsen 2004) and was used to ensure that selected sites are longitudinally spaced throughout the survey reach. Site selection was performed with package *spsurvey* (Kincaid et al. 2019) in program R. A 200-meter sampling reach downstream of each randomly selected location was established for each site (Archdeacon et al. 2015).

2.2 Habitat Monitoring

We estimated mesohabitat depths, velocities, and surface area at each site during each level of water pumping, thus collecting four estimates per site for each of the 10 sites. Each 200-meter reach was divided into 10 transects (i.e., a cross-section) crossing the channel perpendicular to flow at 20 meters apart. Each transect was marked and subsequent surveys were conducted at these same transects. Discharge was estimated using a flow meter at the furthermost upstream transect using standard methods and calculations (Fisher et al. 2012).

The wetted width of each transect was measured (0.01 m) and divided into 11 evenly spaced points across the transect, where measurement 1 and 11 were located on the edges of the wetted width. At each point, we recorded the water depth (0.01 m), water velocity (0.1 m s-1) at 60% depth, the substrate (clay/fines, sand, fine gravel, coarse gravel, cobble, other), and categorical mesohabitat (Table 2). At depths <0.05m, water velocity was not and could not be reliably measured. In total, 10 wetted widths, and 110 systematically placed point measurements of depth, velocity, substrate, and mesohabitat were collected at each site for each level of pumping.

To estimate total site surface area and surface area of each mesohabitat, we calculated the average wetted width of each transect for each site and survey. We multiplied the average wetted width by 200m to obtain a total surface area for each site and survey. Next, we multiplied the total surface area by the percentage of individual point measurements that fell in aquatic habitats (total surface area), and each of the individual mesohabitats, thus obtaining mesohabitat-specific surface area for each site and survey. That is, for an average wetted width of 20 m and 95% of points in aquatic habitats, the total surface area would be 3,800 m^2 ($20m \times 200m \times 0.95 = 3800\ m^2$).

Water temperature was recorded at seven sites beginning with the pumping channel confluence with the river, Site 10, Site 9, Site 7, Site 5, Site 3, and Site 1, as well as at two locations within the LFCC (Figures 4 and 5). Temperature was logged every 30 minutes using Onset ® HOBO ® temperature loggers. Loggers were attached to a u-post with stainless steel wire and suspended just above the substrate within deep areas that were anticipated to maintain water throughout the study, usually the deepest pool within the 200-meter reach. There were not enough temperature loggers to place one per site. Therefore, sites were selected to provide longitudinal coverage over the entire study area.

Water temperature data were summarized starting from the next day (00:00 hrs) after the HOBO was placed in the river and up until the day prior (23:30 hrs) to the HOBO being retrieved at the conclusion of the study (Table 3). Plots of 30-minute observations and average daily temperatures (calculated from 00:00 hrs to 23:00 hrs) were produced to compare readings from the LFCC to the survey sites. The difference between maximum and minimum water temperature was calculated daily to compare variability among sites. The difference between maximum and minimum water temperature was calculated through 11 July, or the day prior to the pumps being entirely turned off.

2.3 Temperature Impact Thresholds

Adult RGSM have a 96-hour lethal concentration limit 50% (LC50) of 31.4 °C (K. Buhl, USGS, personal communication). This was determined through the incipient lethal method (Beitinger et al. 2000) and represents the temperature at which 50% of the fish die. The daily time series of temperature data was analyzed to determine what portion of the readings exceeded this threshold. Temperatures from the day after the temperature loggers were placed into the river (00:00 hrs) through the last reading on 11 July were examined to determine what proportion of the readings exceeded 31.4 °C.

Table 2 - Mesohabitat descriptions used during fish and habitat monitoring in the Rio Grande downstream of BdA, New Mexico.

Type	Description
Isolated Pool	A pool of water with no surface flows, isolated from the rest of the channel.
Backwater	A body of water with low to zero velocity, surrounded by land on three sides, but connected to the main channel on one side and typically oriented perpendicular or counter to mainstem flow direction.
Pool	A low velocity habitat relative to flows in the rest of the channel.
Riffle	A shallow and high velocity habitat where the water surface is irregular and broken by waves.
Run	An area of faster water velocity relative to the rest of the channel with laminar flow.
Shoreline	A mesohabitat sampled adjacent to shore (e.g., shoreline run or shoreline pool).

Table 3 - Date range, number of 30-minute observations, and number of days for temperature data summarization at each site during the fish and habitat study below the BdA, New Mexico.

Site	Date Range	Number of 30 min Observations	Number of Days
Low Flow A	6/25 - 7/15	1009	22
Low Flow B	6/25 - 7/15	1009	22
Pumping Channel/River Confluence	6/18 - 7/15	1345	29
Site 10	6/25 - 7/15	1009	22
Site 9	6/18 - 7/15	1345	29
Site 7	6/18 - 7/15	1345	29
Site 5	6/17 - 7/15	1393	30
Site 3	6/16 - 7/15	1441	31
Site 1	6/16 - 7/15	1441	31

2.4 Fish Monitoring

Fish were collected from each site by conducting 15-20 seine hauls per site using standard procedures for sampling fish from wadable waters (Rabeni et al. 2009; Archdeacon et al. 2020). All fish were counted, standard length of RGSM was recorded (+/-1 mm), and fish were returned to the site of capture. When surface flows ceased at a site, all isolated pools (if any) were sampled using the same methods. All fish were checked for VIE tags.

The length of each seine haul was recorded and multiplied by the width of the seine haul (typically 2.5 m). We used this as an estimate of the area sampled for each seine haul. We summed area sampled for all seine hauls within a site and survey. For display purposes, we present CPUE in units of fish/site, which we calculated as the observed catch divided by the proportion of site sampled.

We calculated site- and survey-specific assemblage metrics including total fish numbers (sum of all fish collected during a sample). We also computed species-specific CPUE for the six most common fish species found in this reach: Red Shiner (Cyprinella lutrensis), Western Mosquitofish (Gambusia affinis), Common Carp (Cyprinus carpio), Channel Catfish (Ictalurus punctatus), River Carpsucker (Carpiodes carpio), and RGSM.

2.5 Fish Movement

During the baseline fish sampling in 15 – 17 June surveys, we used VIE tags to mark the six species of small-bodied fishes (e.g., 30 to 180 mm SL). We used unique colors and body locations for each site (Table 4). During subsequent fish assemblage surveys, we checked all fish for recaptures. Similarly, we examined all fishes for VIE tags during fish rescue. When a tagged fish was captured, the location was recorded (nearest 0.2 km). We used the recapture location data to determine movement from the tagging location.

Table 4 - Site, tag color by body location, and number of each species tagged during fish monitoring in the Rio Grande, New Mexico, 15 – 17 June, 2020.

Site	Tag	Species	Number
1	Orange Left Dorsal	*Red Shiner*	94
		Common Carp	4
2	Orange Right Dorsal	*Red Shiner*	163
		Common Carp	21
		Channel Catfish	6
3	Orange Right & Left Dorsal	*Red Shiner*	103
		Gizzard Shad	2
		Channel Catfish	2
		Common Carp	1
		Flathead Chub	1
4	Green Right Dorsal	*Red Shiner*	136
		Channel Catfish	1
5	Green Left Dorsal	*Red Shiner*	78
		Western Mosquitofish	6
		Channel Catfish	6
		Common Carp	3
		River Carpsucker	2
		Rio Grande Silvery Minnow	1
6	Green Right & Left Dorsal	*Red Shiner*	178
		Common Carp	2
		Rio Grande Silvery Minnow	2
		Channel Catfish	1
		Western Mosquitofish	1
7	Yellow Right Dorsal	*Red Shiner*	131
		Western Mosquitofish	7
		River Carpsucker	4
		Fathead Minnow	2
		Common Carp	1
8	Yellow Left Dorsal	*Red Shiner*	92
		Common Carp	1
		White Bass	1
9	Yellow Right & Left Dorsal	*Red Shiner*	91
		Common Carp	3
		River Carpsucker	3
		Western Mosquitofish	2
		Channel Catfish	2
10	Green Right & Yellow Left Dorsal	*Red Shiner*	132
		Flathead Chub	1
		Common Carp	1

2.6 Fish Rescue

Additional observations were made during fish rescue efforts that were conducted into August 2020. Fish rescue followed standardized protocols (Archdeacon 2016; Archdeacon and Reale 2020). When new drying occurred, we used off-road utility vehicles to access these areas. Once we arrived at areas reduced to isolated pools, we used seines to collect RGSM. As each isolated pool was located, we recorded the river mile (nearest 0.1), measured maximum pool depth, and recorded time of day. Next, we seined the pool and counted all RGSM captured. We used size to categorize RGSM as young-of-year (YOY) or adults, since adults are generally >55 mm SL during summer (Horwitz et al. 2018). All fish, including RGSM were examined for a VIE tag. We categorized all RGSM as alive or dead. All live RGSM were transported and released below the SADD.

We compared the spatial distribution of RGSM (e.g., number of fish per pool) in this sub-reach to the entire San Acacia Reach affected by drying, both in 2020 and 2018. We plotted catch of RGSM per pool by river mile. Due to the COVID-19 in 2020, fish rescue was not performed between South Boundary and Socorro, NM, in May and early June. However, rescue was performed in this reach after re-wetting and subsequent drying occurred in August. Typically, there are fewer adults present after each wet and dry cycle (Archdeacon 2016). Thus, the comparison to both 2018 and the reach below the South Boundary pumps is conservative. There were likely more RGSM present upstream of the South Boundary pumps during the first drying event in 2020 than were observed during drying in August of 2020.

2.7 Analyses

Data were analyzed to determine longitudinal changes in fish numbers, temperature, mesohabitat, and the amount of new drying that occurred with each reduction in pumped flow. We examined spatial and temporal changes in the fish assemblage (e.g., total CPUE) and CPUE of the six most common species. We also examined fish movement before, during, and after drying through fish surveys and fish rescue data. By comparing to long-term demographic RGSM data (for example, see Dudley et al. 2017), we quantified the effects of channel drying in the San Acacia Reach on the October CPUE. Finally, we compared the spatial distribution of RGSM collected during fish rescue in 2018 and 2020 to the rest of the San Acacia Reach.

We used a general linear model to compare 2018 and 2020 fish rescue data. Specifically, we used the total counts of RGSM per pool and related that to river mile, year (as a factor), and the interaction of river mile and year to predict average counts of RGSM. This approach allowed us to explicitly compare 2018 to 2020 and examine any trends in RGSM counts per pool by river mile. Because the RGSM data is count data, we assumed a negative binomial error distribution with a log link (O'Hara and Kotze, 2010).

To determine how RGSM CPUE in this sub-reach affects the range wide RGSM CPUE, we calculated October CPUE for all standard population monitoring sites in the San Acacia Reach from 1993 to 2019. We then compared it to October CPUE calculated for all sites with the sites in the reach downstream of BdA being zero. The worst-case scenario assumption being that these sites would no longer support fish if pumping at the South Boundary of BdA ceased, complete drying occurred without refuge, and flows did not return in time for October surveys. We calculated

CPUE assuming a negative binomial error distribution and used the area seined per site as an offset. We multiplied the estimates by 100 to obtain a more familiar estimate of CPUE, as fish/100 m^2.

