Middle Rio Grande Rio Puerco Reach: Hydraulic Modeling and Silvery Minnow Habitat Analysis 1918-2016

Plan B Technical Report
December 2018

Prepared by:
Kristin LaForge

Advisor:
Dr. Pierre Julien

Colorado State University
Engineering Research Center
Department of Civil and Environmental Engineering
Fort Collins, Colorado 80521

Abstract

The Rio Puerco reach spans about 11 miles of the Middle Rio Grande in central New Mexico. It begins at the confluence with the Rio Puerco and ends at the San Acacia Diversion Dam. This report aims to better understand the Rio Puerco reach's morphodynamic processes and Rio Grande silvery minnow habitat quality. The reach was split into five subreaches (P1, P2, P3, P4 and P5) to facilitate the analysis of spatial and temporal trends in channel morphology and habitat quality.

The hydraulics have been in flux over the past century. For instance, the mean annual discharge and peak flows have decreased since the 2000s. Furthermore, flows in the Rio Grande have become more homogenous due to the instillation of dams and levees in the 1900's. Also, suspended sediment discharge has been declining since the 1970s, resulting in overall channel degradation. These discharge changes have altered the morphology of the river and caused a decrease in stability and overall health of the Rio Grande.

The GIS (Geographic Information System) analysis of aerial photographs and HEC-RAS (Hydrologic Engineering Center- River Analysis System) analyses show geomorphic changes for each subreach. For instance, the current channel width is less than one-fifth of what it was in 1918. This pattern is consistent throughout the subreaches. There has also been a slight increase in sinuosity (P3 has the highest sinuosity), depth, velocity, and median grain size while the slope decreased from 1972-2012. Also, a geomorphic conceptual model shows the channel incising and narrowing.

HEC-RAS and visual observations of aerial photographs with GIS were used to assess habitat conditions ("spawning", "feeding/rearing", and "good" habitat were classified with criteria from Tetra Tech 2014) in 1992, 2002, and 2012. HEC-RAS simulations show the most "spawning" and "feeding/rearing" habitats occur at 3500 cubic feet per a second (cfs) (compared to 600 and 1400 cfs). The majority of "good" habitat is found in the main channel at low flows of 600 cfs and in subreach P2. For all habitat types, habitat area has decreased from 1992-2012.

The GIS habitat analysis is based on finding what habitat features silvery minnows thrive in, identifying and scoring those features with aerial photography, and seeing how the habitat changes spatially and temporally. The best habitat scores occur in early years and when the floodplain is inundated. Comparing photographs taken under similar flow conditions (~600 cfs) shows P2 has the best habitat score. An analysis of the shoreline complexity and length shows the shoreline length has increased since the 1900s due to increased sinuosity, but there is little change in overall complexity.

Comparing both HEC-RAS and GIS analyses at low flow conditions shows P2 has the best habitat and overall habitat quality declined from 1992 to 2012. The decrease in habitat quality is likely due to: (1) a reduction in heterogeneity of discharges; and (2) the channel narrowing and incising causing a loss of connectivity to the floodplain.

Acknowledgements

I would like to thank Colorado State University for my appointment as a Graduate Teaching and Research Assistant. I would also like to thank the United States Bureau of Reclamation for funding this project. This allowed me to pursue a master's degree and complete the analysis for this technical report. I would like to thank Dr. Pierre Julien for his support as a professor and advisor. I would not have been able to accomplish what I did without his constant guidance. I would also like to thank Dr. Ellen Wohl and Dr. Peter Nelson for their guidance as professors and serving on my committee. I also worked closely with Chun-Yao Yang to complete this report (a division of labor is detailed in Appendix H). I greatly appreciate his help and learned a lot from our collaborative effort. Finally, I would like to thank my friends, family, and roommates who offered their love and support throughout my two and a half years at CSU.

Table of Contents

List of Figures

List of Tables

1. Introduction

The Middle Rio Grande is located in central New Mexico and spans about 170 miles from the Cochiti Dam to Elephant Butte Reservoir (Tetra Tech 2002). It has been heavily impacted over the past few centuries due to settlements along the river (Scurlock 1998). For instance, construction of levees, jetty jacks, and dams were put in place throughout the 1900's to control the flow and mitigate extreme floods and droughts. This caused the river to become narrower and more incised than its previous braided and shallow planform (Larsen 2007). This has caused a plethora of problems for agriculture practices and the health of the river. These changes have recently caused a shift towards a more sustainable management of the river in the past few decades (Scurlock 1998; Tetra Tech 2014; Baird 2016).

In response to the decline of the silvery minnow, studies have been done to understand how the Rio Grande functions and how it has been changing (Baird 2014; Bauer 2000; Berry and Lewis 1997; Bovee et al. 2008; Crawford et al. 1993; Easterling 2015; Happ 1948; Horner 2016; Klein et al. 2018a; Larsen 2007; Makar 2010; Massong 2010; MEI 2002; Posner 2017; Richard 2001; Swanson et al. 2010; Tetra Tech 2014; Varyu 2016). These reports only comprise a few of those that have added to the body of knowledge of how the Rio Grande functions and how this affects silvery minnows. Still, a report analyzing the geomorphology and silvery minnow habitat for subreaches within the Rio Puerco reach has not been done before. Therefore, this report intends to give a detailed subreach analysis of the geomorphology and silvery minnow habitat of the Rio Puerco reach.

Objectives of this report:

- Delineate the reach into meaningful subreaches
- Present the flow and sediment discharge history
- Compare the silvery minnow population to peak discharges
- Analyze the geomorphological drivers (sinuosity, width, braiding, bed elevation, bed material, volume change, and hydraulic parameters)
- Create a conceptual geomorphic model to help predict how the river will change in the future
- Analyze how the silvery minnow habitat changes with different flow regimes
- Analyze habitat quality of silvery minnows with remote sensing

1.1. Literature Review

1.1.1. Middle Rio Grande History

Scurlock's commonly cited, comprehensive report on "An Environmental History of the Middle Rio Grande Basin", outlines relevant historical, climatic, and geomorphological events on the Middle Rio Grande. Since the 1400's the Rio Grande has undergone extreme fluctuations in climate. There have been intense floods that resulted in loss of establishments, livestock, and human life. These floods more destructive to settlements, but also provided them with benefits. The floods leached out salts and supplied rich alluvium to the farm land, and helped maintain aquatic ecosystems by connecting the main channel to the floodplains. Droughts had major impacts as well. They sometimes forced settlements to abandon the area in search for better sources of water, which allowed the land to recover in their absence (Scurlock 1998).

Cultural shifts have also heavily impacted the river. Native Americans populated the land around the Middle Rio Grande and lived sustainably off the land for thousands of years. In the 1500's, Spaniards settled in this area and began taking over the farming land and employed irrigation systems. In these irrigation lands, mining and logging practices grew for hundreds of years. Starting in the 1800's, Anglo-Americans settled in the land. With the increase in land use of the years, regulations and agencies were necessary to deal with the growth. As more settlements became larger and more permanent, flooding and droughts needed to be mitigated. Starting in the 1900's levees, dams, and channelization techniques were used to control where and how much the river flowed. At the end of 1900's, there was a shift towards a more sustainable mindset that incorporated farming, water quality, water quantity and ecological needs (Scurlock 1998). This frame of mind is necessary moving forward as well. By focusing on the biological aspect of the river, such as saving endangered species like the silvery minnow, the health of the river can be improved.

1.1.2. Silvery Minnows- An Endangered Species

The Endangered Species Act of 1973 was enacted to prevent native plants and animals from becoming extinct and help preserve natural ecosystems. Without protecting species, the riparian ecosystem's diversity and resiliency will be negatively impacted. A BBC article about endangered species states that "science is telling us that ecosystems provide us with a host of things we can't do without, and that the more diverse each ecosystem is, the better" (Marshall 2015). The degradation of ecosystem functions is problematic because we benefit immensely from the services that healthy ecosystems provide, such as food production and clean water.

Silvery minnows became an endangered species in 1994 (Tetra Tech 2014; U.S. Fish and Wildlife Service 2010), and their decline is a harbinger of the declining ecological health of the Middle Rio Grande (Russo 2018). Currently, the silvery minnow occupies about only seven percent of its historic range (U.S. Fish and Wildlife Service 2010). It is believed to only occur in the Middle Rio Grande from Cochiti Dam to Elephant Butte Reservoir (Bestgen and Platania 1991; Dudley et al. 2005). The Rio Puerco reach falls inside of this range, which is one of the reasons is it being studied. Because silvery minnows are an indicator of the health of the river, great efforts have been made to protect them. Dams, levees, and channelization of the river are likely causes of this (U.S. Fish and Wildlife Service 2007).

1.1.3. Silvery Minnows and the River

The relationship between the geomorphology and the riparian ecosystem is essential to understanding how to save the silvery minnow. The silvery minnow depends on certain characteristics of the Rio Grande to survive. The most important characteristic is the connection of the main channel to the floodplain (Scurlock 1998; Cowley 2002; U.S. Fish and Wildlife

Service 2010; Medley and Shirley 2013; Tetra Tech 2014; Dudley et al. 2016). Most of the spawning and rearing occurs in the floodplains, so silvery minnows need access to the floodplains to propagate. Silvery minnows depend on both the physical parameters of the river and hydrologic regime for floodplain connectivity. Spawning is stimulated by high flows in late April to early May, so these peak flows are very necessary (Cowley 2002).

The in-stream characteristic are also important. Silvery minnows most commonly occupy habitats with debris piles, pools and backwater. They thrive in mostly silt substrate and require low velocities and moderate depths. Also, juvenile requirements are different than adult requirements. Juveniles require even lower velocities, shallower depths, and smaller substrate (Dudley and Platania 1997).

Dams, levees and diversion structures have heavily impacted the hydraulics and fluvial processes of the river. Sediment size has gone up overall, the floodplain is less connected than it has been in the past, water quality has decreased, and the river has become fragmented by dams (Osborne et al. 2012; Larsen 2007). These factors all decrease the habitat quality of silvery minnows. This is evident when looking at the decline of silvery minnow genetic diversity, densities, catch rates, and habitat range (Horner 2016). To prevent the silvery minnow from going extinct, we must study the river processes, understand how this impacts the ecological health of the system, and how to improve it. Looking at smaller scales such as subreaches may offer insight into how the rivers and minnows interact.

1.2. Site Description and Background

1.2.1. Rio Puerco Reach History

Easterling Consultants outlined a history of events in the Rio Puerco reach:

- 1917-1918: River aggraded due to sediment supply from tributary arroyos and overgrazing and the Belen-Socorro uplift. Maps drawn at this point are shown to have a braided planform and variable channel width with numerous mid-channel bars (was only narrow in the confines of mesas).
- 1929: A large flood resulted in aggradation of the study’s floodplain and tall banks. Because of this, the banks were so tall, the floodplain did not aggrade in this section during floods in 1935 and 1941. This is one of only reaches in the Rio Grande where aggrading didn’t happen (Happ 1948).
- 1929-1933: The Middle Rio Grande Conservancy District (MRGCD) constructed irrigation canals and drains. The construction of river side drains left spoil-pile berms in-between the river and the drains which now form the modern-day floodplain (Happ 1948).
- 1934: The San Acacia Diversion Dam (SADD) was constructed (U.S. Bureau of Reclamation).
- 1941: Flood added to floodplain aggradation and bed lowered, increasing the channel capacity.
- 1950’s: Channelization began with jetty jack systems.

- "Crawford et al. (1993) stated that the stabilization period for channelization was from 1953 to 1974. In and around this time period several dams were constructed on the Rio Grande and its tributaries which impacted hydrology, sediment delivery, or both hydrology and sediment delivery" (Easterling Consultants LLC 2015).

- 1972-1992: Channel stabilized and width changes were insignificant
- 1990's: Dredging (which attempted to maintain a stable channel) stopped and was a likely cause of vegetation encroachment and increased narrowing of stream.
  - Most flows now during flood flows that occur in the reach would not remove vegetation from islands or bars (MEI 2006).
- 1962 and 1998: River between Rio Puerco and Rio Salado rose by up to 2 feet. Most of the bed of the river from Rio Salado to the SADD degraded by 1-6 ft. (Bauer 2000).
- Bed material near SADD has coarsened slightly over the years.

1.2.2. Rio Puerco Reach Description and Subreach Delineation

To facilitate local characterization of the reach, the Rio Puerco Reach is divided into five subreaches. The determination of subreaches are based on visible geologic controls and cumulative curves of geomorphic variables including width, slope, depth, and velocity analyzed at a flow of 3000 cfs (cubic feet per a second). The variables were obtained by using HEC-RAS (Hydrologic Engineering Center- River Analysis System) with the geometry files provided by the USBR (United States Bureau of Reclamation). Geometry files from 1992, 2002, and 2012 were used. The proposed definition of subreaches is listed in Table 1. This delineation is used in analyses throughout this report. The delineation is identified by aggradation/degradation lines (agg/deg lines) which are "spaced approximately 500-feet apart and are used to estimate sedimentation and morphological changes in the river channel and floodplain for the entire MRG" (Posner 2017).

Table 1: Rio Puerco Reach subreach delineation.

Subreach Number	Agg-Deg Rangeline Numbers	Notable Geomorphic Controls and Comments
P1	1097-1126	Rio Puerco confluence (1097); Arroyo los Alamos (1126)
P2	1126-1151	Narrow Geologic Control (1151)
P3	1151-1182	Rio Salado (1182)
P4	1182-1191	Alluvial fan downstream of Rio Salado. Subreach where the width changes depending on the most recent Rio Salado high flow events (1191)
P5	1191-1206	San Acacia Diversion Dam (1206)

The Rio Puerco Reach of the Middle Rio Grande spans 10.8 miles from the confluence of Rio Puerco and Rio Grande (agg/deg line 1097) to San Acacia Diversion Dam (agg/deg line 1206) Figure 1. The tributaries that join the Middle Rio Grande in this reach include the Rio Puerco, Salas Arroyo, Arroyo los Alamo, Cañada Ancha and Rio Salado. The confluence of Salas Arroyo is

0.1 miles downstream the confluence of Rio Puerco. Arroyo los Alamo enter the Middle Rio Grande after running through a relatively straight and mildly sloped 3 miles (agg/deg 1126). These confluences are important features of the reach because they carry sediment and act as a local grade control (Easterling Consultants LLC 2015). The channel flows another 3 miles and enters a geologic constriction associated with the San Acacia basalt intrusion (Posner 2017). The river valley becomes narrower and the constriction causes river to bend west. The Rio Salado confluence is located at the end of the constriction. After the confluence, the river valley becomes wide and the river meanders and ends at the SADD (San Acacia Diversion Dam).

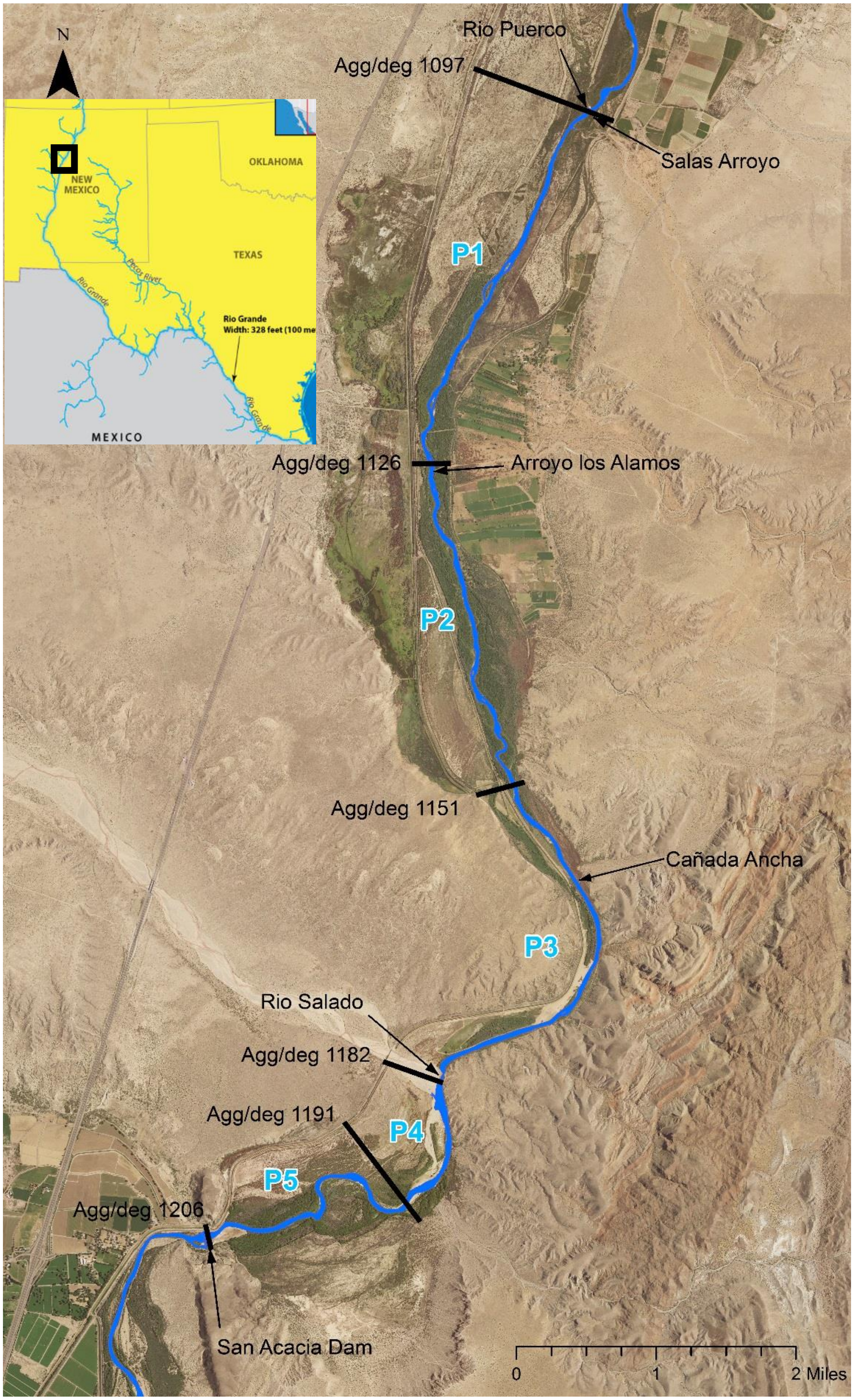


Figure 1: Map of Rio Puerco Reach.

2. Flow and Sediment Discharge Analysis

Available gages near the study reach are found in the USGS (United States Geological Survey) National Water Information System. Table 2 lists the gages that are analyzed in this report.

Table 2: List of USGS gages used in this study.

Station	Station #	Mean daily discharge	Suspended sediment
Rio Grande at Albuquerque	08330000	Oct 1989- Current	Oct 1969 – Sep 2016
Rio Grande at Isleta Lakes Near Isleta	08330875	Oct 2002 - Current	
Rio Grande Near Bosque Farms	08331160	Oct 2007- Current	
Rio Grande at State HWY 346 near Bosque	08331510	Oct 2006 - Current	
Rio Grande Floodway Near Bernardo	08332010	Oct 1990 - Current	Oct 1964 – Sep 2015
Rio Puerco near Bernardo	08353000	Nov 1939 - Current	Oct 1955 – Sep 2015
Rio Grande Floodway at San Acacia	08354900	Oct 1958 - Current	Jan 1959 – Sep 2016

It is important to note that there is a report from USBR by Klein et al. 2018a closely related to this one. Although, the USBR geomorphic analysis was not broken up into subreaches like this one. Therefore, the USBR report provides a great deal of background and summary of this reach, so it is referenced frequently. If Klein et. al 2018a is not referenced, the analysis was done independently for this report.

2.1. Discharge

The daily discharge of the Albuquerque (08330000), Bernardo (08332010) and San Acacia (08354900) are plotted as shown in Figure 2, Figure 3, and Figure 4. No data was available during July 2005 through September 2011 for the Bernardo gage. The plots show seasonal flow patterns: the high flow occurs in April through June, followed by low flow in July to October, and medium flow from November to March. The spring high flow can be attributed to snow melt runoff. However, the spring flow significantly decreases after 2002. Recently, upstream reservoirs have reduced peak flows coming through the Isleta reach. The Rio Puerco is unregulated though, and has large peak flows. They are still lower than peak flows observed in the 1920’s to the 1940’s (MEI 2002 in Klein et al. 2018a).

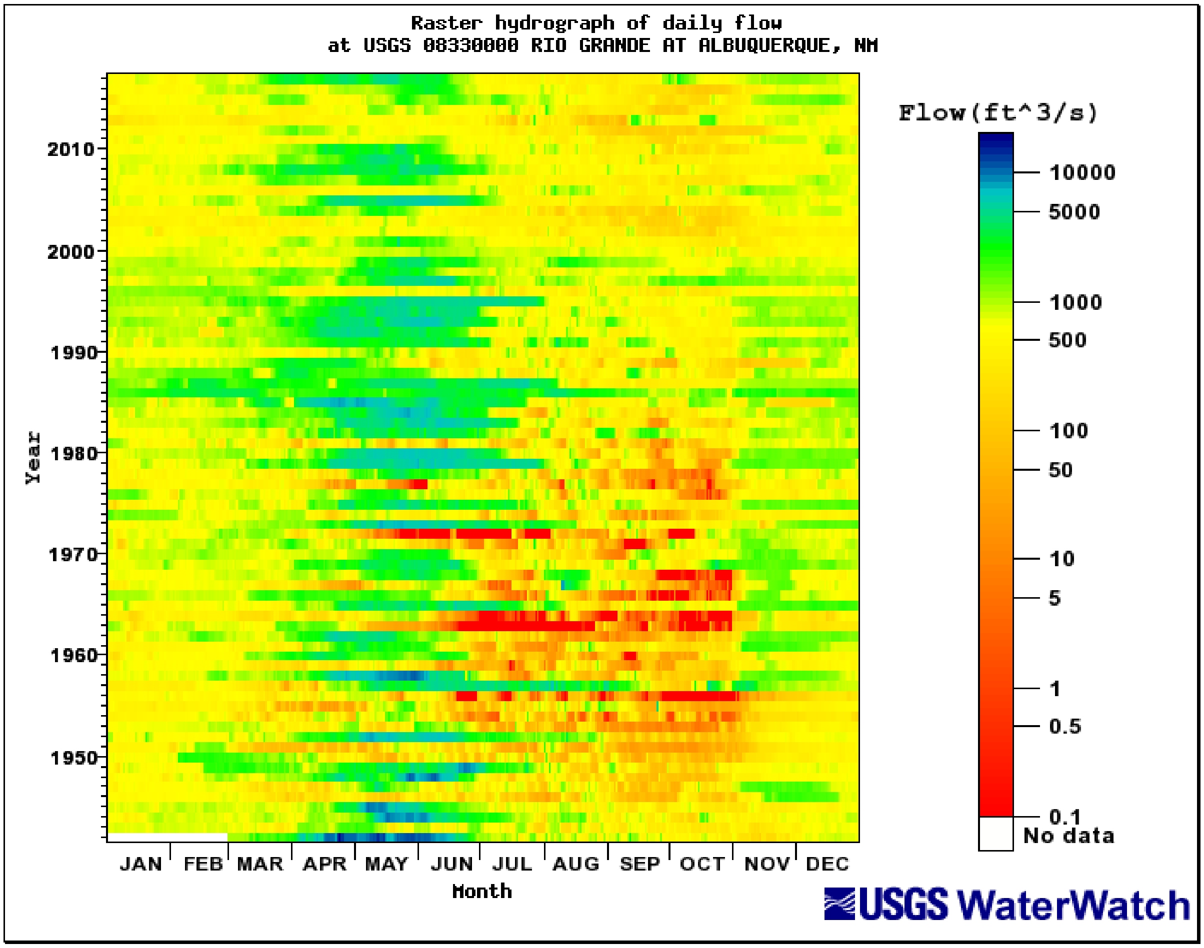


Figure 2: Raster hydrograph for the Rio Grande at Albuquerque (08330000): 1942 to 2017.

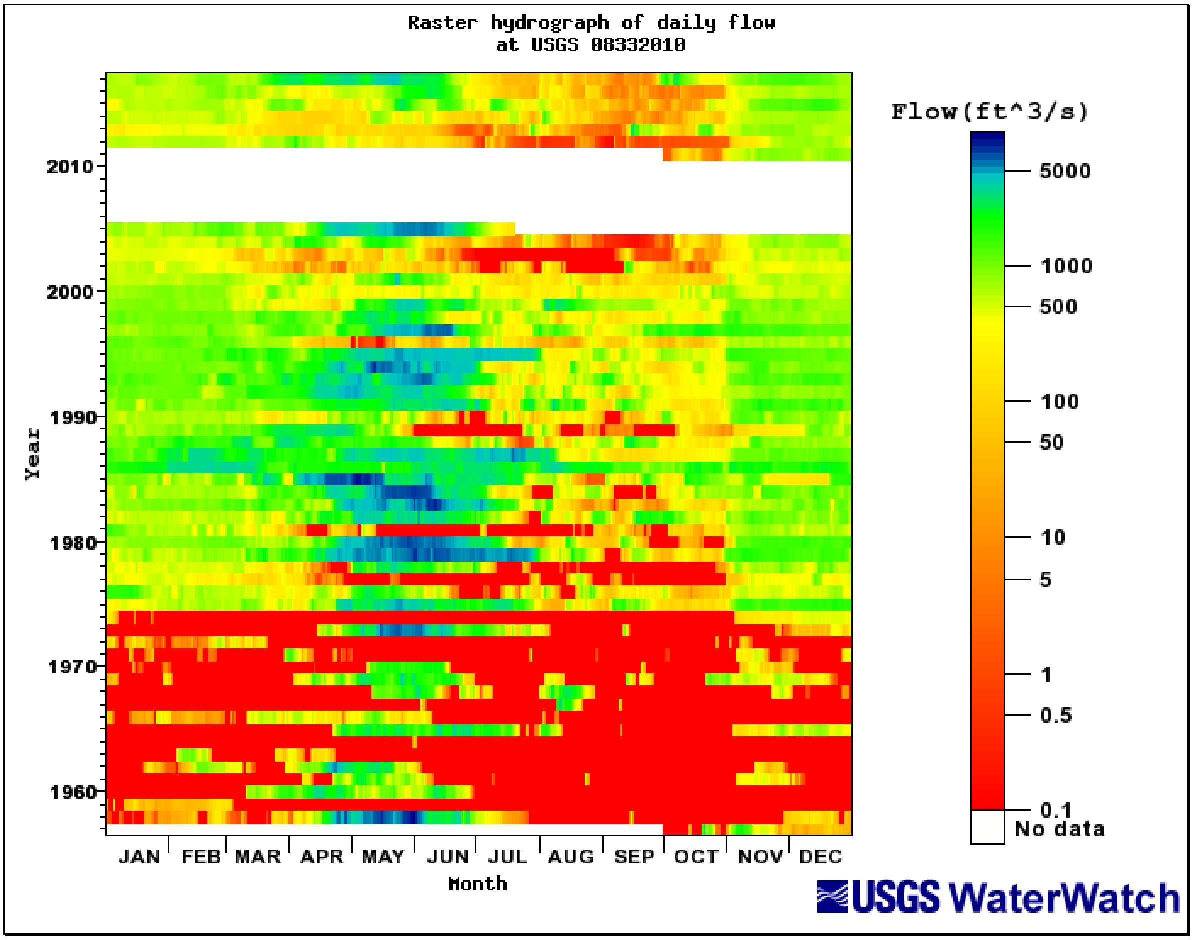


Figure 3: Raster hydrograph for the Rio Grande floodway near Bernardo (08332010): 1958 to 2017.

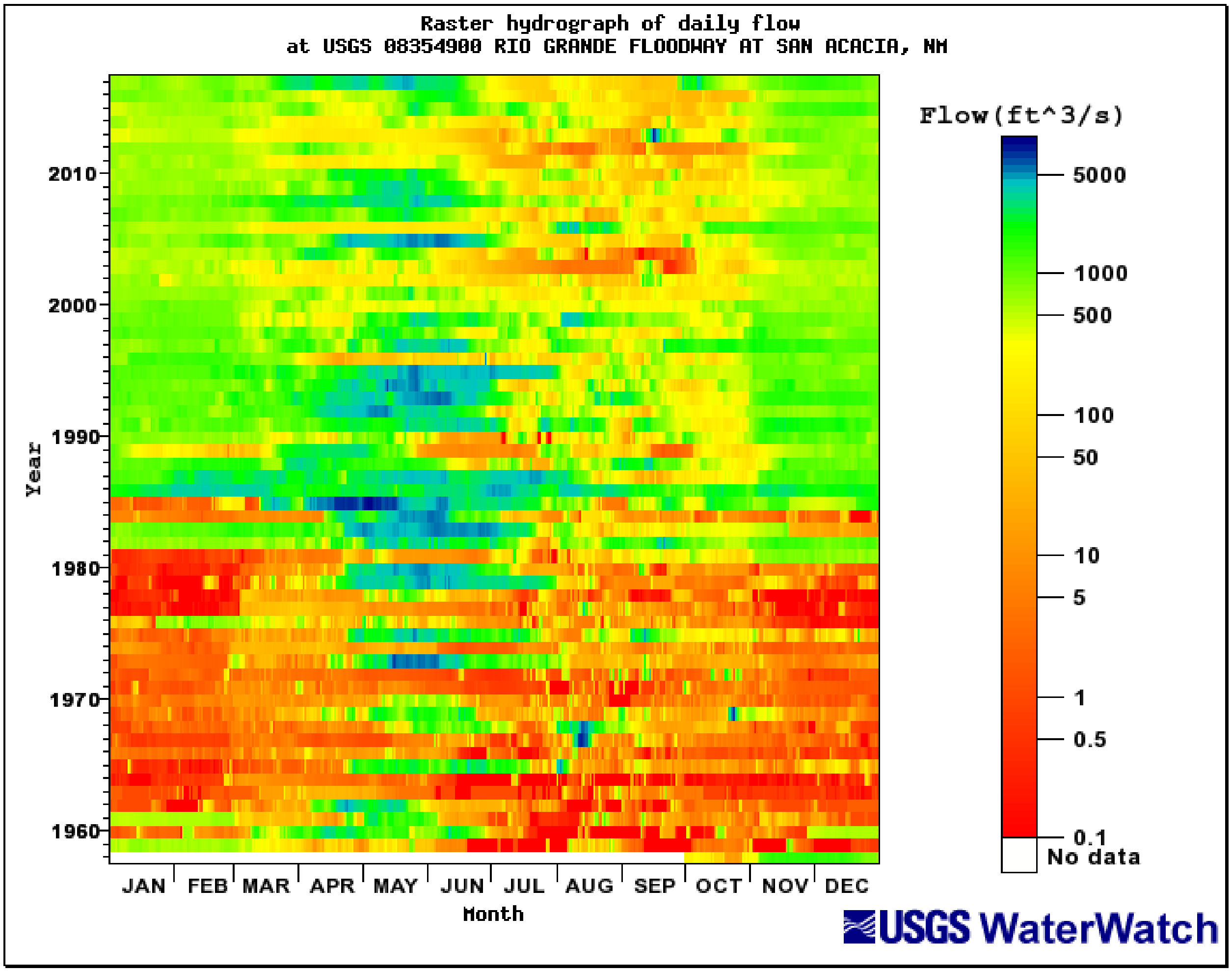


Figure 4: Raster hydrograph for the Rio Grande floodway at San Acacia (08354900): 1958 to 2017.

2.1.1. Single Mass Curves

Single mass curves are used to show changes in annual flow volume over time. The cumulative discharge is presented as a function of time in years. The slope of the line gives the mean annual discharge. Breaks in slope show changes in the flow volume. Figure 5 shows the flow mass curves of gages at Albuquerque, Isleta, Bosque Farms, Bosque, Bernardo, and San Acacia. The annual flow volume shows slight reduction in the downstream direction. The discharge mass curves are divided by the time periods shown in Table 3. The average discharge of each period is listed in Table 2. For the Albuquerque gage (08330000), the annual flow increases from 0.74 million acre-feet to 1.21 million acre-feet after 1978. A decrease in discharge between 1995 and 2010 and another decrease in discharge was found after 2010. Similar trends are found in the other stations as well.

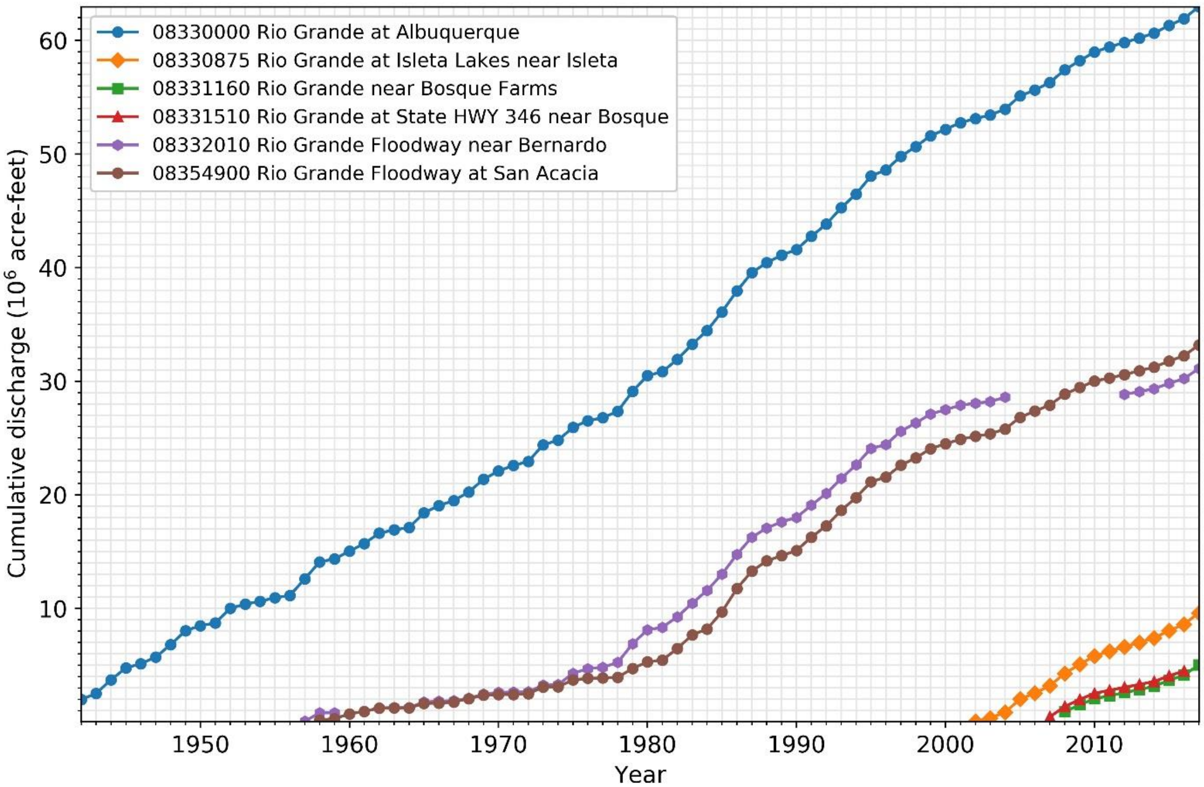


Figure 5: Single mass curves with the cumulative water discharge on the y-axis and the year on the x-axis. The Rio Puerco is not included in this figure.

Table 3: Average discharge at different time periods in million acre-feet.

Time	08330000	08330875	08331160	08331510	08332010	08354900
1958 - 1978	0.74				0.25	0.19
1978 - 1980	1.57				1.44	0.68
1980 - 1981	0.34				0.22	0.16
1981 - 1987	1.45				1.32	1.30
1987 - 1990	0.68				0.58	0.61
1990 - 1995	1.29				1.21	1.21
1995 - 2001	0.78				0.64	0.62
2001 - 2004	0.40	0.29			0.23	0.31
2004 - 2010	0.84	0.83	0.68	0.63		0.70
2010 - 2014	0.42	0.40	0.28	0.26	0.25	0.31
2014 - 2017	0.78	0.73	0.63	0.46	0.59	0.65

2.1.2. Recurrence Interval

Using gages previously mentioned, recurrence intervals were calculated and presented in the report by Klein et al. 2018a and summarized in Table 4.

Table 4: Return periods from Klein et al. 2018a.

Table 4: Discharge at different regulated flood frequencies for the study area modified from Wright (2010), MEI (2002), and Harris and AuBuchon (2016). Annual peak flow from the USGS was used in analysis.

Discharge (cfs)	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year
Albuquerque (MEI (2002))	5,410	7,600	8,940	10,100	11,600	12,600
Albuquerque (Wright (2010))	4,000	6,200	7,500	9,000	10,000	10,000
Albuquerque, 1993-2013	3,370	5,280	6,550	8,100	9,230	10,300
Bernardo (Wright (2010))	4,900	7,700	9,300	11,200	12,500	12,700
Bernardo, 1993-2013	3,290	5,610	7,090	8,820	10,000	11,100
San Acacia (Wright (2010)	7,800	12,000	14,500	17,400	19,300	20,100
San Acacia (Harris, 2016)	4,410	6,380	7,570	8,920	9,820	10,600

Days exceeding certain flow values was also examined by Klein et al. 2018a. There is data at the Albuquerque, Bernardo and San Acacia gages. The data was analyzed in water years instead of the calendar years. From Figure 6 through Figure 8 we can see that the occurrence of high flow drops after 2002. These figures have two years of data added on from the Klein et al. 2018a report.

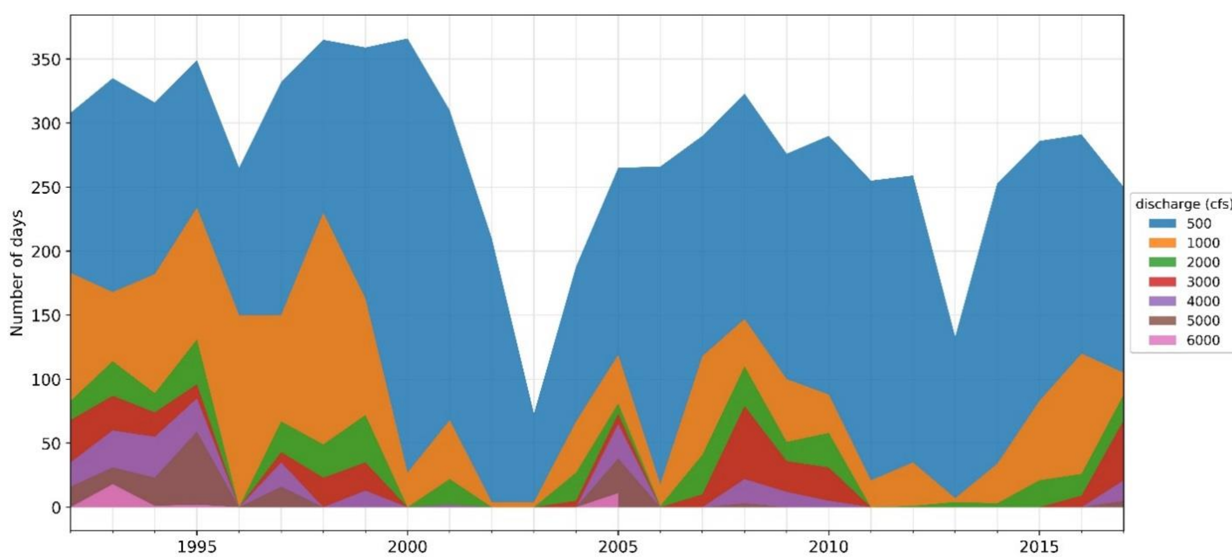


Figure 6: Graph of days exceeding flow values at Albuquerque (08330000) (modified from Klein et al. 2018a).

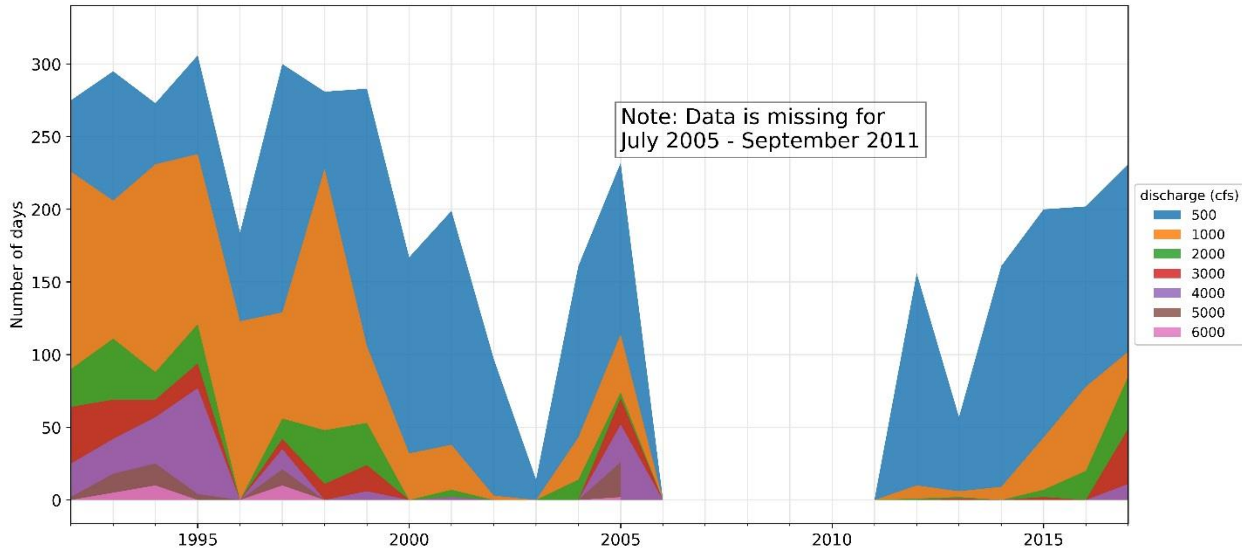


Figure 7: Graph of days exceeding flow values at Bernardo (08332010) (modified from Klein et al. 2018a).

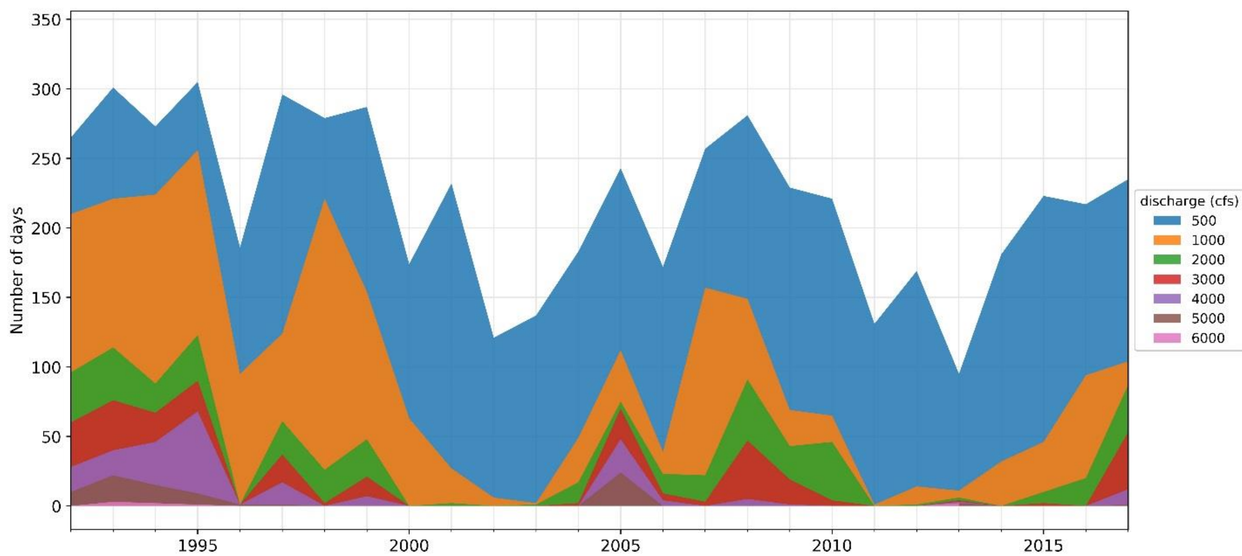


Figure 8: Graph of days exceeding flow values at San Acacia (08354900) (modified from Klein et al. 2018a).

2.1.3. Relation between flow and population of RGSM

According to Dudley et al., the population of RGSM is “closely related to the timing, magnitude, and duration of flows in spring and summer” (Dudley et al. 2016). Figure 9 shows the relation between the population density of RGSM, spring peak discharge, annual mean discharge, and occurrence of flow higher than 2000 cfs at Albuquerque. The change of fish population generally follows the magnitude of spring peak flow and the occurrence of high flow. Figure 10 shows the scatter plots of fish population vs spring peak discharge and fish population vs number of days that discharge was higher than 2000 cfs. This suggests the fish population is positively related to these two variables.