3.0 Results

In general, each reduction in pumping reduced the amount of wetted habitat and habitat quality. Habitats became shallower, slower, and warmer with each reduction in pumping. We collected 32,973 fishes during the 50 sampling events. We observed 15 species of fishes during the surveys, though total catch was dominated by Red Shiner.

3.1 Discharge and Temperature Relationship

Discharge decreased at sites with the reduction in pumped flow (Figure 6). In general, discharge also decreased from upstream to downstream sites as distance increased from the pumps. Sites 2 and 3 had minimal flow (1.0 and 0.40 cfs) when no pumps were running. No other sites maintained flow once the pumping ceased.

Maximum daily water temperature in the main channel (max = 49.3 °C) was considerably higher than water in the LFCC (max = 28.6 °C) and the pumping channel (max = 33 °C; Figure 7). Average daily water temperature was only slightly warmer in the river channel compared to the LFCC; however, diurnal variability in the main channel was much greater than in the LFCC. The difference between maximum and minimum temperature was greater in main channel sites than the LFCC and the pumping channel (Figure 8). On average, water in the main channel had a diel change that ranged from 11.7 °C at Site 3 to 15.5 °C at Site 5, while water pumped from the LFCC had a diel change of 4 °C. Site 3, which maintained flow throughout the study had the lowest diel change in temperature among main channel sites. The LC50 temperature threshold of 31.4°C was never exceeded in the LFCC and less than 1% of observations within the pumping channel exceeded this value (Figure 9). Temperatures of the main channel sites exceeded this value 8.6 to 17.7 % of the time. Site 1 (8.6%) and Site 3 (9.3%) had the lowest number of observations that exceeded the threshold value and were the only two sites that maintained flow with no pumps running.

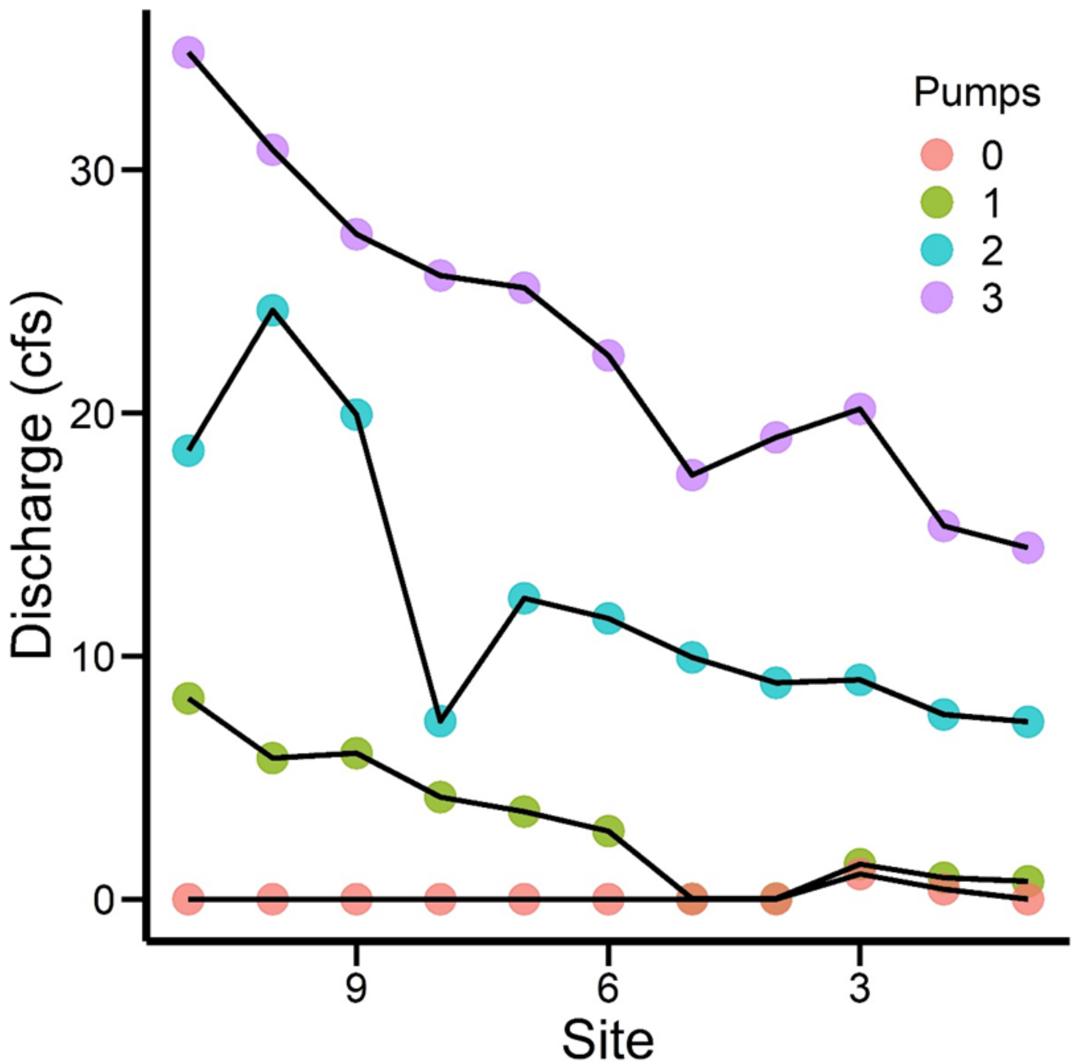

Figure 6- Discharge calculated at each site throughout the study period. Data was collected from June 22-24, 2020 while three pumps ran, June 29-July 1, 2020 while two pumps ran, and July 7-10, 2020 while one pump ran. When all pumping ceased (0 pumps) data was collected on July 16.

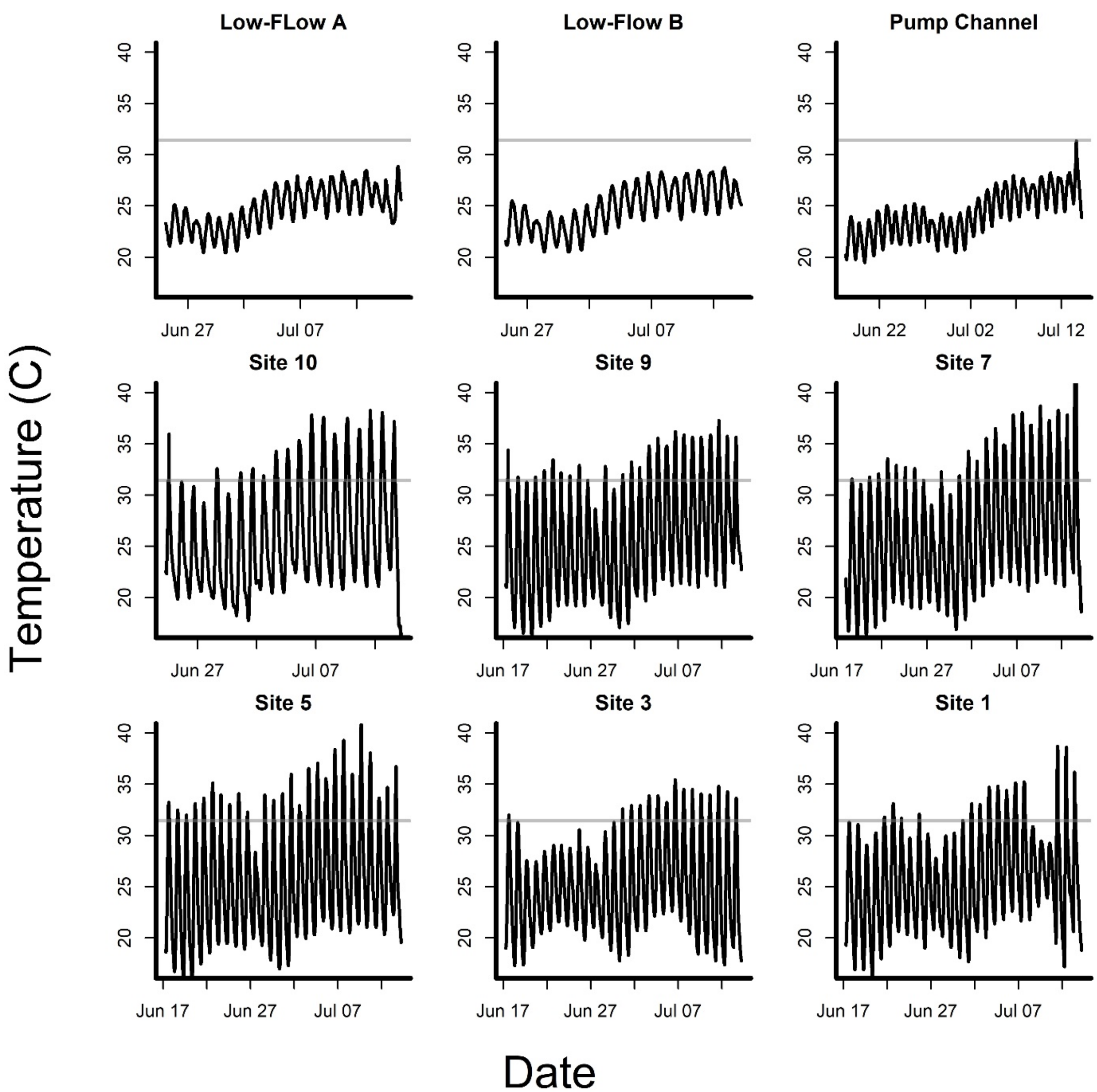

Figure 6 - Water temperature (30-min interval) during 2020 water pumping reductions in the Middle Rio Grande downstream of BdA, New Mexico. The horizontal line is at 31.4 °C, the static temperature at which 50% of RGSM die within 96-hrs.

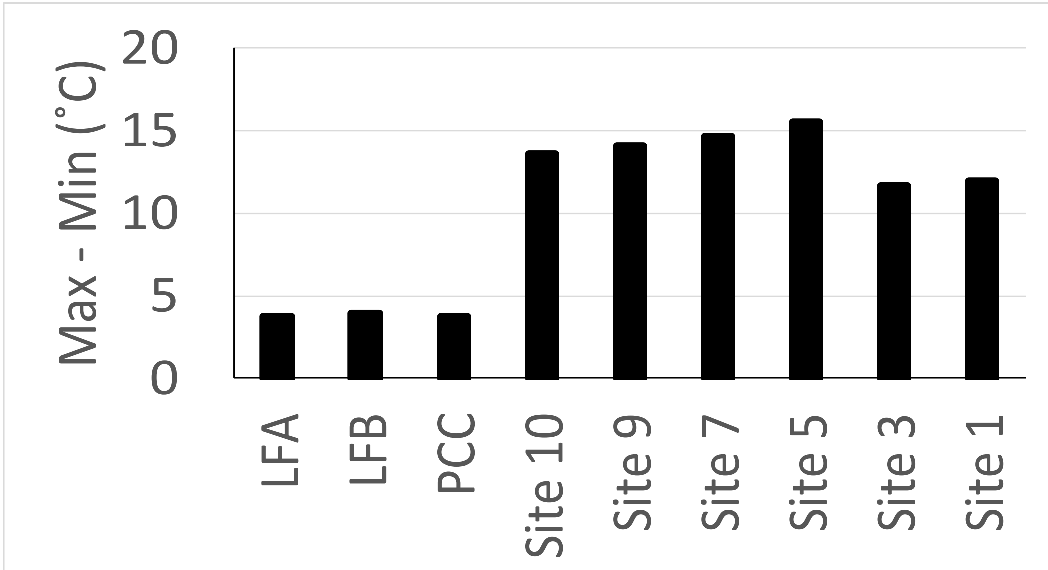

Figure 7 - Average difference between maximum and minimum daily temperature observations.

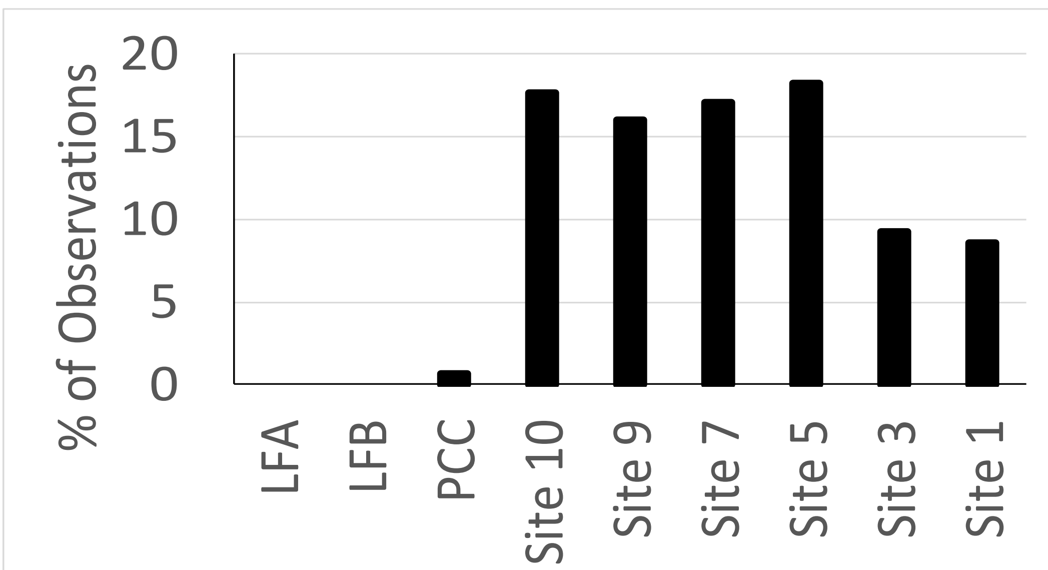

Figure 8 - Percent of temperature observations that exceeded LC50 of 31.4 °C.

3.2 Changes in Habitat

Overall, as pumping was reduced the total amount of available wetted habitat decreased. Most notably, the surface area for run habitat decreased steadily with each reduction in flow (Figure 10). Intermittency was imminent at Sites 4 and 5 with one pump running (<0.1 cfs; Figure 6) but did not occur until all pumps were off. Pool and backwater habitat initially increased after the first pumping reduction, but also decreased with reduction in flow (Figure 10). There was a decreasing trend in amounts of total wetted habitat and runs from upstream to downstream when one to three pumps were operating. However, when all pumps were off, this upstream to downstream trend was no longer present. Two sites had surface flows (Sites 2 and 3), four sites were reduced to isolated pools (Sites 4 and 6-8), and four sites dried completely (Sites 1, 5, 9, and 10)). The surface flow present at Sites 2 and 3 was likely the influence of groundwater seepage from adjacent wetlands.

Depths and velocities were also affected by reductions in pumping, particularly within run habitats (Figure 11). Pool depth and velocity remained relatively constant until the final pump was turned off, but run depth and velocity decreased with each pumping reduction (Figure 11). Site-level depth, velocity, and mesohabitat relationships are shown in Appendix A. Based on current data compiled on RGSM habitat velocities by life stage (see Mortensen et al. 2019, Fig. 8), with maximum target velocities for quality RGSM habitat of 0.4 m/s and 0.3 m/s and maximum depths of 0.6 m and 0.5 m for adults and juveniles, respectively, Figure 11 depicts data relative to those thresholds. At 1 pump and 0 pumps, none of the velocity thresholds were exceeded for either juveniles or adults. At higher pumping levels velocity thresholds were exceeded primarily in the run mesohabitats. Target depth maximum thresholds for habitat quality were exceeded in all pumping scenarios tested, primarily in pools.

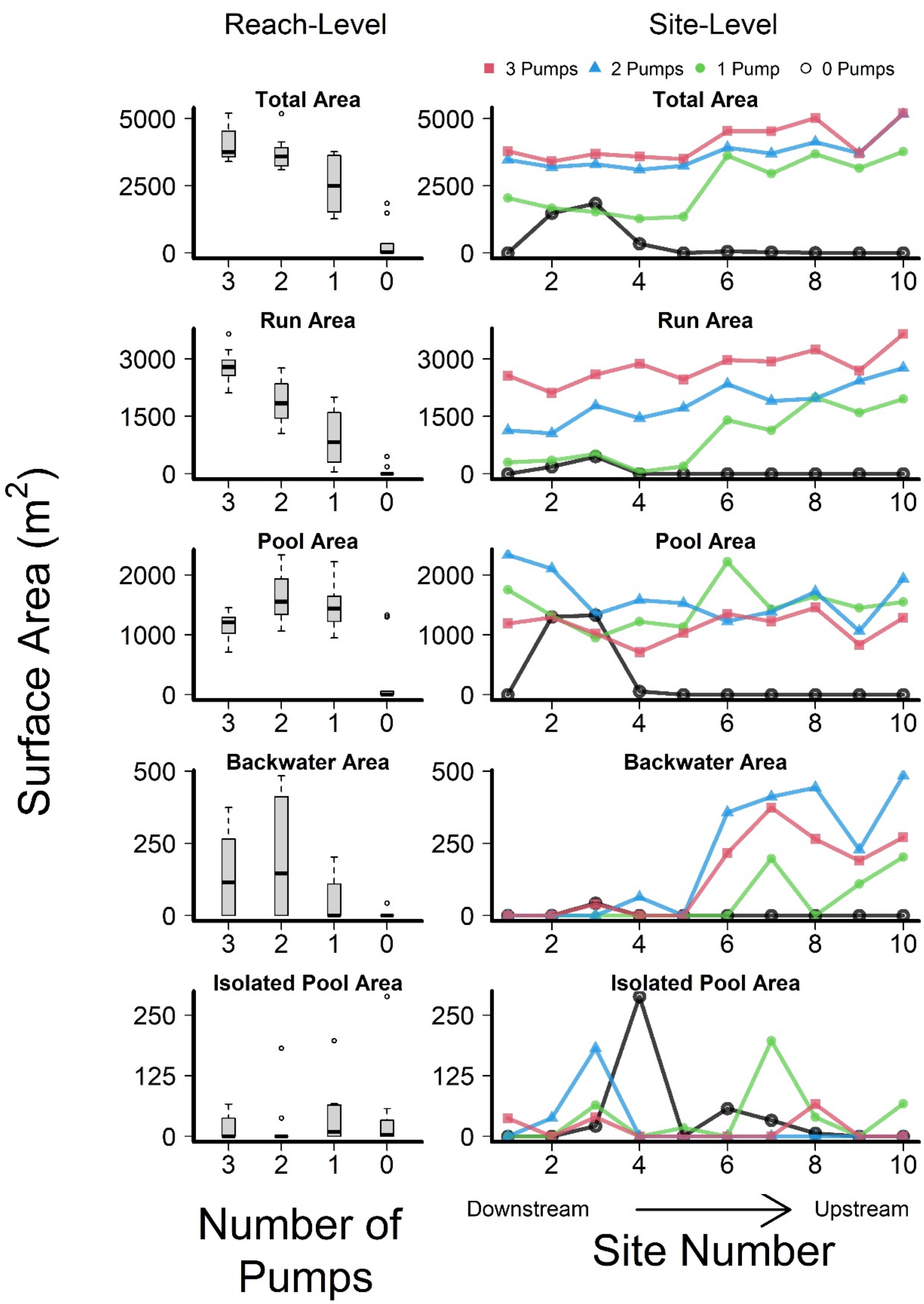

Figure 9 - Changes in amount of each mesohabitat type during pumping reduction and cessation of flows in the Middle Rio Grande, New Mexico, downstream of BdA.

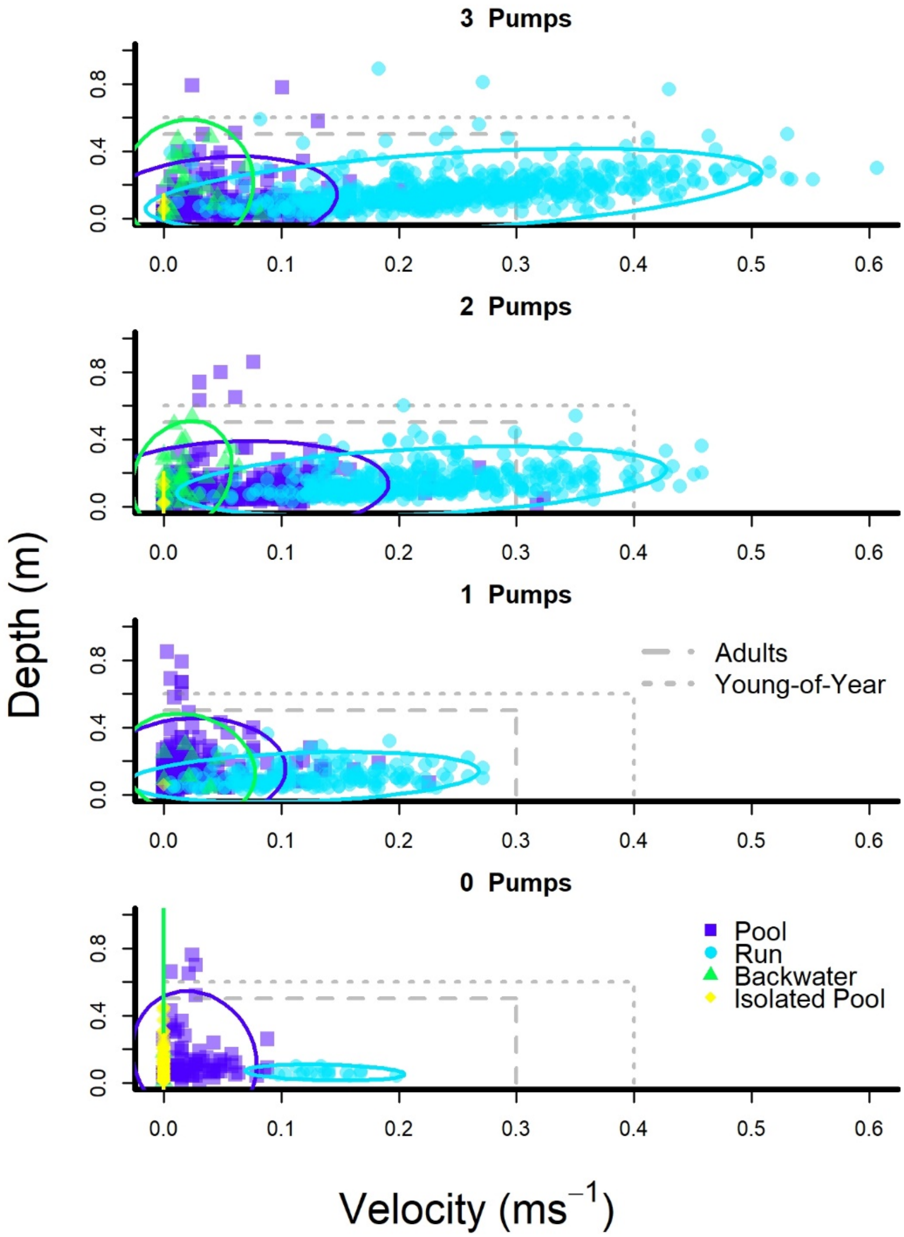

Figure 10 - Changes in depth and velocity of each mesohabitat type during pumping reduction and cessation of flows in the Middle Rio Grande, New Mexico, downstream of BdA. Dashed lines represent the maximum target velocities and depths of habitats for adults and YOY RGSM from Mortensen et al. 2019.