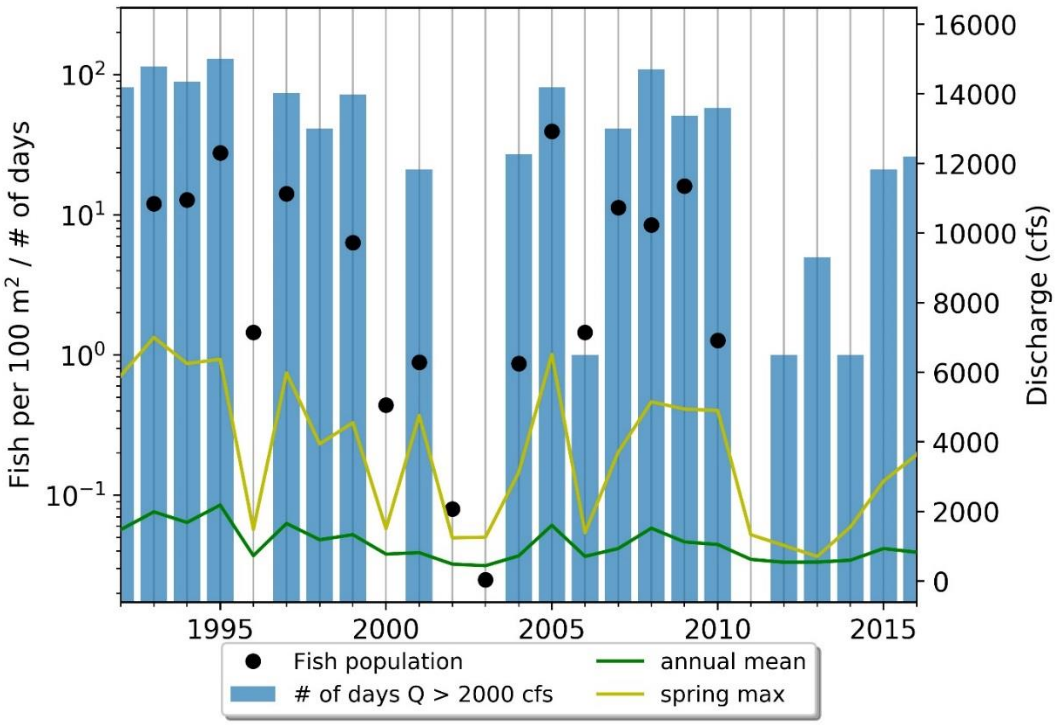


Figure 9: Population of silvery minnow vs annual mean discharge vs spring peak flow vs number of days that discharge is greater than 2000 cfs.

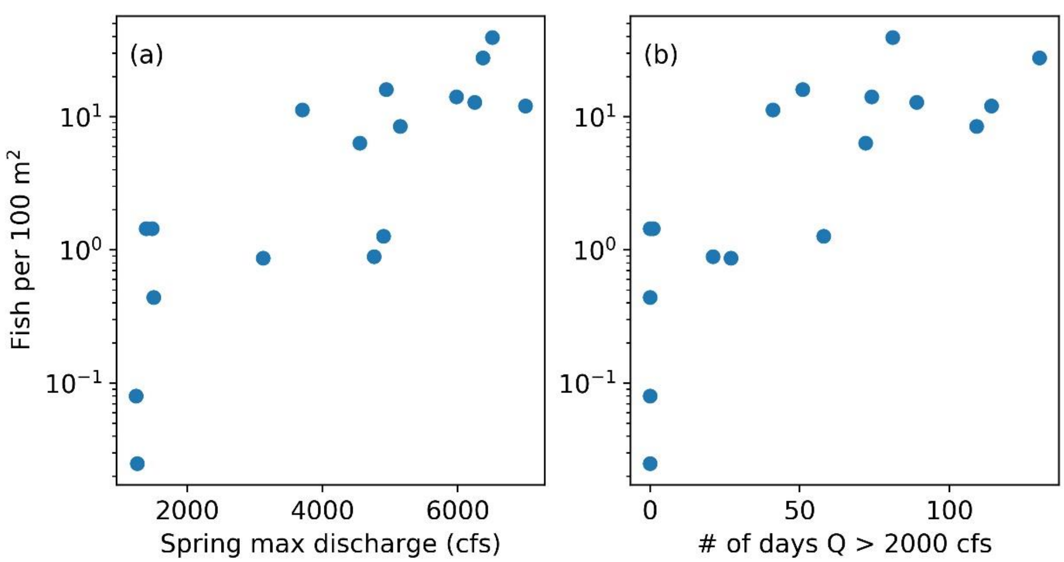


Figure 10: (a) Fish population density vs spring peak discharge, and (b) Fish population density vs number of days discharge is higher than 2000 cfs.

2.2. Precipitation

Precipitation data is collected from areas in between Los Lunas and Sevilleta. The data is from the Bosque Ecosystem Monitoring Program website (Klein et al. 2018a). The average annual and monthly data account for open and vegetated areas. The annual precipitation data summarized by the USBR report is shown in Figure 11.

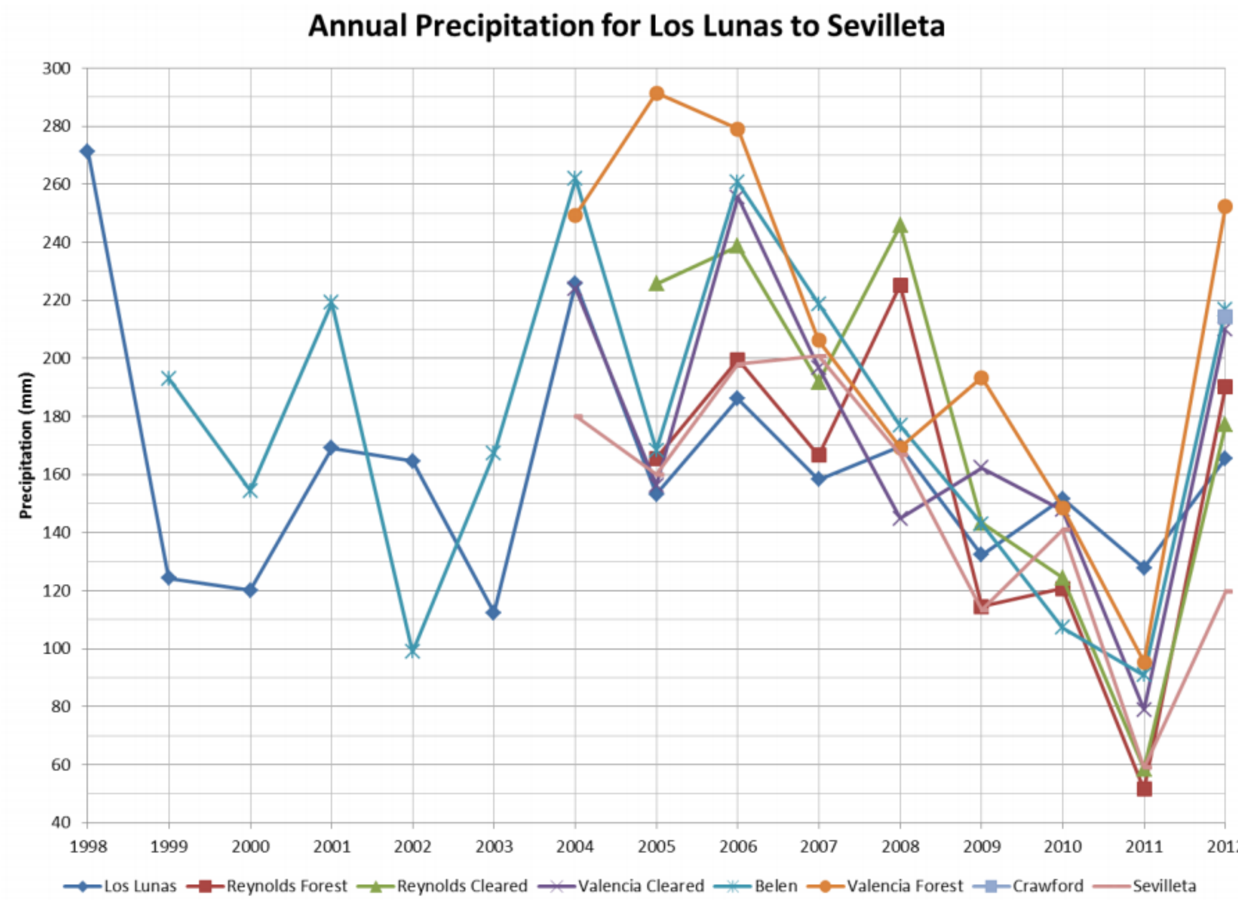


Figure 11: Average annual precipitation graph from 1998-2012 (Klein et al. 2018a).

The precipitation has a sinuous trend. It goes up and down over long periods of time. 1998, 2005 and 2012 have peaks in precipitation. The driest years are around 2002 and 2011. The monthly precipitation data summarized by USBR is shown in Figure 12.

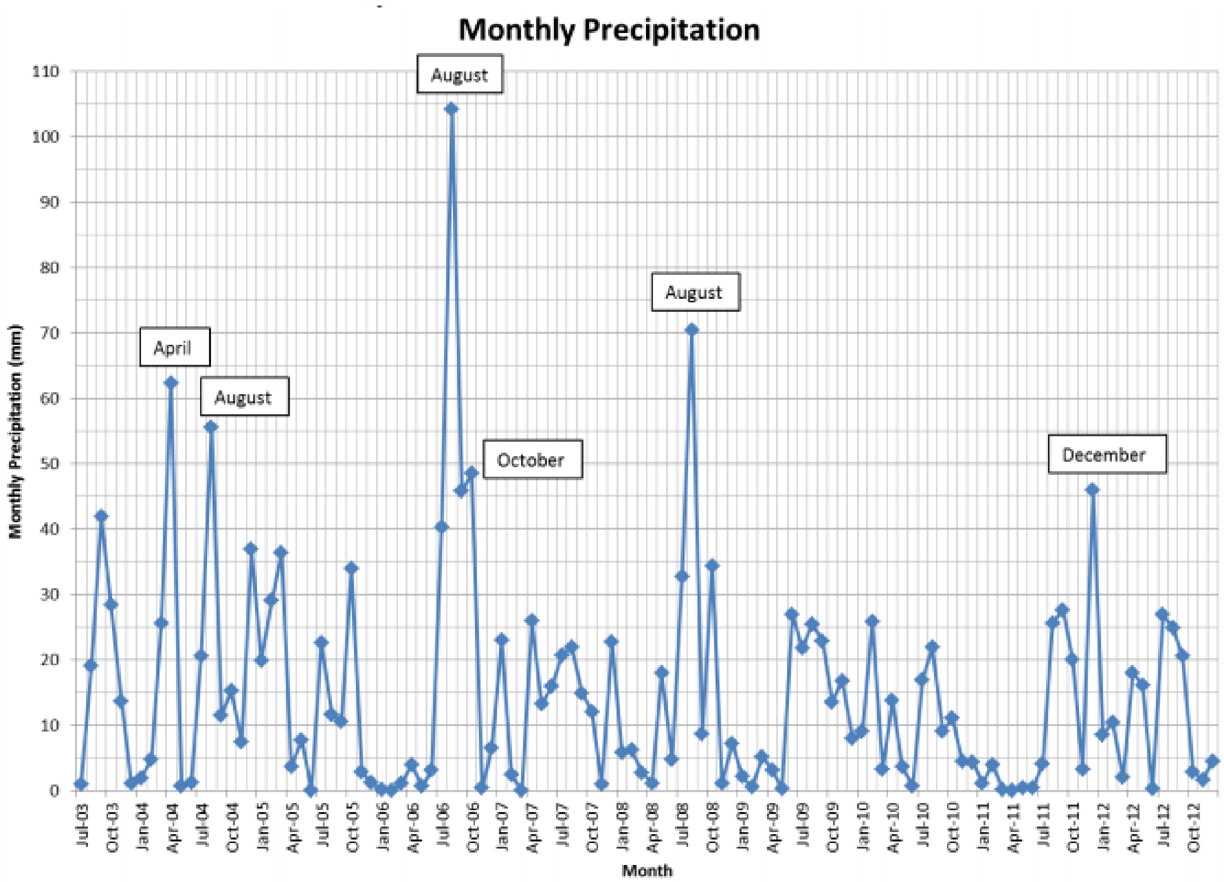


Figure 12: Monthly precipitation graph from Los Lunas to Sevilleta (Klein et al. 2018a).

The highest rainfall events tend to happen in late summer or early fall. Winter and early spring rain events still occur but are less common.

2.3. Suspended Sediment

Single mass curves can also be used to show how the tons of suspended sediment changes over time by graphing cumulative suspended sediment on the y-axis and time on the x-axis. Breaks in slope show these changes. USGS gages pertinent for suspended sediment in this reach are at the Albuquerque (08330000) gage and Bernardo (08332010) gage upstream of the Rio Puerco confluence. The Rio Puerco gage (USGS 0853000) is used for the Rio Puerco single mass curve. The data on the graph is based on annual sediment amounts. Figure 13-Figure 15 show the suspended sediment curves from Klein et al. 2018a.

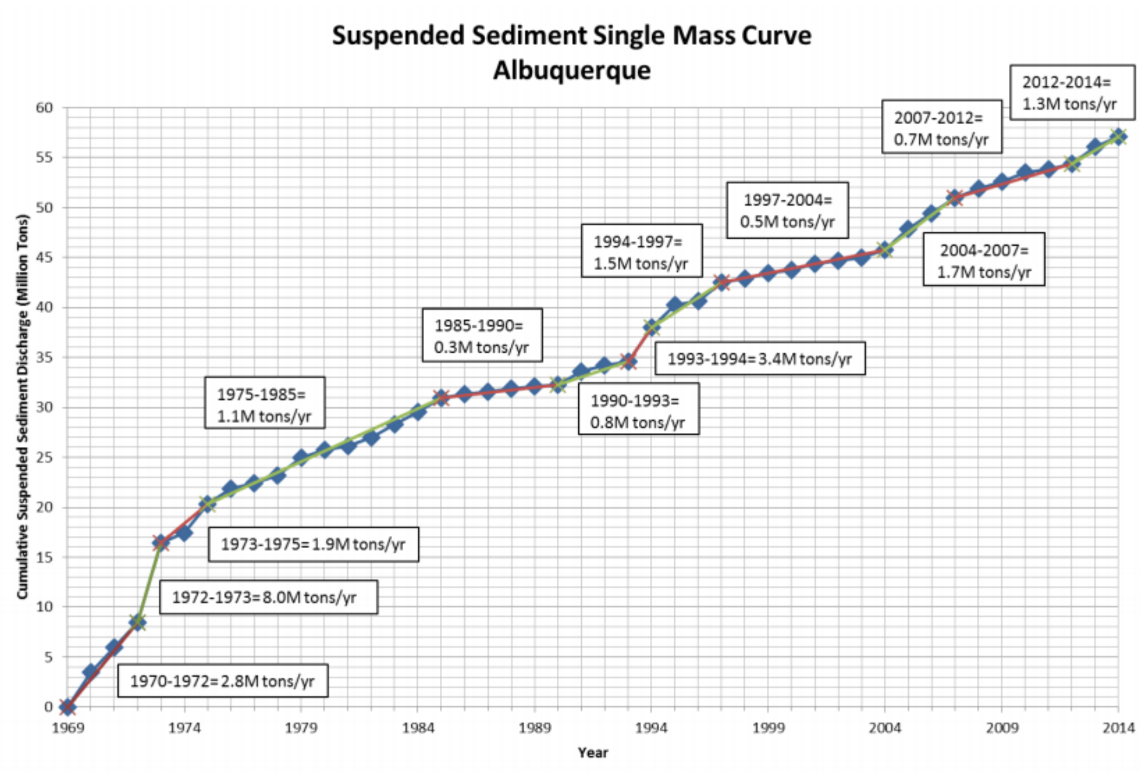


Figure 13: Single mass curve at Albuquerque (08330000) for suspended sediment (Klein et al. 2018a).

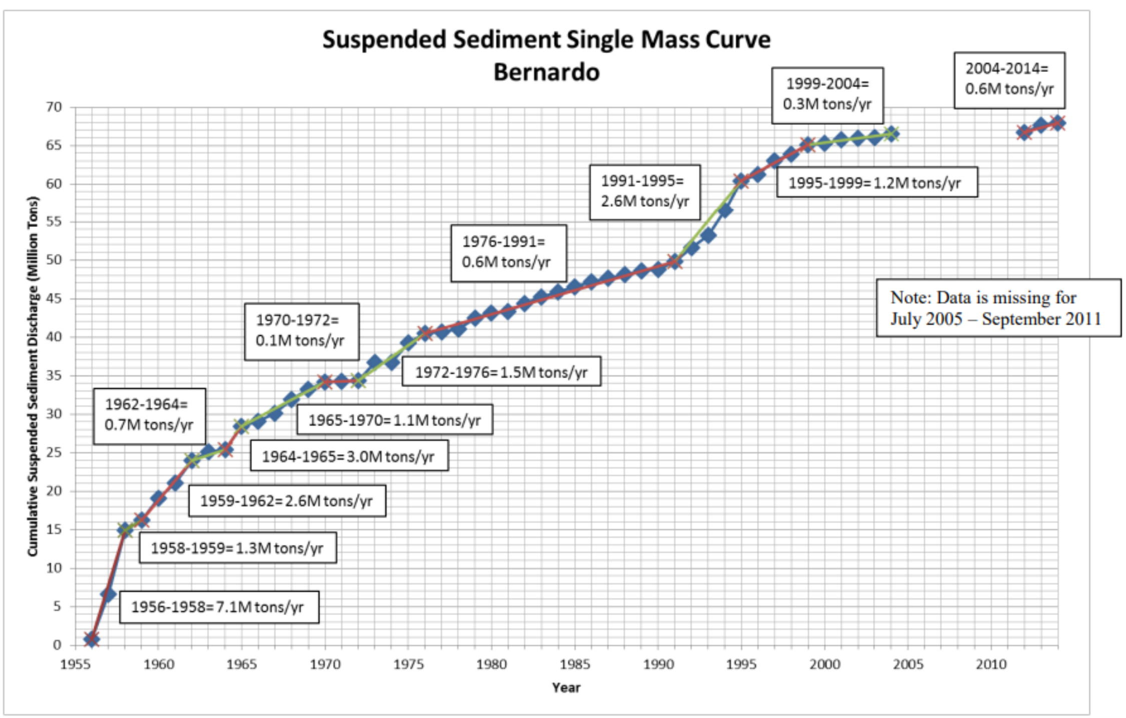


Figure 14: Single mass curve upstream of the Rio Puerco (08332010) for suspended sediment obtained (Klein et al. 2018a).

For both the Albuquerque and Bernardo gages, there is a significant decrease in suspended sediment being transport starting around the 1970's. Also, from 1991 to 1995 there was a large increase in suspended sediment which then decreased and became constant after 1995. The Bernardo and Albuquerque gage have switched back and forth in terms of which one transports more suspended sediment. From the 1970's to the mid 1980's and from the mid 2000's through 2014 the Albuquerque gage showed more sediment yield. In-between those two time periods, the Bernardo gage recorded more suspended sediment transport.

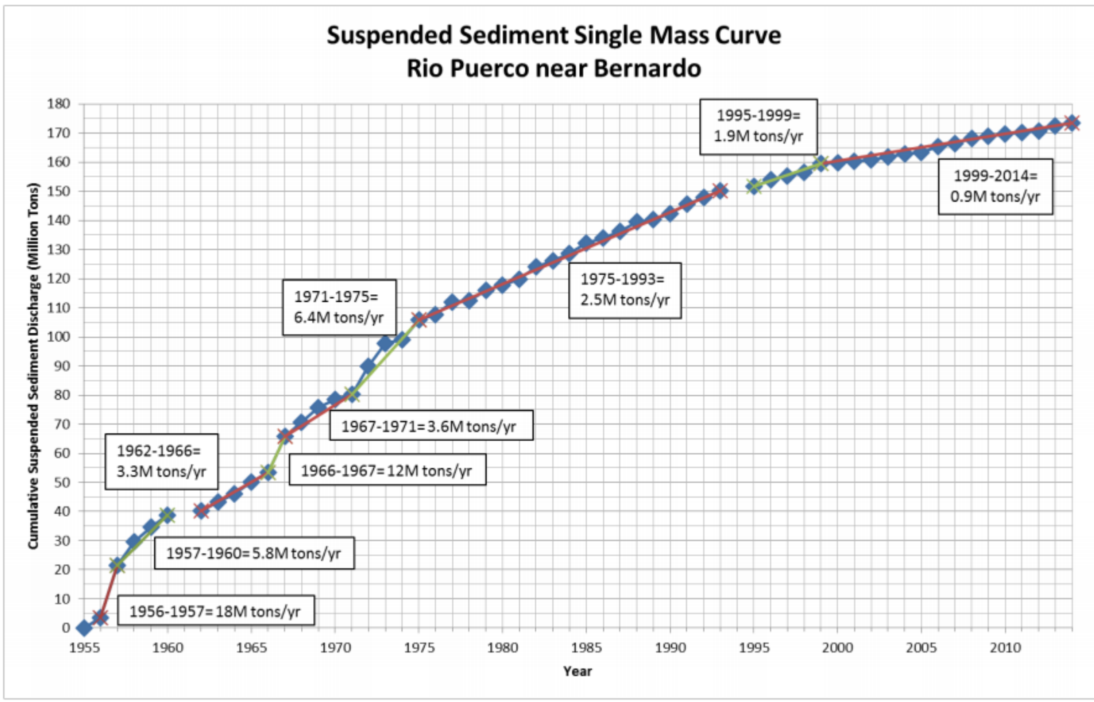


Figure 15: Single mass curve for suspended sediment on the Rio Puerco (08353000) (Klein et al. 2018a).

The Rio Puerco's sediment discharge has decreased since the 1970's. Still, it contributed 70% of the annual suspended sediment volume recorded at the San Acacia gage from the late 1970's through the early 1980's. Now it only contributes about 38% of the annual suspended sediment load (Klein et al. 2018a).

2.4. Double Mass Curves

Double mass curves are used to show how suspended sediment volumes pair with discharge volume annually. By comparing the cumulative discharge and suspended sediment, trends in how much suspended sediment per discharge change each year can be depicted. For instance, if the amount of sediment per unit discharge is the same as the previous year, the slope stays the same. When sediment and discharge change at different rates compared to the previous year, it shows up as a break in slope in the curve. For instance, in 1973 in Figure 16 there is a break in slope because there is distinct change in slope from steeper to less steep. (This figure is from Klein et al. 2018a with a couple years of data added on to the graph). With a lower slope after 1973, there is less suspended sediment per unit discharge than before. A high slope means there is a large amount of sediment per unit discharge, and a low slope means the opposite. Overall, the mean annual suspended sediment concentration per unit discharge has decreased since the 1960's (Klein et al. 2018a) because the slopes on the double mass curves have become less steep overall.

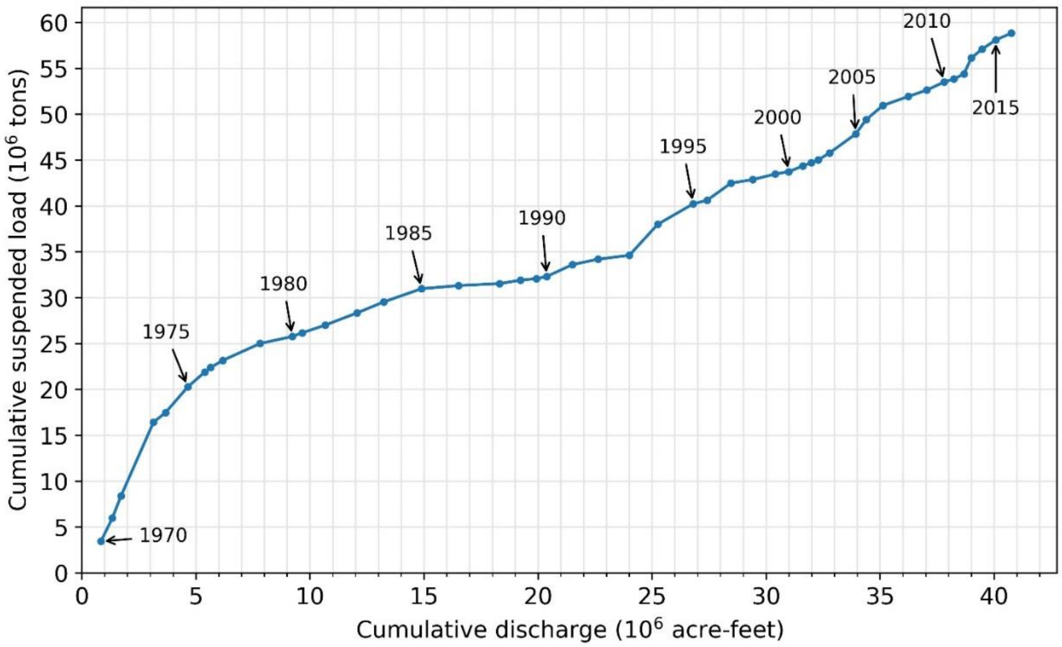


Figure 16: Double mass curve at Albuquerque gage (08330000) from 1970 to 2016 (modified from Klein et al. 2018a).

The highest concentration occurred prior to 1975 at the Albuquerque gage. It decreased from 1985 to the 1990's and then increased again.

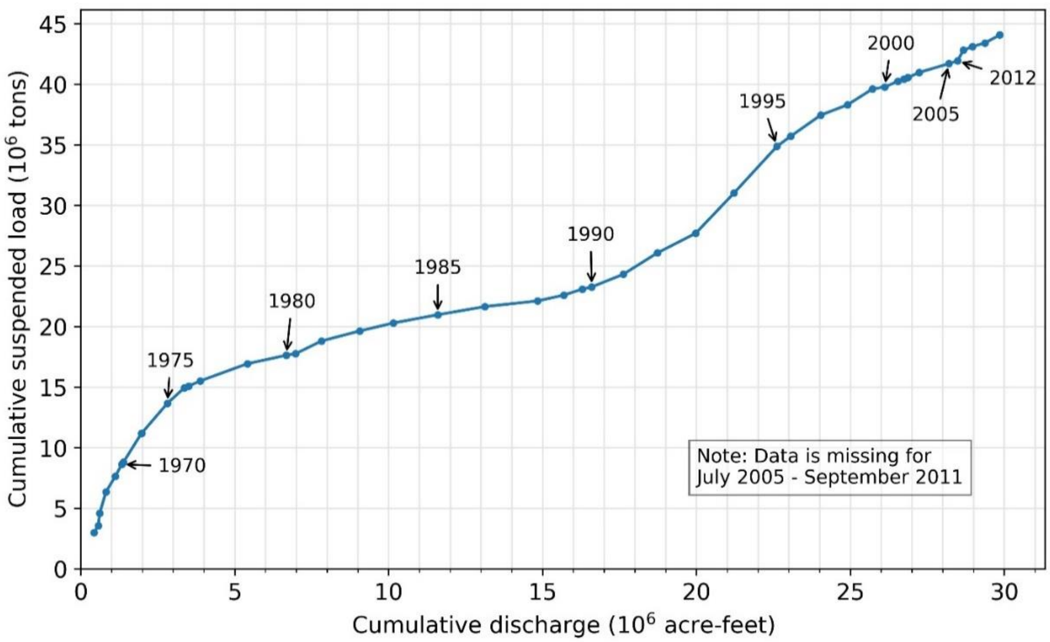


Figure 17: Double mass curve at Bernardo gage (08332010) from 1965 to 2016 (modified from Klein et al. 2018a).

The Bernardo gage shows similar results as the Albuquerque gage. Although, there is a more distinct increase in sediment concentration in the early 1990's in the Bernardo gage.

2.5. Total Load

This section is a presentation of calculations, methods and results from the USBR report. Total load was calculated using the Bureau of Reclamations Automated Modified Einstein Procedure (BORAMEP) with sediment data from the San Acacia gage downstream of the SADD. This is the only gage USBR used to calculate the total load, so it is the only data available for the Rio Puerco Reach. The calculations using BORAMEP included the early 1990's through 2010 (Klein et al. 2018a).

The San Acacia gage shows that the predominant material being transported is sand. Silts and clays are transported less than sand, and gravel is less than 1% of the total load. Also, sand loads are 5 times greater during summer or fall rain events compared to spring snow-melt runoff periods. Gravel moves more during spring snow-melt periods (flows reach above 2000 cfs), whereas sand and smaller particles move during both spring and summer peak flow periods (Klein et al. 2018a).

In Klein et al. 2018a, the effective discharge of 750 cfs was calculated from the total load rating curve trendline. The amount of sediment transported for each discharge was forecasted with the trendline and divided into bins. The results, as shown in Figure 18, show that most sediment is moved at 750 cfs. Even though more material is moved during larger flows, these flows occur infrequently so less sediment is moved at higher flows.

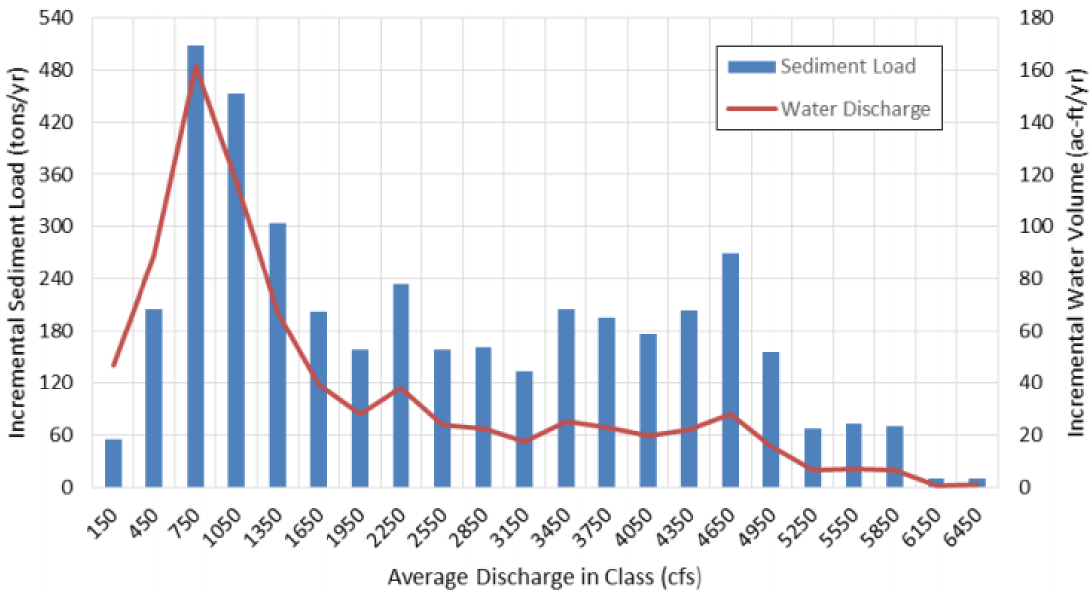


Figure 18: Effective discharge curve at San Acacia from 1995-2010 (Klein et al. 2018a).

3. Geomorphic and River Characteristics

Middle Rio Grande has been changing due to the dynamic of flow and sediment regimes, and the influence of human activities. In this section, geomorphic changes on a temporal scale were analyzed. The analysis was conducted based on aerial photos, cross sectional surveys at agg/deg lines and rangelines, and HEC-RAS simulations. Sinuosity, active channel width, bed elevation, channel volume, and hydraulic variables changes are presented in this section.

3.1. Sinuosity

USBR collected data on sinuosity starting in the 1930's through 2016. Sinuosity has been slightly decreasing over time for the entire reach from the Rio Puerco to the San Acacia diversion dam since the 1930's.

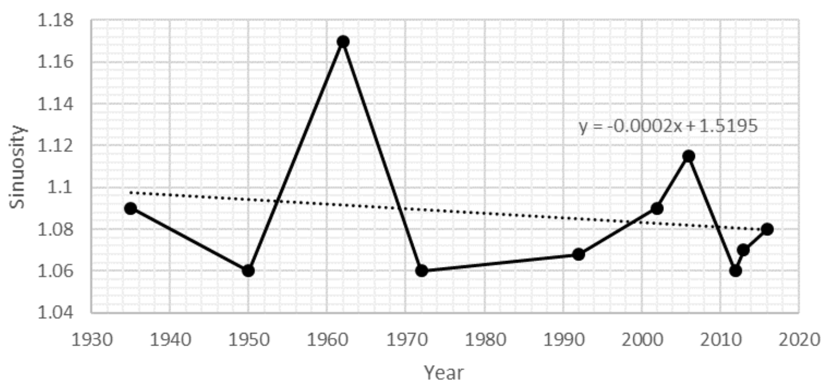


Figure 19. Trend of sinuosity from the Rio Puerco confluence to the San Acacia diversion dam. A negative slope of 0.0002 is observed. The data for this graph was extracted from a graph provided by USBR (Klein et al. 2018a).

Figure 19 show sinuosity in the Rio Puerco to SADD with an overall slightly negative slope. There is a large spike in 1962 and a smaller spike near 2008. There is an increase in sinuosity from the 1970's to the second peak, but then it drops greatly in 2012 and starts increasing again after that. Overall, the sinuosity is near one which indicates a very straight channel.

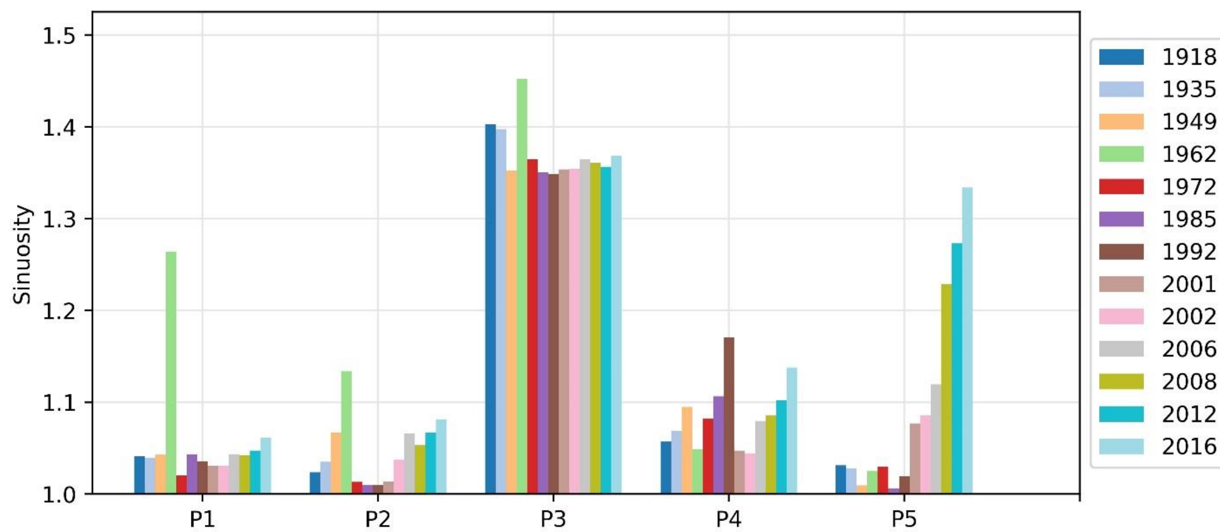


Figure 20: Sinuosity at subreach scale.

Subreach P3 is the most sinuous, which is most likely due to geological constraints. It is unkonwn why there is a spike in sinuosity in 1962.

3.2. Width

The width has generally decreased over time since 1918 in this reach due to channelization, reduction in peak flows, upstream sediment reduction and vegetation encroachment (Culbertson and Dawdy 1964; Crawford et al. 1993; Berry and Lewis 1997; Bauer 2000; MEI 2002; Bauer and Hilldale 2006; Tashjian and Massong 2006; Parametrix 2008; Bauer 2009; Makar 2010; Makar and AuBuchon 2012; Baird 2014 in Klein et al. 2018a). This has made the widths more uniform as well (Crawford et al. 1993; Parametrix 2008; Makar and AuBuchon 2012 in Klein et al. 2018a).

The active channel width is analyzed in detail on a temporal scale between 1918 and 2016. The active channel is defined as non-vegetated channel and is digitized by the USBR's GIS (Geographic Information System) and Remote Sensing Group from the aerial photographs. Measurement of the active channel width is performed by clipping the agg/deg line coverage with the active channel polygon. The average width for each subreach is calculated by averaging the width of all agg/deg lines in the subreaches (Figure 21).

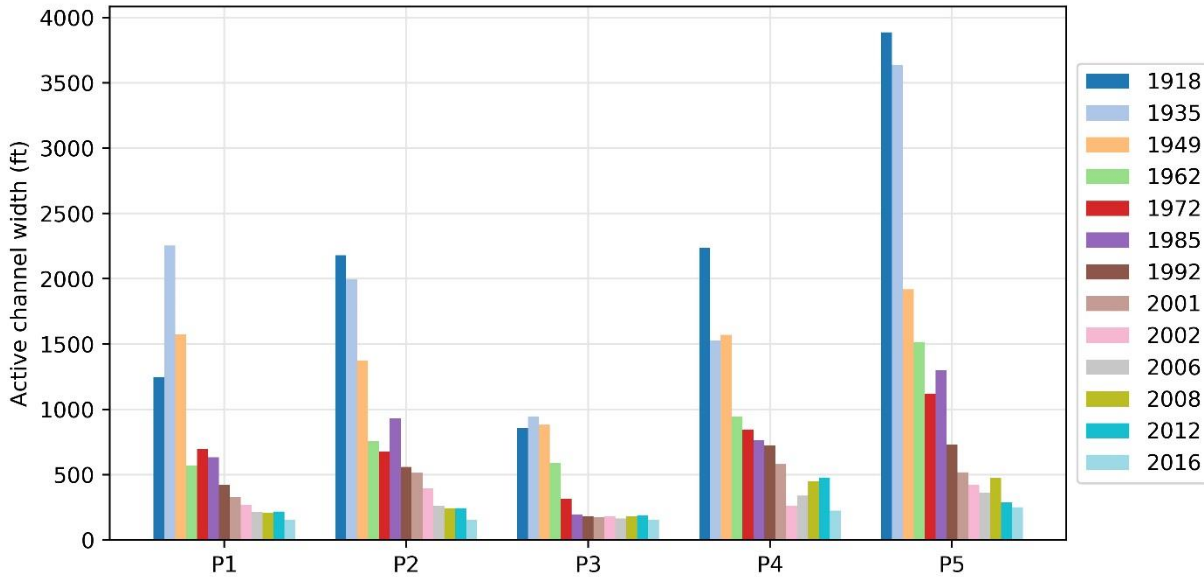


Figure 21: Reach averaged active channel width.

For each subreach, the width has decreased since the early 1900's. The decline in channel width from 1918 to 1962 is the most significant and the biggest decrease is found at subreach P5: 2300 feet over 44 years. There is also a major drop in P5 that occurred from 1935 to 1949. This suggests the width was greatly impacted by the construction of the diversion dam in 1934. P3 is relatively stable because of the geologic constriction. The widths across subreaches tend to drop off dramatically after 1949 because channelization systems started around the 1950's (Easterling Consultants LLC 2015). The decrease in width between 1918 and 1985 is due to the vegetation encroachment on the right bank as seen in the aerial images. The channel and vegetation reach a balance after 1985. Subreach P4 changes back and forth between single-thread and double-thread so we can see the width goes up and down after 2001. The change might be due the fluctuation of sediment supply from Rio Salado since subreach P4 is located right downstream of the Rio Salado.

3.3. Braiding

The number of channels at each agg/deg line is measured from digitized planforms. Figure 22 shows the average number of channels of each subreach.

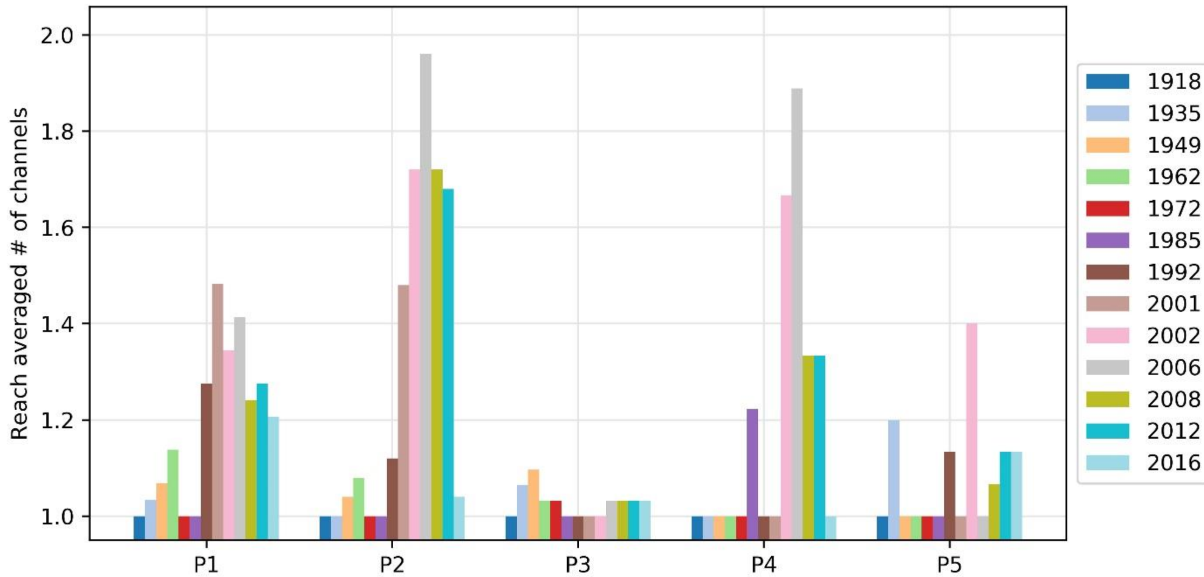


Figure 22: Average number of channels at each subreach.

From the aerial photographs it can be seen that the Rio Puerco Reach was braided between 1935 to around 2005. After 2005 the channel has become anabranching. The number of channels is low for 1962, 1972, and 1982, because the digitized planforms for these years did not capture the bars or islands in the channel. 2002 and 2006 have some of the highest numbers of channels across all subreaches. Braiding has generally decreased from 2002-2012, which makes sense because sinuosity has increased and the slope has decreased as shown in Figure 20 and Figure 26 respectively. In terms of subreaches, P2 and P4 had the most channels throughout time.

3.4. Bed Elevation

The mean bed elevation is used to compare the change in long profile in this report. Cross-section geometry models along agg/deg lines were developed by the Bureau of Reclamation. The geometry models are available for 1962, 1972, 1992, 2002 and 2012. For the models prior to 2012, the cross-section geometry is captured using photogrammetry techniques. The 2012 model is from LiDAR (Klein et al. 2018a). In addition, an underwater prism was developed (Varyu 2013). All the models were using the NAV88 vertical datum.

Figure 23 shows the long profiles of 1962, 1972, 1992, 2002, and 2012. Significant degradation between 1972 and 1992 is observed. Figure 24 shows the change in mean bed elevation for each subreach.

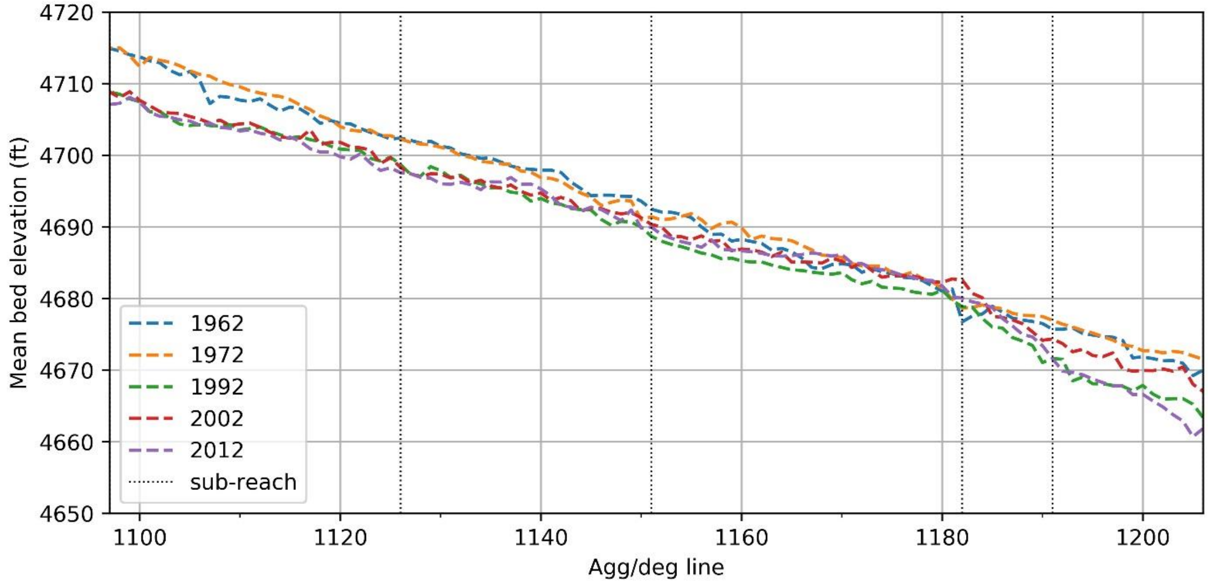


Figure 23: Long profiles for 1962, 1972, 1992, 2002, and 2012.