3.3 Spatial and Temporal Changes in Fish Assemblage

The two fish surveys prior to reduction in pumping were remarkably similar (Figure 12). Fish numbers increased at nearly all sites when pumping was reduced to two pumps, driven largely by increasing numbers of Red Shiner (Figure 12). When reduced to a single pump, total fish numbers exhibited a "U" shape with slightly more fish at Sites 1, 8 and 10, again largely driven by the number of Red Shiner. Total numbers of fish with all pumps off were similar to having all three pumps running. However, this was driven by increasing numbers of Red Shiners and Western Mosquitofish. Overall, with the exception of Red Shiners and Western Mosquitofish, fish generally had stable numbers when pumps were running, regardless of the number of pumps. With no pumps running, all fish numbers decreased compared to when pumps were running, except for Western Mosquitofish, which increased in number with every decrease in pumping (Figure 12).

RGSM were rare throughout; in total 39 RGSM were collected during the monitoring. However, 22 RGSM were collected at Site 3 with a single pump running, including 18 in a single seine haul. This was the single largest collection during the study. That is, 46% of all RGSM collected during the monitoring occurred in a single seine haul out of 799 total seine hauls. The increased numbers of RGSM at Site 3 were not observed in the final survey with no pumps running. Apart from the temporary increase at Site 3, there appeared to be little change in the temporal or spatial structure of RGSM (Figure 12).

Red Shiner was the most numerous species observed overall and during each site-specific survey, sometimes by orders of magnitude (Figure 12). Red Shiners initially increased in numbers when flows were reduced from three to two pumps. Numbers were similar with no pumps or three pumps, but this was driven by the very large numbers collected at Site 3 during the final survey (Figure 12). Common Carp had similar patterns, with a few outlier observations at Site 1 with one pump and Site 9 with two pumps (Figure 12). River Carpsucker again had similar patterns, but showed some spatial structuring, with more fish at upstream sites (Figure 12). Western Mosquitofish increased numbers with each pumping reduction, driven by increasing numbers at Site 3 during each survey (Figure 12).

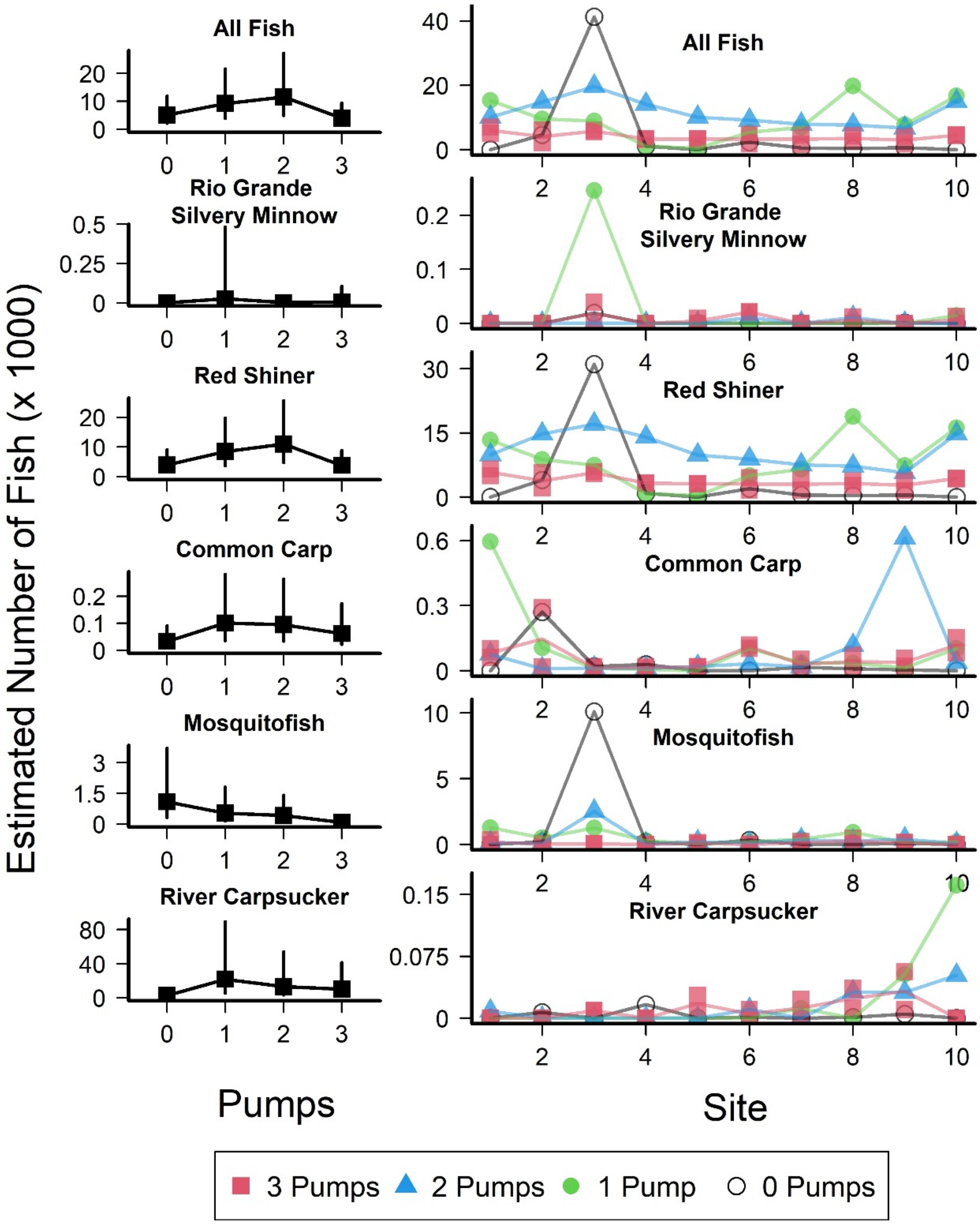

Figure 11 - Changes in total fish CPUE of fish at the reach-level and per site during pumping reduction and cessation of flows in the Middle Rio Grande, New Mexico, downstream of BdA. Error bars represent 95% confidence intervals.

3.4 Fish Movement

Seventy-two Red Shiner were recaptured during repeat fish sampling. All but two were recaptured at the same point as they were marked. Two Red Shiners moved downstream 0.6 km, from Site 8 to Site 7 during the first sampling event after marking these fish, and represented the only fish recaptured during fish monitoring at a site different from where they were marked. During fish rescue activities, an additional 48 Red Shiners and one Common Carp were recaptured. Average movement was 2.5 km upstream but ranged from 2.7 km downstream to 15.2 km upstream from their release site. Sixteen fish moved less than 1 km. A bias toward upstream movement in Red Shiner is evident from fish rescue data (Figure 13). However, only a single VIE-tagged Red Shiner moved to the South Boundary pump channel, traveling 12.4 km upstream from Site 6.

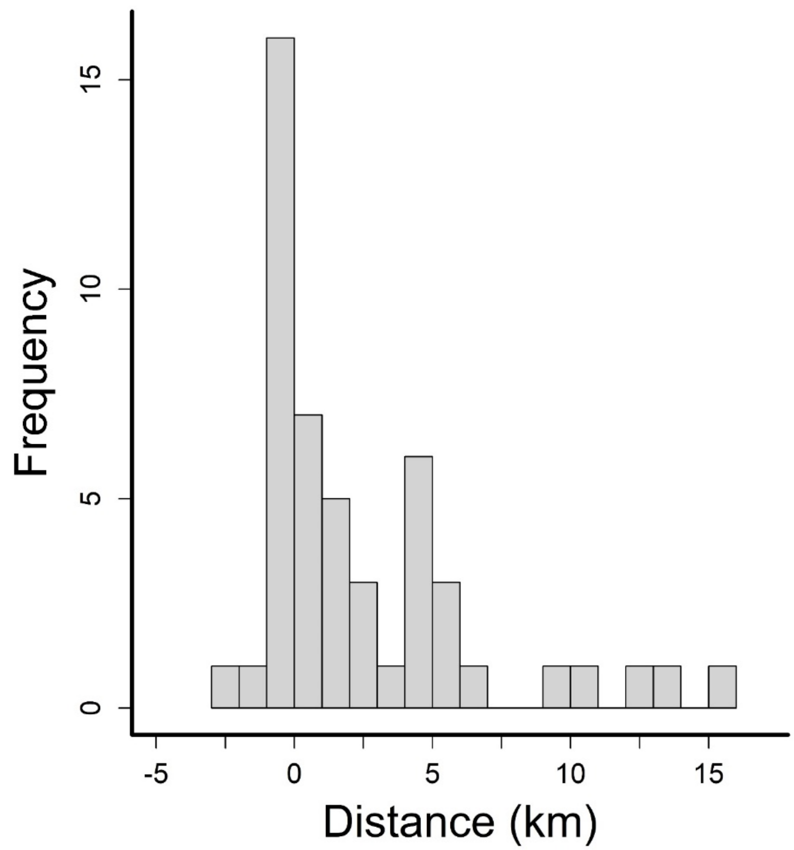

Figure 12 - Movement of Red Shiners away from marking sites, recaptured from isolated pools during streamflow intermittency in the Middle Rio Grande, New Mexico, 2020. Positive distance on x-axis represents upstream, and negative distance represents downstream.

3.5 Fish Rescue

During fish rescue in 2020, we collected 593 RGSM in the San Acacia Reach. Of these, 484 were adults, seven were YOY, and 102 were adults found dead. This is lower compared to that found in 2018, when we collected 6,240 in the same area (6,191 adults, 49 dead). In both years, the number of RGSM below the BdA South Boundary pump station was less than the remainder of the San Acacia Reach (Figure 14). We found statistical ($R^2 = 0.83$) and biologically relevant differences between years and an increasing trend in counts per pool as river mile increased (i.e., in the upstream direction) (Table 5). In 2018, we found an average of ~12 to 170 RGSM per pool, increasing from downstream to upstream, compared to ~0.1 to 40 in 2020 (Figure 14).

Table 5 - Model output relating numbers of RGSM collected in isolated pools during streamflow intermittency to river mile in 2018 and 2020. Estimates are on the log-scale.