The long profiles degraded 5.2, 3.1, 3.0, 3.4, and 6.4 ft. at P1, P2, P3, P4, and P5 respectively, from 1972 to 1992. Between 1992 and 2002, the bed elevation rose 0.4, 0.5, 1.8, 2.3, 3.5 ft. at P1, P2, P3, P4 and P5 respectively. From 2002 to 2012, the river bed degraded. The amount of degradation ranged from 0.1 ft. (P2) to 4.4 ft. (P6).

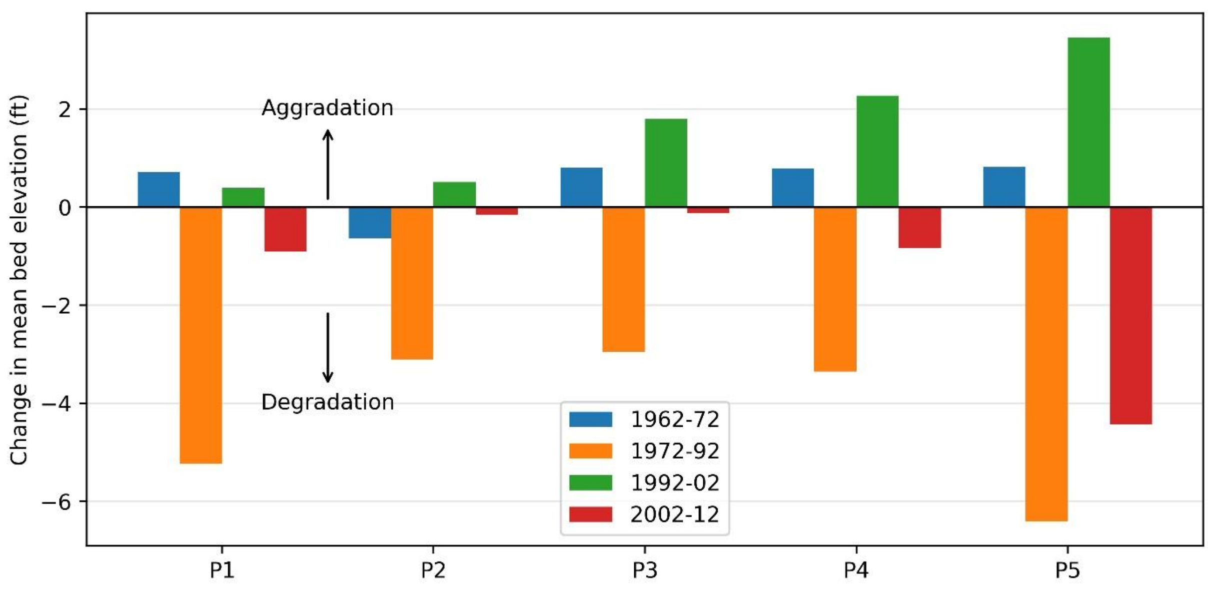


Figure 24: Change in bed elevation.

3.5. Volume Change

The change in main channel sediment volume for the time periods 1962 to 1972, 1972 to 1992, 1992 to 2002, and 2002 to 2012 is analyzed. This analysis follows a procedure by Varyu (2013) which provides an example of how to calculate the volume change. The extent of main channel is determined based on banklines. Banklines are given in the geometry models and are where the active channel intersect the agg/deg line. Due to the dynamic nature of the channel, banklines are likely to shift from year to year. The portion of the cross section within the outer-most right and left location of the banklines from two input datasets are defined as the main channel. The volume change is calculated as the difference in cross section area between two years multiplied by the length. The length is determined as half of distance of a cross section to its upstream cross section plus one-half the distance to the downstream cross section.

Figure 25 presents the main channel volume change of each subreach. The change generally follows the trend in mean channel bed elevation.

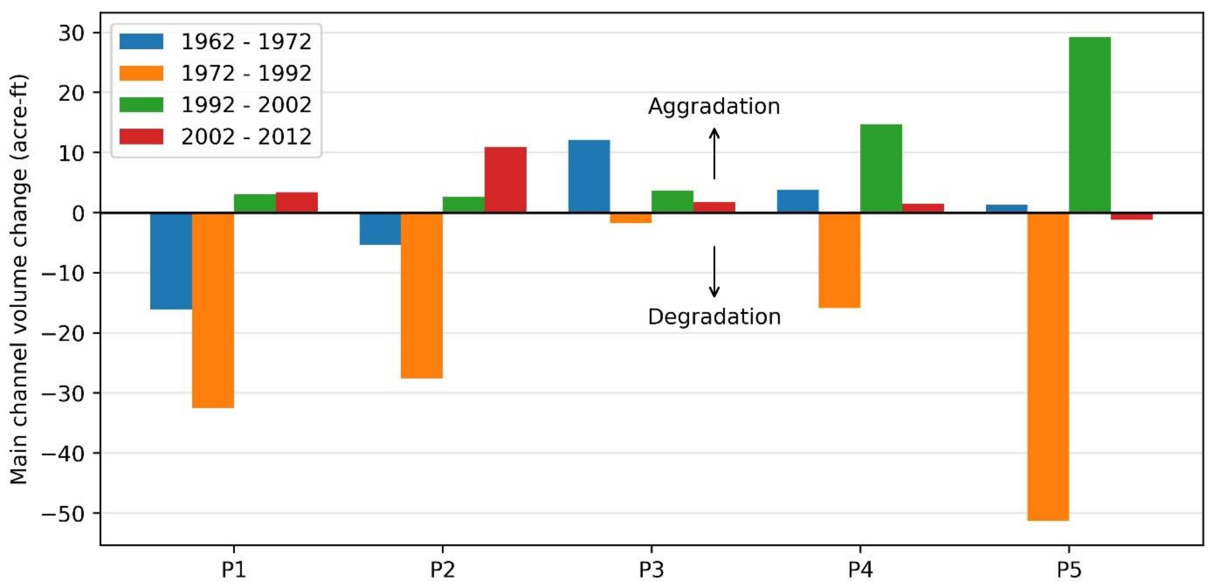


Figure 25: Change in main channel volume.

From 2002 to 2012, most of the reaches show aggradation based on volume change but degradation based on the elevation change. Therefore, the channel is narrowing and incising.

3.6. Bed Material

Bed material samples were collected at rangelines that differ from the agg/deg lines. These rangelines don't date back as far as the agg/deg lines and are also spaced out further. They are used in this analysis because bed material has been surveyed in these rangeline cross-sections. The sediment samples are grouped by decade and the statistical summary of the grain size is shown in Table 6. Overall, the grain size has increased over time. The typical grain size is medium sand at P1, P2, and P3. The gravel found at P4 and P5 is likely coming from Rio Salado (Easterling Consultants LLC 2015).

Table 5: Grain size statistics from the bed material samples in Rio Puerco reach.

	Subreach	Min (mm)	Max (mm)	Mean (mm)	# of samples	# in sand	# in gravel
2000s	P1	0.35	0.37	0.35	4	4	0
	P2	0.14	0.35	0.3	7	7	0
	P3						
	P4	0.35	2.58	1.47	2	1	1
	P5	0.12	0.3	0.19	8	8	0
2010s	P1	0.34	0.35	0.34	2	2	0
	P2	0.36	0.38	0.37	2	2	0
	P3	0.35	0.41	0.38	2	2	0
	P4	13.08	13.08	13.08	1	0	1
	P5	0.56	7.21	1.26	10	9	1

3.7. Flow Depth, Velocity, Width, Wetted Perimeter and Slope

Flow depth, velocity, width, wetted perimeter, and slope are obtained by using HEC-RAS 5.0.3 with the discharge of 3,000 cfs. The flow was chosen based on discussion with USBR. The flow of 3000 cfs is around the mean flow for a spring runoff peak based on a report by MEI in 2006. See section 4.1 for more details. For future considerations, using the effective discharge of 750 cfs may be a viable option for these simulations. Also, the flow of 3000 cfs filled the channel so it was easy to get good data for these parameters. Available years of analysis with HEC-RAS include 1972, 1992, 2002, and 2012. Slope and the average values of depth, velocity, width, and wetted perimeter at subreach scale are plotted in Figure 26. The change between ranges of years is summarized in Table 6.

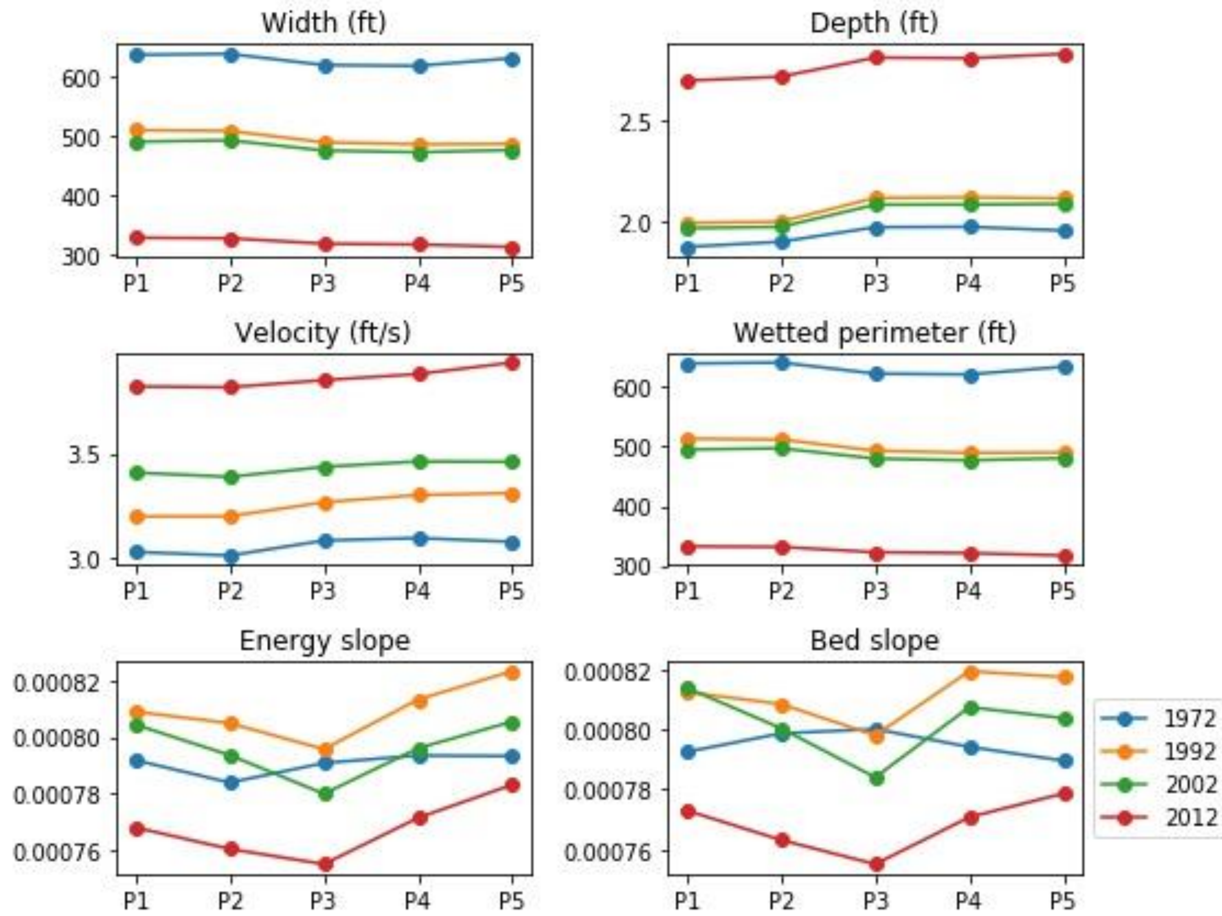


Figure 26: Width, depth, velocity, wetted perimeter, energy slope, and bed slope at each subreach for 1972, 1992, 2002, and 2012 at 3000 cfs.

A continuous decrease in width and increase in velocity was found. The widths and wetted perimeter have decreased about 300 ft. since 1972. The average velocity increased from 3.0 ft/s to 3.8 ft/s. The flow depth increased between 1972 – 1992 and 2002 – 2012, while decreasing between 1992 and 2002. It appears that channel degradation causes the increase in depth and aggradation causes a decrease.

The slope increased from 1972 – 1992 and decreased after 1992. Subreach P3 has the mildest slope.

From 2002-2012 the slope decreases as shown in Figure 26. A braided channel is generally steeper than a single sinuous channel (Julien 2002), so it is expected that the channel becomes more sinuous like it does when the slope decreases from 2002-2012 as shown in Figure 26. During this time period, the channel also becomes less braided as seen in Figure 22 which supports the fact that it becomes more sinuous.

Table 6: Rio Puerco reach channel geometry temporal change summary (+: increase in parameter value; -: decrease in parameter value).

Reach	Year	Width	Bed slope	Depth	Velocity
P1	1972 - 92	-	+	+	+
	1992 - 02	-	+	-	+
	2002 - 12	-	-	+	+
P2	1972 - 92	-	+	+	+
	1992 - 02	-	-	-	+
	2002 - 12	-	-	+	+
P3	1972 - 92	-	-	+	+
	1992 - 02	-	-	-	+
	2002 - 12	-	-	+	+
P4	1972 - 92	-	+	+	+
	1992 - 02	-	-	-	+
	2002 - 12	-	-	+	+
P5	1972 - 92	-	+	+	+
	1992 - 02	-	-	-	+
	2002 - 12	-	-	+	+

3.8. Geomorphic Conceptual Model

Massong et al. (2010) developed a channel planform evolution model for the Rio Grande. The sequence of the planform evolution is outlined in Figure 27.

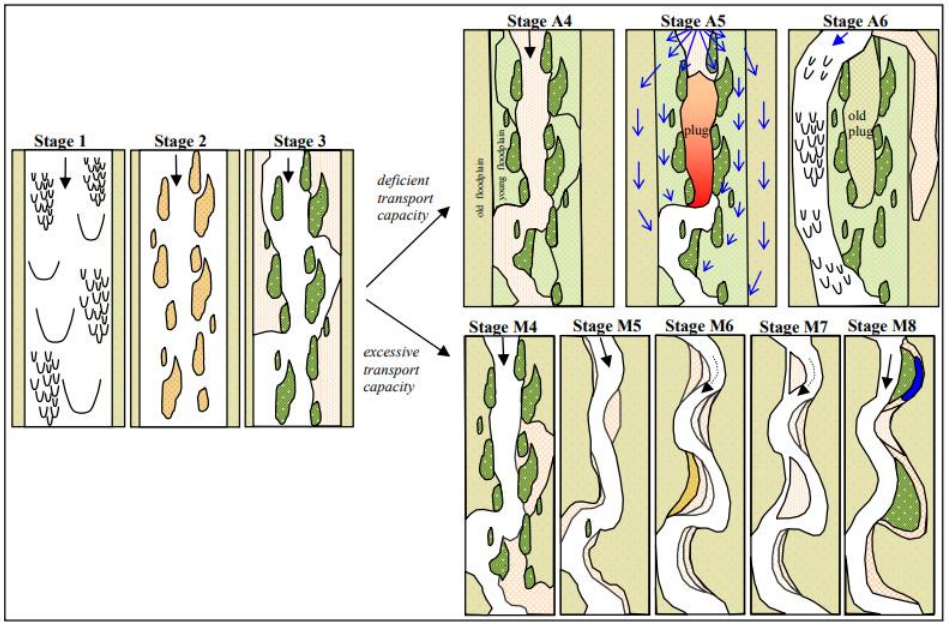


Figure 27: Planform evolution model from Massong et al. (2010). The river undergoes stages 1-3 first and then A4-A6 or M4-M8 depending on the transport capacity.

Stages 1-3 are generally more braided and have a wider planform than later stages. Stage 1 starts with bedforms, then during drought periods stage 2 occurs. Sedimentation and mid-channel bars result in stage 2 due to low flows and deficient transport capacity. Stage 3 occurs when vegetation forms on the mid-channel bars and islands. In the rest of the stages, the river becomes much more channelized. If there is a deficient transport capacity (driven by a reduction flow or sediment supply, or both), A4-A6 occur. In A4-A6 the excess amount of sediment settling on the river bed forms plugs and causes avulsions. If there is an excessive transport capacity, M4-M8 occur. M4-M8 are relevant to the Rio Puerco Reach because it has an excessive transport capacity (Massong et al. 2010).

The entire reach has undergone or is undergoing stages 1-3. Stage 1 and 2 occurred on a large amount of the Middle Rio Grande from 1999-2004. In 2002, low flows allowed vegetation to encroach on the bars, and in 2005, high flows provided an ample supply of water for vegetation to establish, thus forming stage 3 (Massong et al. 2010). The latest classification of the Rio Puerco reach has been M5/M6. USBR assinged planform stages to the Rio Puerco reach over multiple years based on aerial photography in their report from 2018. Their results are in shown in Table 7.

Table 7: Planform classification by stages (Klein et al. 2018a).

Table 15. Channel Classification for the Rio Puerco to San Acacia geomorphic reach

Years	Massong et al. (2010)	Schumm (1977, 1981)
1918	1	2
1935	1	4
1949	1	4
1962	2	3
1972	3/2	2/3
1985	3	2/3
1992	3	8
2002	M4	7
2012	M5/M6	7
2016	M5/M6	7/8

Using these years of data and the classification from Massong et al. (2010), a conceptual model was formed. The intent of this is to understand how the river is changing and where it will end up in the future. The model is formed from a plan view and cross-sectional view of a typical cross-section, and presented with the stages assigned by Klein et al. (2018a). The conceptual geomorphic model for this reach was formed using agg/deg line 1190 and spans from 1962-2016. The plan view was obtained using GIS, and the cross-section was from HEC-RAS.

The conceptual model only dates back to 1962 for a few reasons. First, aerial photography was not available before 1936. Also, the years of cross-sectional data analyzed with HEC-RAS include 1936, 1952, 1962, 1972, 1992, 2002 and 2012. Although there are seven year of available data, the analysis could only start with 1962. Determining which agg/deg cross-section was which before 1962 was difficult because the surveys were not consistent. This is due to agg/deg lines established in 1962 (Posner 2017).

The cross-sections at agg/deg line 1190 from 2016 data was acquired from AutoCAD from rangeline RP-1190 which is in the same location as agg/deg line 1190. The RP-1190 data does not cover as much distance because the survey was not as extensive as the agg/deg lines in previous years. A comparison of the results are shown in Figure 28.

Figure 29 and Figure 30 show the conceptual model with the cross-section and plan views.

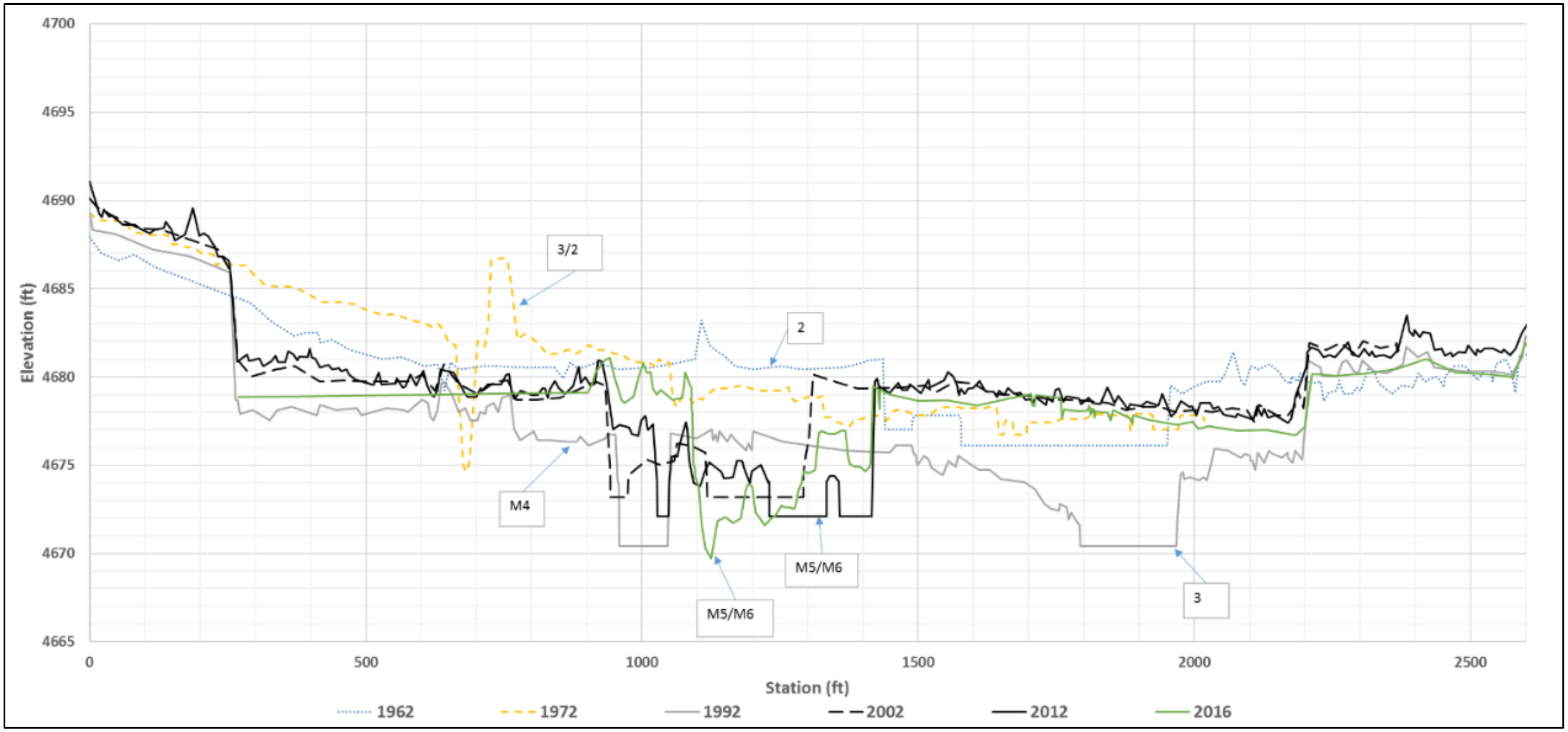


Figure 28: Comparison of cross-section 1190 from 1962-2016. Each stage classified by USBR is in a box and has an arrow pointing to the cross-section that it describes. These cross-sections are not compared after station 2600 because it is far away from the main channel. Also, there is very little variation in that area from year to year.

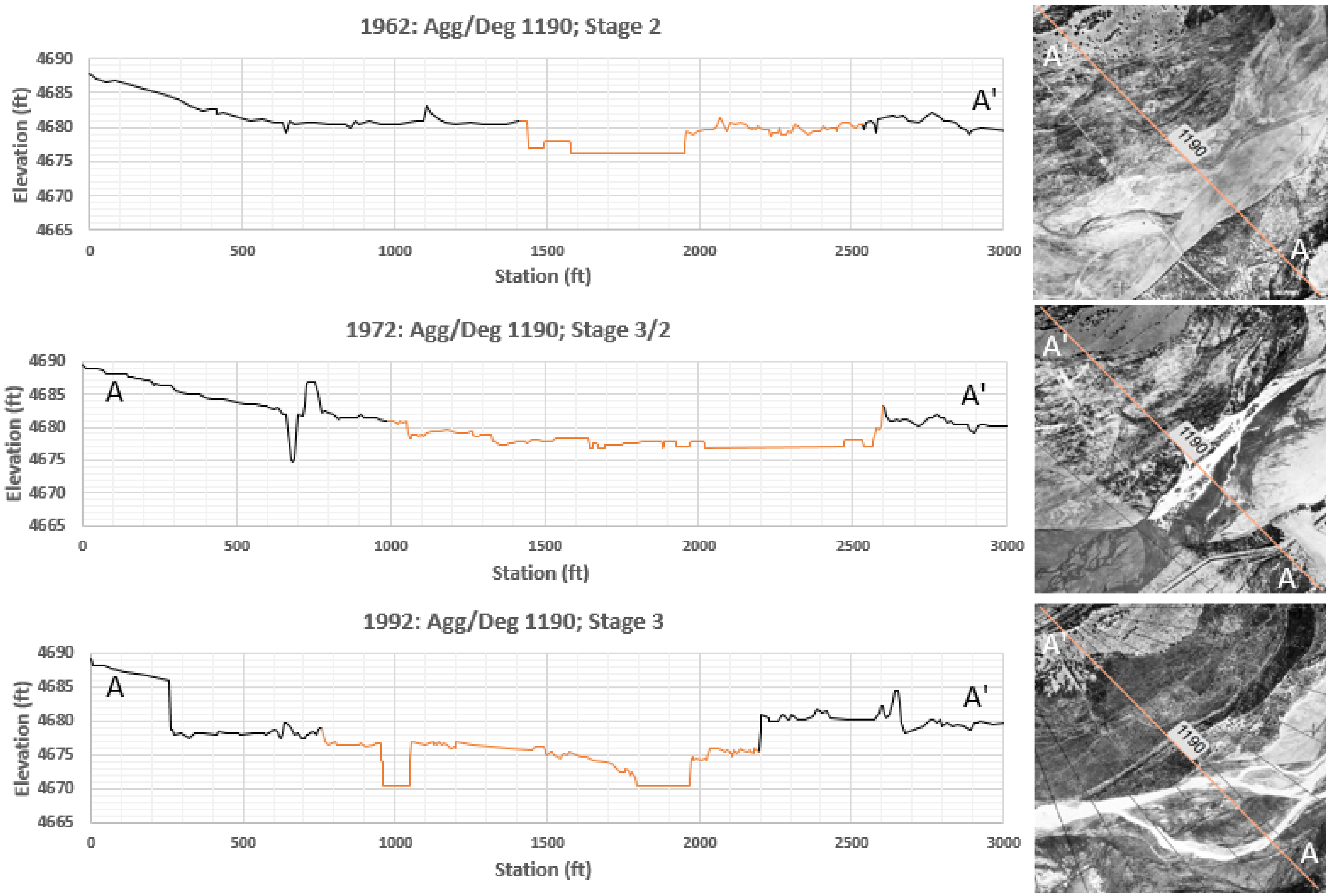


Figure 29: 1962, 1972 and 1992 cross-section and planform views (planform to the right of each corresponding year). A denotes the left bank and A' denotes the right bank. The active channel is in orange and the channel classification is denoted at the top of the graph.

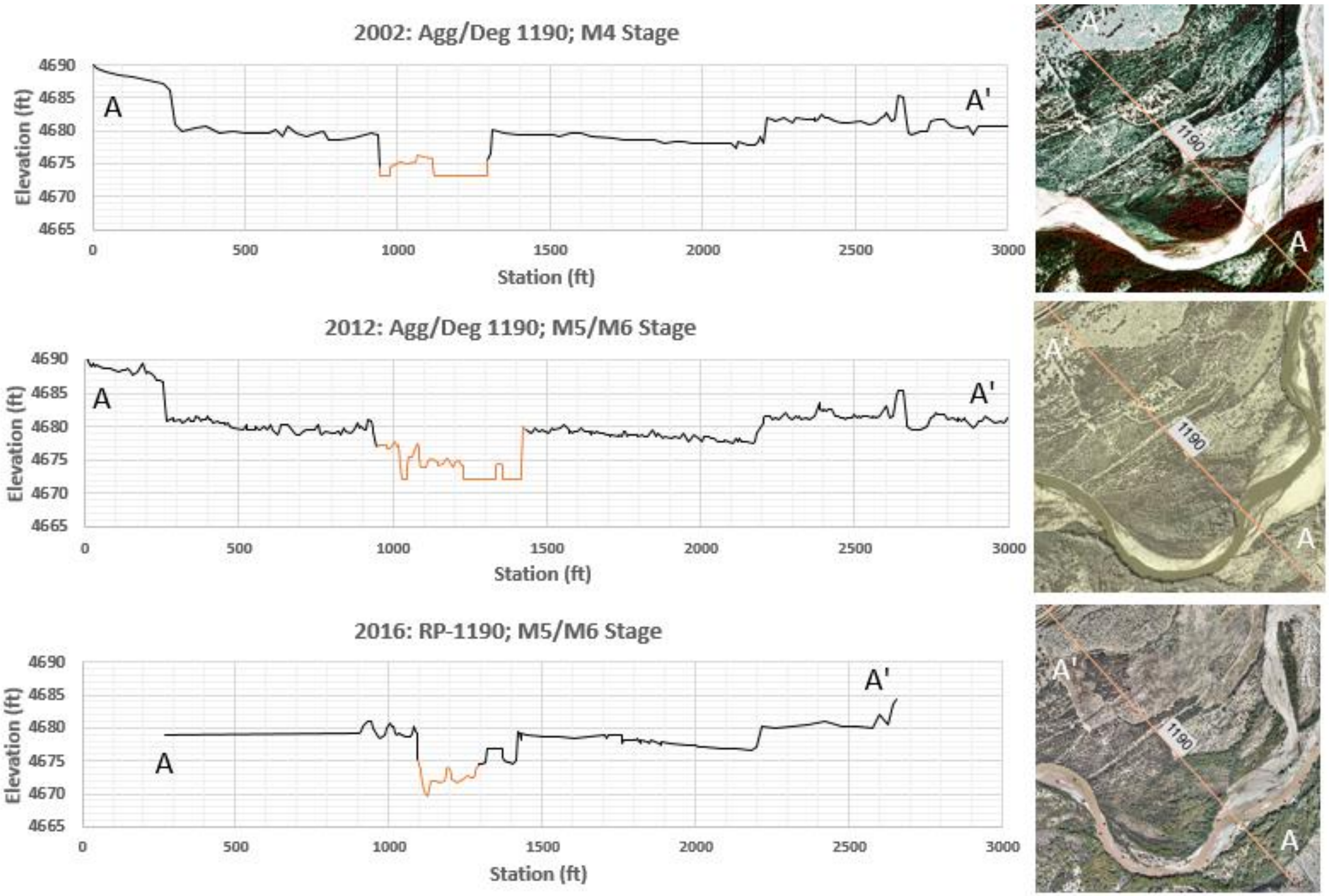


Figure 30: 2002, 2012 and 2016 cross-section and planform views (planform to the right of each corresponding year). A denotes the left bank and A' denotes the right bank. The active channel is in orange and the channel classification is denoted at the top of the graph.

Over time the active channel has become narrower and more incised. This makes sense as the stages progress from 2-M5/M6 and become more of a narrow, single-threaded channel. The active channel width is based on planforms provided by USBR in GIS, and they may differ based on the flow when the photograph was taken. For instance, 1992, 2002, and 2012 are all around 650 cfs. 1972 is around 5 cfs and 2016 is at 40 cfs. The flow in 1962 is also about 650 cfs (Swanson et al. 2010). The active channel should be somewhat comparable though, as it is the area where the mobility of material is occurring and is non-vegetated. Therefore, there should be some consistency from USBR's delineation of the active channel from year to year.

4. HEC-RAS Silvery Minnow Hydraulic Modeling

In this analysis, HEC-RAS 5.0.3 is used to analyze hydraulic conditions at different flow discharges in 1992, 2002, and 2012. The depth and velocity from the HEC-RAS model were used to quantify the location and area of high quality habitat. Flow depth and velocity can help determine the habitat quality of RGSM. Much of the habitat criteria is based on numerical values of depths and velocities associated with different habitats outlined in report by Tetra Tech in 2014.

4.1. Method

HEC-RAS was employed to analyze the hydraulics at different flow conditions. The flows used in HEC-RAS were based on past analyses and practicality. For instance, the 25-day exceedance spring runoff peak flow for dry, mean, and wet years were identified by MEI (2006) to be 1400, 3500, and 5600 cfs, respectively. Spring runoff for the last decade has been lower than past runoffs, so flows of 600, 1400 and 3500 cfs were used for the fish habitat analysis. Spring flow was targeted because the population of RGSM is highly correlated to the connectivity to floodplain in spring. 600 cfs was chosen because several years of aerial photographs were taken with the flow discharge around this value (1992 at 650 cfs, 2002 at 600 cfs, 2006 at 580 cfs and 2012 at 740 cfs). This allows the comparison of HEC-RAS results with aerial photographs which is discussed in the conclusion in section 8.

Three years (1992, 2002, and 2012) were chosen run the various flows to compare the data temporally. These years were chosen because they are around when fish population started being collected and aerial photography is available during these years. Also, these were available years of HEC-RAS cross-sections provided by USBR. An example of a cross-section from 2002 is shown in Figure 31. The 1992 and 2002 are derived by using photogrammetry and the 2012 geometry was derived from LiDAR. The reach from the Rio Puerco confluence to SADD was extracted from the entire Middle Rio Grande HEC-RAS file with additional 10 cross sections adjacent to upstream and downstream ends. Modifications were made to the main channel designation and levee stations to more accurately reflect the flood extent in the aerial photographs (Figure 31). Aerial photographs from April of 2005 (4500 cfs), 2006 January (580 cfs), and 2008 July (1630 cfs), and a digitized flood map of 2005 June (5980 cfs) were used to identified the location of levees. Manning n was set as 0.019 for the main channel and 0.1 for the floodplain according to Klein et al. (2018b). The simulation was run under uniform steady condition.

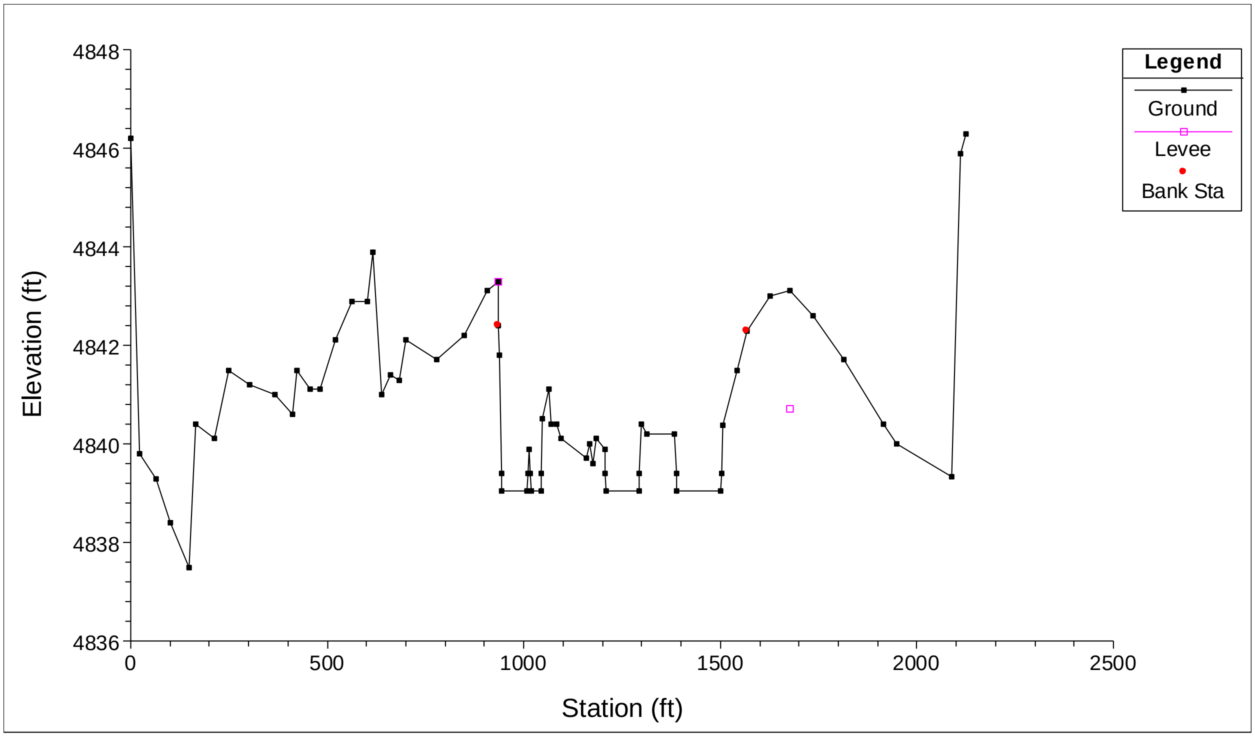


Figure 31: Example of modified levee station: agg/deg 764 (river station 1177) in 2002. The 2005 flood map shows that the flow only overtopped at the right bank. Furthermore, the right bank side channel is found inundated in April of 2005 but not in the aerial photos in January of 2006, so the levee on the right bank is placed between side channel and main channel and at the elevation with flow between 1500 cfs and 3150 cfs. The levee on the left bank is placed at the top of the main channel banks.

Flow depth and velocity for each station at each cross-section are exported to ArcGIS to analyze the habitat spatially. The habitat quality was broken up into subreaches and compared. Because the HEC-RAS geometries were not geo-referenced, a program was developed to compute the coordinate for every station. A point polygon with flow depth, flow velocity, and xy-coordinate for a given flow condition was generated. The point feature was used to create a TIN to generate surface features for depth and velocity. Lastly, depth and velocity were classified and combined based on Table 8. The classes of "Spawning", "Feeding/Rearing", "Good", and "Adequate" were assigned to different depths and velocities and then analyzed spatially through the subreaches.

4.1.1. Habitat Criteria

To understand the quality of silvery minnow habitat and how it is changing, it was useful to classify the habitats into different types. These types of habitats indicate how good the habitat is and what it is used for. For instance, feeding, rearing and spawning habitats are necessary for silvery minnows to propagate. Feeding habitats for silvery minnows include benthic food sources, which includes organic detritus, algae, diatoms, and small invertebrates. For "feeding/rearing" habitat to form, it requires low velocity flow so that the river bed is stable (< 0.5 ft/s (Tetra Tech 2014)) and sufficient sunlight so the algae can grow. Also, spawning habitat is better if it is warm and has a low velocity so eggs don't drift downstream. The warm water triggers spawning and provides the energy for algae to grow and therefore ensures food supply for larval development. "Spawning" habitat tends to be rare because it requires a velocity less than 0.05 ft/s and a depth less than 1.5 ft. to ensure survival of eggs and larvae (Tetra Tech 2014). Inundated floodplains tend to meet "spawning" velocity and depth requirements which is why they are so important. Other categories include "good", "adequate", and "inadequate". "Good" habitat is classified at depths between 0-1.5 ft. and velocities between 0.5-1.5 ft/s. This is due to studies showing silvery minnow is most commonly collected from water less than 1.6 ft. (USFWS 2010 from Tetra Tech 2014) and not swimming well above 1.5 ft/s. Because "good" habitat is habitable, but does not provide prime areas for feeding, rearing, or spawning it is best for the adult life stage of the minnows. "Inadequate" meets none of the ideal habitat criteria. "Inadequate" velocities are above 1.5 ft/s and depths above 1.6 ft. "Adequate" habitat criteria exists because there is a gap between 1.5 ft. and 1.6 ft. depths based on Tetra Tech 2014.

These descriptions of habitats are translated into numerical ranges that fit certain depths and velocities based off of Tetra Tech's report from 2014. Flow depth is divided into four groups: 0 – 1.5 ft., 1.5 ft. – 1.6 ft., and > 1.6 ft. Velocity is broken down into four tiers, 0 – 0.05 ft/s, 0.05 – 0.5 ft/s, 0.5 – 1.5 ft/s, and > 1.5 ft/s. Also, the ideal habitat for RGSM should have flow depths between 0.16 ft. (5 cm) and 1.5 ft. (45 cm) and flow velocity less than 1.5 ft/s (Baird 2016). A summary of the depth and velocities and which habitats they represent is described in Table 8.

Table 8: Habitat Classification based on flow depth and velocity (based on Tetra Tech, 2014).

Depth (ft.)	Velocity (ft./s)			
	0 – 0.05	0.05 – 0.5	0.5 – 1.5	> 1.5
0 – 1.5	Spawning	Feeding/rearing	Good	Inadequate
1.5 – 1.6	Adequate	Adequate	Adequate	Inadequate
>1.6	Inadequate	Inadequate	Inadequate	Inadequate

4.2. Results and Discussion

Figure 32 and Figure 33 illustrate the simulation results of flow depth and velocity at subreach P1 when the discharge is 600, 1400, and 3500 cfs in 2012. As shown in Figure 34, we can identify the location with the flow depth and velocity that is suitable for silvery minnows according to Table 8. Maps for the rest of the reach can be found in Appendix B.

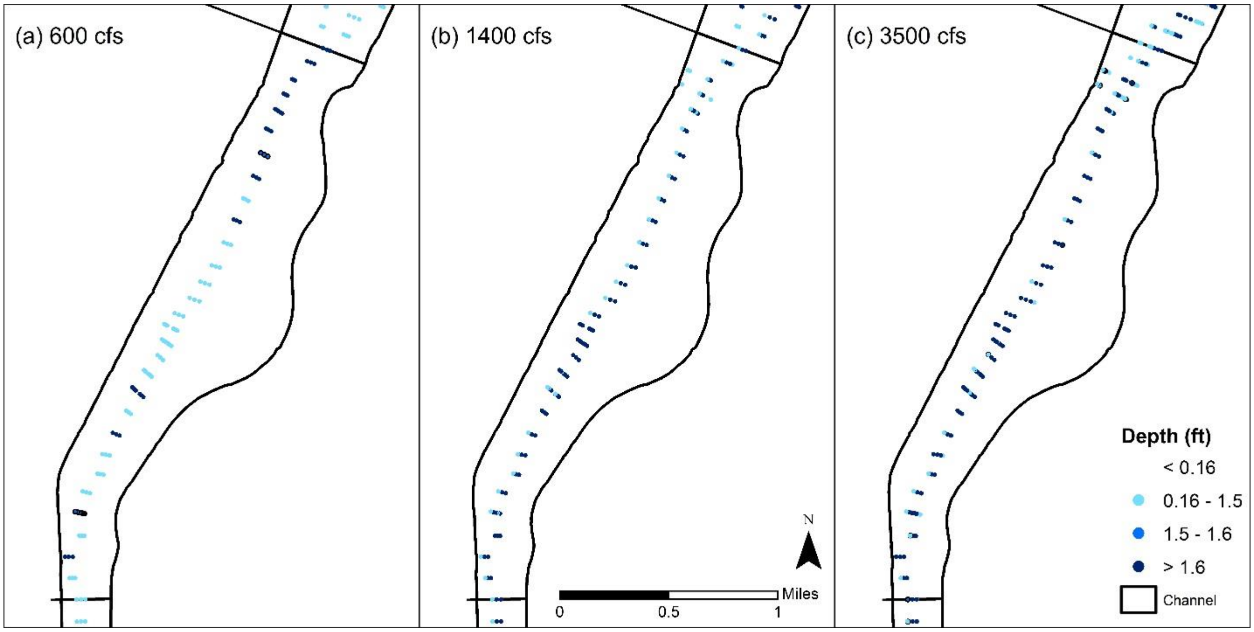


Figure 32: Simulated depth at subreach I1 at flow rate 600, 1400, and 3500 cfs in 2012.

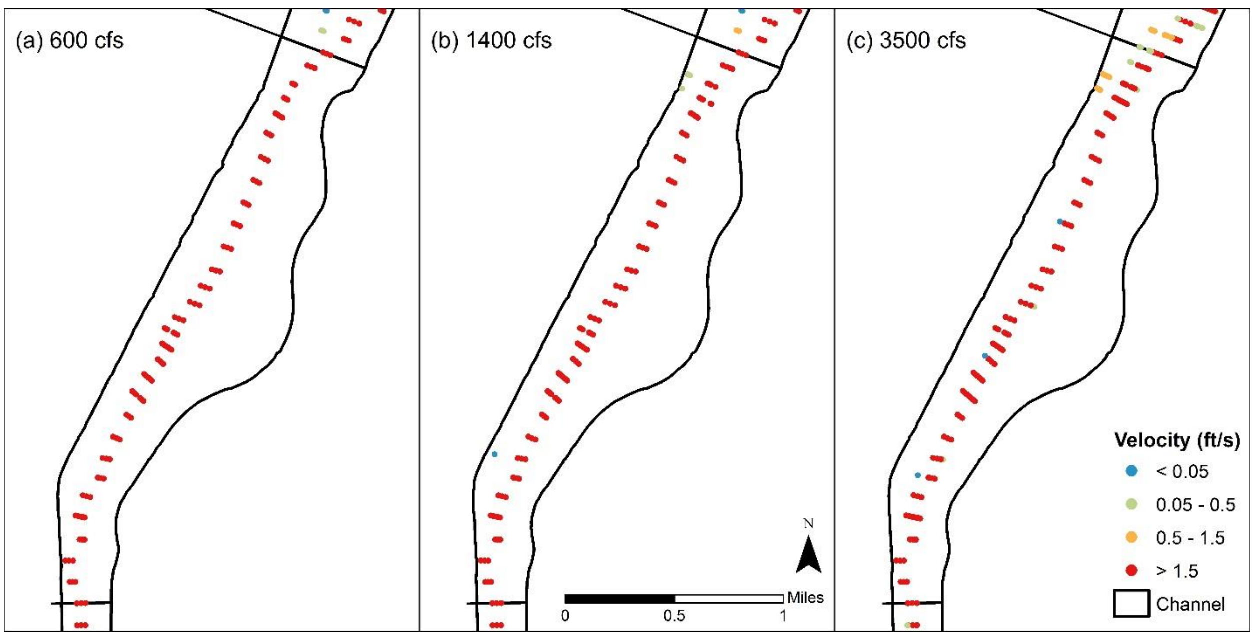


Figure 33: Simulated velocity at subreach I1 at flow rate 600, 1400, and 3500 cfs in 2012.

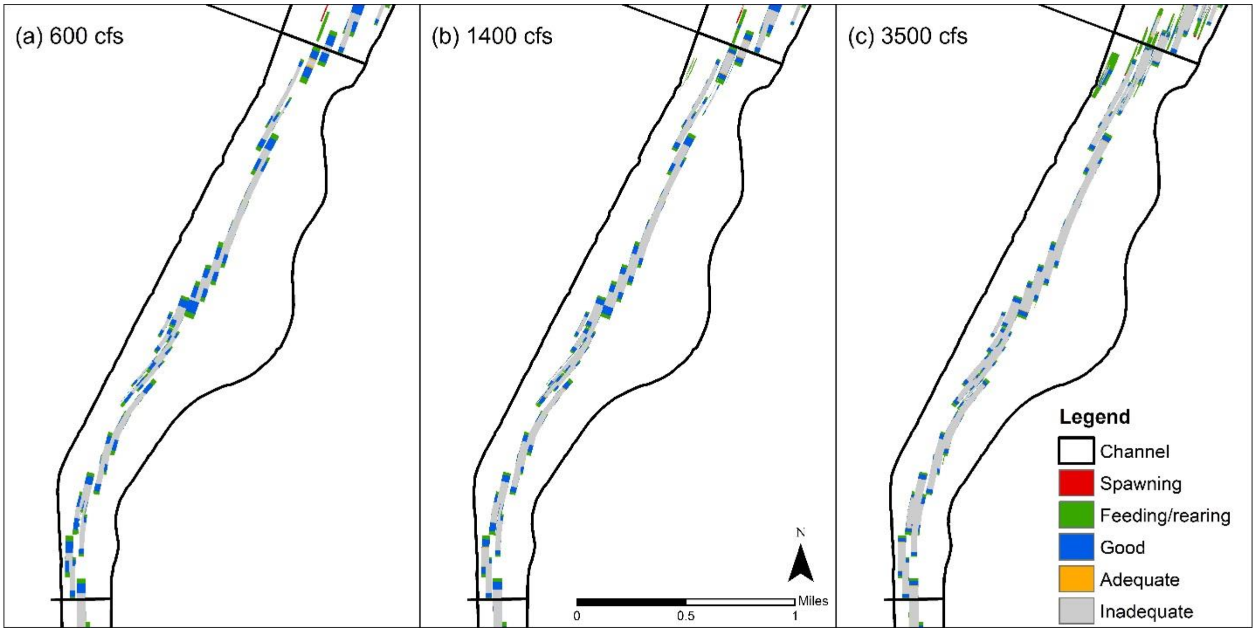


Figure 34: Simulated habitat at subreach P1 at flow rate 600, 1400, and 3500 in 2012.

The results show the area for silvery minnows is limited in the main channel and not much overbank inundation occurs in this reach. The relationship between discharge and “spawning” and “feeding/rearing” area are not consistent for across different subreaches as shown in Figure 35 and Figure 36. The habitat density depicted in (b) in these figures gives a more meaningful representation of the habitat quality because it is weighted by subreach area.

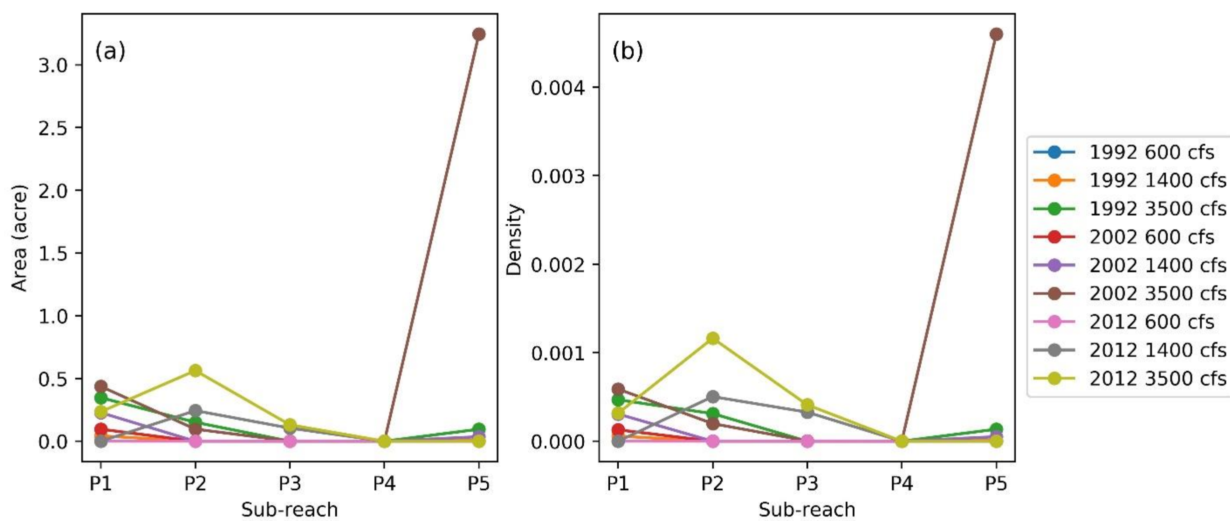


Figure 35: “Spawning” habitat: (a) area, (b) density (area of habitat divided by area of subreach).

It can be seen in Figure 35 and Figure 36 that the amount of “spawning” area is only high in 2002 in subreach P5. This means the habitat quality is high, which is usually correlated with floodplain inundation that starts at 3500 cfs in this reach (Tetra Tech 2014). This may indicate that the floodplain does not inundate at 3500 cfs except at subreach P5 in 2002. Also, there is not an obvious trend of habitat areas between years.

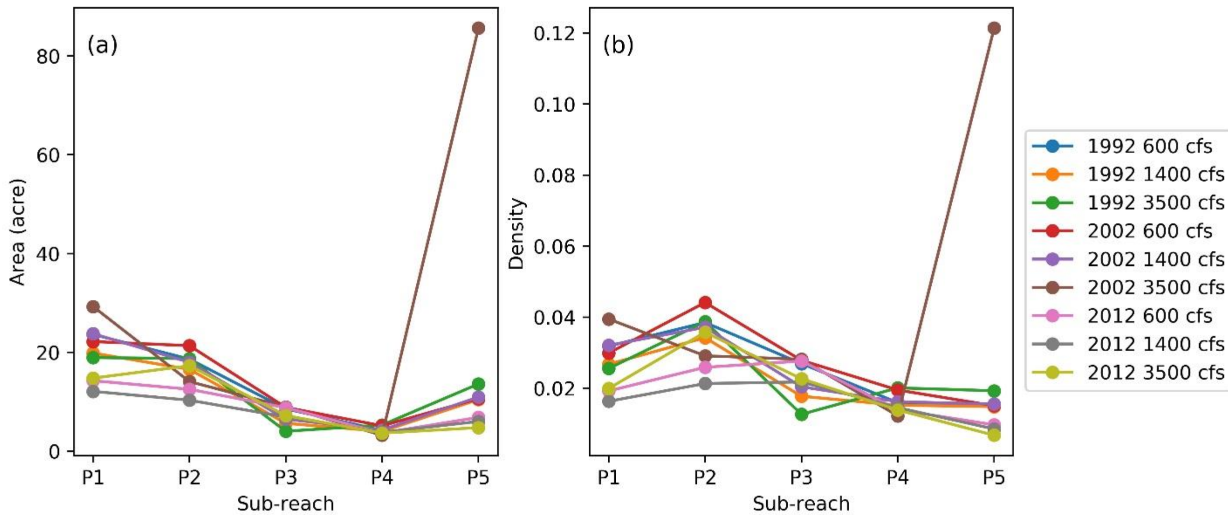


Figure 36: "Feeding/rearing" habitat: (a) area, (b) density (area of habitat divided by area of subreach).

2012 has the lowest scores at all three flows for "feeding/rearing" habitat as shown in Figure 36. Like "spawning" habitat the 3500 cfs flow in 2002 for P5 has the highest area for "feeding/rearing" habitat. Other than P2 in 2005, P2 has the greatest density of habitat for all flows.

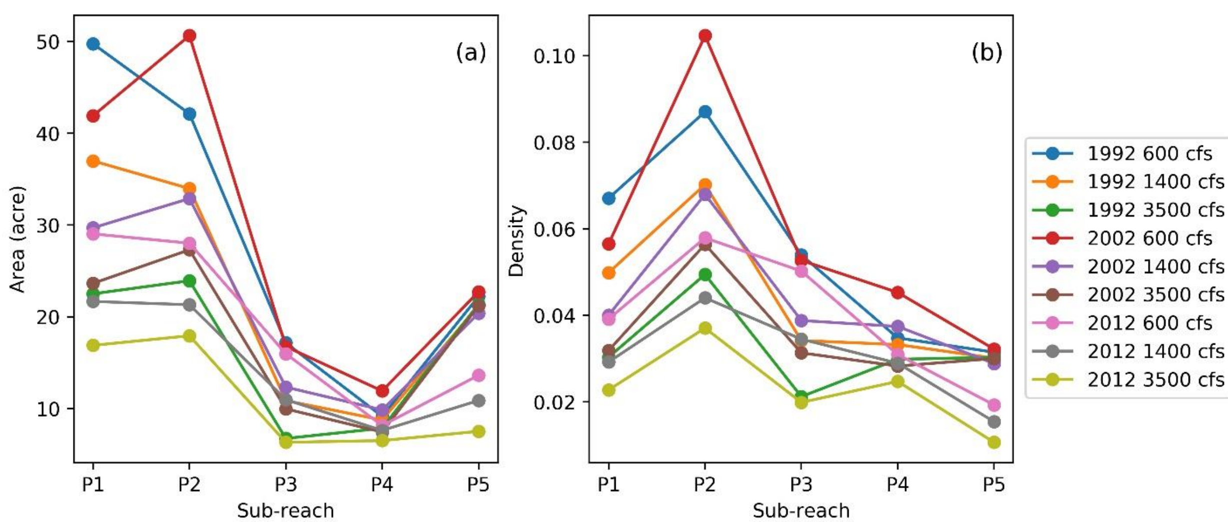


Figure 37: "Good" habitat: (a) area, (b) density (area of habitat divided by area of subreach).

For the "good" habitat, the area is negatively related to discharge. Therefore, the highest density of "good" habitat is at the lowest flow of 600 cfs for all years. This could be due to more accessible channels in the main channel, and shallower areas at low flow providing better habitat. Also, subreach P2 appears to have the majority of "good" in-channel habitat.

When the discharge increases, the area of low velocity in the channel decreases and therefore the area of “good” habitat decreases until floodplain inundation occurs. It would be expected that the “good” habitat would be lowest at 1400 cfs and higher at 3500 cfs when the floodplain becomes inundated (Bovee et al. 2008; Tetra Tech 2014), yet this does not occur. The “good” habitat is lowest at 3500 cfs. This is most likely because a very small amount of inundation occurs starting at 3500 cfs (Tetra Tech 2014), so that area becomes all “feeding/rearing” and “spawning” habitat.

Over time, the “good” habitat has decreased which is consistent with the knowledge of what is happening in the Middle Rio Grande over time (Scurlock 1998; Bovee et al. 2008; Tetra Tech 2014). The reach channelizing and narrowing causes this loss of slow and shallow areas. When looking at the weighted results, P5 in 2002 is best for spawning and “feeding/rearing” whereas P2 has the majority of “good” habitat. This may be because P2 is the most braided or tends to be less sinuous than the other reaches. P5 in 2002 might have better floodplain connectivity but why that occurs is unknown. It is also important to note that even though the simulation shows 3500 cfs has the best habitat quality for P5, the actual flow is not usually that high. For instance, the peak flow in 2002 was only 1920 cfs and peak flows are greatly correlated with silvery minnow population (Dudley et al. 2016).

Overall habitat quality has decreased over time and P2 has the best habitat quality at low flows. The middle flow level of 1400 cfs never has the highest habitat area, and usually has the least amount of quality habitat. The highest “spawning” and “feeding/rearing” habitat is at 3500 cfs. The majority of “good” habitat occurs at 600 cfs.

5. Silvery Minnow Habitat Criteria

5.1. Introduction

This section outlines how silvery minnow habitat can be analyzed with GIS (Geographic Information System) from aerial photography. It covers methods, results and discussion of the findings. The analysis is based on finding what habitat features silvery minnows thrive in, identifying those features in the same reach over different years, and seeing how the habitat changes spatially and temporally. A future goal is to link this analysis to how habitat affects fish population densities.

5.2. Methods

5.2.1. Data Use/Aerial Photography

Analyzing orthographic aerial photography over many years can show how silvery minnow habitat has changed over time. Once we know how the habitat is changing and how this is related to fish population, habitat suitability can be improved. Though fish population is not analyzed in this report, this analysis is set up to be able to compare habitat quality to fish population data sets in the future. Because consistent fish population data collection began in 1993, the analysis of aerial photography started with the closest year to that: 1992. The following years after 1992 were analyzed:

Table 9. The year, month and flow corresponding aerial photographs used for this study. Data from Klein et al., 2018a, Swanson et al., 2010 and GIS metadata provided by USBR.

Year	Month	Flow (cfs):
2016	October	40[SA]
2012	January	740[SA]
2008	July	1630[I]
2008	June	4990[I]
2006	January	580[SA]
2005	June	5980[I]
2005	April	4500[I]
2002	February	600[SA]
2001	February	687[A]
1992	February	650[SA]

[I] Isleta gage daily average discharge
[SA] San Acacia gage daily average discharge
[A] Albuquerque gage daily average discharge

The years analyzed are based on availability of data from USBR starting with 1992, so there is not a consistent spacing of years. The uncertainty created by varying image quality is also a limitation of analyzing the photographs. This is a known limitation based on many other studies using aerial photography to map fish habitat quality (Holmes and Hayes 2011; Perschbacher 2011). Other limitations include the flow being variable within the reach and between years, limited amounts of data, the analysis being subjective, limited data aids such as LiDAR and thermal imagery, and ability to ground truth the data (Holmes and Hayes, 2011; Perschbacher 2011). Also, different flows expose different features in the river so it is difficult to compare different years with varying flows.

These limitations can be addressed. For instance, picking only years that have the same flow can allow the habitat analysis to be compared. For instance, if the river were static, the same features would be show up over varying years at the same exact flow in the same place. Comparing different years around the same flow can lead to answers about how the morphology and features of the river are changing. Using this framework, 1992, 2001, 2002, 2006, and 2012 all have flows around 650 cfs so these ones are chosen to compare habitat quality, based on changing physical features, to each other. To keep it as consistent as possible, 2001 is not used because it uses flow data from a different gage than the rest.

Though it would be useful to analyze habitat that meet the needs of different life history stages of silvery minnows, it is not plausible to do a thorough analysis of this with the given set of aerial photography. High flows around the same value across many years would be necessary to see how much the floodplain inundates and how the habitat quality changes over time. Aerial photography analyzed during low and peak flows can still be analyzed because this can give insight into habitat quality spatially and across different flow regimes. Still, the focus must be on analyzing adult silvery minnow habitat in the main channel because that is the available habitat for the comparable photographs at 650 cfs. Analyzing this low flow of 650 cfs may be very useful because the Middle Rio Grande has experienced lower and less peak flows than it has in the past. This trend is expected to continue, so focusing on lower discharges that don't lead to floodplain inundation may be more a more realistic focus for improving silvery minnow habitat (Drew Baird, personal communication, June 19th, 2018).

To make the analysis as objective as possible, a detailed description of discernable habitat features were given. This is still a challenge because distinctions between features such as islands, bars, bedforms and shoreline complexity are not always clear. Also, more LiDAR or thermal imagery data would help make these distinctions. Lastly, ground truthing to test the analysis with actual field surveys can be done in the future.

Even with limitations, there are advantages of using remote sensing for habitat analysis. The amount of habitat that can be mapped in a short amount of time can be very useful (Holmes and Hayes 2011; Perschbacher 2011). For this study, it took less than a day to map 50 miles of river habitat for one year. This mapping technique allows a researcher to take a cursory look at a large area and find large-scale trends. Also, this exact type of habitat analysis for this exact reach has not been done before (Torres 2007; Klein et al. 2018a).

5.2.2. Criteria Development

The criteria developed is based on literature that discusses physical features of silvery minnow habitat. That criteria from research is then simplified and shortened based on practicality and ability to analyze it based quality of aerial photography. Physical features determined to be important based on literature include: bankline complexity, main channel complexity, side channels, backwater, bars, islands, confluences, and pools. Limited suspended sediment, suitable amounts of vegetation, and a correct range of temperatures are all important aspects of the functioning ecosystem as well. Lastly, connection to the floodplain is paramount. These components of the river are important because they are representative of suitable silvery minnow habitat that requires low velocities, shallow depths, diverse habitat, silt and sand substrate, and good water quality (Tetra Tech 2014; Cluer and Thorne 2014; Bovee et al. 2008; Bestgen et al. 2003; Dudley and Platania 1997).

Even though all these features are important, only a handful of these can be accurately measured from aerial photography using GIS. These include bankline complexity, main channel complexity, side channels, backwaters, bars, islands, and confluences. Therefore, the habitat requirements that can be physically depicted from aerial photographs are narrowed down to low velocities, shallow depths, and habitat diversity (In this criterion diverse habitat is defined as anything that adds to spatial heterogeneity of the physical habitat topographically or with features such as debris piles).

There are a few reasons why certain features are not included. For instance, suspended sediment can sometimes be analyzed by looking at the color of the water, yet the aerial photographs vary so much spatially and temporally, it is impossible to analyze visually. Substrate is too hard to analyze because aerial photography from most years is not detailed enough. Also, temperature is something that cannot be seen on the imagery. Isolated pools can be seen from aerial imagery, but it is hard to determine how connected the pools are to the main channel, so they are removed as well. Floodplain connectivity is also almost impossible to determine and quantify just by looking at features from aerial photography. This is mostly due to inundated areas being hard to identify at high flows. There is also not enough aerial photography capturing high flows to compare over time. There are only three data sets of photography that show signs of inundation. When there is inundation, it is identified as shoreline complexity, so floodplain connectivity can be roughly compared in these years.

Vegetation is not included in this list because vegetation is incorporated indirectly through certain habitat features. For instance, vegetation indicates complexity on bars, shorelines, or islands which affects habitat scores. It also affects how wide side channels are, which impacts the habitat area, and the likelihood that a channel gets inundated during high flows. It further adds complexity because vegetation provides shade to regulate temperatures and produces leaf litter. Leaf litter provides nutrients to feed algae and diatoms that in turn feed silvery minnows. Temperature regulation is also very important for the minnow (Tetra Tech 2014;

Bovee et al. 2008; Bestgen et al. 2003; Dudley and Platania 1997). Therefore, vegetation density in the active channel is incorporated through other habitat features.

Also, though runs and pools would be useful to identify (Dudley et al. 2016), they are unable to be identified from the set of aerial photography given. Identifying runs and pools have been a focus of other studies identifying habitat features with remote sensing. They were able to do this by using ground truthing to identify where the pools and runs were and use that information to identify the features in aerial photography (Holmes and Hayes 2011; Perschbacher 2011). Ground truthing was not an option for this study. Using agg/deg cross-sectional data from HEC-RAS to identify pools and runs could be an option as well, but these lines are far apart so the data would not be as accurate.

The following schematic in Figure 38 shows the main features that were considered for the criteria.

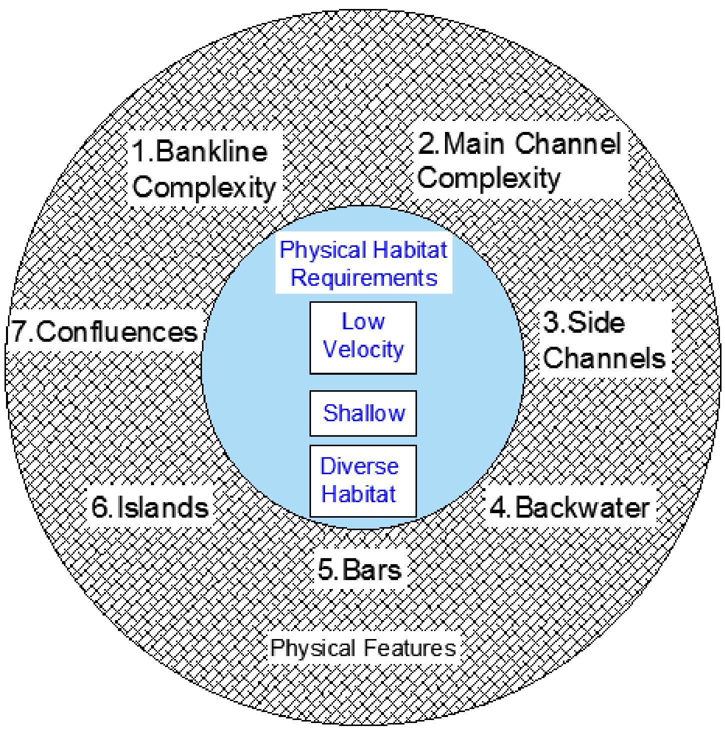


Figure 38. Physical habitat requirements are listed in the blue inner circle. Physical features that meet these requirements and can be seen from aerial photography are in the outer circle.

Overall, certain physical features that may indicate good quality silvery minnow habitat can be analyzed with GIS from aerial photography. These include features such as backwaters, secondary channels, and debris piles. These components of the river create low velocities, shallow depths and diverse habitats that are crucial for silvery minnow survival. By identifying features in the river, giving those features a score based on habitat suitability, and comparing the scores spatially and across time we can see how the physical habitat is changing.

5.2.3. General Guidelines for Scoring and Mapping

Each habitat feature is identified with a point using GIS and identified with a criteria that has a number and letter. The criteria is correlated with a habitat feature (number), subdivided into the quality of that feature (letter), and given a score based on the quality of the habitat. The score is determined from literature review and is outlined in Appendix A. Table 10-Table 12 outline and briefly describe the criteria, what type of habitat it is and the score it receives. The entire outline of features which pictures and a description of what they are is given in Appendix A.

Table 10: Habitat type, criteria and scores. Scores range from 1-5 and are further explained in Table 12.

	Shoreline Complexity			Main Channel Complexity		Side Channels					Backwater		Bars			Islands						Confluences	
Criteria:	1a	1b	1c	2a	2b	3a	3b	3c	3d	3f	4a	4b	5a	5b	5c	6a	6b	6c	6d	6e	6f	7a	7b
Score:	4	3	2	4	3	4	3	2	3	5	5	4	5	2	1	3	2	1	1	4	3	4	3

Table 11: Brief description of habitat types and scores.

Habitat Description	Criteria	Score
Complex Shoreline	1a	4
Less Complex Shoreline	1b	3
Less Complex, Less Accessible Shoreline	1c	2
Main Channel Complexity (Large)	2a	4
Main Channel Complexity (Small)	2b	3
Large, Easily Accessible Dry Side Channel	3a	4
Medium, Easily Accessible Dry Side Channel	3b	3
Small, Less Accessible Dry Side Channel	3c	2
Non-Complex Wetted Side Channel	3d	3
Complex Wetted Side Channel	3f	5
Large Backwater	4a	5
Small Backwater	4b	4
Complex Bar	5a	5
Simple Vegetated Bar	5b	2
Simple Unvegetated Bar	5c	1
Large Unvegetated Island	6a	3
Small Unvegetated Island	6c	2
Large Vegetated Island	6b	1
Small Vegetated Island	6d	1
Large Complex Island	6e	4
Small Complex Island	6f	3
Active Confluence	7a	4
Inactive Confluence	7b	3

Table 12: Score Criteria. Each category depicts habitat that is beneficial to silvery minnows. 5 provides the most optimum habitat and 1 provides the least amount of benefits.

Score	***Habitat Description***
1	Low chance of becoming inundated, in main channel, small features, and low complexity of topography.
2	Low chance of becoming inundated, in main channel or could be in margins, bigger features than 1 or smaller than 3, and low complexity of topography.
3	Medium chance of becoming inundated, in main channel or near shoreline, bigger features than 2 or smaller than 4, and medium complexity of topography.
4	High likelihood of becoming inundated on side channel, or inundated but not very complex in main channel. Bigger features than 3 or smaller than 5.
5	Areas that are currently inundated with water and form complex flow with shallow areas and low velocities. Tend to be isolated from the main channel. Large features with high topographic complexity.

The amount of points given for a feature is based on agg/deg polygons (area between each line). For instance, if an island spans over two agg/deg polygons it is given two points. The same is done for every feature including side channels. The longer the side channel, the more points it gets because it provides more silvery minnow habitat. Figure 39a. depicts scoring with islands and channels across agg/deg lines.

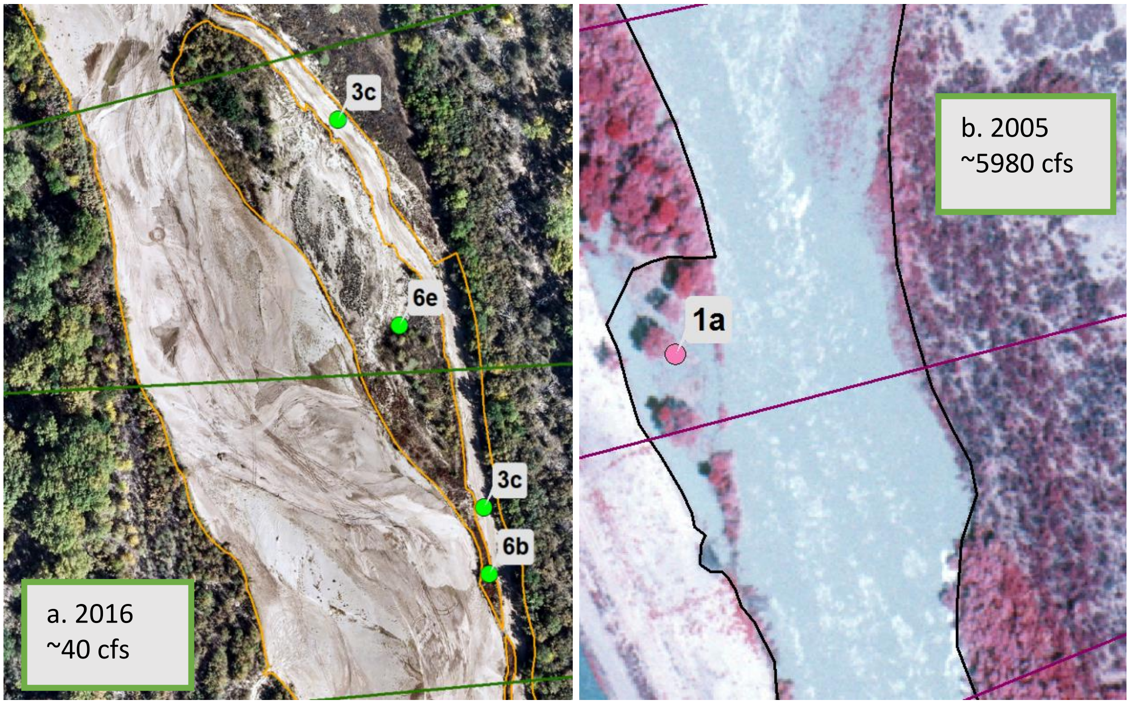


Figure 39: a. A dry side channel (3c) and islands (6b and 6e) are depicted above in an aerial photograph from 2016. Agg/Deg lines are shown in green lines perpendicular to the main channel. The active channel is outlined in orange. b. 1a depicts shoreline complexity in an aerial photograph from June of 2005. Agg/Deg lines are shown in purple perpendicular to the main channel. The active channel is outlined in black. The flow is going to the bottom of the page for both images.

In Figure 39a., the channel and the island span over two polygon lengths so they are each given a point in each polygon. The criteria is not exact, but instead an estimate of how many features there are. The criteria is not meant to map feature areas, but instead depict the amount of features that offer suitable habitat to get a general idea of what changes are occurring. In Figure 39b. 1a is counted once instead of twice in this example. Even though the channel complexity spans over two agg/deg polygons, it only occupies the length along one agg/deg polygon so it is counted once.

For each year, the points are mapped and the scores are assigned as shown in Figure 40.

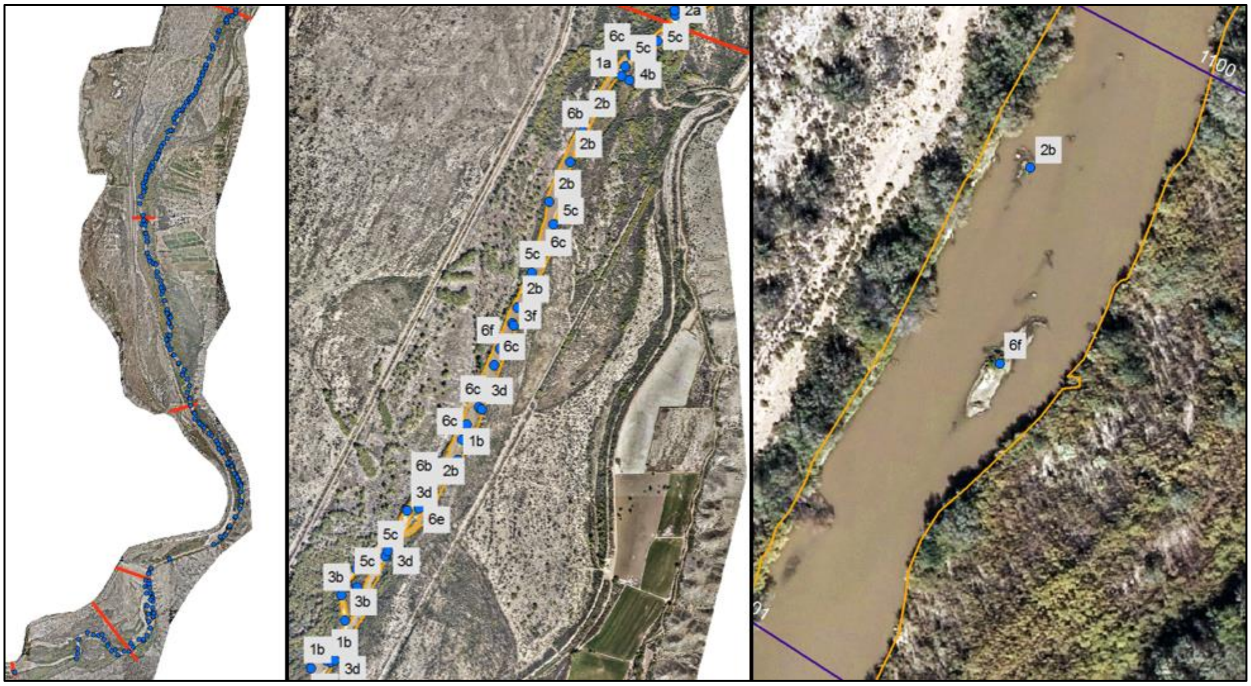


Figure 40: Examples of points being assigned zoomed in at three different magnitudes. The right is the furthest zoomed in and depicts points between two agg/deg lines. The left most image is the entire Rio Puerco Reach. Blue dots are points assigned to features and the orange line outlines the active channel.

The results are compiled and compared in a few different ways shown in the following sections.

5.2.4. Methods of Analysis

5.2.4.1. Overall Habitat Score

An overall score for each year was calculated as well as a count for how many of each habitat types there were in the Rio Puerco reach. An overall score was calculated by subreach as well.

5.2.4.2. Subreach Delineation

Each year with available photographs is analyzed. The points are broken up and grouped into subreaches using ArcGIS. Scores given to different habitat types are added up within each subreach and compared across years. Because the subreaches have different areas, the scores are weighted by area by computing the score per ft^2. The score is divided by the area and multiplied by a multiple of 10 that makes the data easy to work with. Below is a sample calculation:

$$Raw\ score\ for\ P1\ in\ 1992: 170$$

$$Area\ for\ P1: 32{,}305{,}506\ ft^2$$

$$Multiple\ of\ 10: 10{,}000{,}000$$

$$Weighted\ score: \frac{170}{32{,}305{,}506 ft^2} * 10{,}000{,}000 = 52.6$$

Also, the number of points in each subreach are counted and grouped into categories such as shoreline complexity, side channels, backwater etc. These scores are weighted as well. The following habitat features are grouped into the associated categories in Table 13. This is done to reduce the amount of graphs needed to compare how the habitat changes over time. When the habitat types are quite similar and mainly vary by size instead of quality, they were grouped.

Table 13: Habitat types grouped into broader categories.

Complex Shoreline	1a, 1b, 1c
Main Channel Complexity	2a, 2b
Easily Accessible Dry Side Channels	3a, 3b
Less Accessible Dry Side Channels	3c
Non-Complex Wetted Side Channel	3d
Complex Wetted Side Channel	3f
Backwater	4a, 4b
Complex Bars	5a
Simple Bars	5b, 5c
Unvegetated Islands	6a, 6c
Vegetated Islands	6b, 6d
Complex Islands	6f, 6e
Active Confluence	7a
Inactive Confluence	7b

5.2.4.3. Agg/Deg Line Delineation

Using ArcGIS, the points were broken up and grouped into agg/deg polygons divided by each agg/deg line. Each polygon was given one value. This value is the summation of the criteria score given to the points based on the type of habitat outlined in section 5.2.3. The polygon was given a color based on its value. The colors in agg/deg polygons were visualized in the five subreaches using ArcGIS.

5.3. Results

5.3.1. Overall Habitat Score

Table 14 summarizes the analysis.

Table 14: Summary of total habitat score, flows, and number of habitat types for each year. The comparable years are highlighted in blue.

				Shoreline Complexity			Main Channel Complexity		Side Channels					Backwater		Bars			Islands						Confluences	
Year	Month	Total Habitat Score	Flow (cfs)	1a	1b	1c	2a	2b	3a	3b	3c	3d	3f	4a	4b	5a	5b	5c	6a	6b	6c	6d	6e	6f	7a	7b
1992	February	596	650^{SA}	9	2	1	10	10	0	6	6	18	18	1	0	18	20	20	0	7	0	2	14	18	0	9
2001	February	422	687^{A}	5	3	0	14	9	2	8	0	5	5	0	0	12	13	19	4	3	8	0	15	7	2	6
2002	February	481	600^{SA}	3	1	0	14	7	0	2	0	21	13	0	0	7	23	11	5	0	7	2	20	0	0	0
2005	April	623	4500^{I}	15	5	1	13	11	0	0	0	21	14	9	0	20	9	4	1	2	2	2	26	7	4	3
2005	June	479	5980^{I}	3	3	2	0	3	0	1	0	13	10	0	0	43	3	1	0	0	1	7	22	5	2	4
2006	January	415	580^{SA}	4	15	0	4	12	1	9	4	13	4	1	0	0	32	15	0	3	2	1	17	8	1	5
2008	June	488	4990^{I}	14	1	0	7	3	0	4	0	20	5	3	1	27	9	1	2	5	0	6	16	6	0	6
2008	July	415	1630^{I}	5	9	3	6	4	0	4	5	21	10	2	3	5	9	2	1	14	5	7	12	4	0	7
2012	January	429	740^{SA}	8	8	0	2	6	1	22	5	16	4	1	0	5	14	20	2	5	10	3	7	16	1	4
2016	October	2430	40^{SA}	59	54	49	82	80	2	74	17	30	54	16	12	14	47	140	12	54	19	37	17	12	0	2

Note: Flows at different gages are given the follow subcripts: ^{I} Isleta gage daily average discharge, ^{SA} San Acacia gage daily average discharge, ^{A} Albuquerque gage daily average discharge

Overall, 2016 had the highest score and 2006 and July of 2008 had the lowest score. The rest of the scores only vary by a couple hundred points so the differences are somewhat negligible. Out of the comparable years, 1992 has the highest score by over 100 points and 2002 is the next highest. 2002, 2006 and 2012 still all have very similar scores.

2016 has the highest amount of all types of habitat features with a few exceptions. June of 2005 has the most complex bars, April of 2005 has the most complex islands, and 1992 has the most confluences.

5.3.2. Subreach Delineation

The total scores for the four years with photographs taken around 650 cfs are compared in Figure 41.

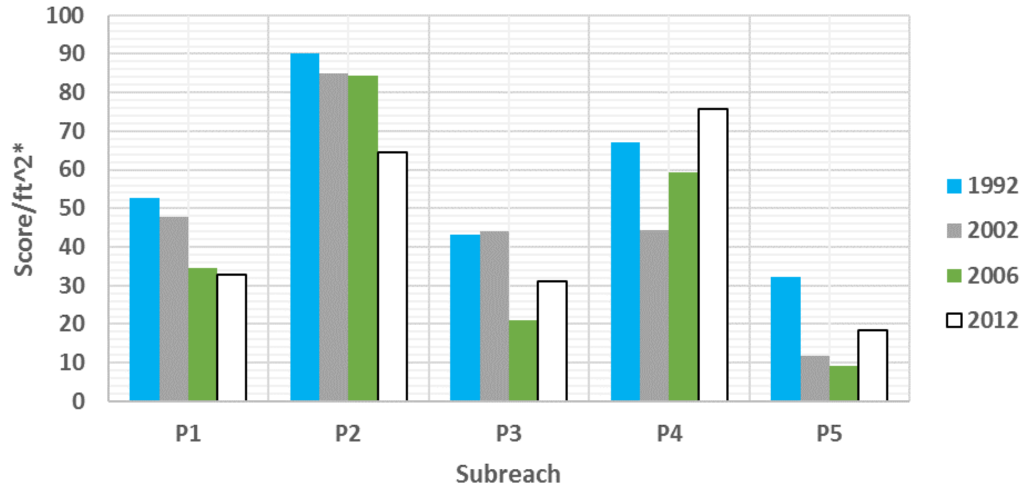


*Figure 41: The column graph shows the overall habitat scores in each of the four comparable years in each subreach. *Score/ft² is the score weighted for area of the subreach as discussed in section 5.2.4.2.*

Subreach P2 has overall highest scores for 1992, 2002, and 2006 and P4 has the highest score in 2012. P5 contains the lowest scores of each of the years. The scores in 2006 and 2012 generally tend to be lower than those in 1992 and 2002, but there is not a dramatic change over the years. 1992 has the top score in P1, P2 and P5 and second top score in P3 and P4.

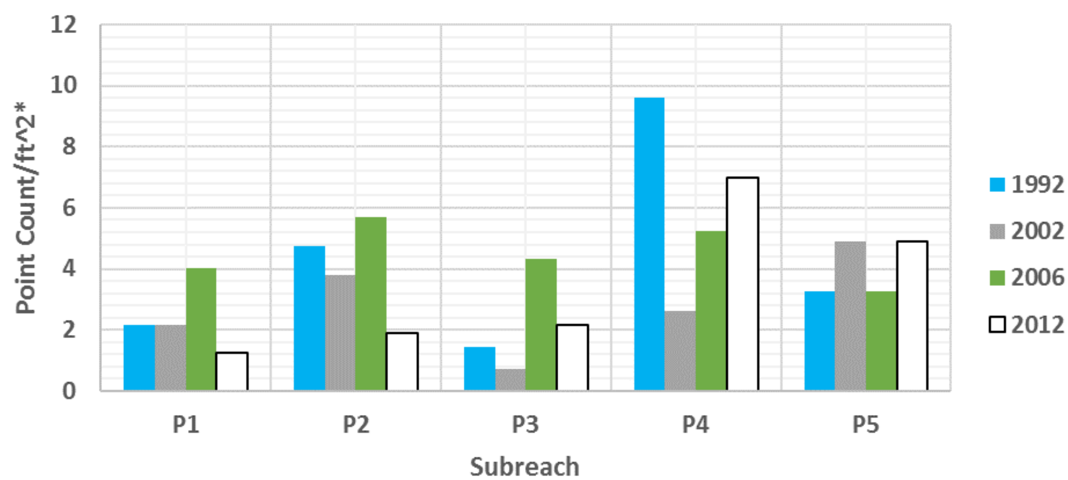


*Figure 42: The column graph shows the amount of simple bars in each of the four comparable years in each subreach. *The point count/ft² is the number of points counted and weighted for area of the subreach as discussed in section 5.2.4.2.*

Over time, the simple bars do not show a trend favoring any year's score. From P1-P3 2006 has the highest score, then in P4 1992 is highest, and in P5 2002 and 2015 are tied for the highest score. Looking at similar graphs like this one that are listed in Appendix C, there are other trends that can be analyzed. For instance, complex islands and complex bars have generally decreased over time. Easily accessible dry side channels and less accessible dry channel have increased over time. The rest of the parameters don't show consistent enough patterns to draw conclusions from. The overall scores comparing all years are shown in Figure 43.

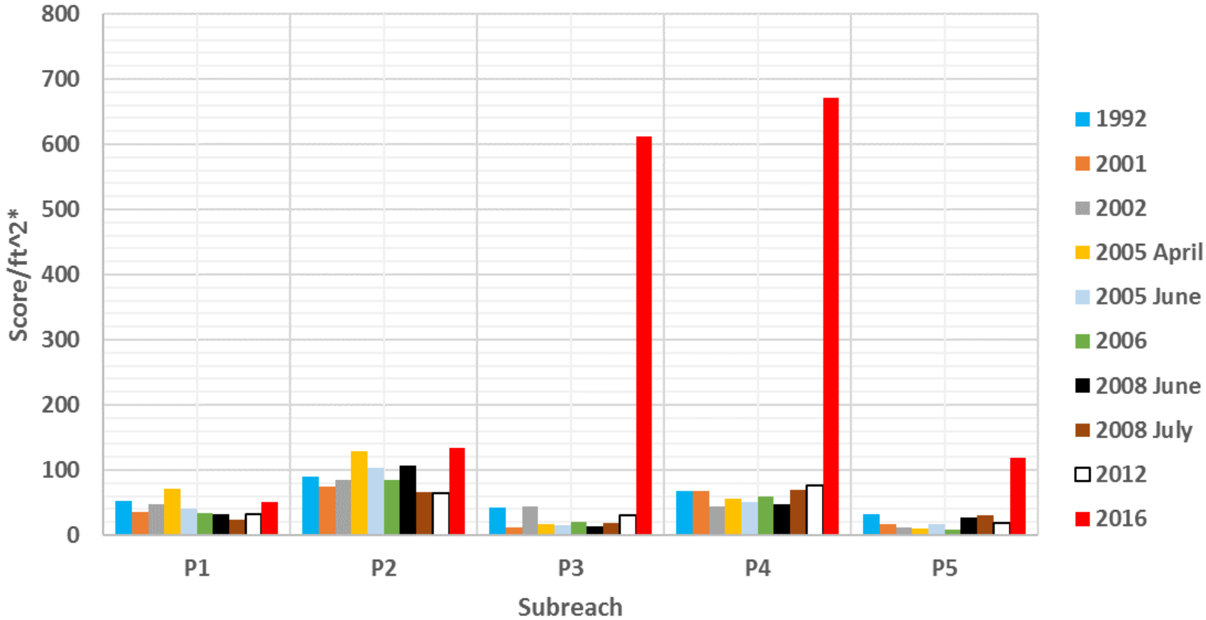


*Figure 43: The column graph shows the overall score for all years in each subreach. *Score/ft^2 is the score weighted for area of the subreach as discussed in section 5.2.4.2.*

2016 has major peaks in P3-P5 subreaches. These are areas have adequate flow because of the Rio Puerco confluence. Just upstream of the Rio Puerco reach the flow is closer to zero. The 40 cfs is based off of the SADD just downstream of this reach.