Term	Estimate (SE)	F-value	P-value
Intercept	-0.1 (0.78)	NA	NA
River Mile	0.052 (0.009)	5.58	<0.00001
Year (2020)	-7.81 (1.09)	-7.19	<0.00001
River Mile * Year	0.064 (0.014)	4.70	<0.00001

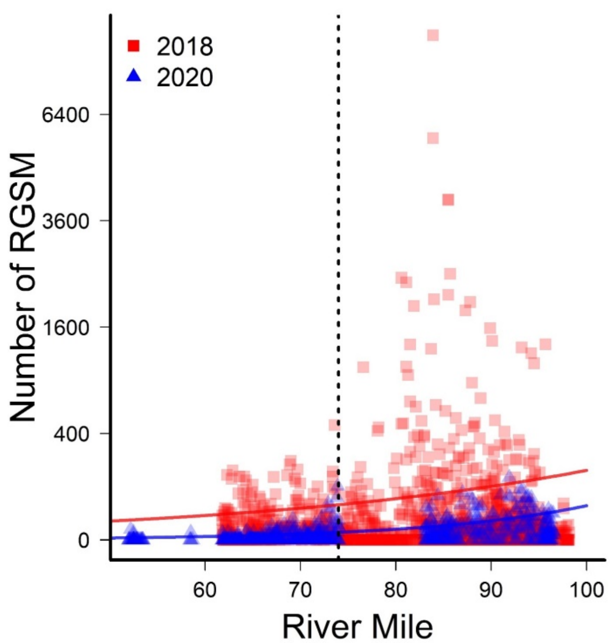

Figure 13 - RGSM collected per pool, by river mile, during fish rescue in 2018 and 2020 in the San Acacia Reach of the Middle Rio Grande, New Mexico. Solid lines are the estimated means from a generalized linear model, dashed line represents the location of the BdA South Boundary pump station. Note the y-axis is on the quadratic scale for display.

3.6 Effects of channel drying on the October CPUE

Figures 15 and 16 illustrate how CPUE and site occupancy, respectively, would have been impacted under the worst-case scenario where all sites below the South Boundary dry and are not recolonized. Based on the analysis conducted, sites downstream of the BdA South Boundary pump channel contributed little to the October CPUE calculated for the San Acacia Reach between 2001, the first year pumping quantities were recorded, and 2019 (Figure 15). However, the downstream sites did contribute as much as 33% to site occupancy rates (Figure 16). Figure 15 shows mean CPUE for the San Acacia Reach decreasing only slightly in most years when the lower sites were assumed to be zero, and rarely were the lower sites critical in keeping the CPUE above the target thresholds of 0.3, 1.0 or 5.0 CPUE (2006 & 2010) as outlined under the current Biological Opinion issued in 2016.

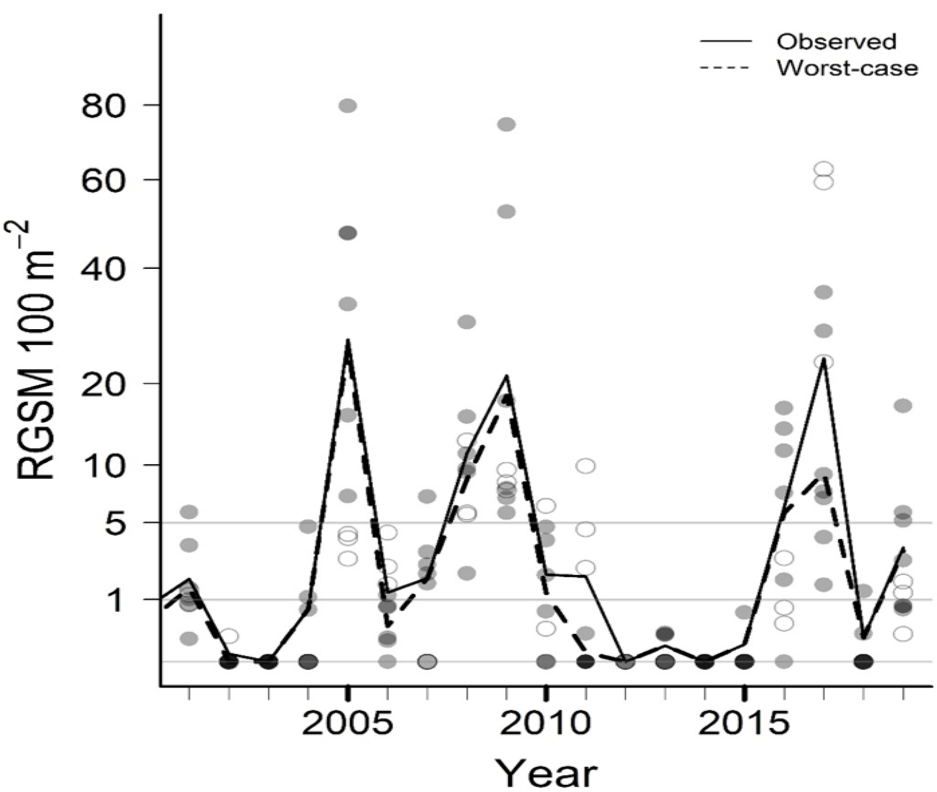

Figure 14 - Comparison of observed RGSM CPUE and occupancy rates to hypothetical worst-case scenario with consistent drying of the three southern-most sampling locations in the San Acacia Reach of the Middle Rio Grande, New Mexico, from 2001 to 2019. The solid line represents the average CPUE for each year as reported. The dotted line represents how the average would change under a worst-case scenario where the three southern-most sampling locations were dry and contributed zero fish toward the average. The points are the CPUE calculated at all sampling sites within the San Acacia Reach each year. Solid points represent sites upstream of the BdA South Boundary pump station and open points are downstream. Points are semi-transparent to increase visibility when overlap occurs. Horizontal lines indicate the three CPUE target thresholds under the 2016 Biological Opinion (0.3, 1.0 & 5.0 fish/100 m^2).

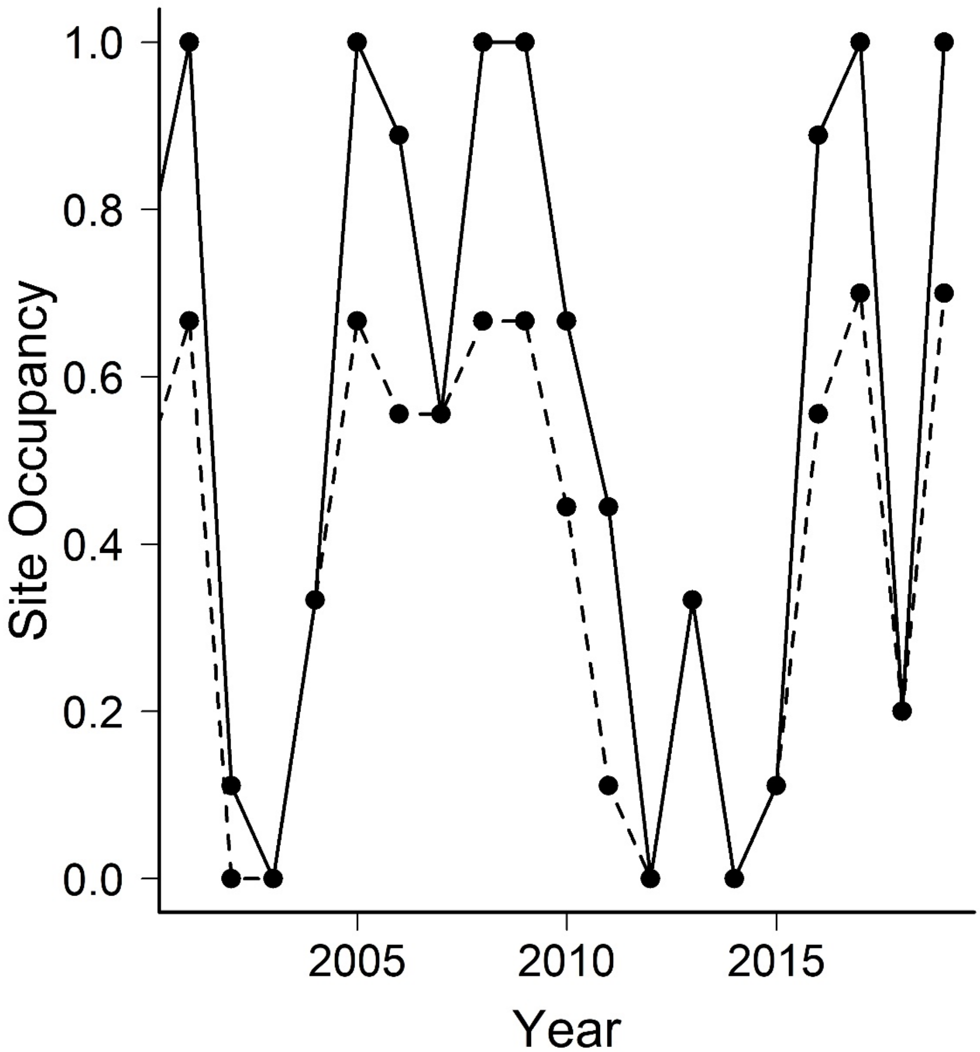

Figure 15 - Comparison of observed RGSM occupancy rates (solid lines) and hypothetical worst-case scenarios of increased drying (dashed lines) in the San Acacia Reach of the Middle Rio Grande, New Mexico, from 2001 to 2019. Under the worst-case scenario, sampling locations downstream of the pump station were assumed to be zero due to dry river conditions.

Wanting to further explore the relationship between pumping and CPUE, we used the pumping records provided in Table 1 and the CPUE calculated at each sampling location within the San Acacia Reach between 2001 and 2019. Figure 17 shows the negative relationship between the amount of water pumped (AF) and CPUE, but correlation is not causation. Importantly, pumping was often higher (Table 1, Figure 1) in years with low spring runoff than during years with high snowmelt runoff. RGSM densities have been related to high spring runoff years (Archdeacon 2016).