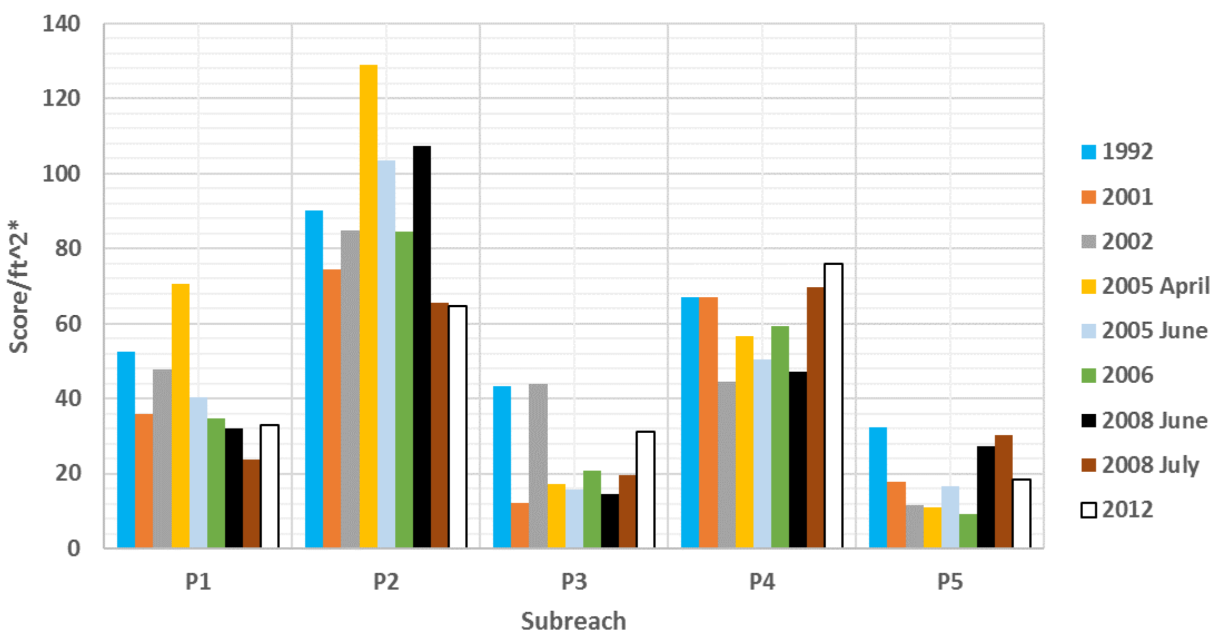


*Figure 44: The column graph shows the overall score without 2016 in every year in each subreach. * Score/ft^2 is the score weighted for area of the subreach as discussed in section 5.2.4.2.*

When taking 2016 out of the graph it is easier to compare the other years. The highest scores in the subreaches in Figure 44 tend to occur most consistently in 1992 and in subreach P2. April of 2005 and June of 2008 have some high peaks, but are not consistently high. All other years and flows vary and are in the middle of the range of high and low point counts/ft^2. Comparing the different habitat types of all years does not prove very useful, because there are too many variables to find any trends.

5.3.3. Agg/Deg Line Delineation

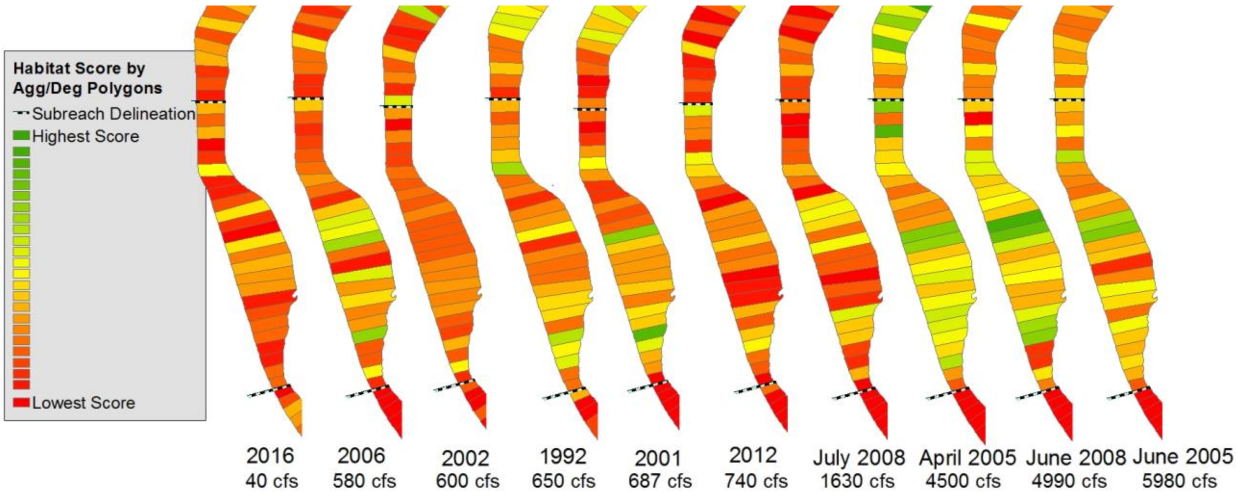


Figure 45: Subreach P2 summation of habitat scores indicated by the color scheme in the legend and separated by agg/deg lines. Green represents the highest scores, red is the lowest score, and yellow falls in the middle range of scores in the spectrum. The flows increase from lowest on the left (2016) to the highest flow on the right (June 2005).

The years with the highest scores are in June of 2008 and April 2005 in subreach P2 based on color of the bands. They have the highest proportion of green polygons and the darkest green polygons. 2016, 2012, July of 2008 and 2002 have the lowest scores overall with the highest proportion of red, orange and yellow bands. The rest of the subreaches for the Isleta reach are in Appendix E.

The lowest scored subreach is P3 because all years had the most amount of red polygons. There is not a noticeable difference between all the other subreaches. The rest of the subreaches vary in habitat quality over the years. For instance, 2002, 2006, July of 2008, and 2012 have higher proportions of red polygons. Also, 1992, April and June of 2005, June of 2008, and 2016 tend to have more green polygons in their subreaches.

The most obvious trend is that as the flow increases, habitat score tends to increase.

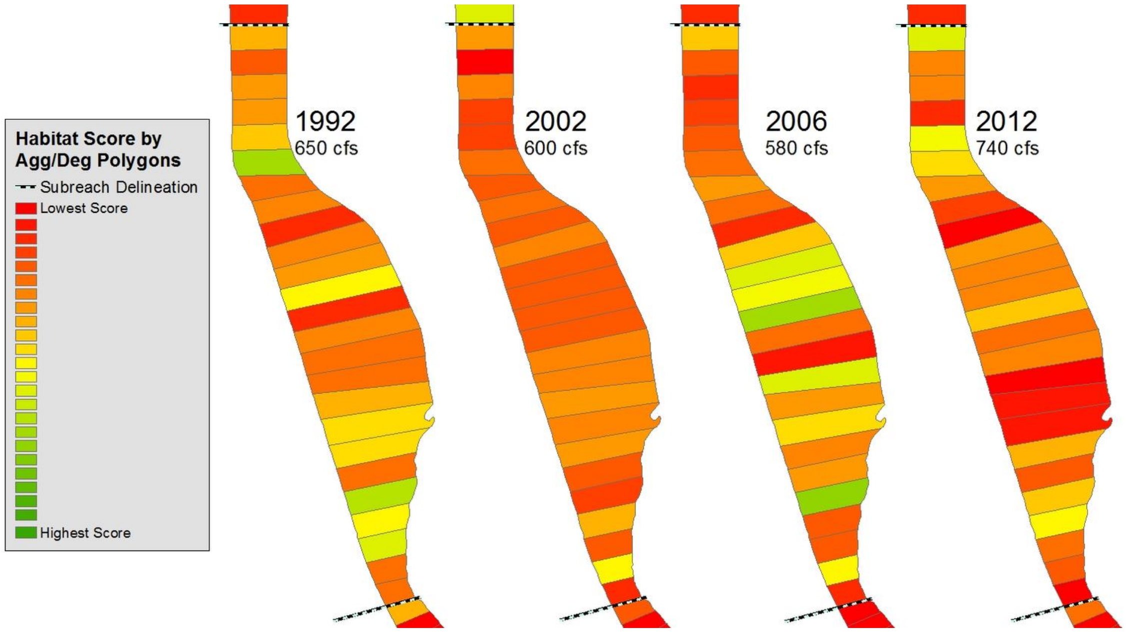


Figure 46: Subreach P2 summation of habitat scores indicated by the color scheme in the legend and separated by agg/deg lines. Only years around 650 cfs are shown. 2001 is excluded because location of the gage is far away from this study site, so this information is not as accurate.

Looking at just the four comparable years, 1992 and 2006 appear to have higher scores in this subreach compared to 2002 and 2012. Subreaches P1 and P3-P5 are in appendix F. There is not a consistent trend when comparing these four years over the whole reach. By taking a cursory look at how many green polygons appear in each subreach in each year, the order of higher to lower quality habitat can be estimated. 1992 has the most amount of green polygons, then 2006 and 2012 are very similar and 2002 has the lowest scores. Again, P3 is consistently populated by just red polygons throughout the years.

5.4. Discussion

The overall habitat score, subreach delineation scores, and agg/deg line delineation figures generally share the same results. Looking at the comparable years, 1992 and 2002 have better habitat than 2006 and 2012. This makes sense because habitat quality for silvery minnows in the Middle Rio Grande has been decreasing over time (Scurlock 1998; Bovee et al. 2008; Tetra Tech 2014). For subreaches, P2 and P4 have the best in-channel habitat when comparing these years.

When comparing all the years, 2016 consistently has the highest scores. June and April of 2005, June of 2008, and 1992 also have high scores. 2006, July of 2008 and 2012 generally have the lowest scores.

June of 2005, with a flow of 5980 cfs, has a couple of the highest peaks mostly likely because of its high flow. By looking at the aerial photography, it is evident that the floodplain is inundated. This is further supported by the fact that significant floodplain inundation begins at 5000 cfs in the Rio Puerco reach (Tetra Tech 2014) and the aerial photographs in this year are taken when the flow was 5980 cfs. Floodplain inundation is extremely important for the survival of silvery minnows, especially during their spawning stages (Dudley and Platania 1997; Bovee et al. 2008; Tetra Tech 2014; Klein et al. 2018a). Also, it has been shown that “prolonged high flows during spring were most predictive of increased density” (Dudley et al. 2016). It is also interesting to note that there is only one photograph that captured a flow above 5000 cfs which may be why the other scores are not as high as June in 2005. April of 2005 also has a flow that causes a small amount of inundation which would explain why it has higher habitat scores.

The scores may be low in July of 2008 due to the flow of 1630 cfs. This flow is suboptimum for silvery minnow as suggested by a study done on silvery minnow by Bovee et al. (2008). The study was done in 2008 in a few small reaches (1-2 km each) downstream of the Rio Puerco and upstream of the SADD. They mapped out adult and juvenile hydraulic habitat in the study areas at flows up to 1000 cfs. Looking at connectivity, woody debris, depths and velocities, they found that habitat areas were reduced when flows exceeded 150 cfs mainly because of flow depth and velocity as shown in Figure 47. In stream habitat such as connectivity and woody debris decreased over time as well for flows exceeding 150 cfs (Bovee et al. 2008).

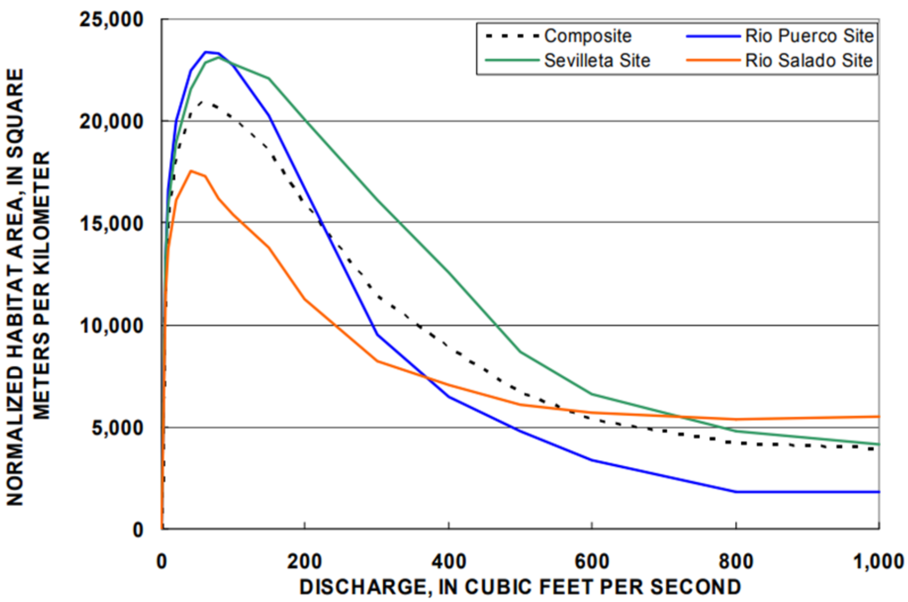


Figure 47: Habitat area for silvery minnows (H. amarus) from Bovee et al. (2008).

This study also suggests why the 2016 score is so high for this reach. Figure 47 shows that the habitat area is very high at lower flows. In 2016, the flow is at 40 cfs, so the habitat area should be high based on Bovee et al. (2008). The habitat score developed for this report may be high because the flow uncovers many features cause them to appear very complex, thus giving it a high score. It uncovers bars, islands, bedforms, debris piles and increased the shoreline complexity with such a low flow. Though the low flows create adequate complexity, velocities and depths for silvery minnow spawning and rearing in theory, low flow conditions do not create the appropriate spawning environment. Unless spawning is triggered by high flows that connect to the floodplain, silvery minnows' eggs and juveniles do not tend to survive. Exactly how spawning is trigged and what exactly allow eggs and juveniles to survive is still unknown (Robert Dudley and Steven Platania, personal communication, September 13th, 2018).

Though low flows provide habitat that fits numerically into spawning, rearing and feeding, they are not likely to be areas where silvery minnows will spawn and feed. This may be because these areas are not continuous like floodplains and they could likely get swept away from drifting into close-by faster waters. Low flows can also be correlated with very turbid water, which limits primary productivity so silvery minnow have less to feed on. Water temperature on the floodplain may be a major spawning trigger as well. For instance, the water can be much cooler in the main channel than on the floodplain. Also, the minimum flow properties (duration, timing, magnitude, etc.) to stimulate a spawning event remains unknown, although it is probably greater than 1500 cfs. In-channel spawning does occur, but it does not provide an area for egg/larval retention that the floodplain can (Tetra Tech 2014). Overall, there is less retention for main channel spawning versus floodplain spawning (Jake Mortensen and Robert Dudley, personal communication, December 4th, 2018)

For all years, subreach P2 and P4 have the highest score and P5 has the lowest. P2 may have the highest score because it is more braided and less sinuous than other subreaches, or it may be due to local changes in that subreach that were not analyzed in this report. The difference between P4 and P5 may be due to locations relative to the SADD and how that affects the hydraulic parameters. P5 is closer to the dam, which has a higher the velocity, energy slope, bed slope, and depth. Also, the wetted perimeter and width decrease as shown in Figure 26. These parameters create a low quality habitat for silvery minnows. P4 on the other hand is just downstream of the Rio Salado, which could impact the habitat quality because of the sediment supply. Also, confluences tend to be hotspots for biodiversity (Cluer and Thorne 2013).

Complex islands and bars decreasing could mean, the channel is becoming less braided. Dry side channels are also becoming more abundant, meaning the main channel is becoming more incised and the side channels are less accessible.

6. Shoreline Complexity

Shoreline complexity incorporates some silvery minnow habitat criteria, yet also incorporates geomorphic parameters for its analysis. Because it combines aspects from section 3 and geomorphic characteristics that could fit into section 5, shoreline complexity stands alone as its own section.

6.1. Methods

Two aspects of the shoreline were analyzed: the length of the shoreline and habitat features that indicate complex shoreline. The set of data used to analyze these aspects is shown in Table 15.

Table 15: Years of the photographs used for analyzing the shoreline complexity.

1992	February
2001	February
2002	February
2005	June
2006	January
2008	July
2012	January
2016	October

These are the years with planforms supplied by the USBR available. Data before 1992 is not used for the same reason it is not used in the habitat criteria analysis. Records of fish population before 1993 is not available, so it would be impossible to relate fish population to geomorphic trends before the early 1990's. April of 2005 and June of 2008 are excluded because planforms were not drawn for these photographs. It is unknown how each year's planform was drawn and how they differed, so there may be inconsistencies that affect the lengths.

Features including complex shoreline (1a, 1b, and 1c), bank attached bars (5a, 5b, and 5c), backwater (4a, 4b), and confluences (7a,7b) were considered to impact shoreline complexity. These points and their scores were used to find a habitat shoreline complexity score. Whatever points fall into each subreach were multiplied by their corresponding score and added up to get an overall score for each subreach in each year. These scores were weighted by area by using the same method as outlined in section 5.2.4.2.

The length of the shoreline is also an indicator of complexity. It was measured using ArcGIS by breaking up the active channel outline provided by USBR into subreaches as shown in Figure 48. The rest of the planform drawings are shown in Appendix D. The cumulative length of the right and left bank was used to compare each subreach in each year. To account for different sizes of the subreaches, the length was weighted. This was accomplished by drawing a straight line between each subsequent subreach delineation line perpendicular to the river. Then the cumulative shoreline lengths were divided by the straight line and multiplied by 10 to get a weighted length index.

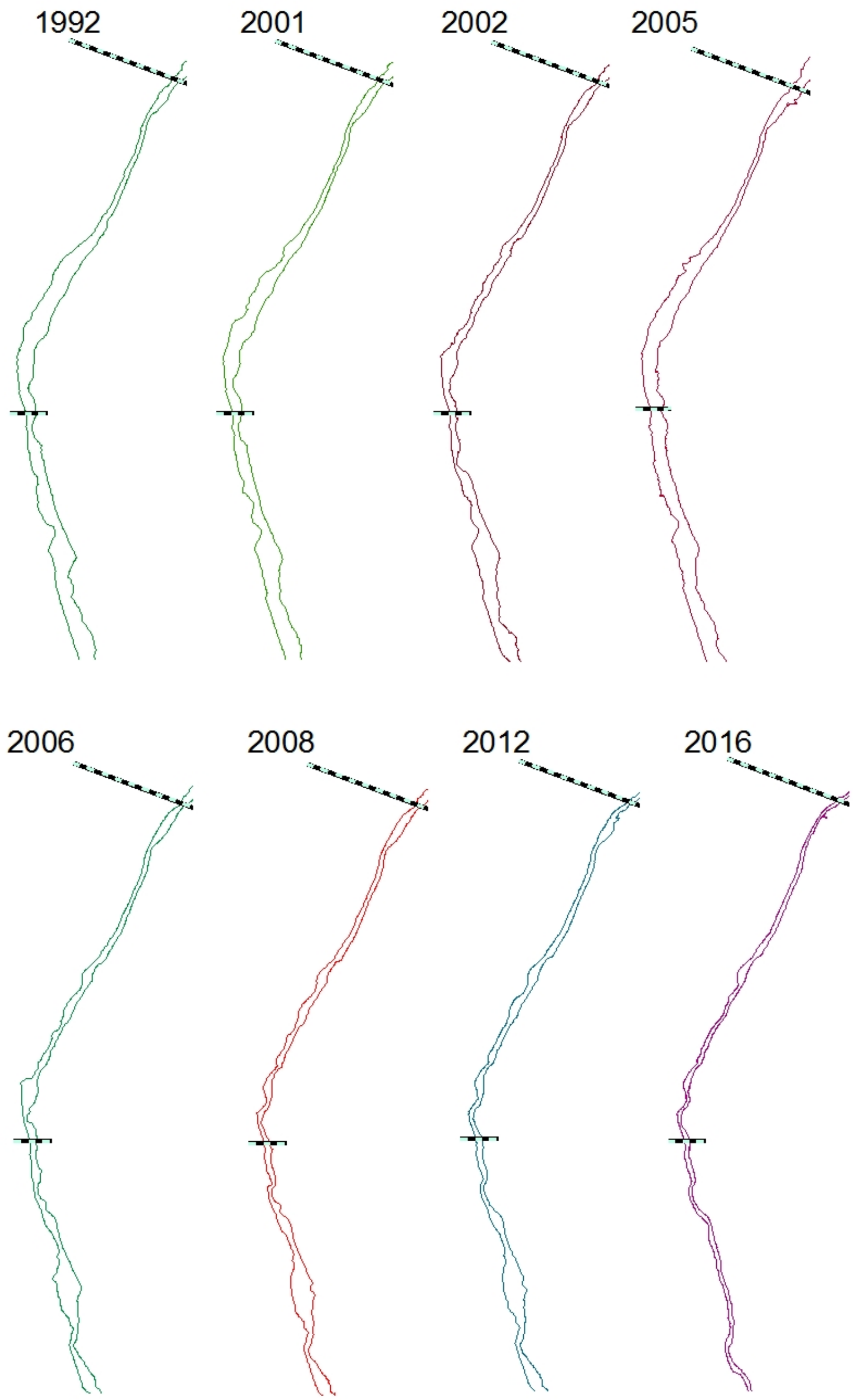


Figure 48: Subreach P1 shoreline length shown with the planform drawing from USBR for each year. The subreach is within the bounds of the perpendicular lines to the planform.

The weight length index and the weighted habitat score were then added together to get an overall shoreline complexity score. They were weighted to be on the same order of magnitude so they when they were added up, each would equally impact the overall score. These overall scores were compared across all years and across the comparable years at 650 cfs. The length of each subreach was also compared across every year and in the comparable years with 650 cfs. The individual parameters were also compared to the overall scores for each year and subreach.

6.2. Results

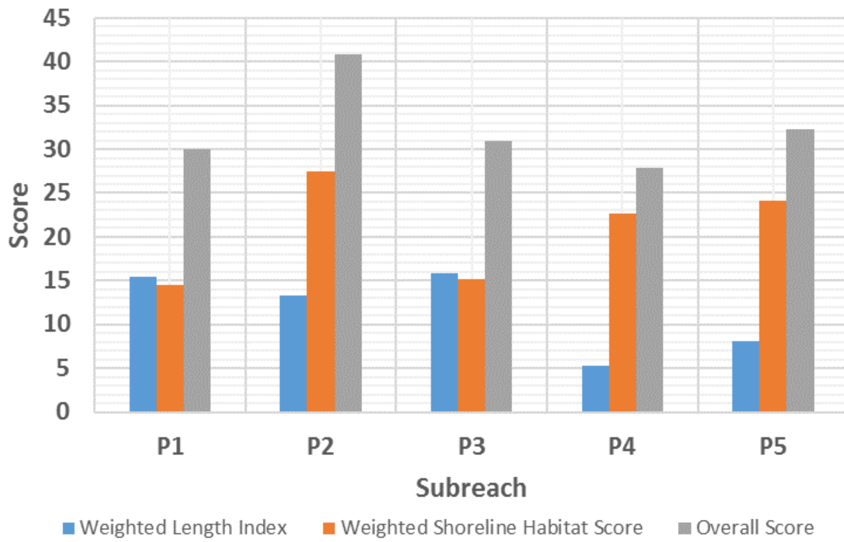


Figure 49: Two parameters for analyzing shoreline complexity are compared and added up to show the overall score in 1992.

The overall complexity scores show that P2 is the most complex in 1992. The rest of the scores in the subreaches are lower and similar to each other. There is not consistent trend in the other years as shown in Appendix D. The shoreline complexity habitat score and the length of the shoreline do not seem to be correlated.

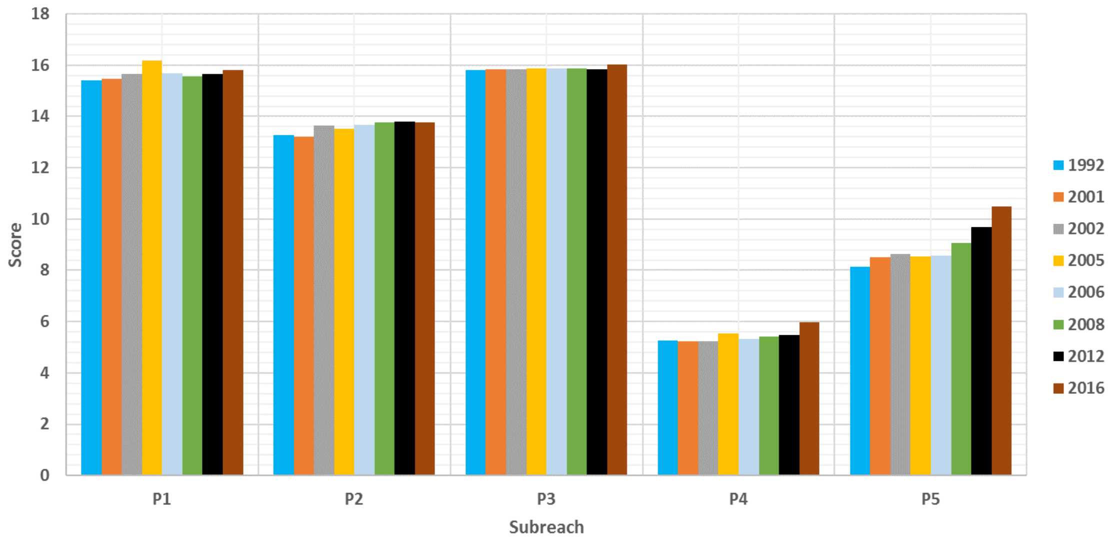


Figure 50: The weighted length of the shoreline is compared over every subreach and every year.

When comparing the lengths only across years, there is a slight increase in length as time goes on.

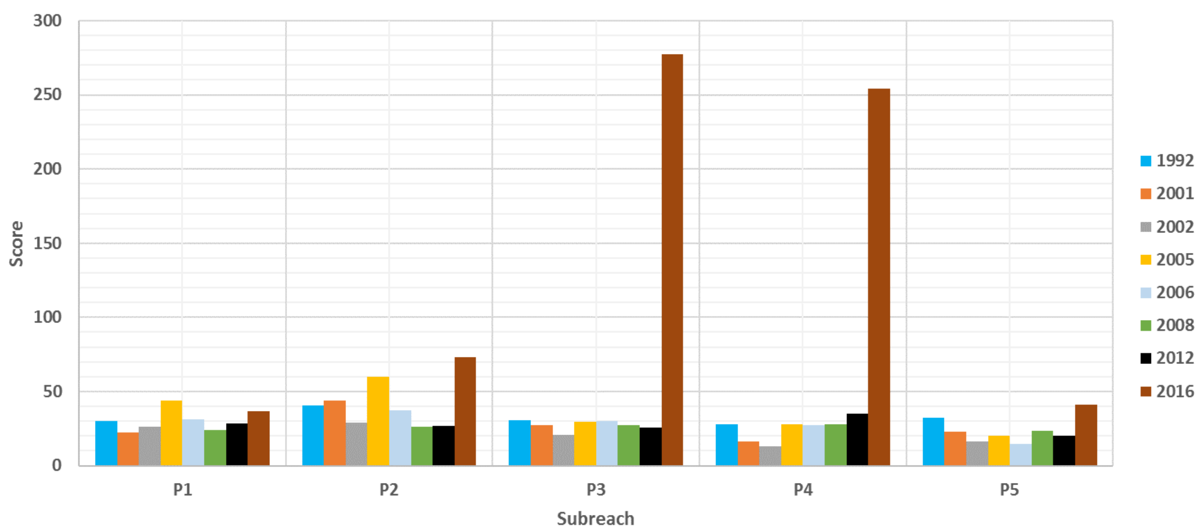


Figure 51: The overall score for shoreline complexity is compared over every subreach and every year.

The overall score has more variation among the years, and 2016 still has the highest scores in each subreach except in P1.

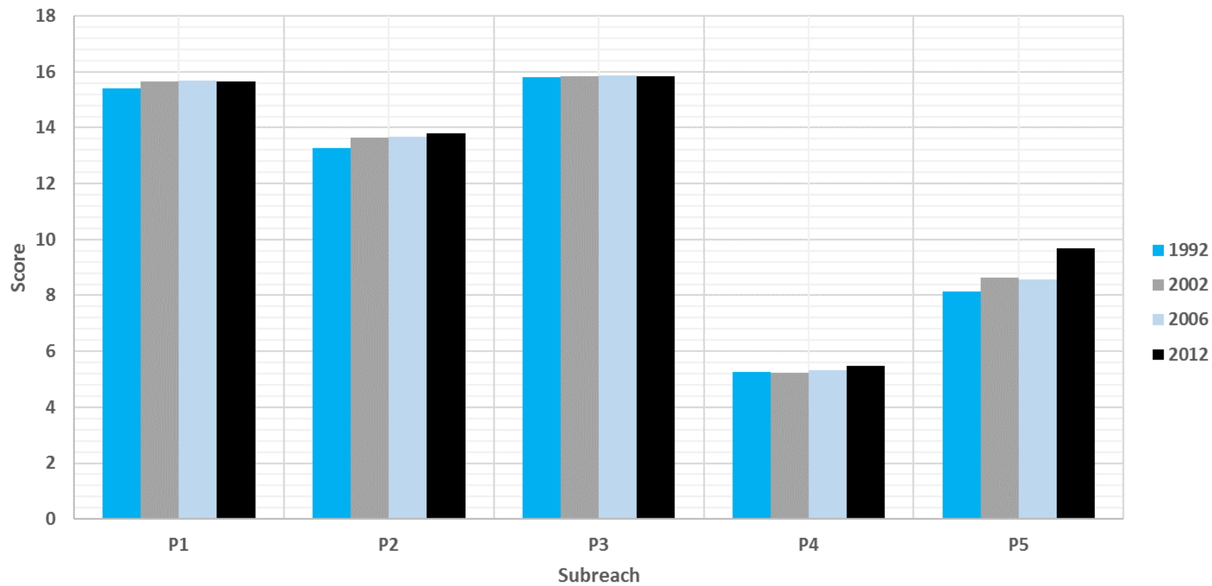


Figure 52: The weighted length of the shoreline is compared over every subreach during years with a flow around 650 cfs when the aerial photograph was taken.

There is not much change in any of the subreaches over the years, but in some subreaches the length goes up slightly.

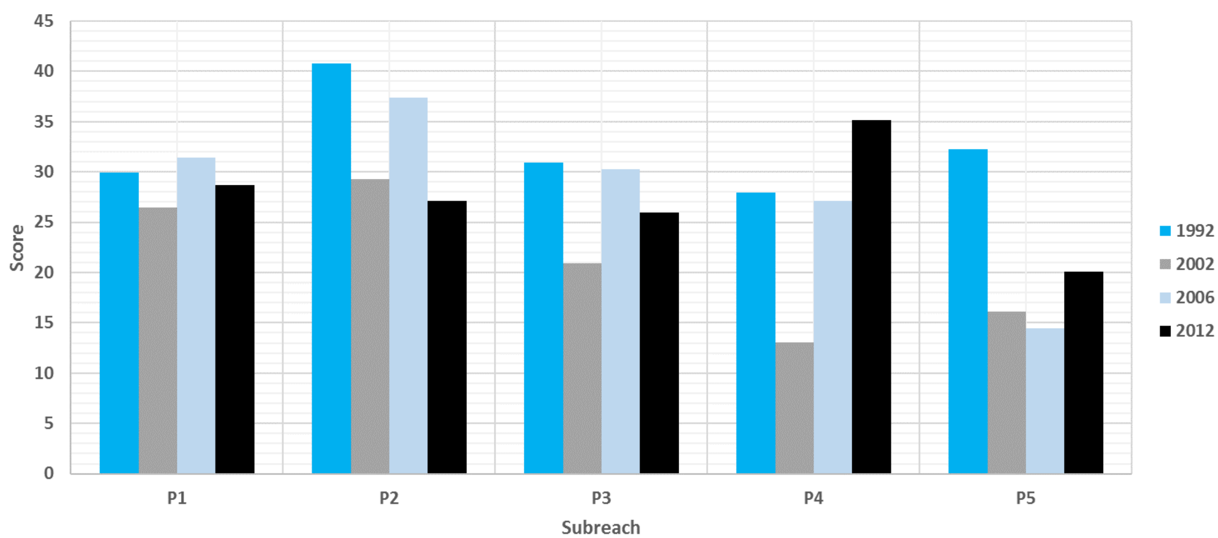


Figure 53: The overall score for shoreline complexity is compared over every subreach during years with a flow around 650 cfs when the aerial photograph was taken.

Throughout these years, each subreach has a different trend. There is not much consistency for the overall score.

In each of these figures where the years and only lengths are compared, the overall trend is the same. P1-P3 are the most complex and P4 and P5 are less so. When looking at the overall score, there is not an obvious trend.

6.3. Discussion

P1-P3 may be have a longer shoreline than P4 and P5 because P4 and P5 are closest to the SADD. The closer the position to the dam, the higher the velocity, energy slope, bed slope, and depth. Also, the wetted perimeter and width decrease in the downstream direction as shown in Figure 26. These occurrences indicate that the channel is straighter in P3-P5, which is consistent with decreasing shoreline complexity. There are not any other consistent trends, especially when looking at the overall scores. 2016 may be more complex because the flow is so low that the channel is more sinuous as mentioned in the discussion in 5.4. Near the downstream end of the reach, there are “basalt-capped mesas on both sides of the river” that creates a natural geological constriction of the width (Easterling Consultants LLC 2015). This may also be impacting the channel complexity in certain subreaches as well.

The length increasing over time since the 1990’s may be due to sinuosity slightly increasing, braiding decreasing and width decreased. Because islands and side channels are not factored into the channel length and complexity, the results are not reflective of changing heterogeneity, but instead just sinuosity increasing.

7. Summary of HEC-RAS and GIS Habitat Analysis

To showcase the methods used for habitat analysis, figures representing one subreach at two flow conditions are presented. The rest of the subreaches at these flow conditions are in Appendix G.

Subreach P2 is depicted in Figure 54 and Figure 55 because it is the subreach that provides the best habitat, as determined from HEC-RAS and GIS analyses. There is also a great amount of habitat variability in this subreach. This allows us to see what the variability looks like when comparing HEC-RAS and GIS images side-by-sided. Only a portion of the subreach is shown so the points and figures are decipherable.

A low and high flow were the two different conditions chosen to be visualized. The low flow analyzed is in 1992 at 650 cfs in GIS and 600 cfs in HEC-RAS shown in Figure 54. The high flow is analyzed at 4500 cfs in GIS in 2005 and 3500 cfs in HEC-RAS in 2002 shown in Figure 55. The difference in years and flows in the high flow analysis come from limitations in available data. The HEC-RAS simulation includes low, medium and high flows from 1992, 2002, and 2012. The only high flow data from aerial photographs analyzed is in 2005. The closest match for year and flow data to 3500 cfs from 2002 in HEC-RAS is aerial photography from April of 2005 at 4500 cfs. Therefore, the high flow results are not perfectly comparable because there is a difference in time and flow.

The top half of Figure 54 and Figure 55 (a) and (b) are from HEC-RAS and the bottom half (c and d) are from GIS. They both depict a portion of subreach P2. The results show that the HEC-RAS and GIS analyses are somewhat comparable. Where there is a large area of good quality habitat from HEC-RAS there tends to be more habitat features mapped in GIS as seen in Figure 55. The trend does not always occur such as in Figure 54 which shows less correlation between the two analyses. Still, previous sections (4.2 and 1.1) show quantitatively how the two methods are closely correlated. These figures are mainly presented to get a visual idea of what the habitat and results look like.

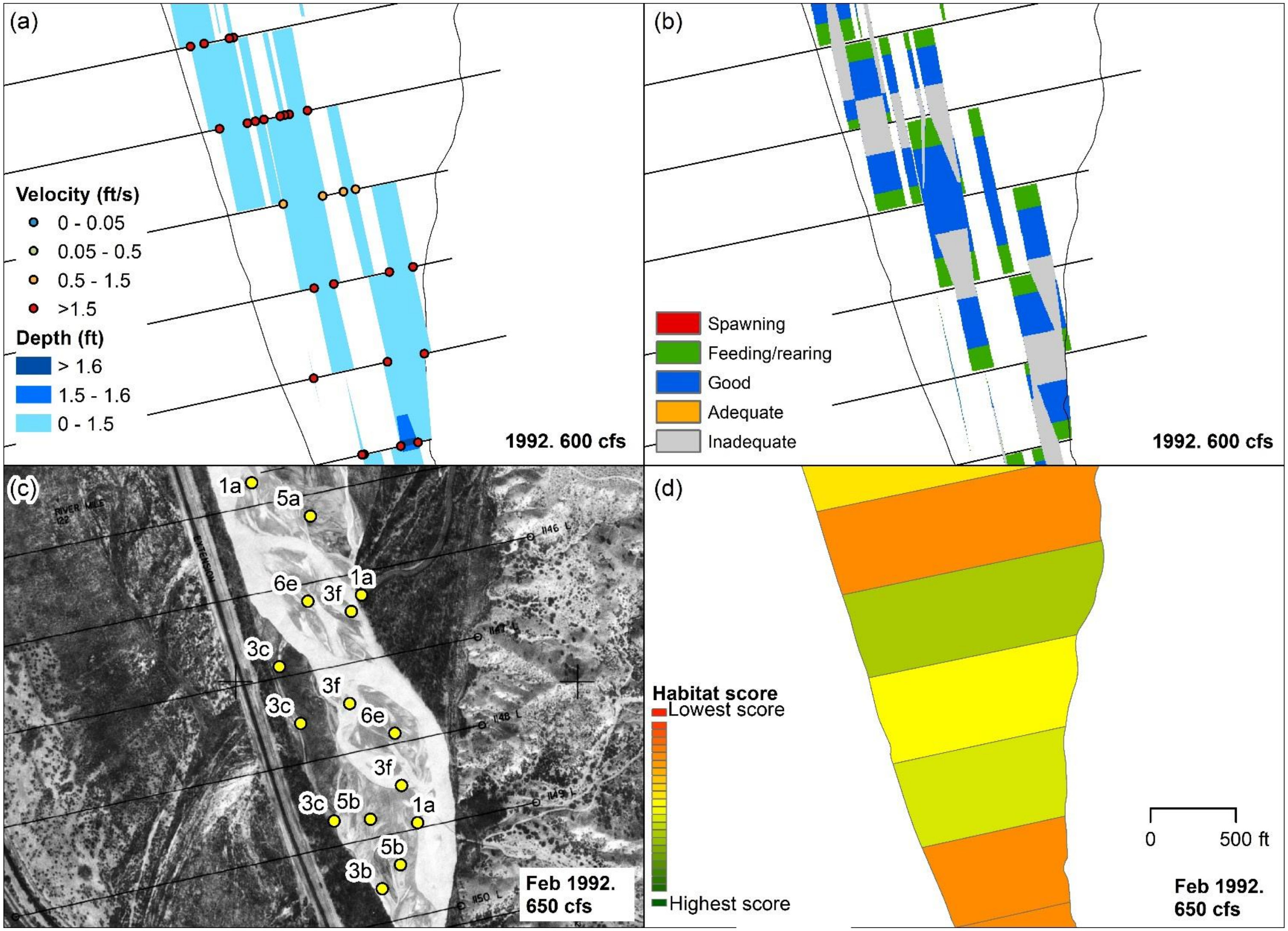


Figure 54: Summary of HEC-RAS and GIS habitat at subreach P2, agg/deg 1145 to 1150. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. The description of these points is given in Appendix A and section 5.2.3. (d) Habitat color scheme based on habitat features.

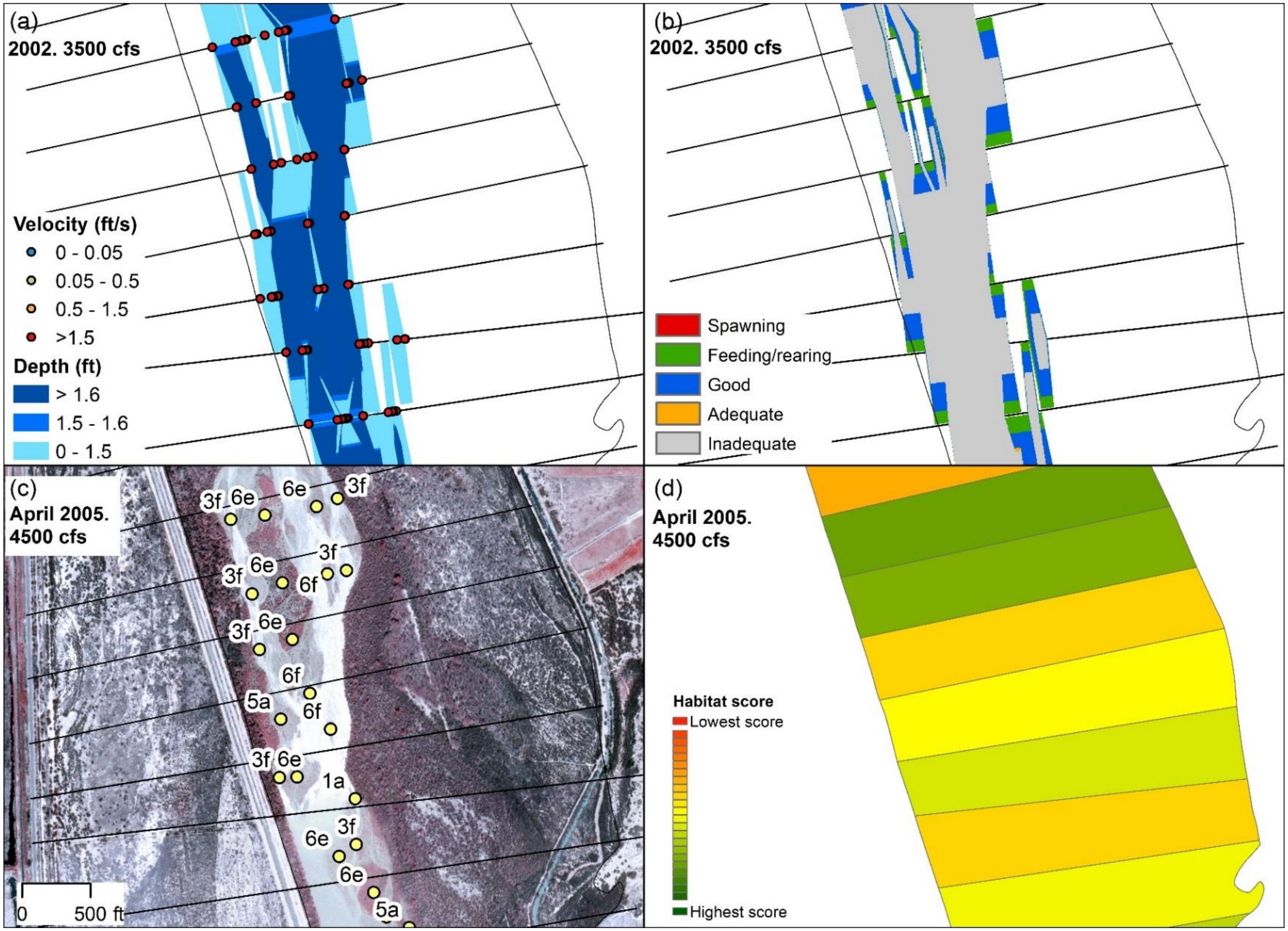


Figure 55: Summary of HEC-RAS and GIS habitat at subreach P2, agg/deg 1137 to 1143. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. The description of these points is given in Appendix A and section 5.2.3. (d) Habitat color scheme based on habitat features.

8. Conclusion

The Rio Puerco reach was analyzed to find hydrologic, hydraulic, geomorphic, and habitat trends between 1918 and 2016. Although, not all analyses spanned this long. For instance, the habitat analysis started in 1992 because fish population data started in 1993. Also, sediment and discharge gages don't always date back to 1918 and HEC-RAS data only goes back to 1935. This reach covers about 11 miles from the Rio Puerco to the San Acacia Diversion Dam (SADD) and has many tributaries. There have been many geomorphic changes since 1918 due to anthropogenic influences such as installing channelization systems in the 1950's and dams such as the SADD (San Acacia Diversion Dam) in 1934.

Several techniques were used to analyze trends along the river as well as silvery minnow habitat. Reports already done on the Rio Grande and input from USBR were used to craft the objectives and goals of this technical report. Hydrologic and hydraulic trends were mainly taken from a report by Klein et al. 2018a and raw data used for the rest of the analyses on this reach were from USBR. HEC-RAS and GIS were used to find the geomorphic and river characteristics such as sinuosity, width, how braided the channel is, bed elevation, volume change, and other hydraulic parameters. A conceptual geomorphic analysis was used to understand how the river has changed and how it will change in the future. HEC-RAS was also used to simulate flows in different years to find quantities and locations of "spawning", "feeding/rearing", "good", "adequate" or "inadequate" habitat. GIS was used to map habitat quality over different years using aerial photography. The geomorphic, HEC-RAS and GIS analyses of the river were broken up into subreaches to get detailed results. The reach and subreach analyses were used to find trends in hydraulics, geomorphology and habitat quality.

- Annual water volume has been reduced recently (since the 2000's). Peak discharges have become less frequent, shorter and have decreased in the past few decades. Flow has become homogenized.
- Annual suspended sediment discharge in the Rio Grande and Rio Puerco has decreased since the 1970's. The effective discharge for suspended sediment has also decreased from 900 to 750 cfs since 1995.
- Most subreaches have increased in sinuosity, decreased in width, become more incised, and sediment size has increased. The subreaches have also increased in depth and velocity while decreasing in wetted perimeter, energy slope and bed slope.
- A conceptual geomorphic model shows the channel is becoming more incised and less connected to its floodplain. Losing connection to the floodplain is extremely detrimental to the silvery minnow, along with the other geomorphic changes listed above.
- In the HEC-RAS analysis, the best "spawning" and "feeding/rearing" habitat occur when the flows are at 3500 cfs (compared to 600 and 1400 cfs). The best "spawning" and "feeding/rearing" habitat occurs in subreach P5 in 2002. The "good" habitat has decreased in area over time and is highest in subreach P2.

- For the GIS analysis, the lowest scores for flows are around 1500 cfs. The highest scores occur in earlier years or when the flow is high enough to connect the main channel to the floodplain (above 3500 cfs). 2016 also has a comparatively very high score because it has such as low flow that the channel appears very complex. Comparing all years, P2 and P4 have the best scores. When comparing years of photographs at 650 cfs, P2 has the best overall habitat score.
    - GIS was used mainly to compare habitats across low flow scenarios because of limited aerial photographs. This still may be useful because low flows are becoming more common and high flows are less common.
- To numerically compare the GIS and HEC-RAS analyses, the results at 600 cfs were used. At low flows the two methods are highly correlated with each other. 1992 and 2002 habitats have higher scores than in 2012 for both the GIS and HEC-RAS analysis.
    - Subreach P2 provides the best in-channel habitat. Also, flows above 3500 cfs tend to provide the best overall habitat because it connects the channel to the floodplain. Flows around 1400 cfs usually provide the least amount of quality habitat.
- There is not a consistent trend with shoreline complexity, but the length has been slightly increasing since the 1990's.
- Silvery minnow's habitat quality has been decreasing over time due to a more incised channel, increased depth and velocity, increased sediment size and disconnection to the floodplain.

The Rio Grande is naturally very dynamic, yet anthropogenic influences have caused alterations that have accelerated changes unnaturally. This has greatly affected the ecological health and usability of the river.

8.1. Future Research

Though the low flows create adequate complexity, velocities and depths for silvery minnow spawning and rearing in theory, low flow conditions do not always create the appropriate spawning environment. Exactly how spawning is trigged and what exactly allow eggs and juveniles to survive is still unknown. Though releasing floodplain connecting flows from dams periodically during the spring would help solve this issue, it is not a viable option. The water in the Rio Grande is already apportioned to those who have a legal right to it. Figuring out how to trigger spawning and keep minnows alive throughout every stage of their life cycle is key. This may mean changing geometry of the river so the floodplain is inundated at lower flows and pairing this with laboratory experiments to see what exactly triggers spawning. These experiments could involve simulating high flow conditions for floodplain inundation as well as temperature or nutrient levels. Another option would be to do a detailed silvery minnow population study on a subreach such as P2 that has a high habitat score compared to one that has a low score like P1. Finding links between channel morphology, hydraulics, ecology, water quality, hydrology and fish population could lead to answers that will help them survive.

References

Baird, D. C. (2014). Historical Rio Grande Channel Width Design Literature Review Summary, U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group. Denver, CO, 42 p.

Baird, D. C. (2016). *Rio Grande silvery minnow habitat restoration design review*, Department of the Interior, Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group. Denver, CO.

Bauer, T.R. (2000). *Morphology of the Middle Rio Grande from Bernalillo Bridge to San Acacia Diversion Dam, New Mexico*, Colorado State University, Fort Collins, CO.

Bauer, T.R. (2009). *Sediment Evolution on the Middle Rio Grande, New Mexico*, U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group. Denver, CO. 36 p.

Bauer, T.R., and Hilldale, R. (2006). *Sediment Model for the Middle Rio Grande – Phase 2: Isleta Diversion Dam to San Acacia Diversion Dam*. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group. Denver, CO. 295 pp.

Berry, K. L., and Lewis, K. (1997). *Historical Documentation of Middle Rio Grande Flood Protection Projects, Corrales to San Marcial*. Office of Contract Archeology, University of New Mexico, Albuquerque, NM.

Bestgen, K. R., Mefford, B., Bundy, J., Walford, C., Compton B., Seal S., and Sorensen T. (2003). *Swimming performance of Rio Grande silvery minnow. Final Report to U.S. Bureau of Reclamation, Albuquerque Area Office, New Mexico*. Colorado State University, Larval Fish Laboratory Contribution 132, 70 p.

Bestgen, K.R., and Platania S.P. (1991). "Status and Conservation of the Rio Grande Silvery Minnow, Hybognathus amarus." The Southwestern Naturalist. 36 (2), 225-232

Bovee, K.D., Waddle, T.J., and Spears, J.M. (2008). "Streamflow and endangered species habitat in the lower Isleta reach of the middle Rio Grande." U.S. Geological Survey. Open-File Report 2008-1323, 1-177

Cluer, B., and Thorne, C. (2014). "A stream evolution model integrating habitat and ecosystem benefits." *River Research and Applications*, 30(2), 135–154.

Cowley, D.E. (2002). "Water Requirements for Endangered Species- Rio Grande Silvery Minnow (Hybognathus Amarus)." New Mexico Water Resources Research Institute. 97-107

Crawford, C. S., and Cully, A. C., Leutheuser, R., Sifuentes, M. S., White, L. H., and Wilber, J. P. (1993). *Middle Rio Grande ecosystem: Bosque biological management plan*, Middle Rio Grande Biological Interagency team, Albuquerque, NM, 320p.

Culbertson, J. K., and Dawdy, D. R. (1964). “A study of fluvial characteristics and hydraulic variables, Middle Rio Grande, New Mexico.” *U.S. Geological Survey, Professional Paper 1498-F*, Washington, D.C., 82 p.

Dudley, R. K., and Platania, S. P. (1997). *Habitat use of Rio Grande silvery minnow*. Division of Fishes, Museum of Southwestern Biology, Department of Biology, University of New Mexico.

Dudley, R.K., Platania, S.P., and Gottlieb, S.J. (2005). *Rio Grande Silvery Minnow Population Monitoring Program Results from 2004*. American Southwest Ichthyological Research Foundation, Albuquerque, NM, 184 p.

Dudley, R. K., Platania, S. P., and White, G. C. (2016). *Rio Grande Silvery Minnow population monitoring results from February to December 2015*, American Southwest Ichthyological Researchers, LLC, Albuquerque, New Mexico.

Easterling Consultants LLC, and Tetra Tech. (2015). “Geomorphic and Hydraulic Assessment of the Rio Grande from the Rio Puerco to San Acacia Diversion Dam 1998 to 2015.” Middle Rio Grande Project Hydrographic Data Collection. U.S. Bureau of Reclamation, Albuquerque, New Mexico, 1-37

Happ, S.C. (1948). “Sedimentation in the Middle Rio Grande Valley, New Mexico.” Bulletin of the Geological Society of America. 59, 1191 – 1216

Holmes, R., and Hayes, J., (2011). “Broad-scale Trout Habitat Mapping for Streams (Using Aerial Photography and GIS).” 1979, 1-40

Horner, C. (2016). “Middle Rio Grande Habitat Suitability Criteria” technical report, presented to Colorado State University, CO, in partial fulfillment of the requirements for the degree of Master of Science

Klein, M., Herrington, C., AuBuchon, J., and Lampert, T. (2018a). *Isleta to San Acacia Geomorphic Analysis*, U.S. Bureau of Reclamation, Reclamation River Analysis Group, Albuquerque, New Mexico.

Klein, M., Herrington, C., AuBuchon, J., and Lampert, T. (2018b). *Isleta to San Acacia Hydraulic Modeling Report*, U.S. Bureau of Reclamation, Reclamation River Analysis Group, Albuquerque, New Mexico.

Julien, P.Y. (2002). *River Mechanics,* Cambridge University Press, New York

Larsen, A. (2007). “Hydraulic Modeling Analysis of the Middle Rio Grande – Escondida Reach, New Mexico” thesis, presented to Colorado State University, CO, in partial fulfillment of the requirements for the degree of Master of Science.

Makar, P. (2010). *Channel Characteristics of the Middle Rio Grande, New Mexico*. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO, 48 p.

Makar, P. and AuBuchon, J. (2012). *Channel Conditions and Dynamics of the Middle Rio Grande*, U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, Albuquerque, NM, 108 p.

Marshall, M. (2015). “Earth - What is the point of saving endangered species?” *BBC News, BBC*, <http://www.bbc.com/earth/story/20150715-why-save-an-endangered-species> (Jul. 4, 2018).

Massong, T., Paula, M., and Bauer, T. (2010). “Planform Evolution Model for the Middle Rio Grande, NM.” *2nd Joint Federal Interagency Conference, Las Vegas, NV, June 27 - July 1, 2010*.

Medley, C.N., and Shirley, P.D. (2013). "Review and reinterpretation of Rio Grande silvery minnow reproductive ecology using egg biology, life history, hydrology, and geomorphology information" *U.S. National Park Service Publications and Papers.* 133.

MEI. (2002). *Geomorphic and Sedimentologic Investigations of the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir*, Mussetter Engineering, Inc., Fort Collins, CO, 220 p.

MEI. (2006). “Evaluation of Bar Morphology, Distribution and Dynamics as Indices of Fluvial Processes in the Middle Rio Grande, New Mexico.” Report prepared for the New Mexico Interstate Stream Commission and the Middle Rio Grande Endangered Species Act Collaborative Program.

Osborne, M. J., Carson, E. W., and Turner, T. F. (2012). “Genetic monitoring and complex population dynamics: insights from a 12-year study of the Rio Grande silvery minnow.” *Evolutionary Applications*, 5(6), 553–574.

Parametrix. (2008). *Restoration analysis and recommendations for the Isleta Reach of the Middle Rio Grande, NM*, Parametrix, Inc. Albuquerque, NM, 292 p.

Perschbacher, J. (2011). *The Use of Aerial Imagery to Map In-Stream Physical Habitat Related to Summer Distribution of Juvenile Salmonids in a Southcentral Alaskan Stream*, University of Alaska Fairbanks, Fairbanks, AK.

Posner, A. J. (2017). Channel Conditions and Dynamics of the Middle Rio Grande River. Albuquerque, New Mexico.

Russo, B. (2018). “An Endangered Fish Out of Water.” Earth Island Journal. News of the World Environment, < http://www.earthisland.org/journal/index.php/elist/eListRead/an_endangered_fish_out_of_water/> (July. 4, 2018)

Scurlock, D. (1998). “From the Rio to the Sierra: an environmental history of the Middle Rio Grande Basin.” *General Technical Report RMRS-GTR-5. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station*, *440 p.*

Swanson, B., Meyer, G., and Coonrod, J. (2010). *Coupling of Hydrologic/Hydraulic Models and Aerial Photographs through Time, Rio Grande near Albuquerque, New Mexico: Report Documentary 2007 Work*. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Tashjian, P. and Massong, T. (2006). "The Implications of Recent Floodplain Evolution on Habitat within the Middle Rio Grande, NM." *2006 Federal interagency Sedimentation Conference*, 9 p.

Tetra Tech. (2002). *Development of the Middle Rio Grande FLO-2D Flood Routing Model Cochiti Dam to Elephant Butte Reservoir.* Tetra Tech, Inc. 48 p.

Tetra Tech. (2014). *Ecohydrological Relationships along the Middle Rio Grande of New Mexico for the Endangered Rio Grande Silvery Minnow*. US Army Corps of Engineers, Albuquerque district, Albuquerque, New Mexico, 109 p.

Torres, L.T. (2007). *Habitat Availability for Rio Grande Silvery Minnow (Hybognathus amarus) Pena Blanca, Rio Grande, New Mexico*, University of New Mexico, Albuquerque, New Mexico.

U.S. Bureau of Reclamation. (n.d.). "PROJECTS & FACILITIES." Central Valley Project - Mid-Pacific Region | Bureau of Reclamation, <https://www.usbr.gov/projects/index.php?id=130> (Aug. 9, 2018).

U.S. Fish and Wildlife Service. (2007). "Rio Grande Silvery Minnow (Hybognathus amarus)." Draft Revised Recovery Plan, Albuquerque, New Mexico, 174 p.

U.S. Fish and Wildlife Service. (2010). "Rio Grande Silvery Minnow Recovery Plan, First Revision" Southwest Region U.S. Fish and Wildlife Service Albuquerque, New Mexico, 210 p.

Varyu, D. (2013). *Aggradation / Degradation Volume Calculations: 2002-2012*. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group. Denver, CO.

Varyu, D. (2016). *SRH-1D Numerical Model for the Middle Rio Grande: Isleta Diversion Dam to San Acacia Diversion Dam*. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Sedimentation and River Hydraulics Group. Denver, CO.

Appendix A - Habitat Criteria

Bankline complexity:

Bankline complexity criteria

1a. Bankline juts out greatly, forms a small inlet, is rocky or has diverse substrate (vegetated islands, sandy banks and water inundating some parts of the bank). Provides a great amount of habitat, potentially causes eddies.	
1b. Bankline juts out or caves in slightly and is somewhat diverse. Provides some amount of habitat.	
1c. Possible access to more complex shoreline during higher flows (outside of active channel so it is less accessible)	

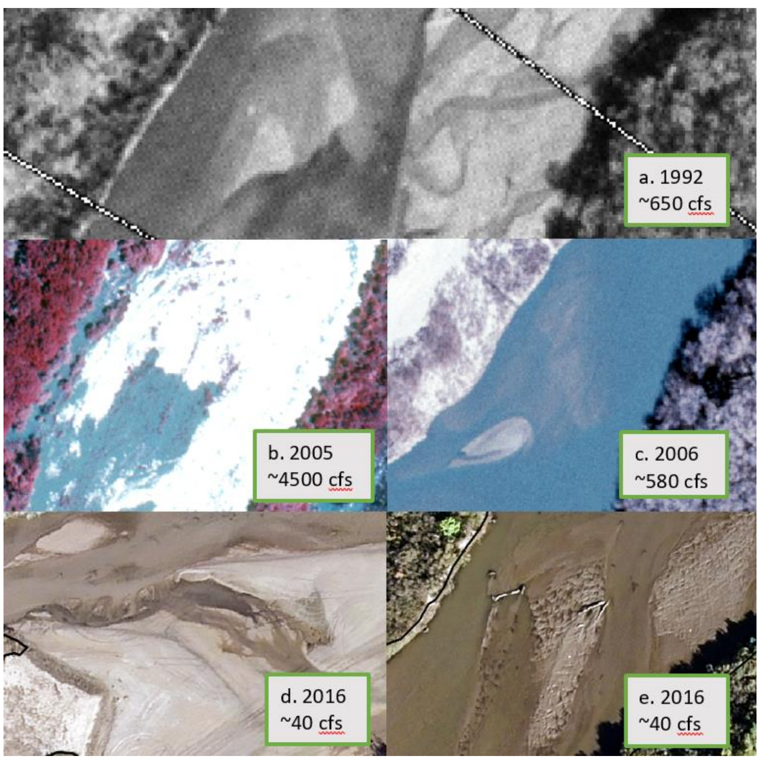
Bankline complexity scores

	Shoreline Complexity		
Criteria	1a	1b	1c
Score	4	3	2

Complex margins, or shorelines, are very important for silvery minnow habitat because they cause lower velocities, eddies, and shallower waters (Bovee et al. 2008). 1a has the most complex shoreline with inlets, channels that cause eddies, lower velocities, and diverse water levels. This is not classified as backwater because backwater has a more definite channel away from the main flow. Backwater is also more isolated from the main channel, so it would have lower velocities and would score higher than 1a. 1b offers a refuge, yet it is a simple inlet and the area of complexity is not as large as 1a, so it counts for less habitat points than 1a. 1c is even less diverse and gets the lowest score for bankline complexity. It has the potential to become inundated and provide habitat, but is less accessible than bankline in the active channel. Most banklines analyzed have an active channel outline (provided by USBR) that matches with the water surface. In 2016 though, the water surface is much lower than the active channel so channel complexity is based on the active channel outline instead of the water surface.

Main Channel Complexity:

The clarity and quality of aerial photographs varies across years, within the reaches, and between different flow conditions. This makes it hard to analyze small features of the habitat criteria across the years of photographs provided. For instance, debris piles and bedforms can only be distinguished in highest quality photographs from 2016. The figure below shows the difference in quality of the photographs.

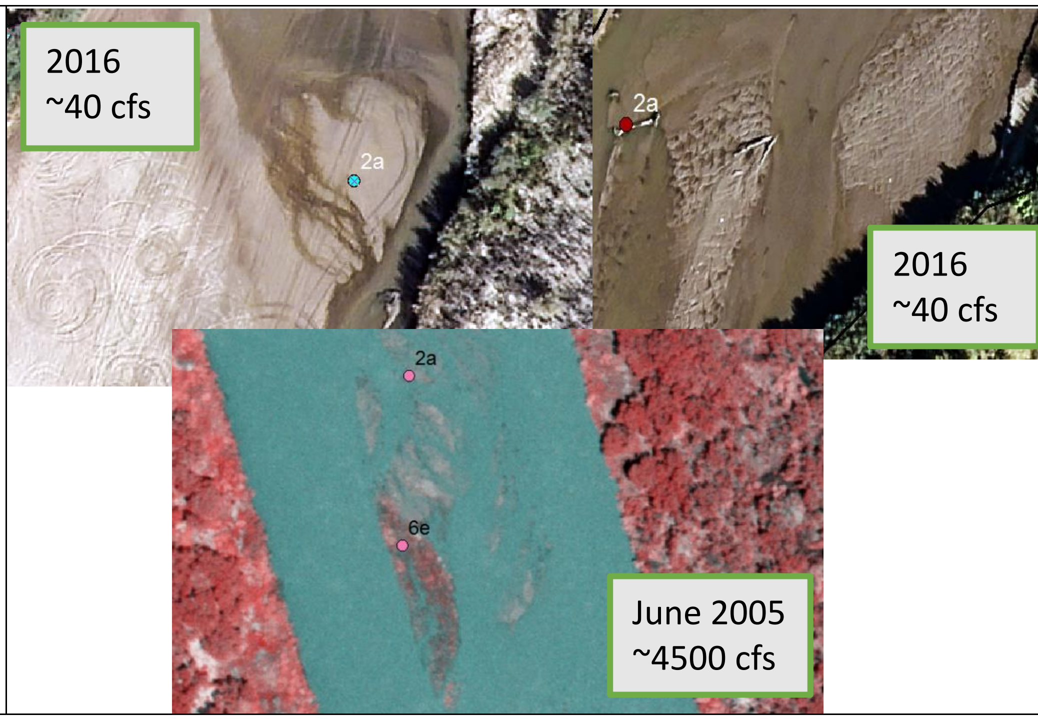


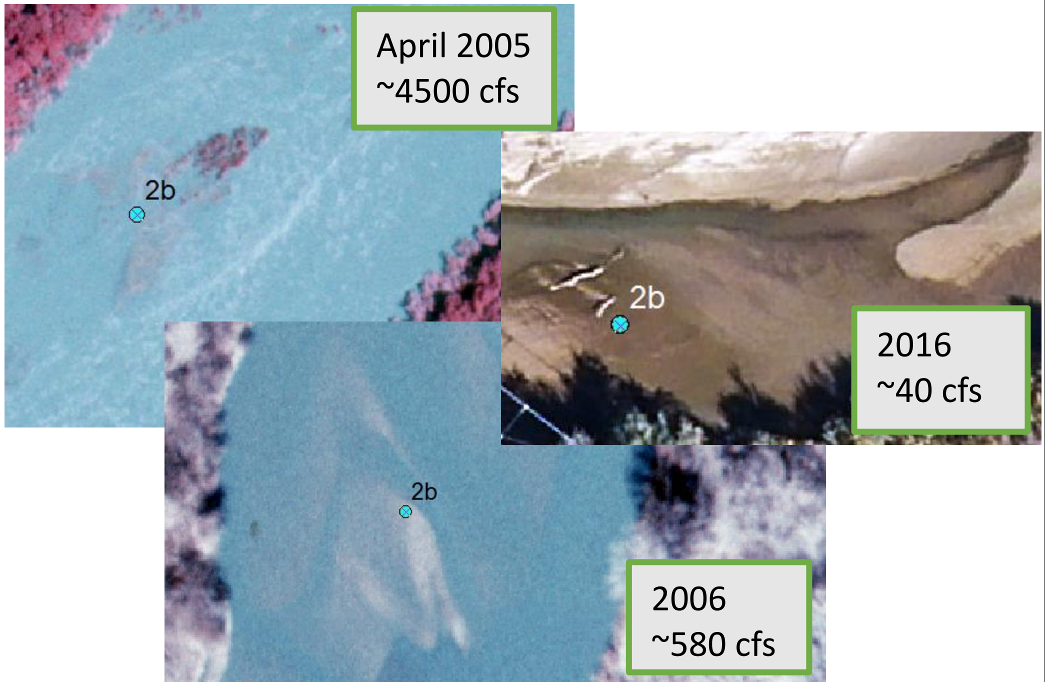
A set of aerial photography that shows the differences in close up quality. The zoom in each picture is as follows: a. 1:1000, b. 1:1500, c. 1:800, d. 1:600, e. 1:500). 1992 zoomed away by twice as much as 2016 gives a much more pixilated image than in 2016. 2016 has much better resolution even compared to 2006 (and 2008 which is not depicted here). 2005 has areas where light is reflecting off the water that makes it difficult to see what is happening in the channel. It also depicts the variability of flows and how that affects what is seen.

Therefore, lumping together features that require close up analysis that create main channel complexity is necessary. These features include bedforms, low flow complexity, substrate or formations causing shallow waters, and debris piles.

All of these images vary by a great amount, but they all depict low flow features that are diverse so they could all be identified as the same criteria (2a). Counting these smaller features together does not change the overall score very much because they all serve similar purposes of creating complex flow, eddies, and shallower waters. For example, in 2016 (2d.) more of the river is exposed, so it appears much more complex at a low flow. 2e. is in a higher flow area, yet has debris piles and bedforms that cause ripples which could be suitable as well. In the bottom left corner of 2b. and center of 2c. images, bedforms or low geologic features could be the result of what is seen. These look like shallow and physically diverse areas, so they receive a high suitability score as well. In 1992, the complexity is hard to see at a small scale, but shallow areas with various geomorphic features can still be identified.

Main channel complexity criteria

2a. Large debris piles/low-flow complexity in the main channel (possibly braided). Large substrate/ formations create shallow depths	

2b. Small to Medium sized debris piles/low-flow complexity in main channel. Medium substrate/ formations create shallow depths	

	Main Channel Complexity	
Criteria	2a	2b
Score	4	3

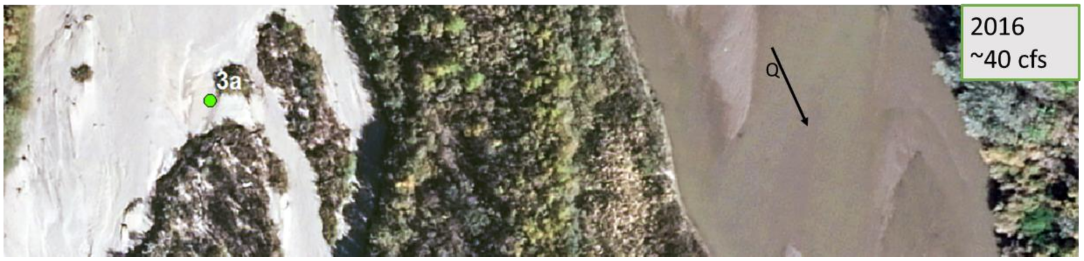
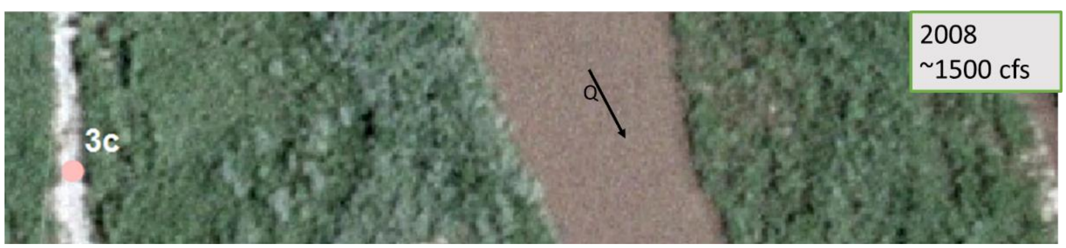
Main channel complexity scores

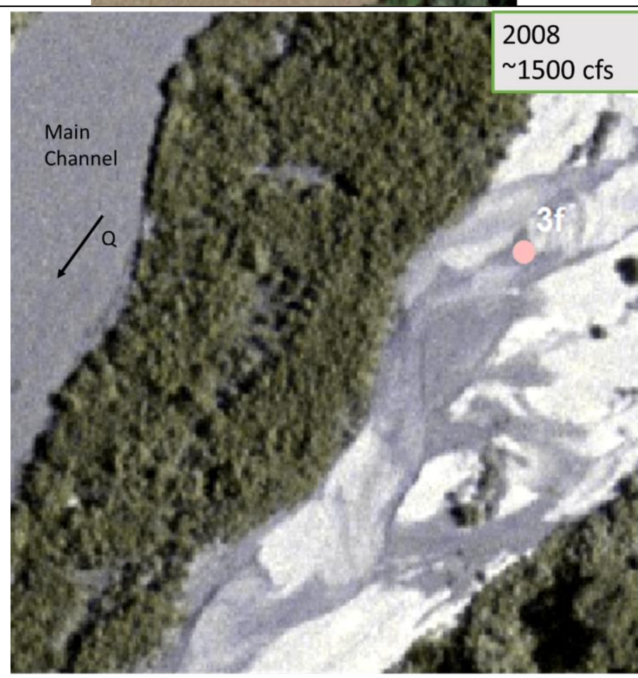
In-channel complexity, extensive debris piles, bedforms and formations are depicted in above. Bedforms, channel complexity and debris piles all offer suitable habitat for fish (Bovee et al., 2008, Cluer, Thorne 2013, Tetra Tech, 2014). Therefore, main-channel complexity scores are relatively height. In 2b, there are images of debris piles and substrate formations that are less extensive as those depicted in 2a figures. Because both 2a and 2b are in the main channel that experiences higher velocities, the scores are not as high as backwater or complex side channels. They are still high because they offer refuge to silvery minnows when side channels or backwaters are not accessible at high flows. 2a is given one more point that 2b because it is bigger and generally more complex than 2b.

*Note: 2a is differentiated from an island or mid channel bar based on level of inundation. If the island is underwater so much that it is broken up into too many formations to count, or there is not an obvious continuous stretch of land, it is counted as substrate/formations.

Side channels:

Side channels criteria

<table>
<tr>
<td>3a. Dry bed- 3+ parallel side channels are in active channel. Channels appear accessible and wide</td>
<td>
</td>
</tr>
<tr>
<td>3b. Dry bed- 1-2 side channels are in active channel and appear accessible- wide (50 + feet)</td>
<td>
</td>
</tr>
<tr>
<td>3c. Dry bed- 1-2 side channels are in active channel and appear accessible- narrow or not as accessible</td>
<td>
</td>
</tr>
</table>

3d. Wet channel- simple and generally not braided- single threaded channel	
3f. Wet channel- Side channels are complex and winding (may cause eddies and slower flows). 2+ channels- braided	

Side channels score

	Side Channels				
Criteria	3a	3b	3c	3d	3f
Score	4	3	2	3	5

A report by Tetra Tech found that complex, braided and anastomosing channels provide the best habitat suitability for silvery minnows (Tetra Tech 2014). Therefore, the more complex and accessible the side channel is, the greater the habitat score. For instance, 3f has the highest score because it has braided features that create eddies and low velocity flows. 3f is also underwater, so it is proven to be accessible. The next highest ranked is 3a because it is the most complex of the dry channels. If the river gets a large flow, this area could become inundated and create shallow, low velocity complex channels for silvery minnows to occupy (3a-3d and 3f are within the active channel delineated by USBR). Next, 3b and 3d are all ranked the same. 3b provides habitat during higher flows, but is less complex and accessible than 3a channels. 3d is ranked similarly because while it is more accessible, there are higher velocities and deeper depths at higher flows. Finally, 3c offers the least suitable habitat because the channels are narrower than 3b channels. The more narrow the less habitat area. Also, 3c is narrower because there is a higher density of vegetation, which indicates that this area is less likely to become inundated and provide habitat. Overall, side channels are given relatively high scores because they are essential for high flow situations when the silvery minnow needs to be connected to more diverse areas with slower velocities.

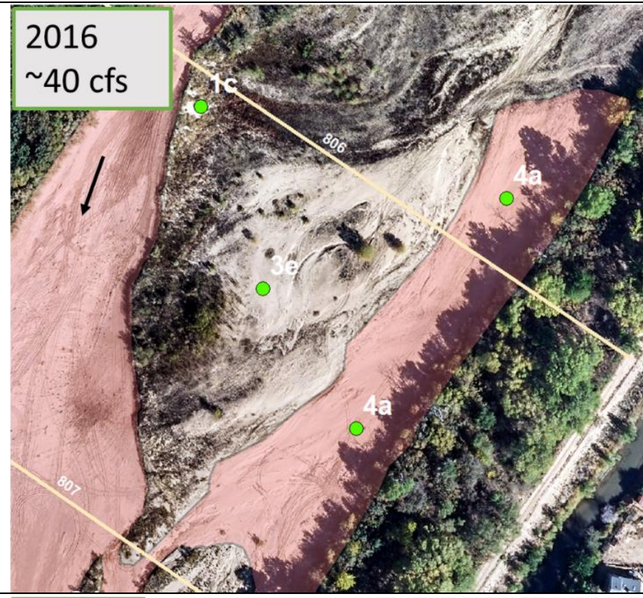
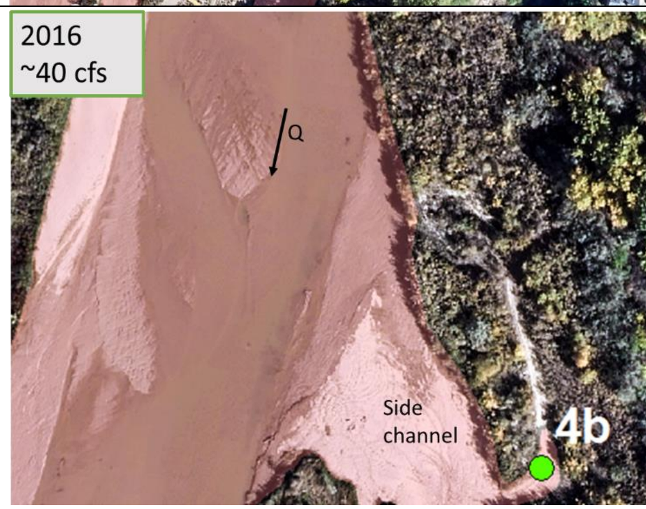
Areas that can become inundated at very high flows are disregarded because they are too hard to analyze the areas beyond the active channel from year to year. The dry channels are identified by being within the active channel. Areas that could become inundated beyond the active channel are too subjective to analyze. For instance, the density of vegetation and previous years of flow areas give an idea of what channels could potentially become inundated. Using LiDAR data also helps with the analysis, but there is only LiDAR available for 2012. This makes analyzing areas that could be inundated in other years inconsistent. Even though potential channels for inundation are highly important for the life cycle of silvery minnows, there is not enough data to effectively analyze them. If there were aerial photographs compared across years that had the same high flow that inundate the floodplain, temporal trends in habitat could be analyzed.

As Middle Rio Grande has become more and more incised over time and peak flows are reducing, the availability of the floodplain habitat is greatly decreasing over the years (Tetra Tech 2014). Because the analysis is focused on the main channel for adult silvery minnows (all that can be analyzed across years at about 650 cfs), channels accessible during a large flood are not considered. This channel would be called 3e, but was removed from the analysis.

*Note: 3f could be confused with 1a because it is near the shoreline. They are differentiated because 3f is generally a complete, yet braided, channel with many offshoots. 1a does not have continuous flow through that section and does not take the form of a channel. 3f is generally more extensive than 1a.

Hydraulic backwater:

Hydraulic backwater criteria

<table>
<tr><td>4a. Backwater extending back > 100 ft., wide and appear accessible</td><td>
</td></tr>
<tr><td>4b. Backwater extending back < 100 ft., not as accessible or wide</td><td>
</td></tr>
</table>

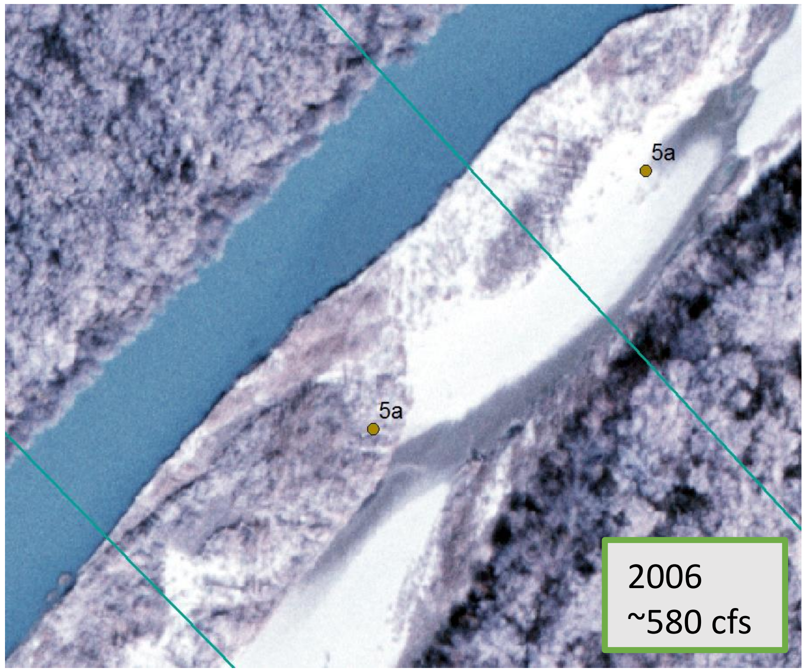
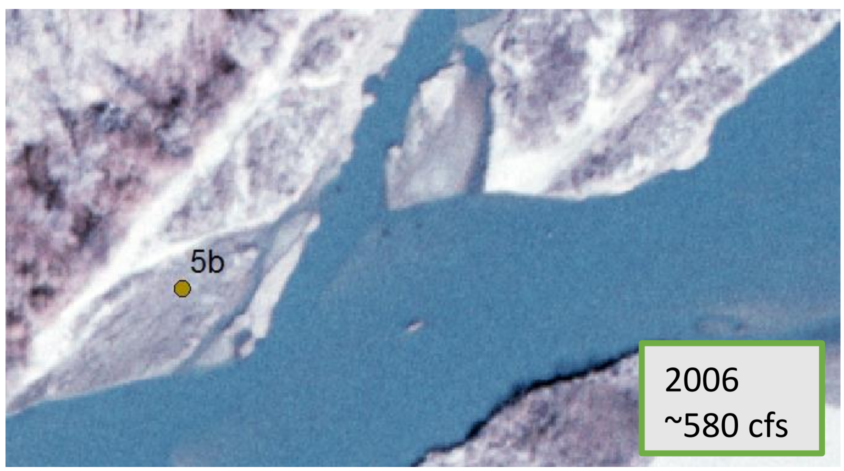
Hydraulic backwater scores

	Backwater	
Criteria	4a	4b
Score	5	4

The backwater is determined by the active channel outline provided by USBR. In the figures depicting 4a and 4b, the water does not actually flow in these channels, yet it has been delineated as a place where water would normally flow. Backwaters are an essential component of silvery minnow habitat because they provide very low velocities that are near zero. The backwaters are especially important for larvae and juvenile silvery minnows when they first hatch and grow (Bovee et al. 2008). 4a is much larger than 4b so it provides more suitable habitat, and therefore receives a higher score.

Bank-attached bars:

Bank-attached bars criteria

5a. Bar is large and provides shallow channels and complex habitat	
5b. Bar is small and provides some silvery minnow habitat (some vegetation)	

5c. Non-vegetated bar with little geomorphic variability	

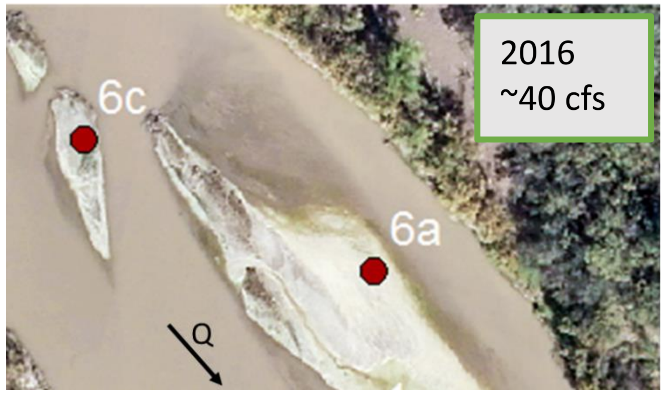
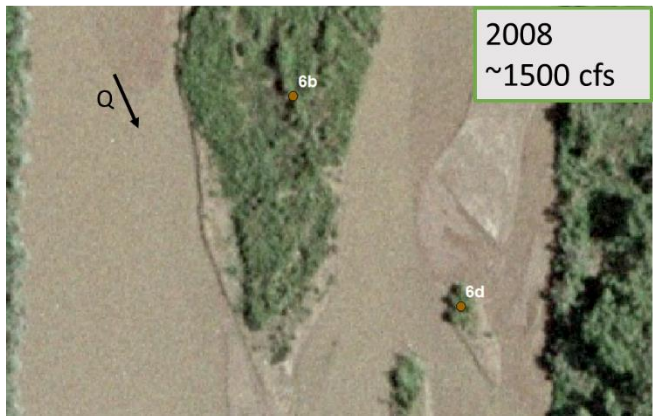
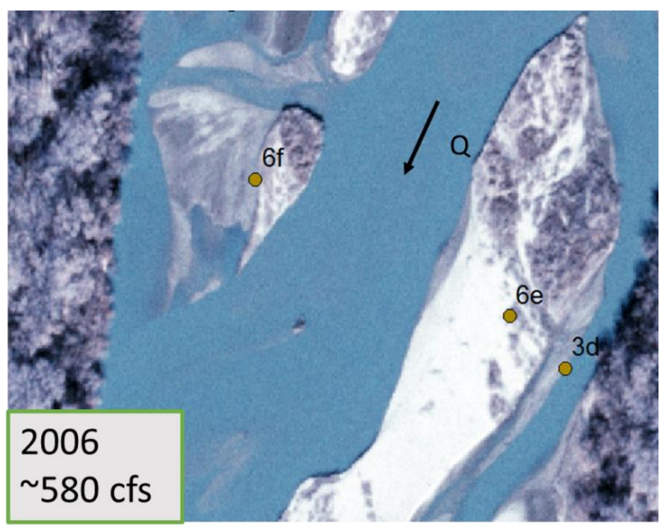
Bank-attached bars scores

	Bars		
Criteria	5a	5b	5c
Score	4	2	1

Bars provide some habitat during high flows, yet they do not provide extensive spawning areas for silvery minnows. Because bank-attached bars are not very complex in their topography, only the most complex and extensive structural features provide in-channel habitat. Even when their complexity is evident and may provide some in channel habitat for adults, this does not always translate into optimum spawning habitat (Tetra Tech 2014). Bars still provide important habitat features during higher flows because they offer shallower habitat than the main channel if they become inundated so they are given a relatively high score. The more complex the bar, the more suitable the habitat is for silvery minnows. For instance, 5a is generally characterized by having more complex geomorphic features, small side channels or vegetation that would provide lower velocity areas and shelter from predators (Cluer and Thorne 2014). 5a is similar to 1a (shoreline complexity), so they must be differentiated. 5a is identified as being much larger and wider than 1a. 5b has less of these features, and 5c does provide overall shallower habitat at higher flows, yet it adds little topographic complexity to the habitat.

Islands/Mid-channel Bars:

Islands/mid-channel bar criteria

6a. Large and non-vegetated 6c. Small and non-vegetated	
6b. Large and vegetated 6d. Small and vegetated	
6e. Large- Some vegetation and some bare ground (Around 50% uniform veg cover over whole island). Could also have shoreline complexity or braided features within island. 6f. Small- Some vegetation and some bare ground (Around 50% uniform veg cover over whole island). Could also have shoreline complexity or braided features within island.	

Islands/mid-channel bar scores

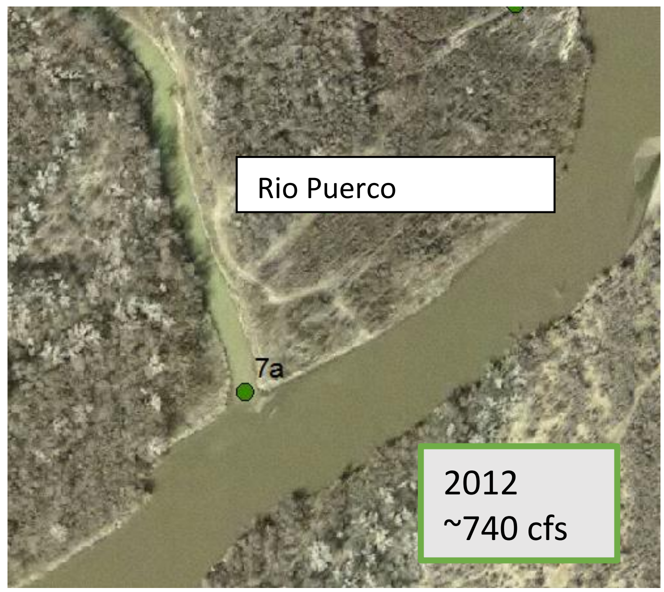
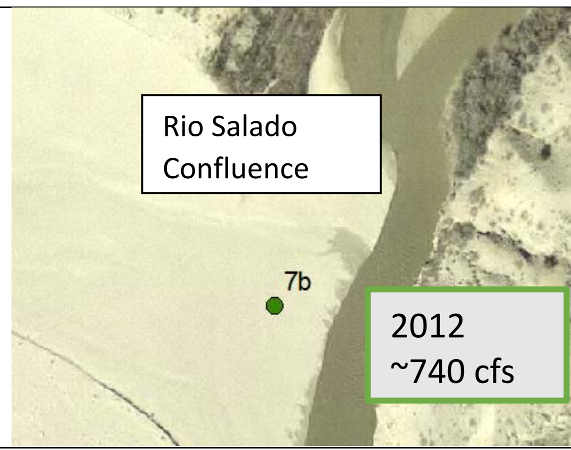
	Islands					
Criteria	6a	6b	6c	6d	6e	6f
Score	3	2	1	1	4	3

Islands in this section area defined as not being attached to the bank and are also referred to as mid-channel bars. An island or mid-channel bar is differentiated from a bank-attached bar based on what it is surrounded by. If there is an obvious, continuous separation from the bar and the shoreline, it is considered an island/mid-channel bar. It can be surrounded by water on both sides, a dry channel on both sides, or water on one side and dry channel on the other. A bank-attached bar has no major side-channels going through it that cause obvious and continuous separation from the bank.

Islands provide habitat to silvery minnows in a similar manner to bank-attached bars. During higher flows, the islands could become partially or fully inundated which helps in-channel habitat, yet is not necessarily most suitable for spawning (Tetra Tech 2014). 6e gets the highest score because it generally has some vegetation, small channels or backwaters within the island providing complex topography and habitat. 6f is a smaller version of 6e so it gets a lower score by one. 6a has no vegetation which indicates it is more accessible at higher flows, and 6b is less accessible because it is densely vegetation. Therefore, 6a has a slightly higher score than 6b. Small islands that are not complex have little to no impact on habitat suitability (Tetra Tech 2014) so these are given the lowest score (6b and 6c). A large island (6a,6b,6e) is considered to reach across one agg/deg polygon, and a small island (6c,6d,6f) spans across half or less of the polygon. Exceptions to this rule may occur when an island is very skinny so it may be considered small instead of large even if it spans across the entire polygon.