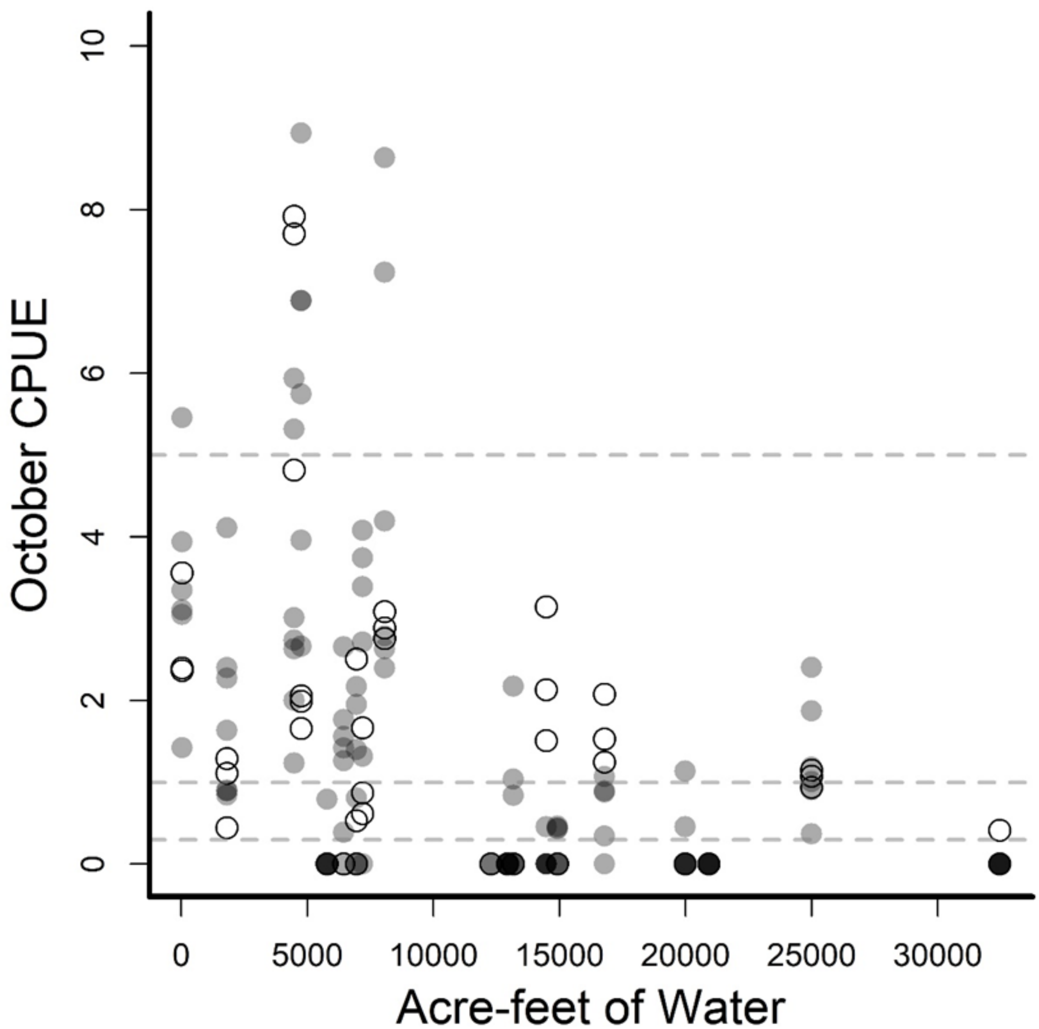

Figure 17- Relationship between October CPUE and water pumped at all locations within the San Acacia Reach between 2001and 2019. The points are the CPUE calculated at each sampling site. Solid points represent sites upstream of the BdA south boundary pump station and open points are downstream. Points are semi-transparent to increase visibility when overlap occurs. The horizontal dashed lines indicate the three CPUE target thresholds under the 2016 Biological Opinion (0.3, 1.0 & 5.0 fish/100 m²).

4.0 Discussion

During the experiment, we noted that reductions in surface flows affected the availability of faster run habitats more than other habitats up until all surface flow ceased. Temperature was driven by daily cycles and fluctuated >10 °C in river sites, while the LFCC was thermally buffered and only fluctuated about 5 °C each day. Temperatures in the river channel regularly exceeded critical thermal thresholds for RGSM. The fish assemblage changed very little at most sites until all surface flows ceased. We found little evidence of fish movement in response to changes in surface flows, as only a small percentage of Red Shiner and one Common Carp were discovered to have moved. We suggest that the observed increase in densities at some sites (as flow was reduced) were related to decreases in wetted area concentrating fish, rather than strategic movement, thus increasing capture efficiency. This is consistent with other studies that RGSM likely arrive in refugial pools by chance as opposed to directed movement to escape drying (Archdeacon and Reale 2020).

Temporally, as surface flows decreased, loss of available habitat was expected. However, run habitat, particularly faster runs, was affected differentially. With each reduction in the pumping rate, approximately 25% of the run habitat was lost, and velocities decreased, suggesting a linear relation between total run habitat and discharge. Total available habitat showed a somewhat non-linear decline with reductions in discharge, whereas pool and backwater habitats initially increased in availability, before declining. Overall, depths were reduced with each reduction in discharge, but runs were most affected. Deeper, swifter habitats were most prone to losses in availability. While these types of mesohabitat may contribute less to overall RGSM habitat, runs provide the important element of connectivity. Decreased depths and amount of run habitat results in decreased lateral and longitudinal hydrologic connection, preventing fish from dispersing. As discharge was reduced, these connection habitats transitioned to shallower, slower habitats – i.e., improved quality RGSM habitat based on criteria most recently compiled in Mortensen et al. (2019) – before the onset of intermittency and loss of habitat altogether due to drying.

Spatially, as surface flows decreased, a loss of habitat quantity in the downstream direction from pumping was expected, and in general this was the trend observed. Upstream sites had higher discharge and therefore had more total surface area. There were generally slightly more runs at upstream sites for all pumping rates. Pool area was relatively constant upstream to downstream. However, there was a significant trend of more backwaters at upstream sites for all pumping rates until pumping ceased.

Temperatures varied widely throughout each day at the six sites in the river channel where temperature was monitored, sometimes exceeding the LC50 temperature criteria. However, the diel variation was similar at all sites, except Site 3. Site 3 likely receives some groundwater input, which lowered the temperature and daily variation. Temperatures increased throughout the study, but this was likely a reflection of air temperatures and not decreases in discharge, as this also occurred at the LFCC sites. The LFCC did not experience as much variation in temperature throughout the day, likely due to overall volume, shape of the channel, and groundwater input. These findings highlight the importance of groundwater connections for mitigating extreme temperatures that may damage fishes.

In contrast to changes in habitat quantity and quality, the fish assemblage at sites remained relatively unchanged during flow recessions. A few notable changes occurred at Site 3 during flow reductions, including the collection of 22 RGSM at Site 3 when a single pump was running. However, numbers of fish at Site 3 dropped to previous levels during the final sampling event despite Site 3 being one of only two sites still containing surface flows. Other species showed relatively unchanged numbers within a site among sampling events, with few exceptions. Overall, we found very little evidence of directed movement to escape drying. That is, while some species showed increased densities during specific samples at specific sites, there was no overall trend of increasing densities at specific sites concurrent with decreasing densities at remaining sites that would imply movement away from drying as seen in other systems (Davey and Kelly, 2007). Indeed, increases or decreases at sites appeared to be uniform across sites with each reduction in streamflow, signaling changes in capture efficiency or recruitment, rather than movement away from sites that dry to areas of refuge. With only a single pump running for seven days, fish had ample time to seek out refuge areas, but were still present in large numbers in isolated pools during surveys and during fish rescue.

When all pumps were turned off, surface water remained present at Sites 2 and 3 while the remaining sites either dried completely or had no surface flow. Although we did not observe any clear, structured changes in fish numbers that suggest movement toward wetted refuge areas, there are a few intriguing observations worth noting. With no pumps running, we did observe an increase in total fishes present at Site 3 which suggests some fishes moved to this refuge area from other areas to avoid stranding in isolated pools. Additionally, with one pump running, the largest collection of RGSM was made at Site 3 which also suggests some movement to refuge areas. However, these were both isolated observations and the weight of evidence suggesting limited or no movement to avoid drying at the population level was much greater.

In addition, Site 2 remained consistently wet throughout the entire study but experienced a decrease in fish numbers as intermittency began at other sites. For a consistent and true trend of fish movement from sites to escape stranding in isolated pools, we would expect to observe increasing numbers of fish at Site 2, and decreasing numbers of fish at sites elsewhere as pumping was reduced and discharge declined. Instead, we observed little change in fish presence at sites prior to intermittency, with fish still present at all sites in large numbers until sites dried completely. In fact, many of the isolated pools contained hundreds to thousands of fishes, indicating a reluctance or inability to move prior to those pools being fully isolated. Possibly, the lack of change in water quality provides no signal for fish that flow reduction is occurring. During rescue efforts in 2020, we recovered nearly 600 RGSM from isolated pools, despite flow recession being drawn out over three weeks, providing multiple flow reduction cues and ample time to move.

Based on our observations in this study, we cannot definitively state that fish do not make long-distance movements to refuge areas in response to drying. However, we do assert that there was no clear population-level movement across multiple fish species. Thousands of fish remained at sites and were stranded in isolated pools despite a very gradual flow recession, with no clear evidence of directed movement to refuge. It is much more likely that observed greater distance movements are individual dispersers and there is a continuum of fish movement within each species, from stationary to highly mobile (Wells et al. 2017).

While the movement of all species was limited, the fraction of Red Shiners that did move demonstrated a clear bias toward upstream movement, moving away from tagging sites during the study. The majority of these recaptures occurred during fish monitoring efforts at the site of tagging. However, during fish rescue, we made >40 additional captures, including an individual moving upstream ~15 km (e.g., a highly mobile disperser). Separate movement data for RGSM show significant movements initially biased in the downstream direction from release sites. Although highly variable after the initial release (B. Stout, Utah State University, personal communication), this indicates potential for individual variability in movement patterns.

In 2018, we found a similar pattern, with a clear increasing trend in numbers stranded in pools when moving upstream. However, in 2018, all three pumps were shut down over a four-day period. In 2020, we observed the same spatial pattern of RGSM occurrences, despite a much slower rate of recession and RGSM having several weeks to move away from areas prone to drying. Further, in 2020 we found RGSM scattered throughout the entire sub-reach. If any of the species in the sub-reach were reacting to drying and making large-scale, population-level movements to refuge areas, we should have noted few fish in isolated pools, coupled with increasing numbers near refuge areas (upstream, downstream, Sites 2 and 3). Thus, the movements observed during this effort likely represent individual dispersers (Hawkes 2009) and not directed movement toward refuges. However, other studies have found fishes exhibiting movements away from streamflow intermittency to refuges, inferred either by spatio-temporal shifts in density (Davey and Kelly 2007) or direct observation of tagged fish (Storer et al. 2020).

As a group, there is very little evidence of minnows with life histories similar to RGSM (see Worthington et al. 2018) specifically seeking out refuge prior to streamflow intermittency (see also Ruppel et al. 2020). A lack of direct response toward refuge areas during streamflow intermittency has several management implications for the MRG. The "string of pearls" concept for managing RGSM within the MRG has suggested that the best management strategy during periods of low flow is for agencies to create many smaller areas of refuge ("pearls") for RGSM to use until there is once again enough water in the system to connect the river. Species that show site fidelity and homing behavior toward refuge areas (Storer et al. 2020) would likely benefit from this strategy. However, based on our observations the RGSM population is unlikely to significantly respond. Some RGSM may arrive at these areas by chance as part of dispersal movements, or by moving short distances from adjacent river sections as assemblages concentrate into remaining wetted habitats. Still, the majority will remain stranded and perish (Archdeacon and Reale 2020). Because RGSM do not appear to make large-scale movements to refuge areas, providing consistent flows to larger, more suitable perennial reaches are more important for population persistence than providing a series of smaller, disconnected refuge areas (Fahrig and Merriam 1985; Fagan 2002). One important caveat is the influence these smaller wetted areas might have on stream temperature. If these areas provide relatively cooler refuges, fish may seek them out to escape extreme temperature fluctuations of the type observed in the river sites. However, these must occur at a landscape scale to be beneficial to the overall population and fish must be able to return to the main channel for spawning. While these areas could be beneficial for mitigating extreme temperatures, they could also function as ecological traps if fish are not able to reproduce (Schlaepfer et al. 2002).

The high numbers at Site 3 were driven by very large collections of Red Shiner and Western Mosquitofish. We made no effort to separate out YOY fishes. However, our observations suggest that these numbers were inflated by continuous recruitment of Red Shiner during low flows, as observed in other species (Kerezsy et al. 2011; Hopper et al. 2019). The increasing fish densities with reductions in surface flows observed at some sites may be attributable to recruitment of some species to seining gear or increased sampling efficiency. As habitable surface area decreases, fishes are more concentrated, inflating CPUE numbers. While this hinders our ability to infer movement, it remains an important observation on the long-term effects of low flows on the fish assemblage, namely the result of a shift toward more tolerant "extremophile" species (Ostrand and Wilde 2001;

Hopper et al. 2020). Ultimately, many fish perished during intermittency through stranding in isolated pools during this study.

Based on our analysis using the demographic RGSM monitoring data collected between 2001 and 2019, ceasing to run pumps at the South Boundary of BdA would only marginally affect the range-wide October CPUE, annually reported to the Service under the 2016 Biological Opinion. CPUE generally exceeds the thresholds enforced by the Service in years when spring runoff is high and fails to meet the thresholds when spring runoff is low (Archdeacon et al. 2020). Because CPUE is averaged over 20 (years 1993 – 2016) or 30 (years 2017 – 2019) sites, and there are generally fewer fish in this sub-reach compared to the upstream areas, the contribution of the three southernmost sampling locations was determined to neither significantly increase nor decrease the annual range-wide October CPUE. Based on past observations, if the three southernmost long-term population monitoring sites dry and are not recolonized before October surveys, the overall impact on CPUE is likely to be minimal.

Conversely, occupancy was affected. Under the assumption of worst-case scenarios where drying leads to local extirpation and no recolonization occurs before October demographic monitoring, there would be a 33% reduction in occupancy within the San Acacia Reach (3 of 10 sites), and 10% overall reduction in range wide occupancy (3 out of 30 sites). Both abundance and distribution are important components for recovery of endangered species. Being very common is an important hedge against extinction, and rare species are disproportionately vulnerable to extirpation (Gaston 2008). The more widely distributed a species is, the less likely it is a single catastrophic event could result in extirpation (Gonzales 1998, Boyce et al. 2002). Although drying in these sites affects species distribution, it is temporary as the abundance of these sites tends to rebound quickly under favorable spring streamflow conditions following dry years. This likely helps to repopulate upstream areas that previously dried. Without pumping, capacity is diminished in dry years and increases the importance of occupancy at upstream sites, presumably changing the dynamics of recolonization in the San Acacia Reach following intermittency.

We observed an inverse relationship between the amount of water pumped (AF) and October CPUE. This does not indicate that pumping has a negative impact on the survival of the RGSM in the San Acacia Reach. Instead, increased pumping is an indicator of system-wide water shortages and often severe drying within the river channel. Pumping was used at the bottom of a stressed system to provide a lifeline to endangered fish, and in that limited capacity, it has been effective. However, offsetting extreme conditions by providing a minimal amount of water for survival is not a management strategy that works towards recovery, nor is it sustainable from a cost perspective.

The river channel throughout much of this reach is perched (Fluke et al. 2019), meaning that the channel no longer occupies the lowest elevation within the floodplain. In many years water is flowing through the valley, but not in the river. Water tends to naturally collect and seep into lower lying areas (such as the LFCC and the wetlands near river mile 60), thus the benefits of pumping will always be limited and localized. To forgo a constant struggle against gravity and to work towards recovery of the RGSM, river realignment options should be investigated.

5.0 Conclusions

This study intentionally ramped down flow rates from mechanical pumps to observe changes in habitat quantity, habitat quality, fish assemblage, and refuge-use strategies including movement in the lower San Acacia Reach of the Middle Rio Grande that regularly experiences river drying. Objectives of the study were met and allow for the following key conclusions:

Habitat Quantity and Quality

- Reductions in pumping reduced the total amount of available wetted habitat based on surface area and mesohabitat diversity in the upstream to downstream direction, with runs experiencing the most consistent decline (~25%) with each reduction in discharge.
- Reductions in pumping resulted in habitats transitioning to shallower, slower habitats, initially improving the quality of RGSM habitat based on velocity and depth criteria in Mortensen et al. (2019), before the onset of intermittency and loss of habitat altogether due to drying.
- All six temperature monitoring locations within the main channel experienced greater diel variability and at times exceeded the LC50 value of 31.4 °C, while temperature monitoring locations in the LFCC showed far less diel variability and never exceeded the LC50.
- The cessation of pumping corresponded with drying downstream through most of the study reach, and the limited portion that maintained surface flow became isolated.

Fish Assemblage

- Fish assemblage did not appear to be negatively impacted until supplemental pumping stopped completely, with some species increasing during the study period likely due to recruitment.
- RGSM was rare, and abundance was negatively impacted by drying.

Refuge-use Strategies including Movement

- There was no evidence of clear, directed population-level movement to refuges or pools that persisted throughout the study.
- Based on this study's observations, fish movement was not affected by the reductions in discharge/pumping until drying occurred and created fragmentation and inherent barriers to movement.
- Overall movement of fishes during this study was low, though some Red Shiner made substantial movements (over 10 km) that were apparently not related to stream drying.

Overall Findings

If pumping ceases at the South Boundary of BdA under current operations and infrastructure conditions, we are likely to observe:

- A small impact to the annual RGSM October CPUE,
- A temporary reduction in site occupancy up to 33% under the worst-case scenario, and

- A loss of individuals that assist with recolonizing upstream areas after water returns to the river channel.

6.0 Management Recommendations

This study contributes to adaptive management efforts under the 2016 Biological Opinion by Reclamation and its BO Partners, including broader efforts underway to examine management options in the San Acacia Reach. Findings from this study allow for the following key management recommendations.

Short term recommendations:

- Focus available flows upstream in cooler, larger, and higher quality habitat that can more easily maintain connectivity with the river to enhance recolonization potential;
- Provide gravitational flows from drainage ditches that maintain connectivity among habitat types to support survivorship during drying events.

Longer term recommendations:

- To eliminate the constant management practices of redistributing water from lower lying areas, investigate realigning the river to the lowest point in the floodplain to facilitate and take advantage of water naturally collecting in the river channel.

7.0 Future Research

The findings from this study provide data on observed changes in habitat amount, habitat quality, fish assemblage, and refuge-use strategies over the course of one season. There are a number of potential applications for these findings related to both water and species management which help illustrate guidelines for future research as part of adaptive management under the 2016 BO. Recommendations for future research include the following:

- Repeat evaluation in future years, with differing river conditions, such as higher or more prolonged spring runoff, monsoonal inputs, and modified infrastructure or operational changes as those are implemented, including if future gravitational inputs are developed in lieu of the mechanical pumping. This would allow for comparison to 2020 results and provide additional data, refining our understanding of key variables.
- Repeat evaluation in future years, with different antecedent RGSM conditions, such as years with higher RGSM population abundance, greater spawning response leading up to drying events, and different proportions of hatchery-supplemented fish in the system. This would allow for comparison to 2020 results for key species parameters.
- Develop a method for normalizing CPUE to river area to account for increased capture efficiency during periods of low flow and alleviate skewing of CPUE calculations.

- Continue investigations into how management of drying and use of refugia can be optimized to support survival and recolonization.
- Conduct further investigations into the colonization patterns of RGSM following drying events, including variation in patterns of upstream and downstream directed movements.

8.0 Acknowledgements

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9.0 Data Availability Statement

Data are available at http://dx.doi.org/10.17632/y8fnbz9j2x.1

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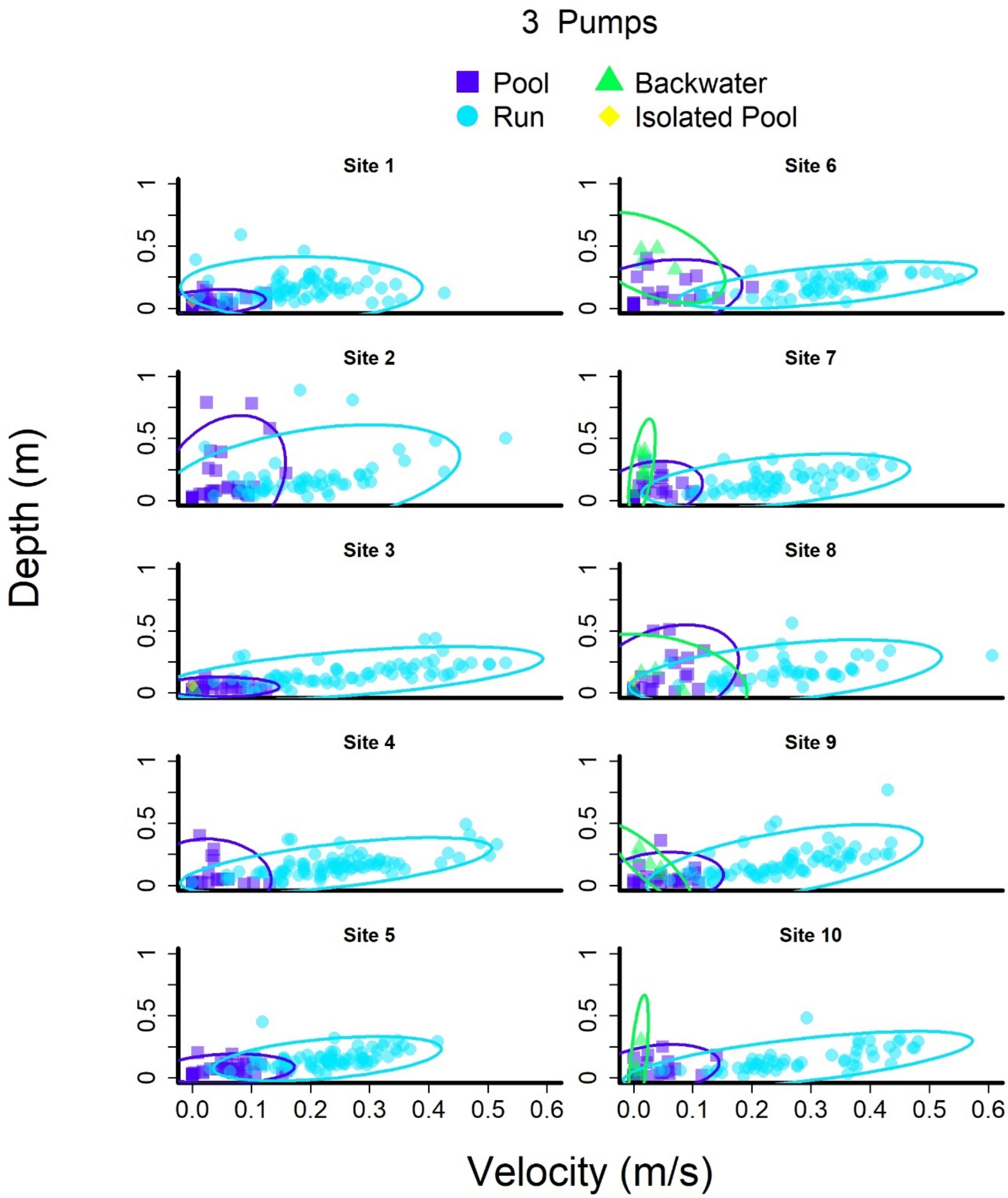
Appendix A: Supplemental Figures