Confluences:

Confluences criteria

7a. Active confluence- wet	
7b. Active confluence- dry	

Confluence scores

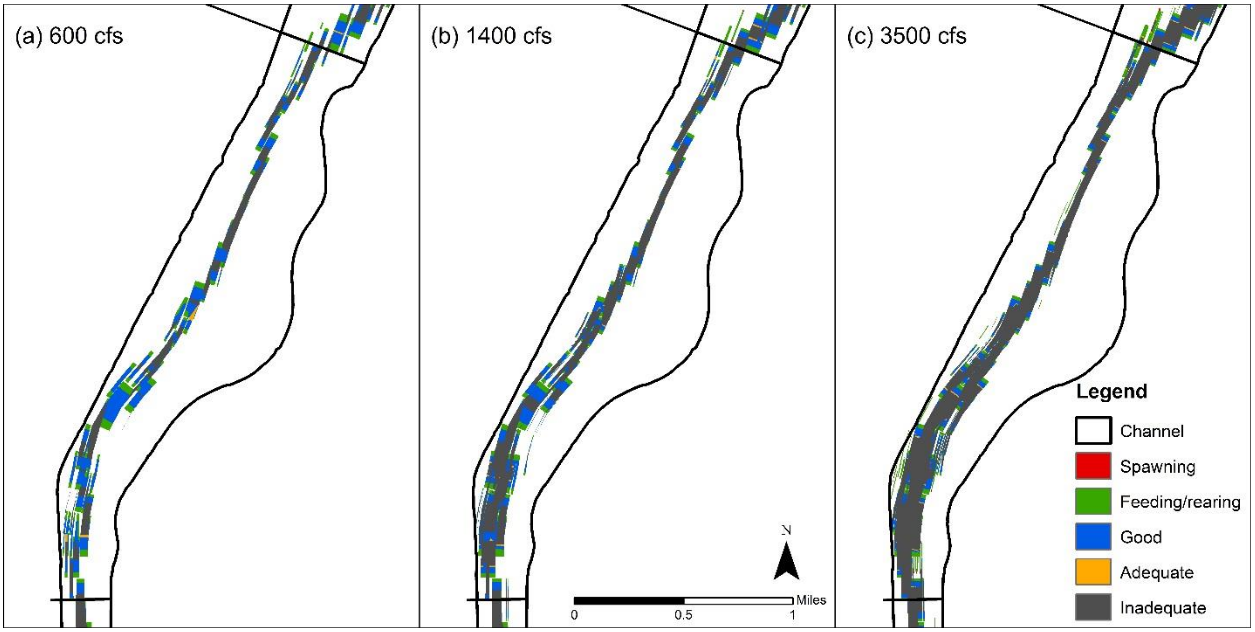
	Wet Confluence	Dry Confluence
Criteria	7a	7b
Score	4	3

Confluences are spots where eddies, accelerating and decelerating velocities, sediment deposits, and large wood tend to accumulate. These factors create ecological hotspots (Cluer and Thorne 2014). Confluences are given a relatively high score because of this. If the confluence does not appear to be active or is disconnected from the Rio Grande, it is not included in the analysis. Also, spots where irrigation canals are not counted as confluences because their flow is variable and cannot be compared across years. While these aren't counted as confluences, they are designated as shoreline complexity or backwater depending on how the "irrigation confluence" interacts with the main channel. Wet, active confluences are given a higher score than dry ones because they provide habitat instead of just channel margin complexity.

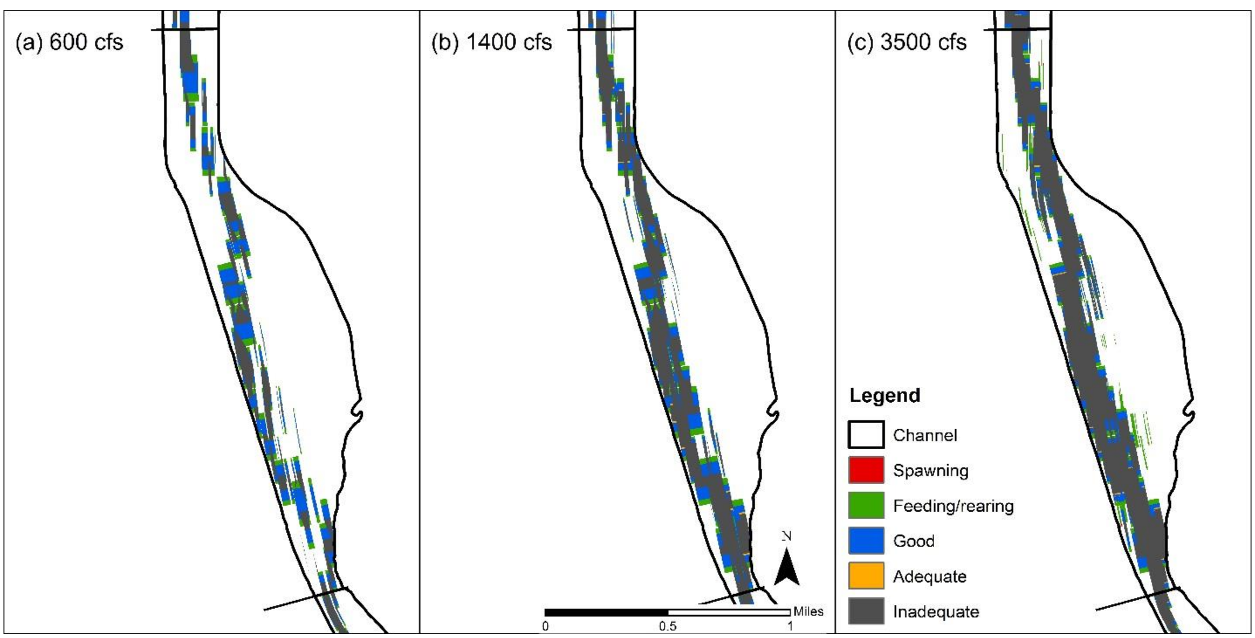
Appendix B - HEC-RAS

(a) 1992

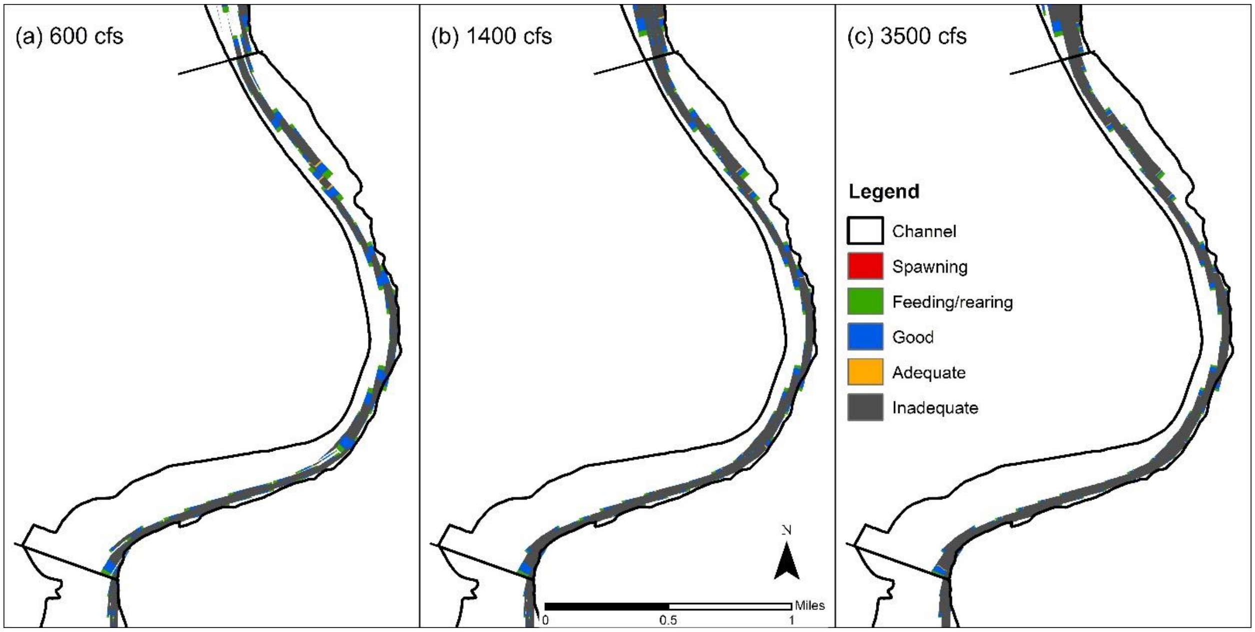
P1



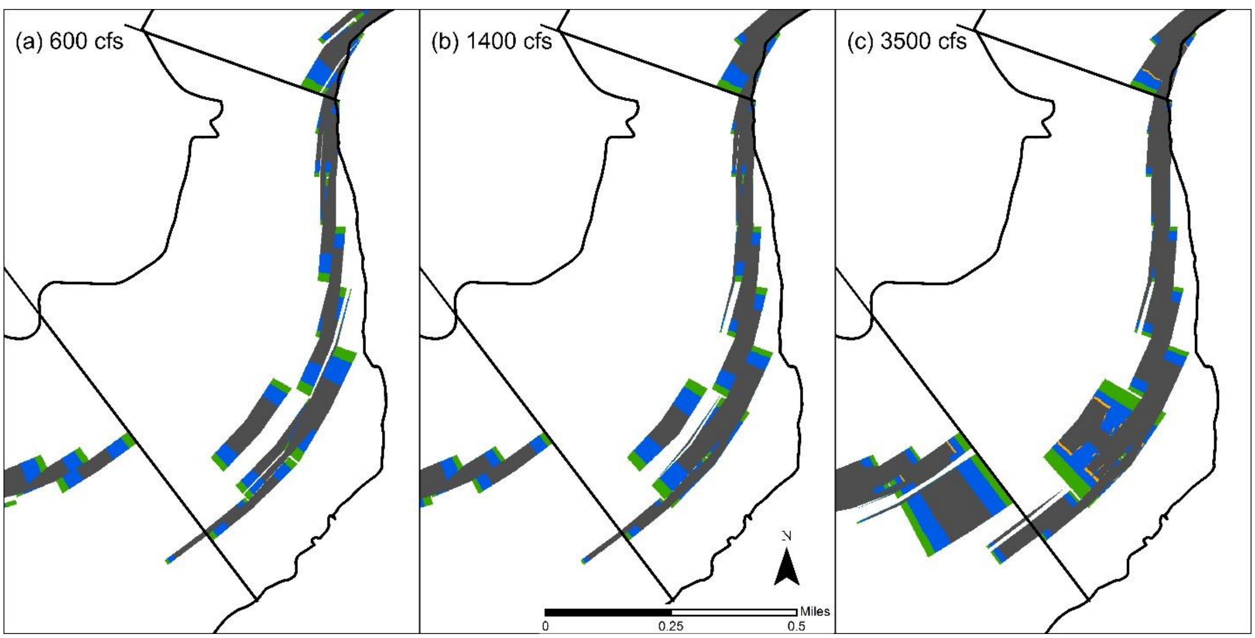
P2



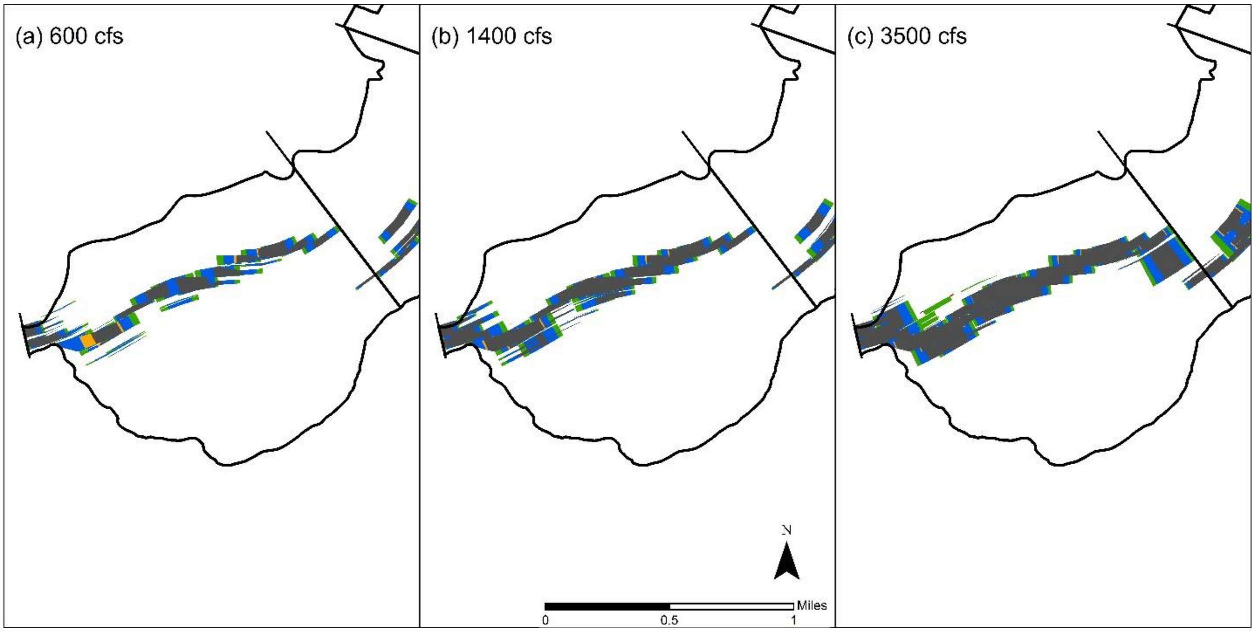
P3


(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate
N
Miles
0
0.5
1

P4

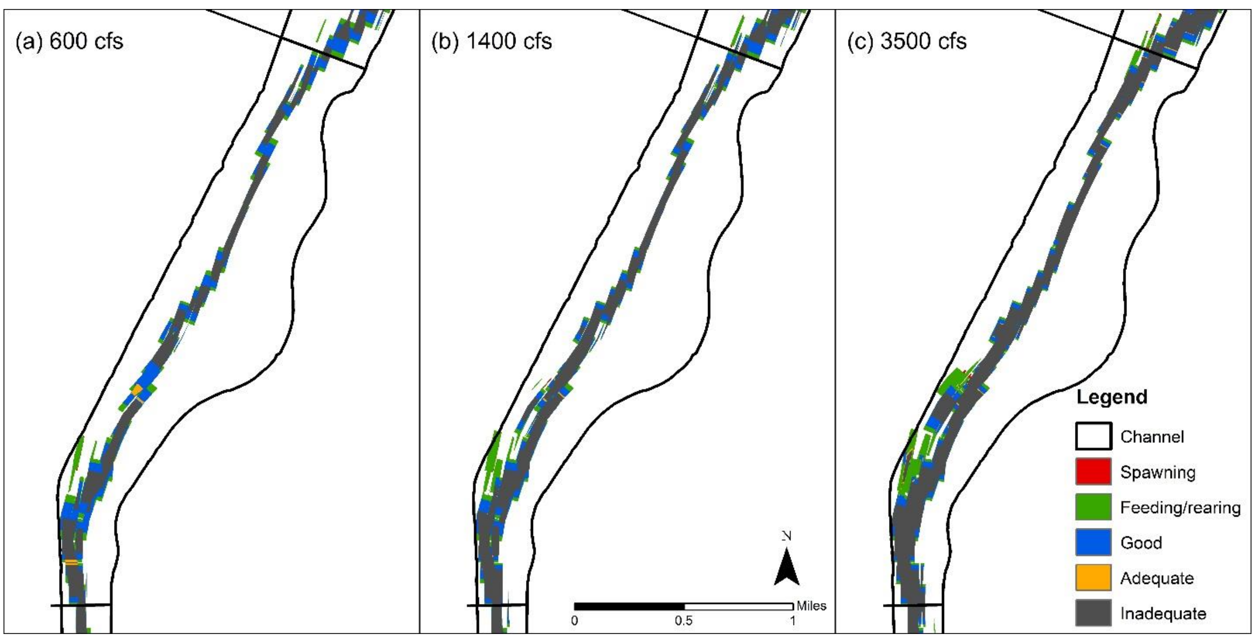

(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
Miles
0
0.25
0.5

P5

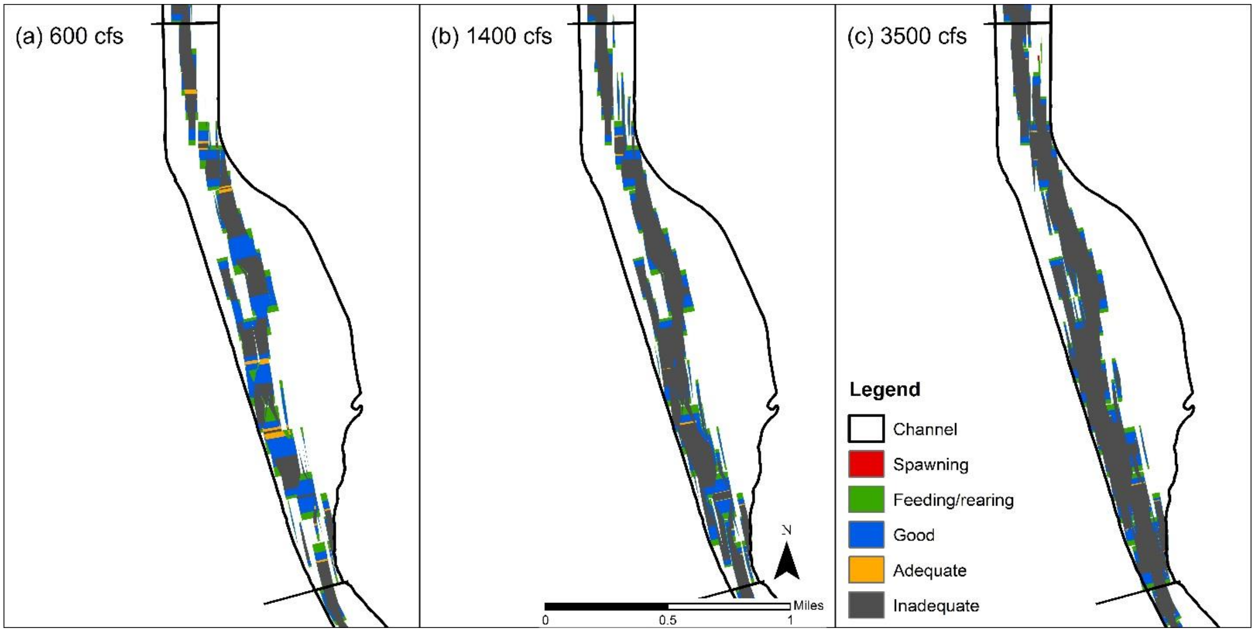

(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
Miles
0
0.5
1

(b) 2002

P1

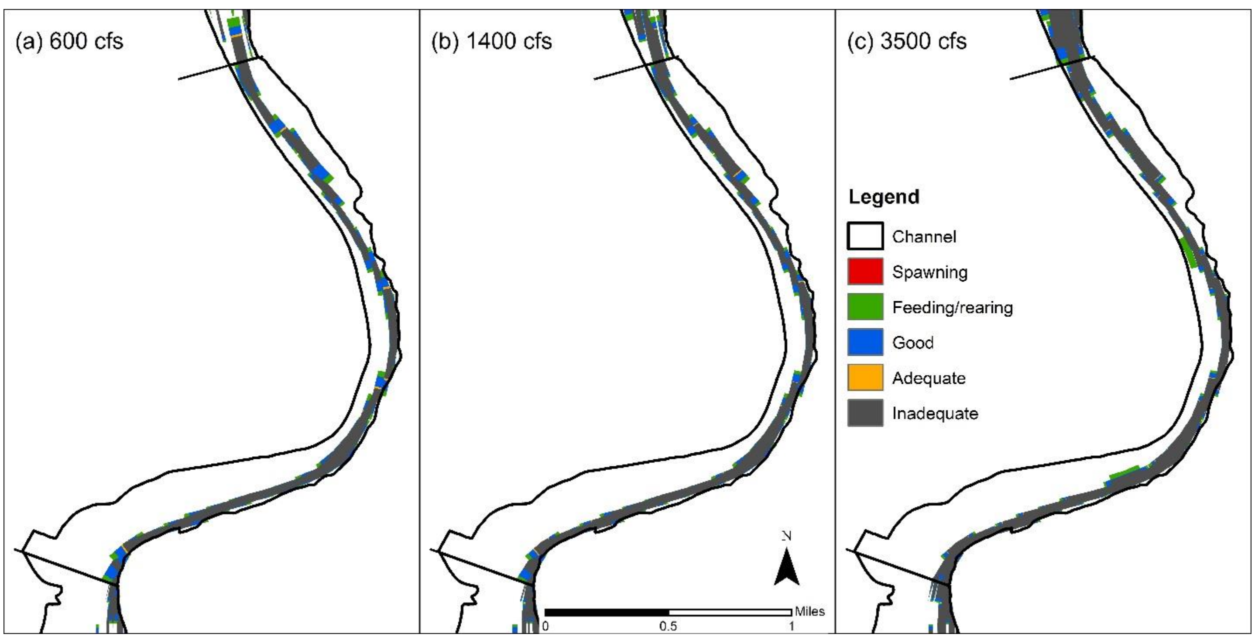

(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
Miles
0
0.5
1
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate

P2



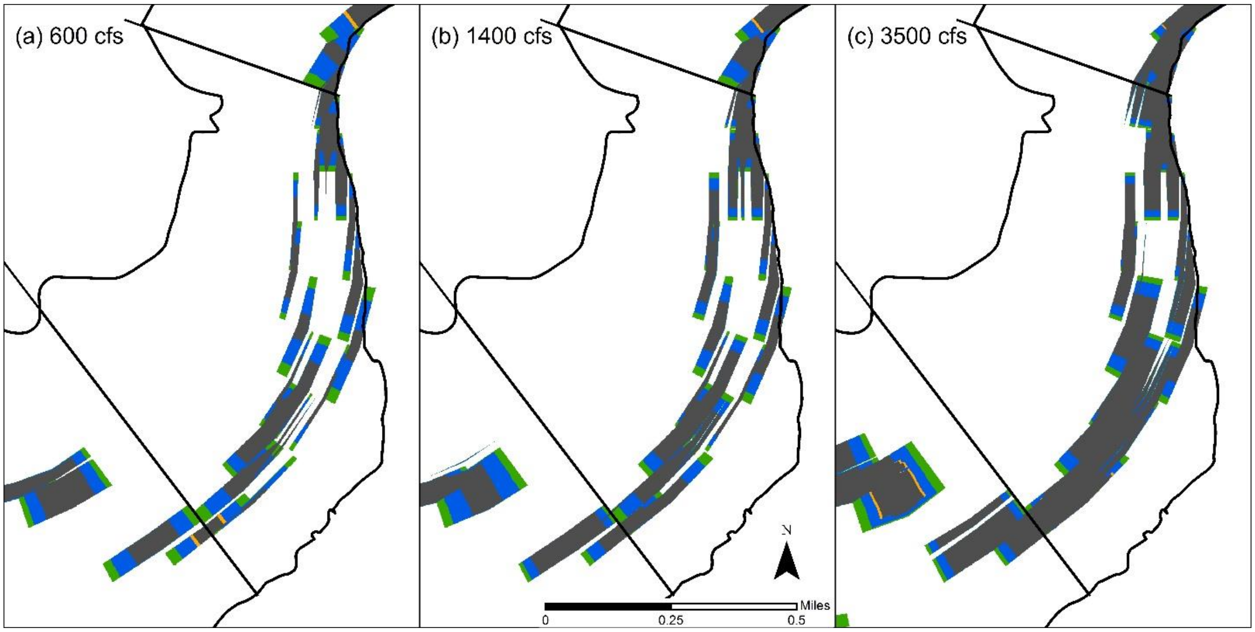
(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate
N
Miles
0
0.5
1

P3

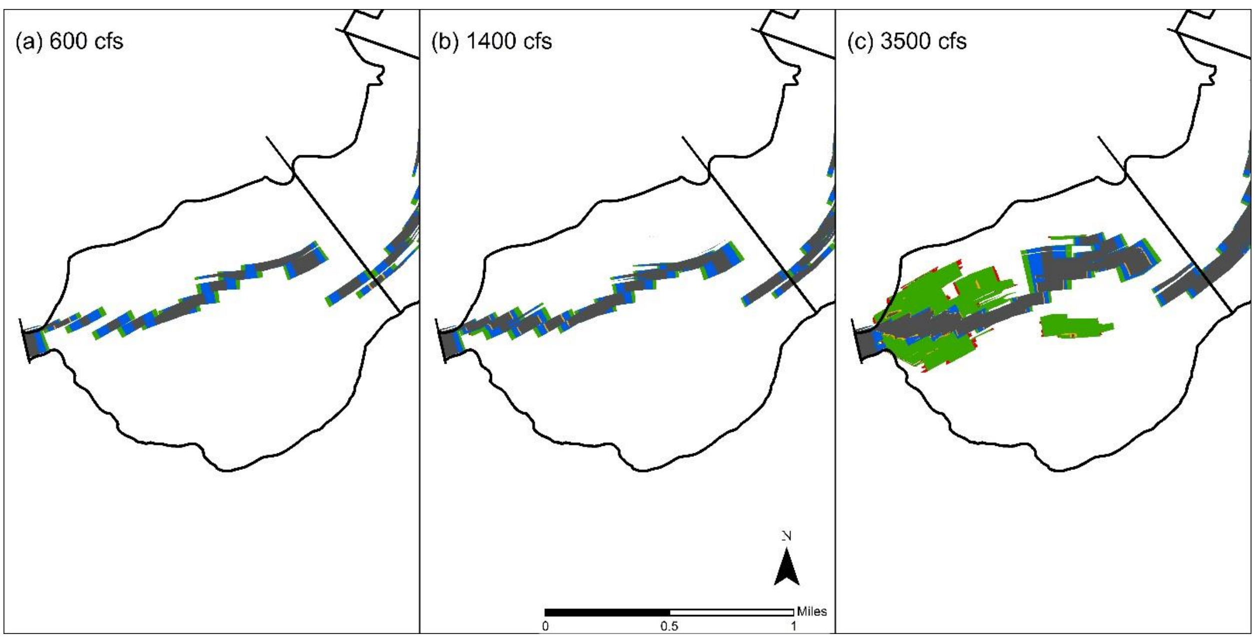


(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate
N
Miles
0
0.5
1

P4

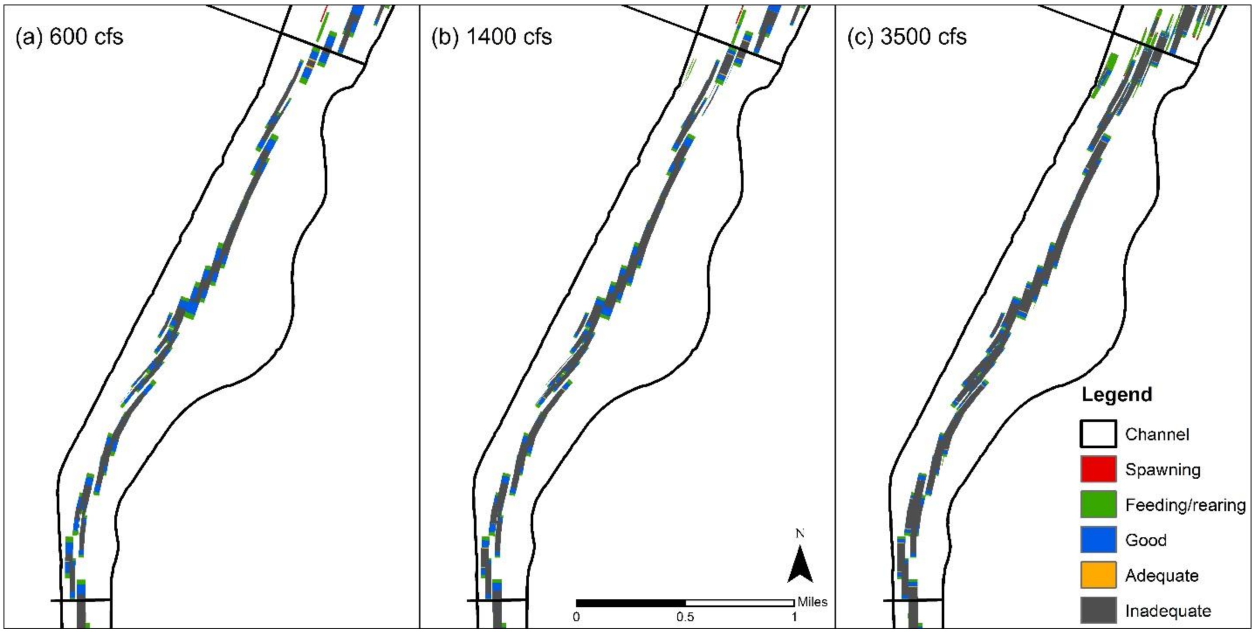

(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
0
0.25
0.5
Miles

P5


(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
0
0.5
1
Miles

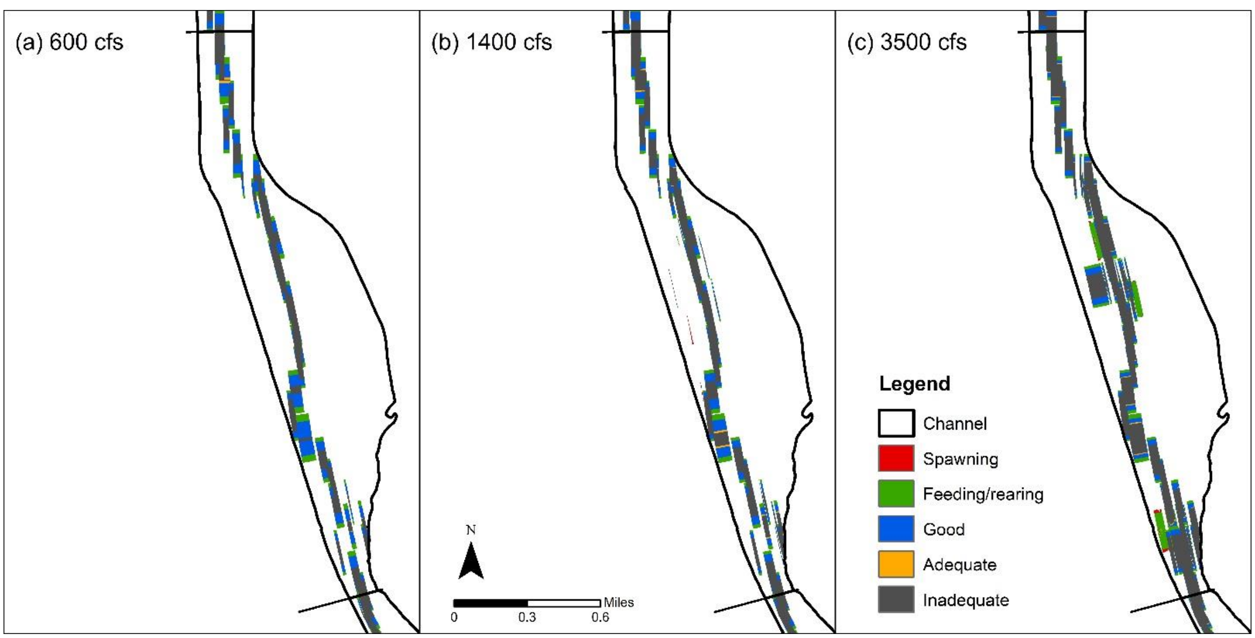
(c) 2012

P1



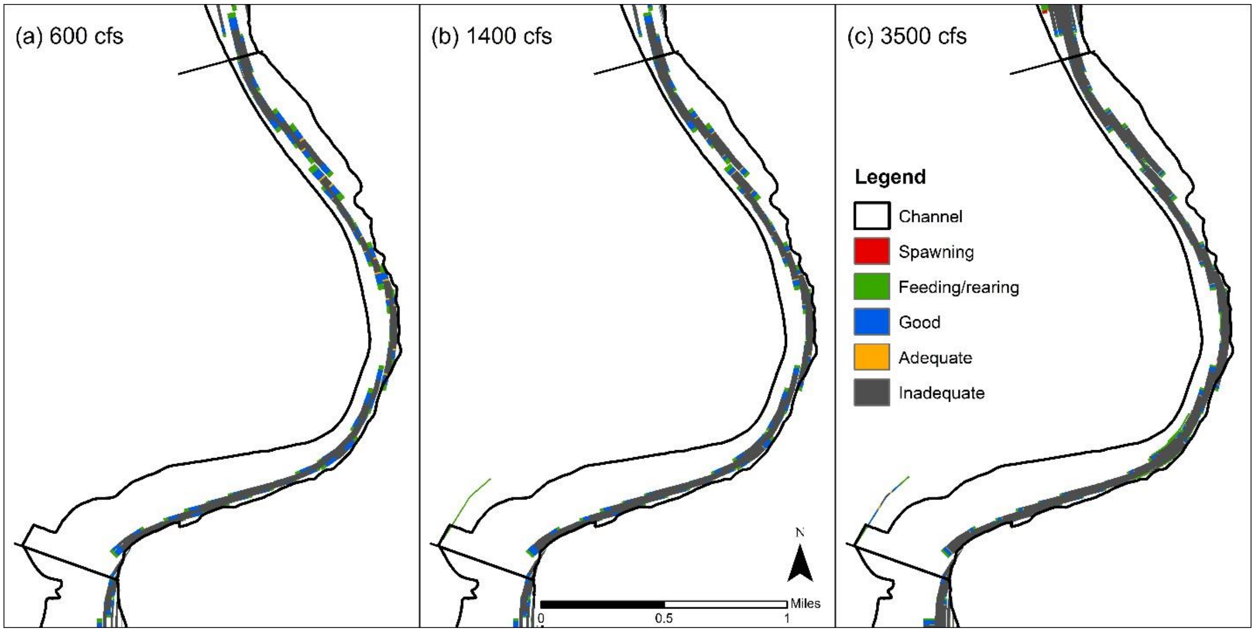
(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
0
0.5
1
Miles
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate

P2



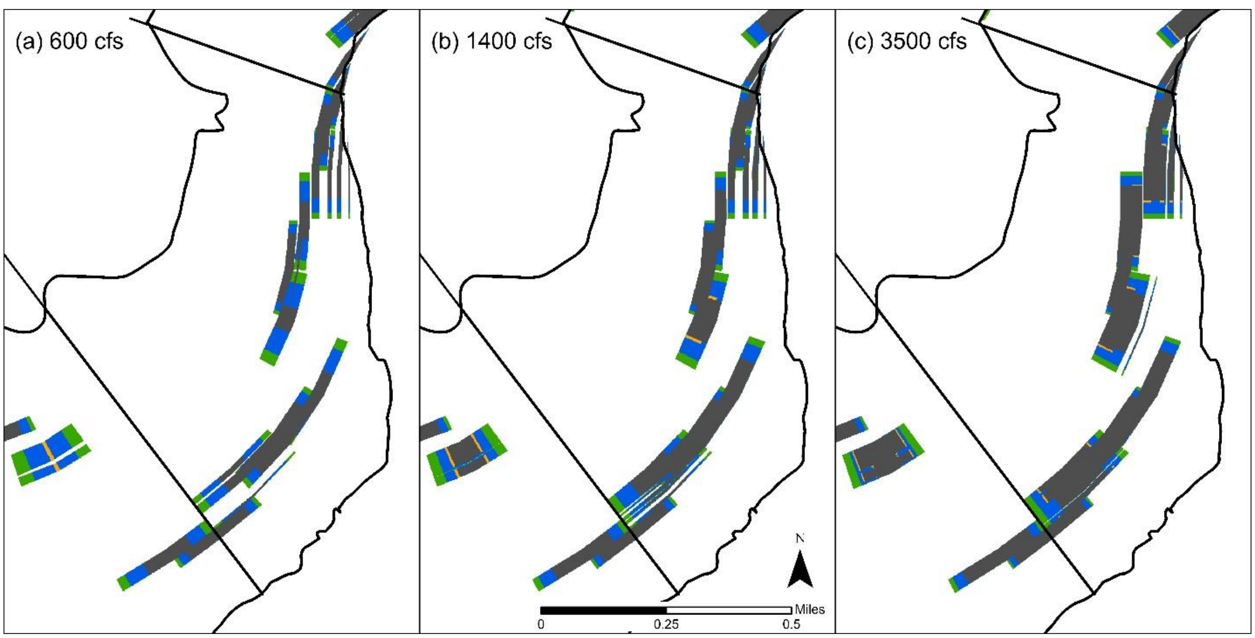
(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
0
0.3
0.6
Miles
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate

P3



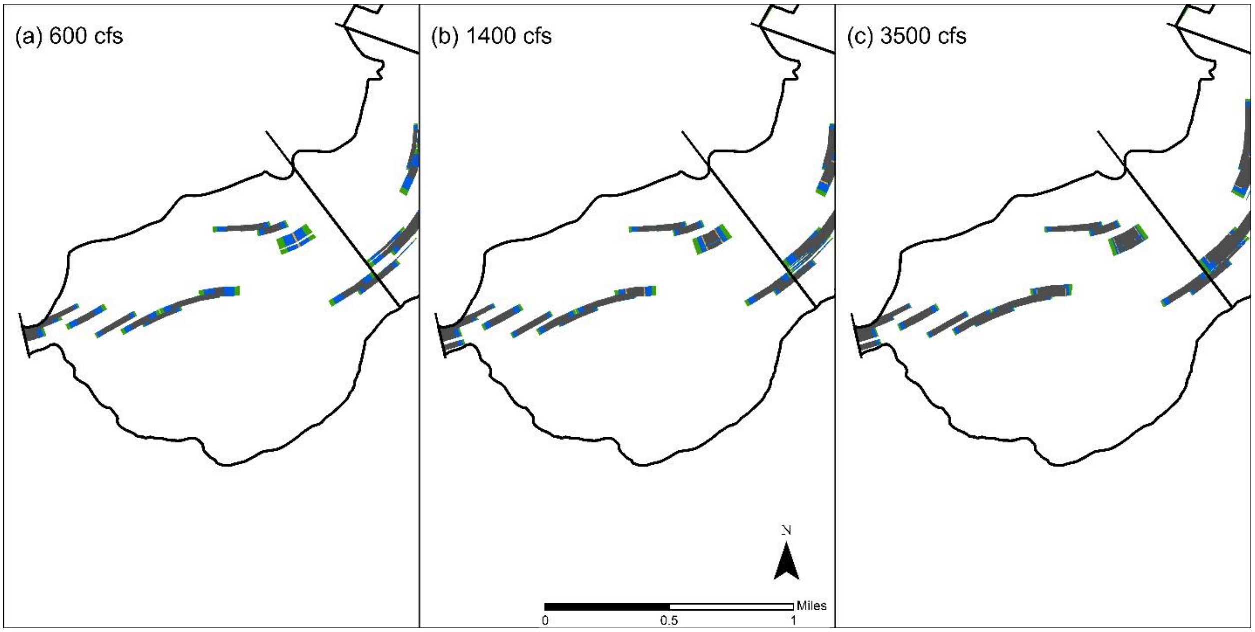
(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
Legend
Channel
Spawning
Feeding/rearing
Good
Adequate
Inadequate
N
Miles
0
0.5
1

P4

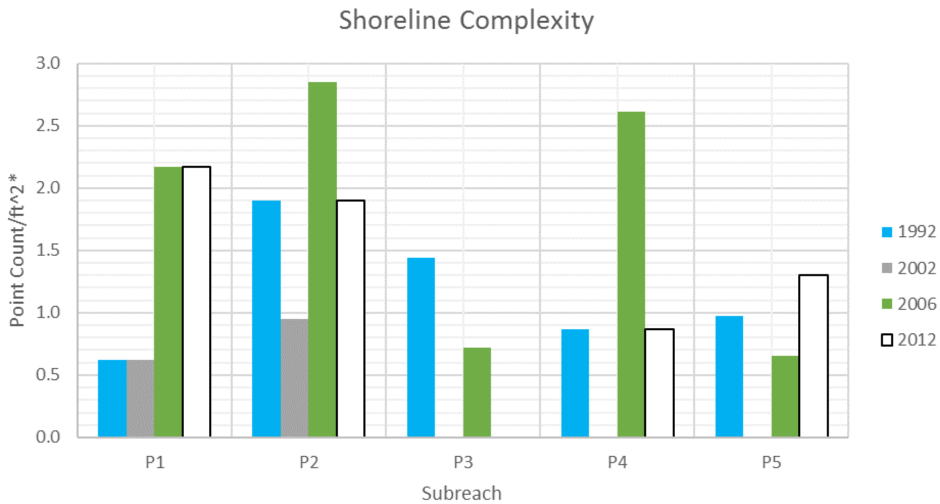


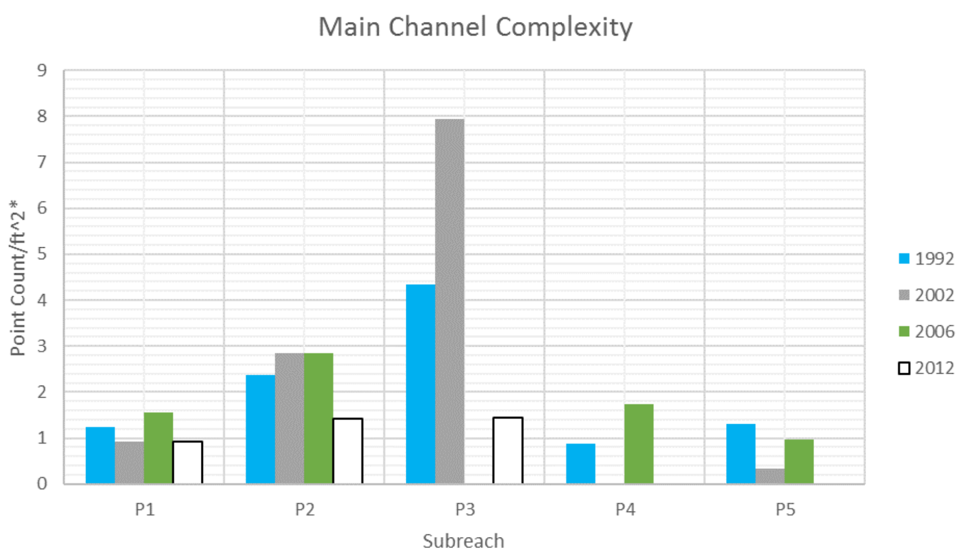
(a) 600 cfs
(b) 1400 cfs
(c) 3500 cfs
N
Miles
0
0.25
0.5

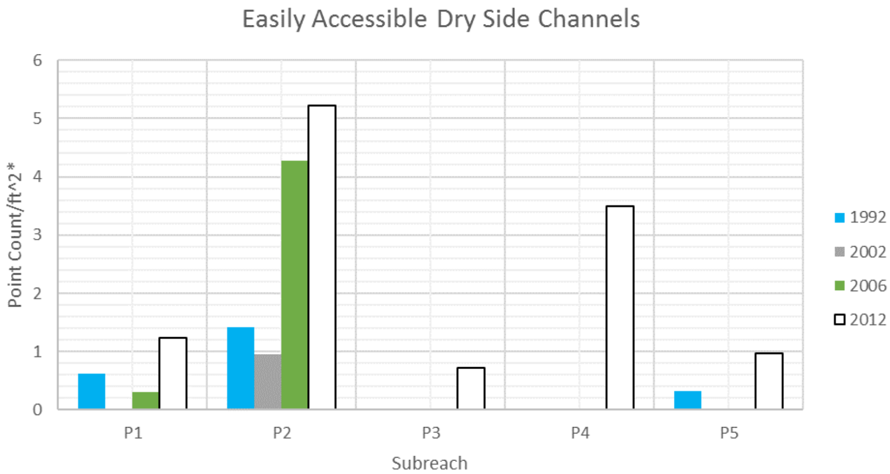
P5

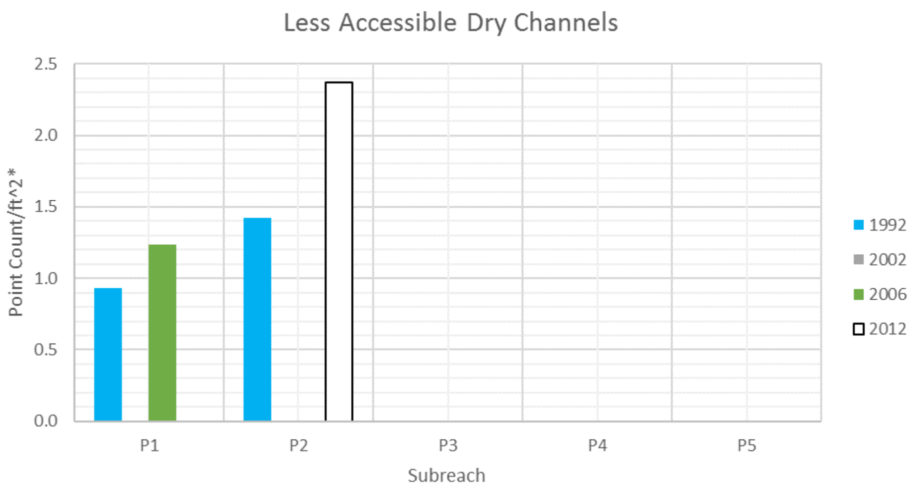


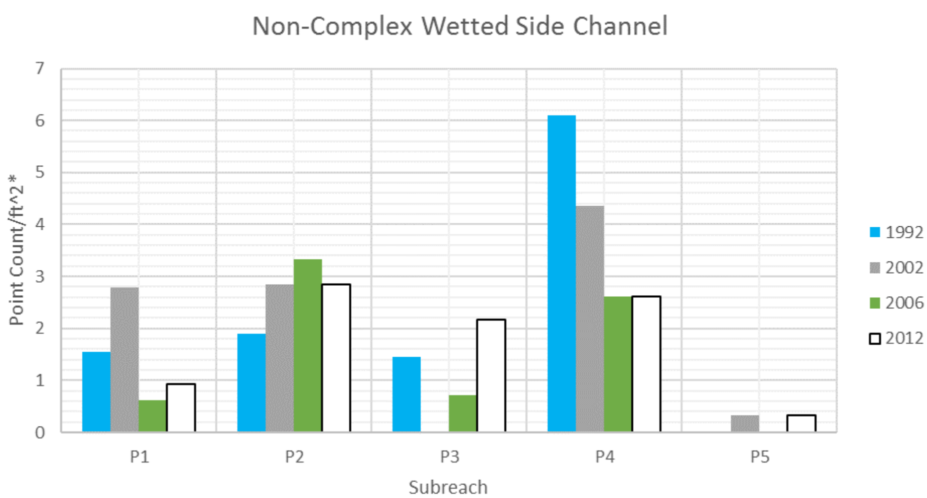
Appendix C - Habitat Counts (Years with flows around 650 cfs)