3 Pumps
Pool
Run
Backwater
Isolated Pool
Site 1
Site 2
Site 3
Site 4
Site 5
Site 6
Site 7
Site 8
Site 9
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Depth (m)
Velocity (m/s)
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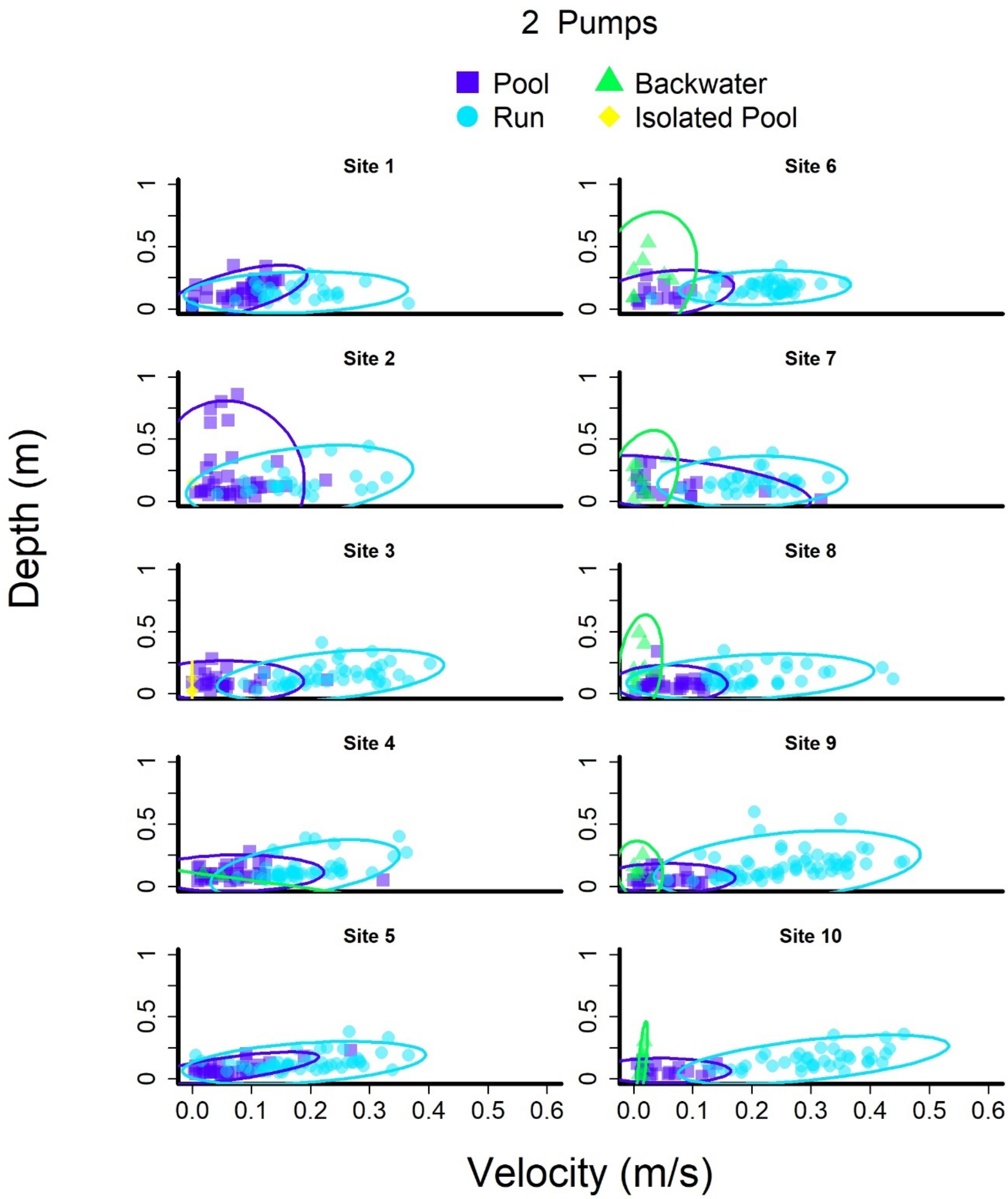
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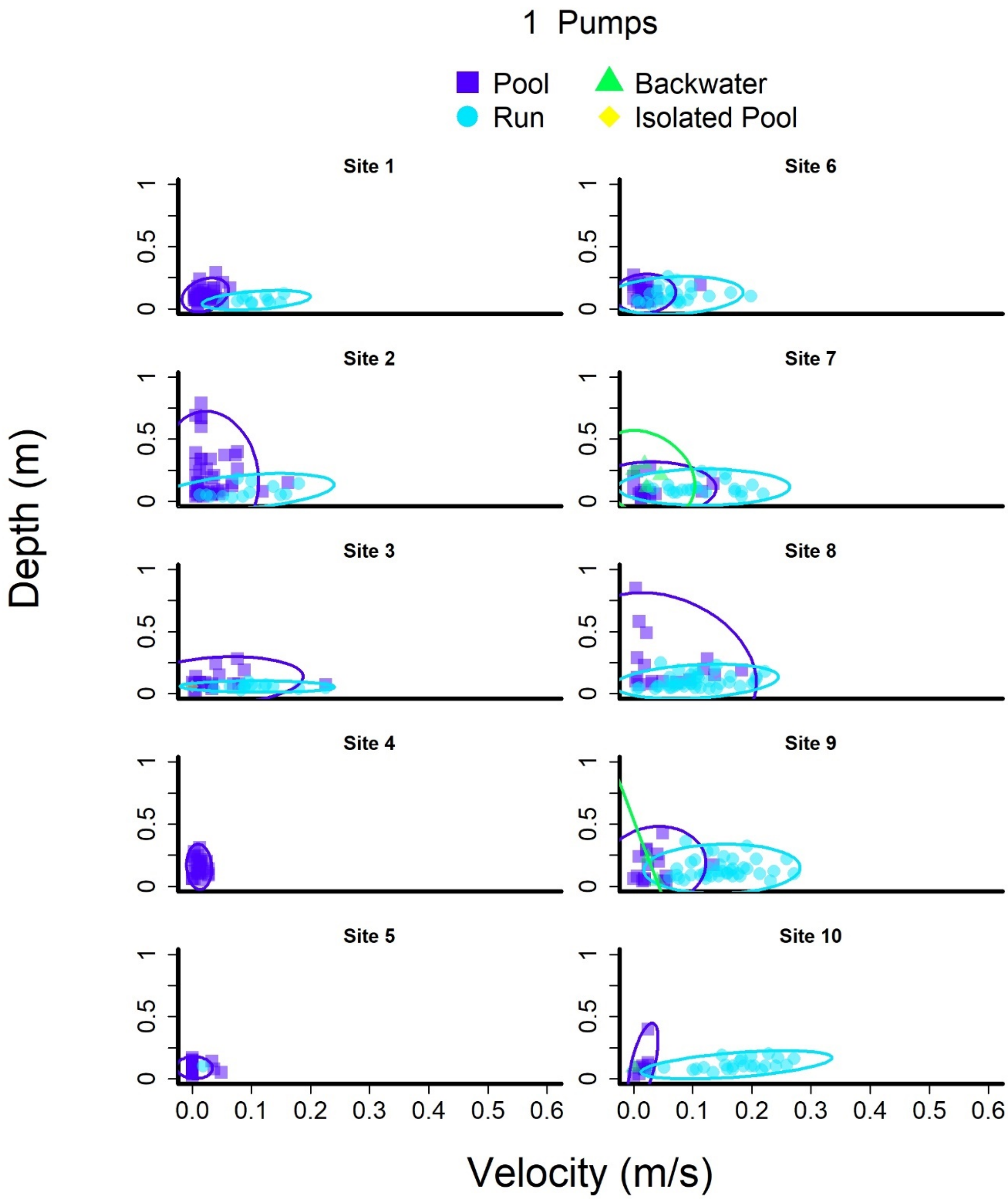

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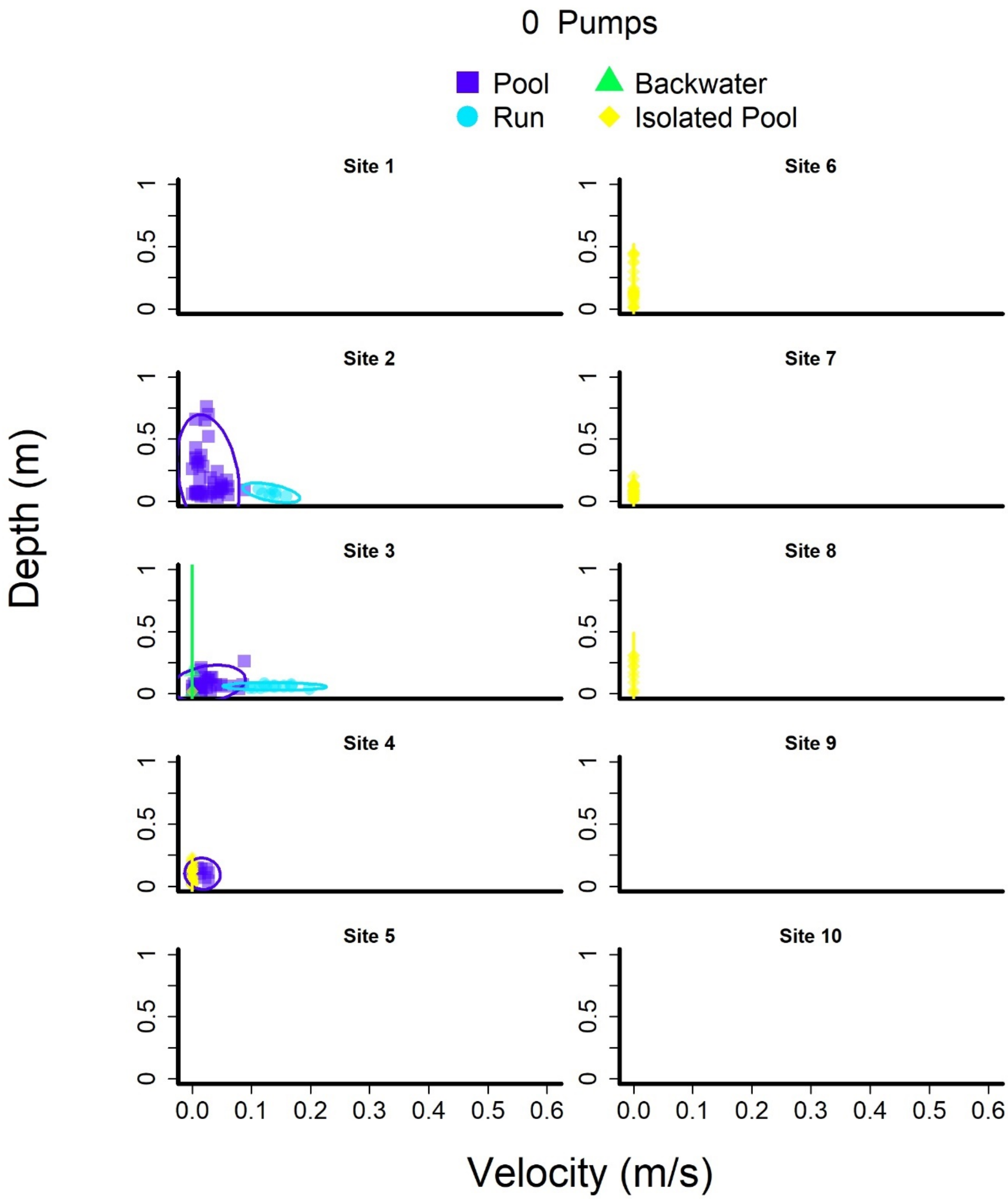
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