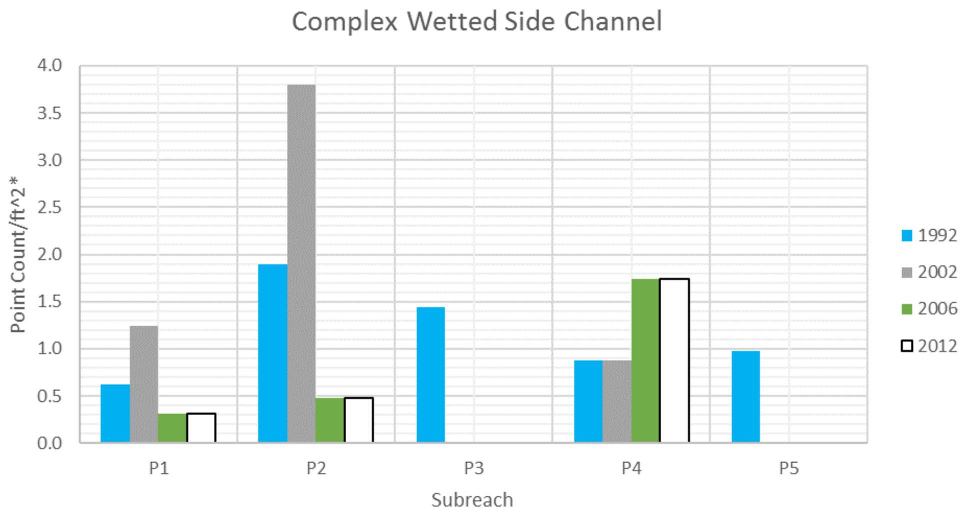


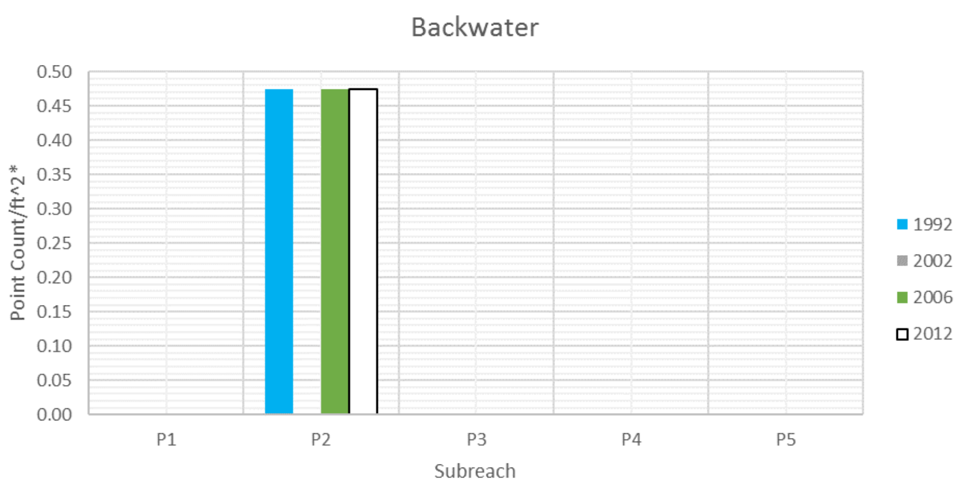


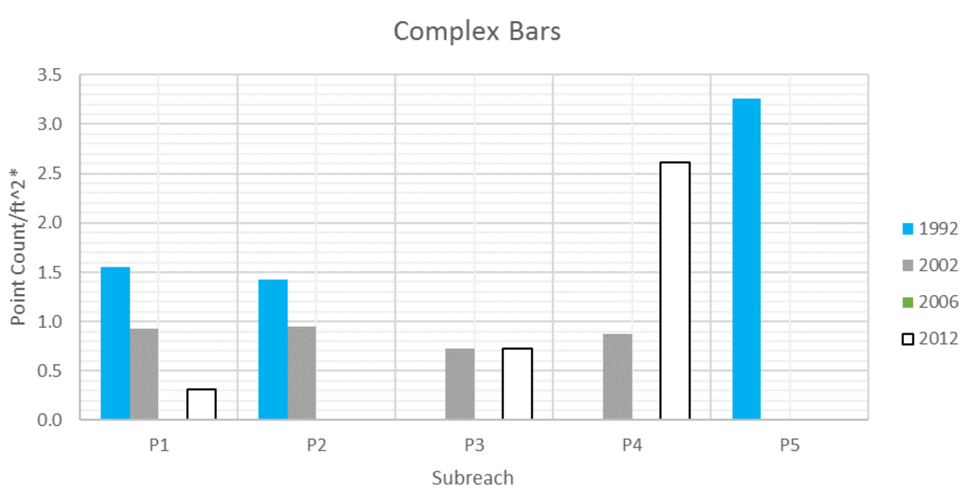

Easily Accessible Dry Side Channels
Point Count/ft^2*
6
5
4
3
2
1
0
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

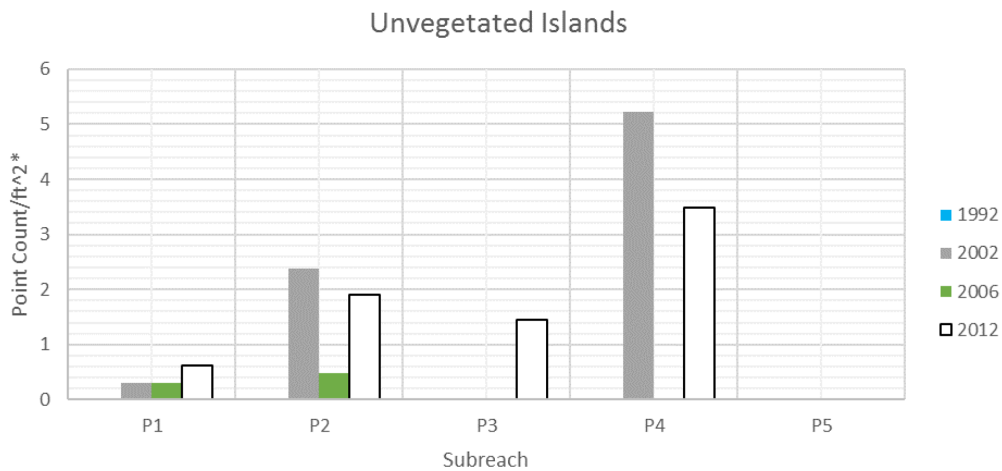

Less Accessible Dry Channels
Point Count/ft^2*
2.5
2.0
1.5
1.0
0.5
0.0
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012


Non-Complex Wetted Side Channel
Point Count/ft^2*
7
6
5
4
3
2
1
0
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

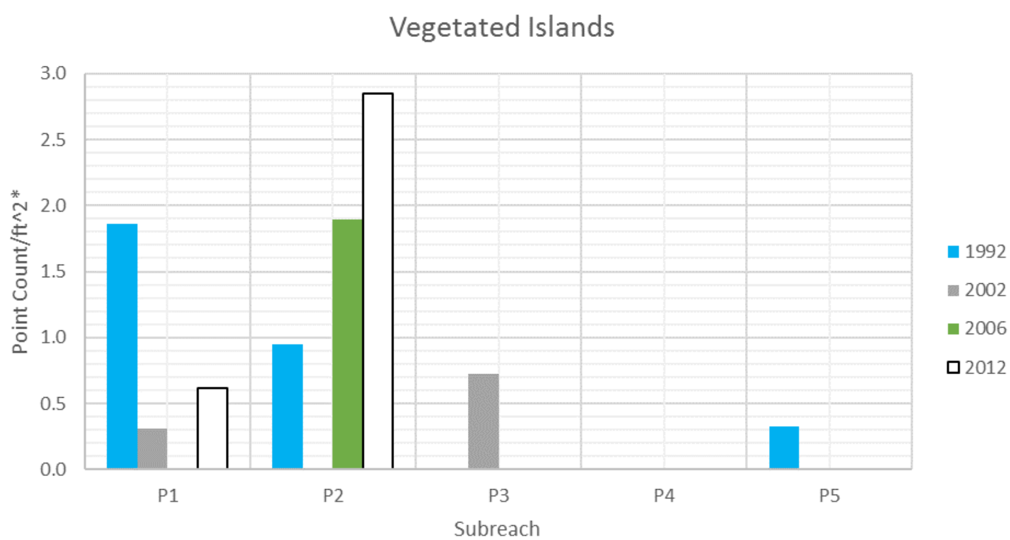

Complex Wetted Side Channel
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Point Count/ft^2*
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012


Backwater
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Point Count/ft^2*
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

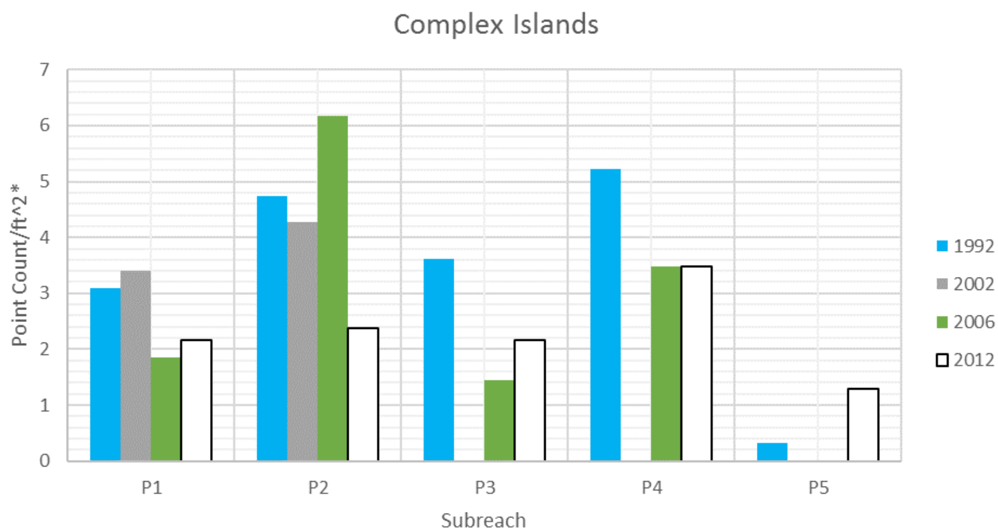

Complex Bars
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Point Count/ft^2*
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

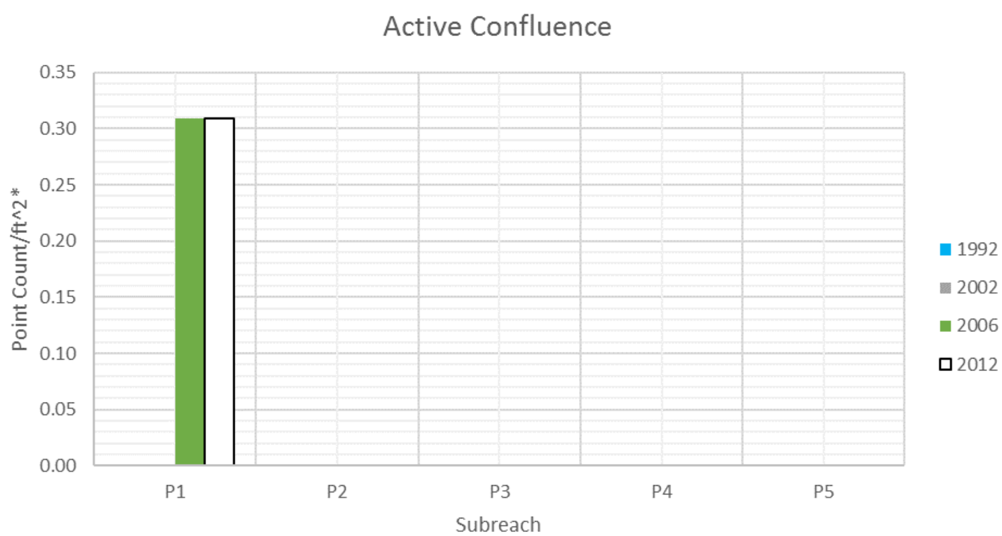


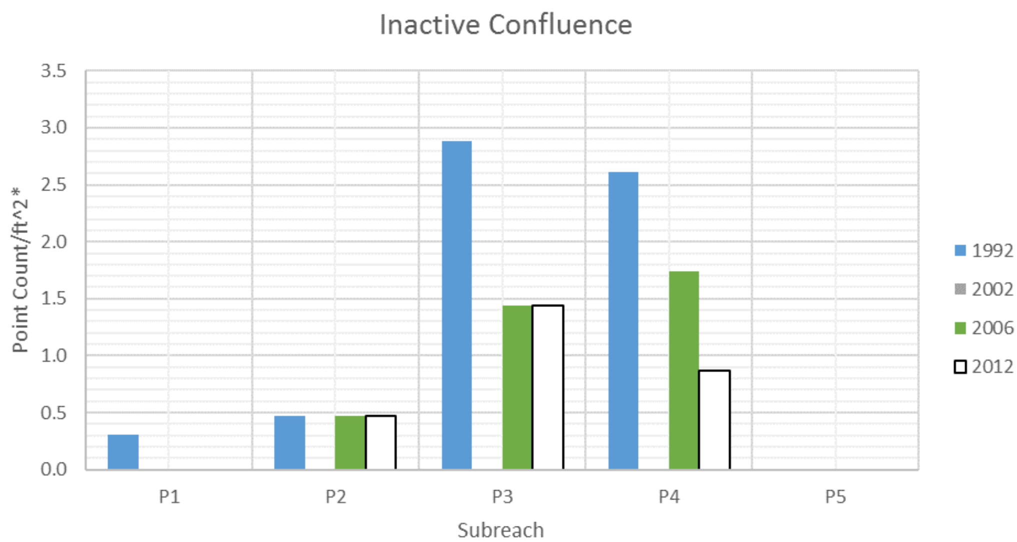
Unvegetated Islands
Point Count/ft^2*
6
5
4
3
2
1
0
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012



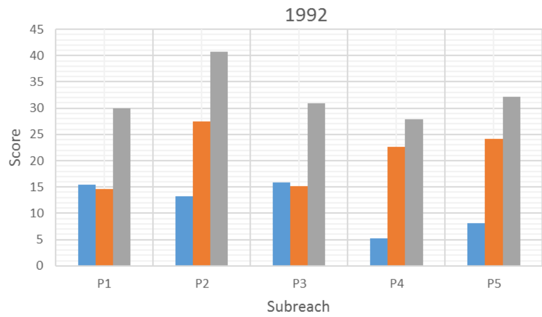
Vegetated Islands
Point Count/ft^2*
3.0
2.5
2.0
1.5
1.0
0.5
0.0
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

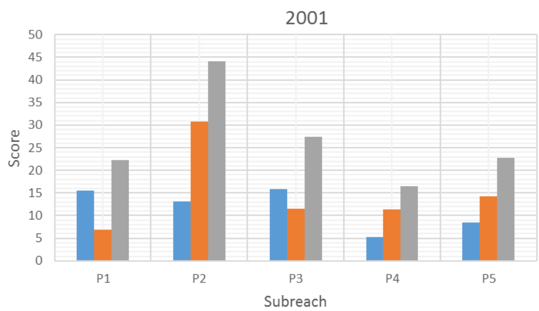

Complex Islands
Point Count/ft^2*
0
1
2
3
4
5
6
7
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

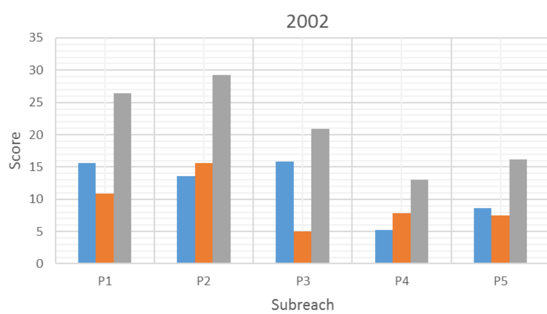

Active Confluence
Point Count/ft^2*
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

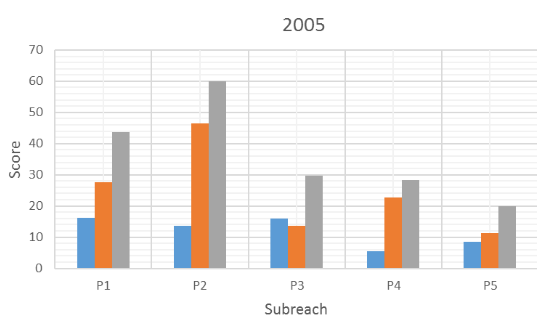

Inactive Confluence
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Point Count/ft^2*
P1
P2
P3
P4
P5
Subreach
1992
2002
2006
2012

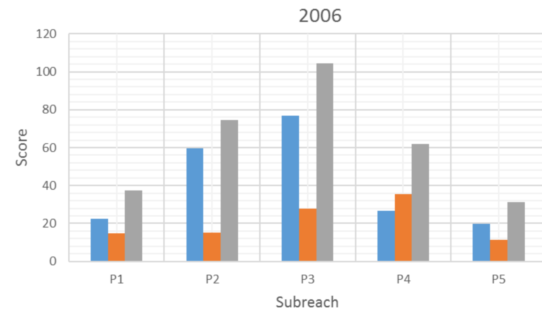
Appendix D - Shoreline Complexity

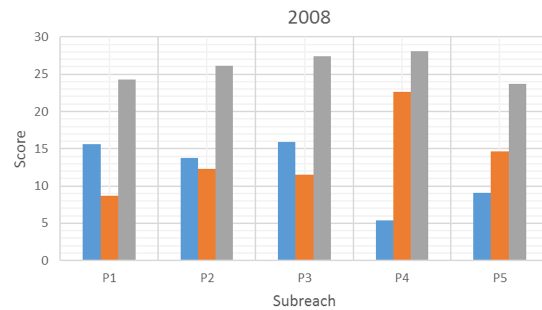


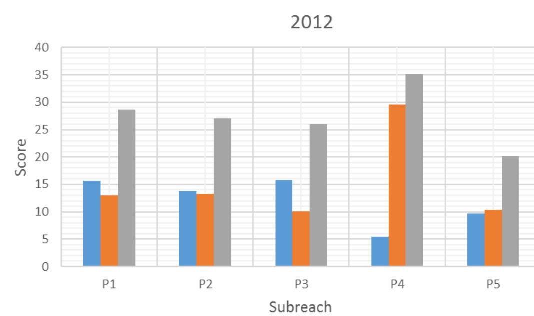


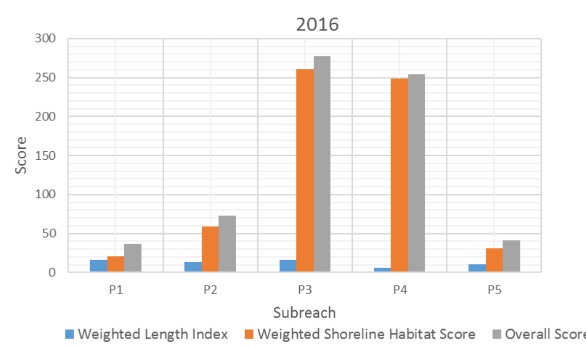


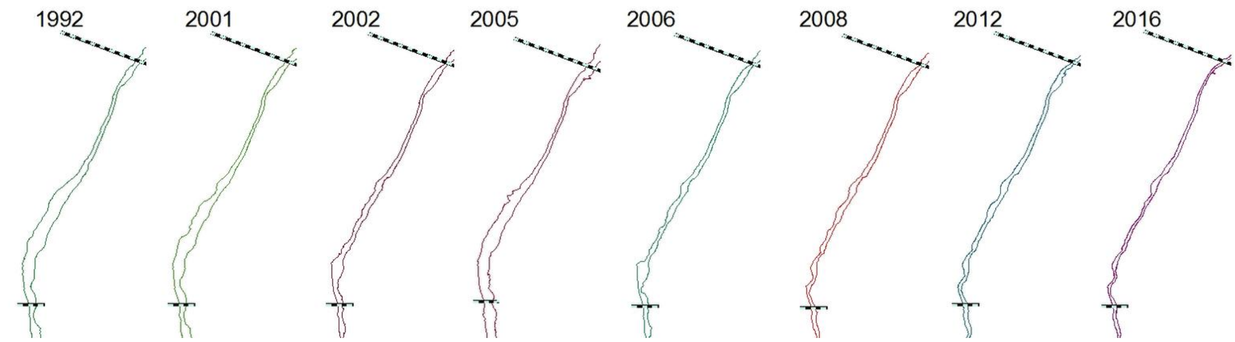




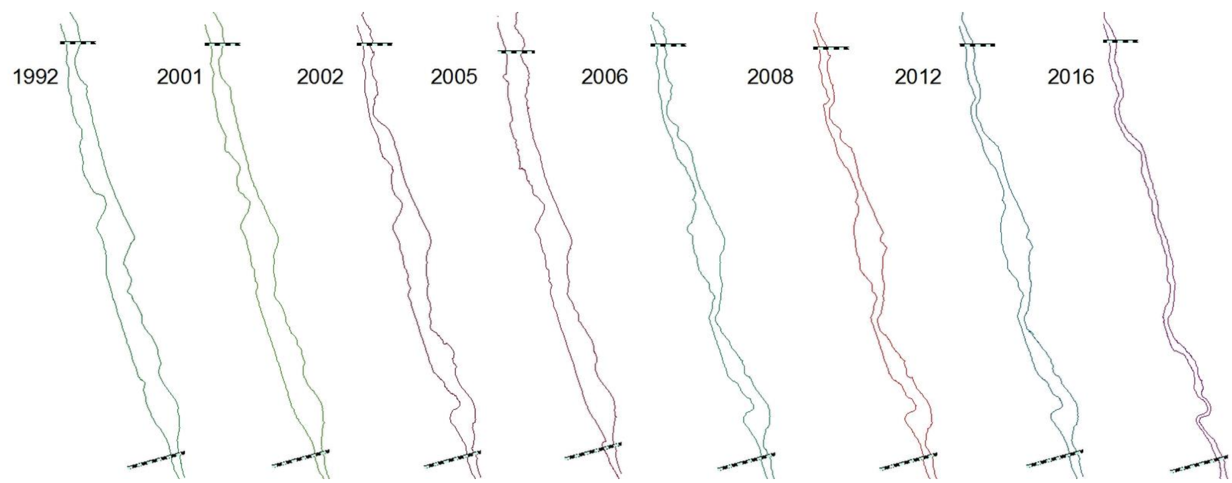







1992
2001
2002
2005
2006
2008
2012
2016

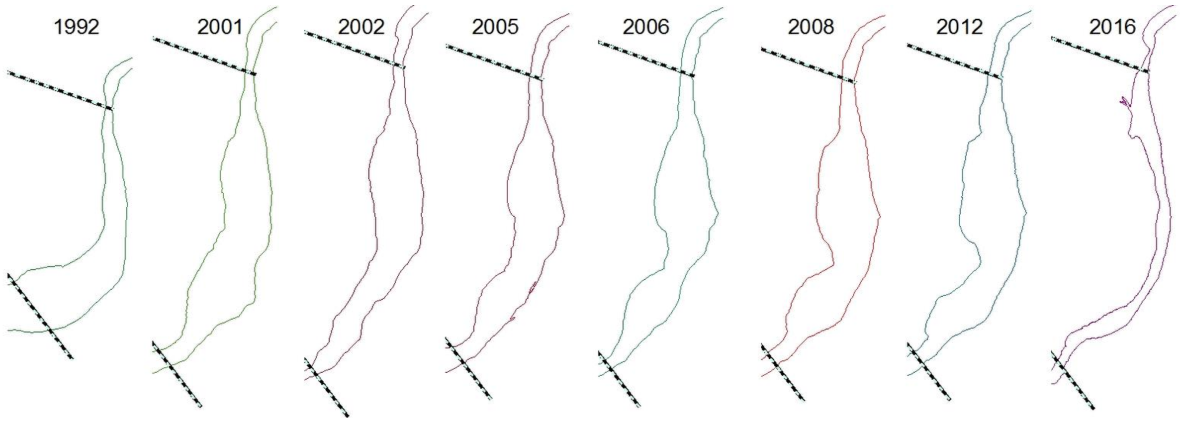
P1


1992
2001
2002
2005
2006
2008
2012
2016

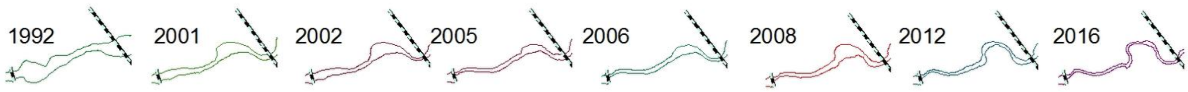
P2


1992
2001
2002
2005
2006
2008
2012
2016

P3

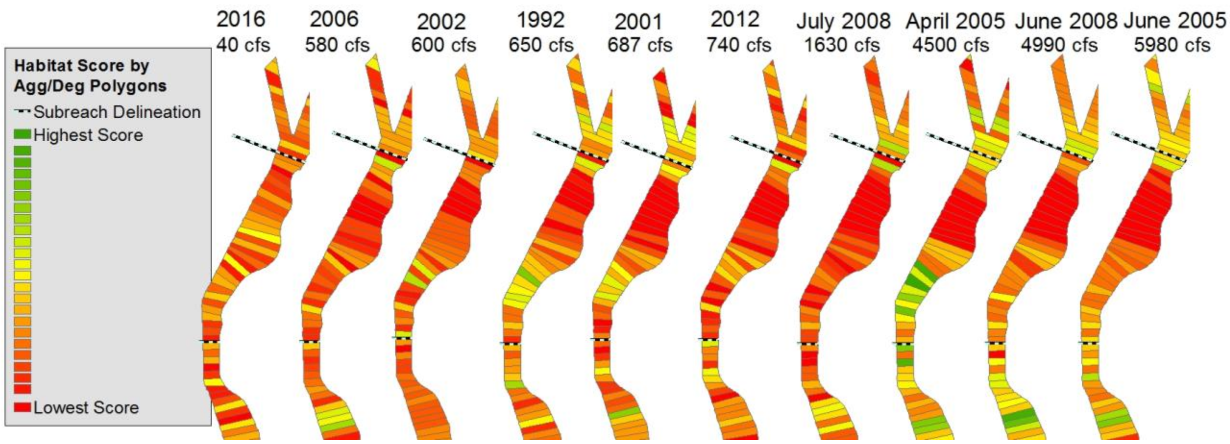

1992
2001
2002
2005
2006
2008
2012
2016

P4

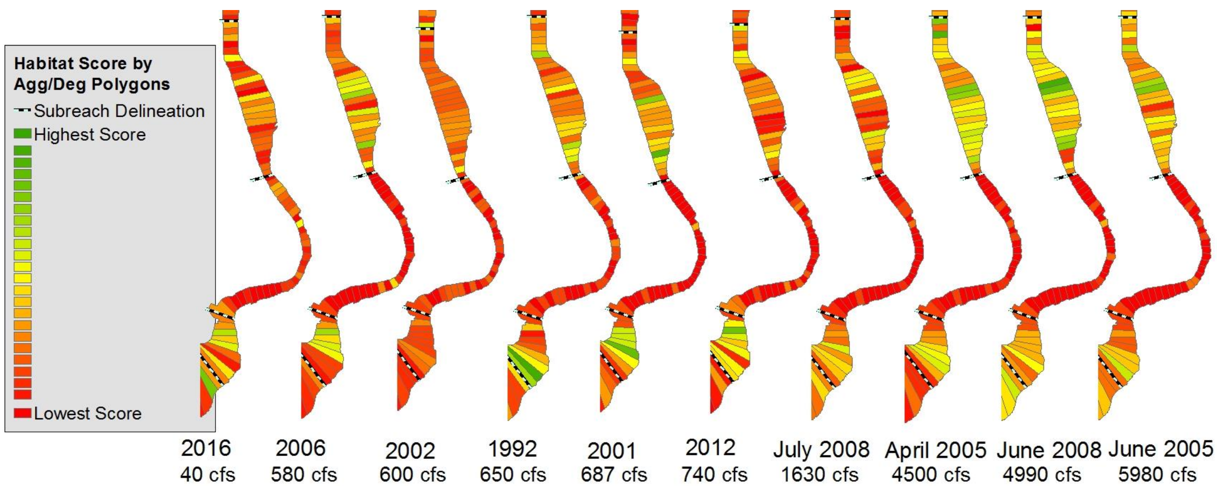

1992
2001
2002
2005
2006
2008
2012
2016

P5

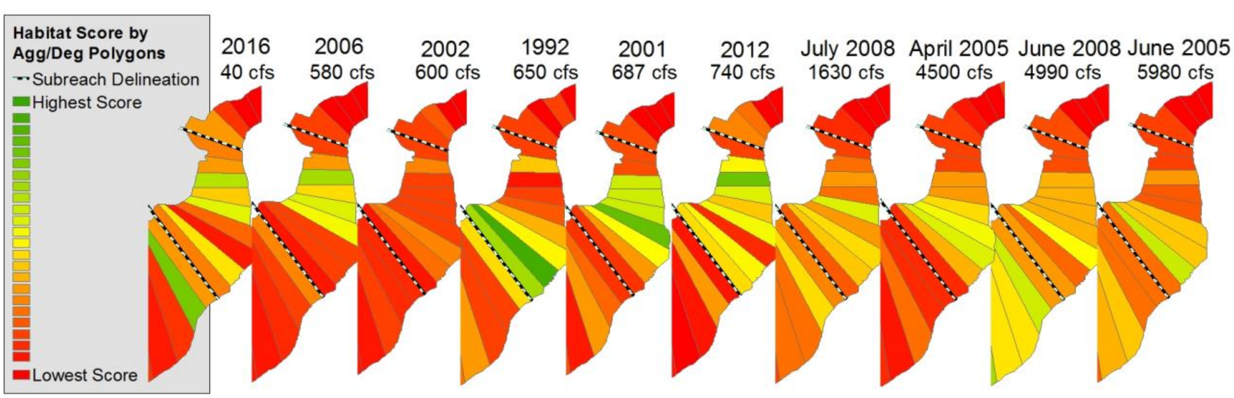
Appendix E - Habitat Score by Subreach (All Years)



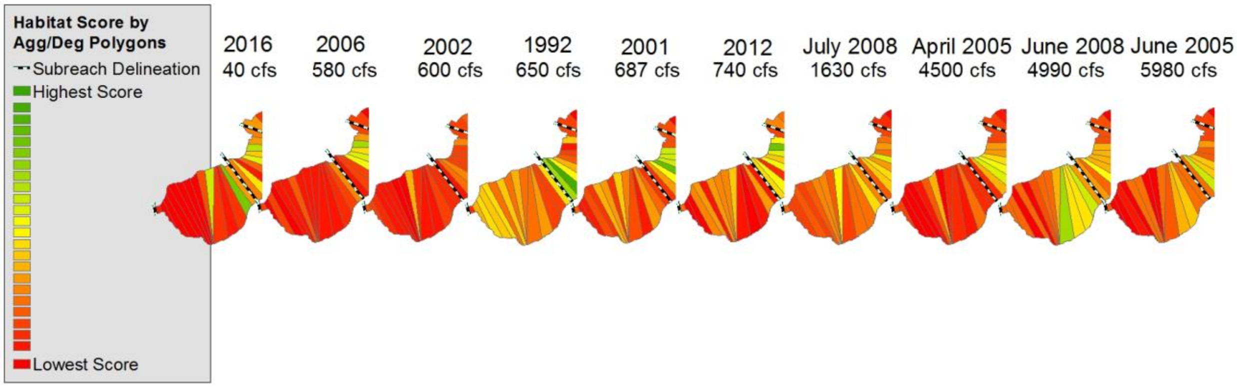
P1



P3

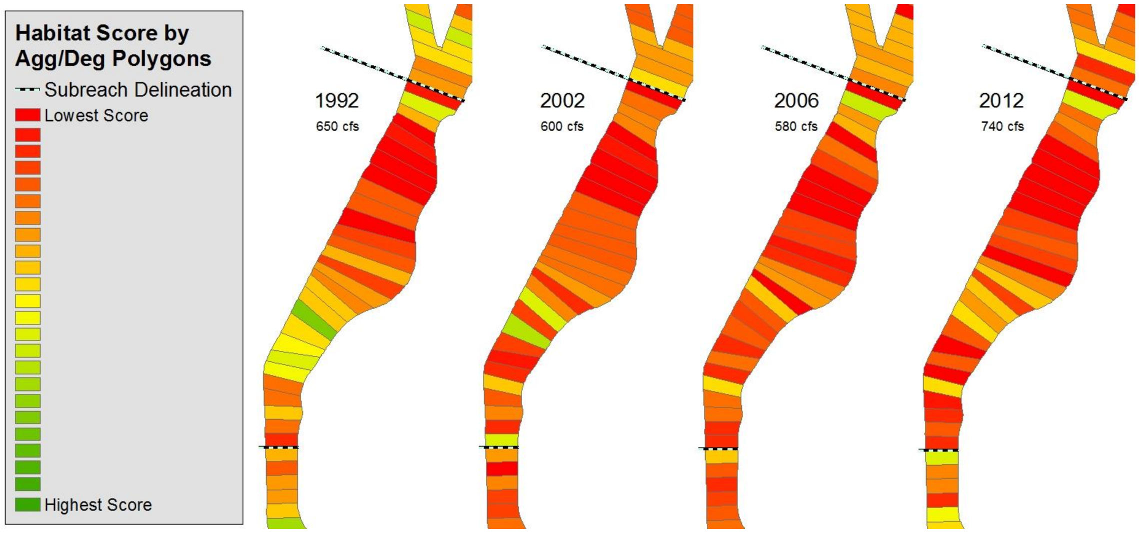


P4

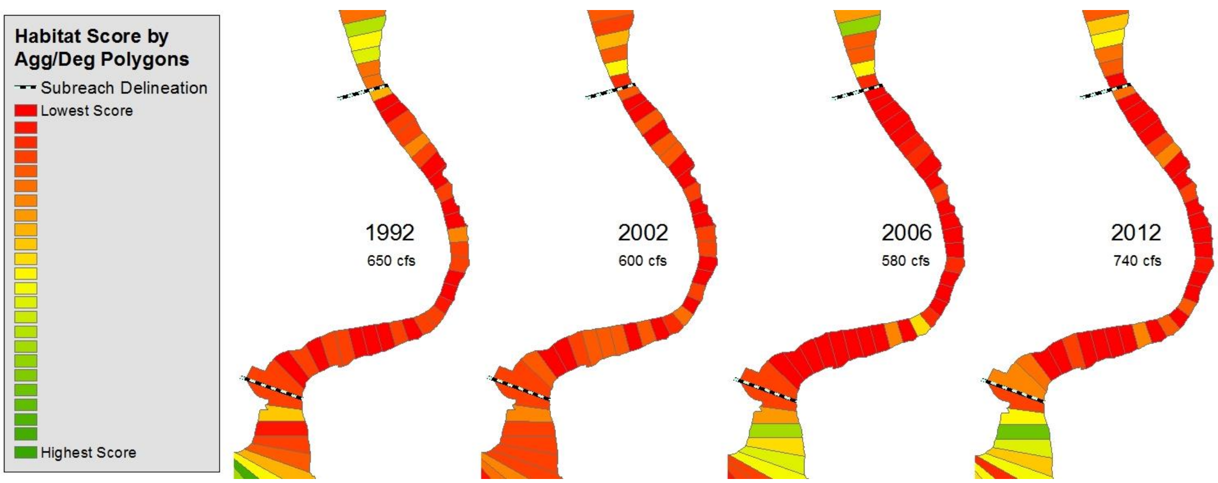

Habitat Score by
Agg/Deg Polygons
Subreach Delineation
Highest Score
Lowest Score
2016
40 cfs
2006
580 cfs
2002
600 cfs
1992
650 cfs
2001
687 cfs
2012
740 cfs
July 2008
1630 cfs
April 2005
4500 cfs
June 2008
4990 cfs
June 2005
5980 cfs

P5

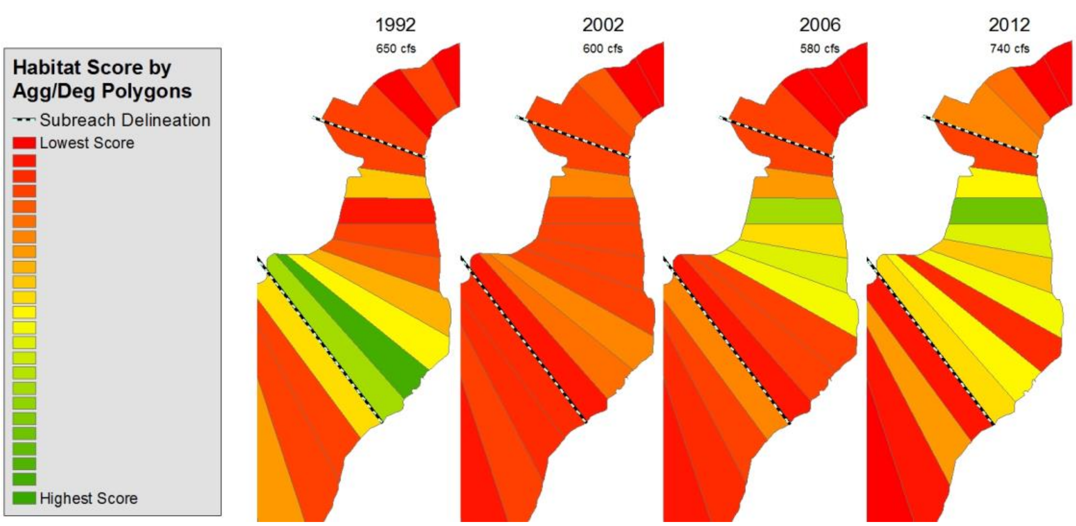
Appendix F - Habitat Score by Subreach (Years with flows around 650 cfs)



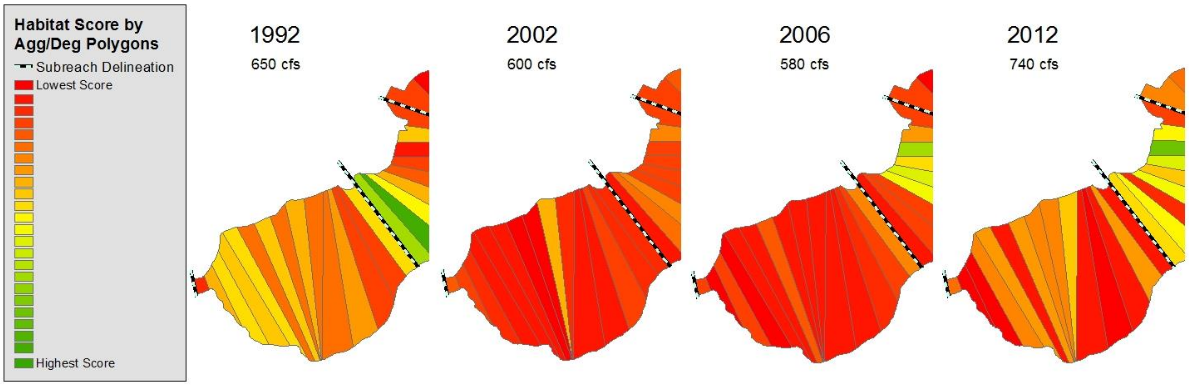
P1



P3

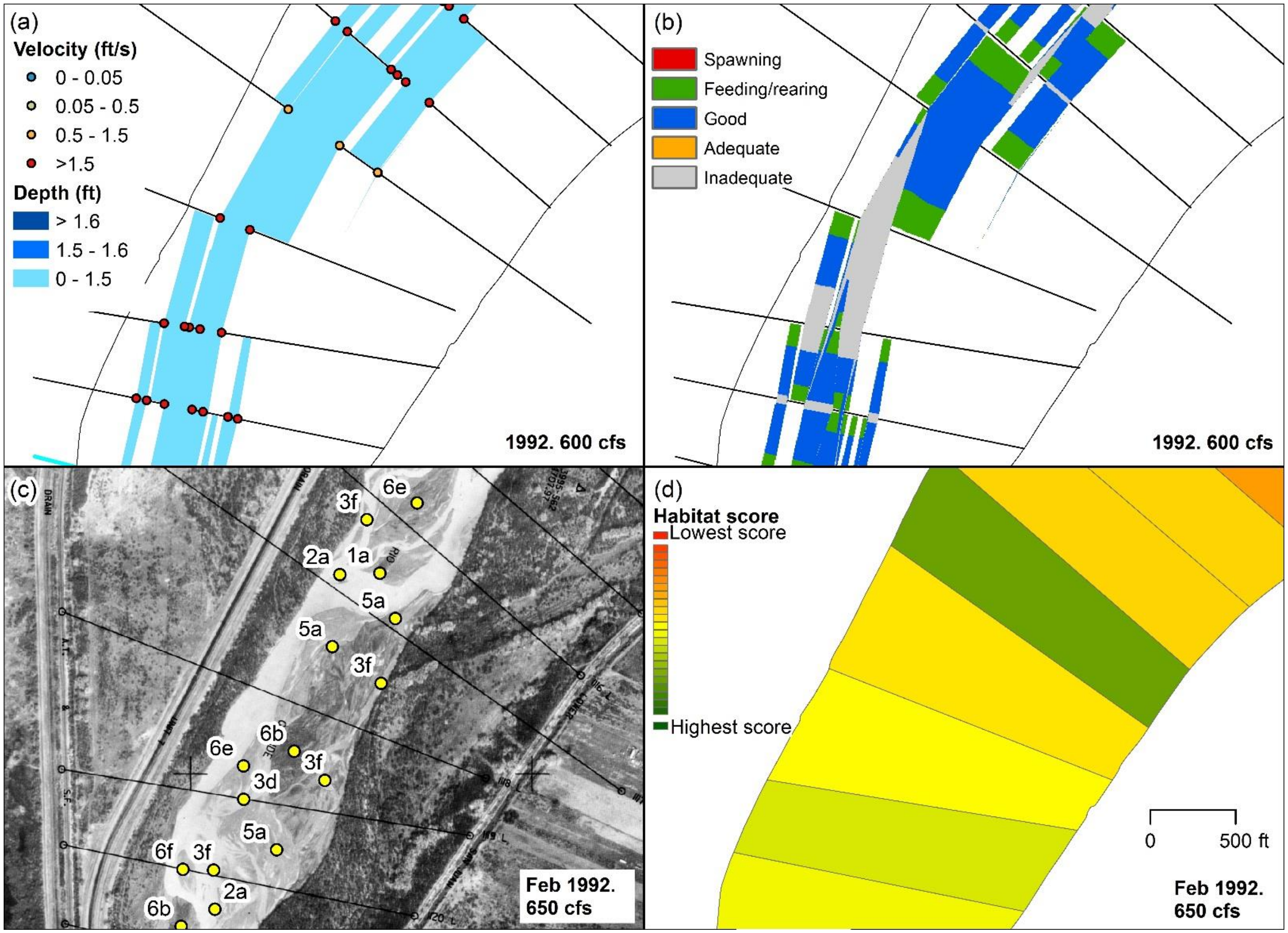


P4

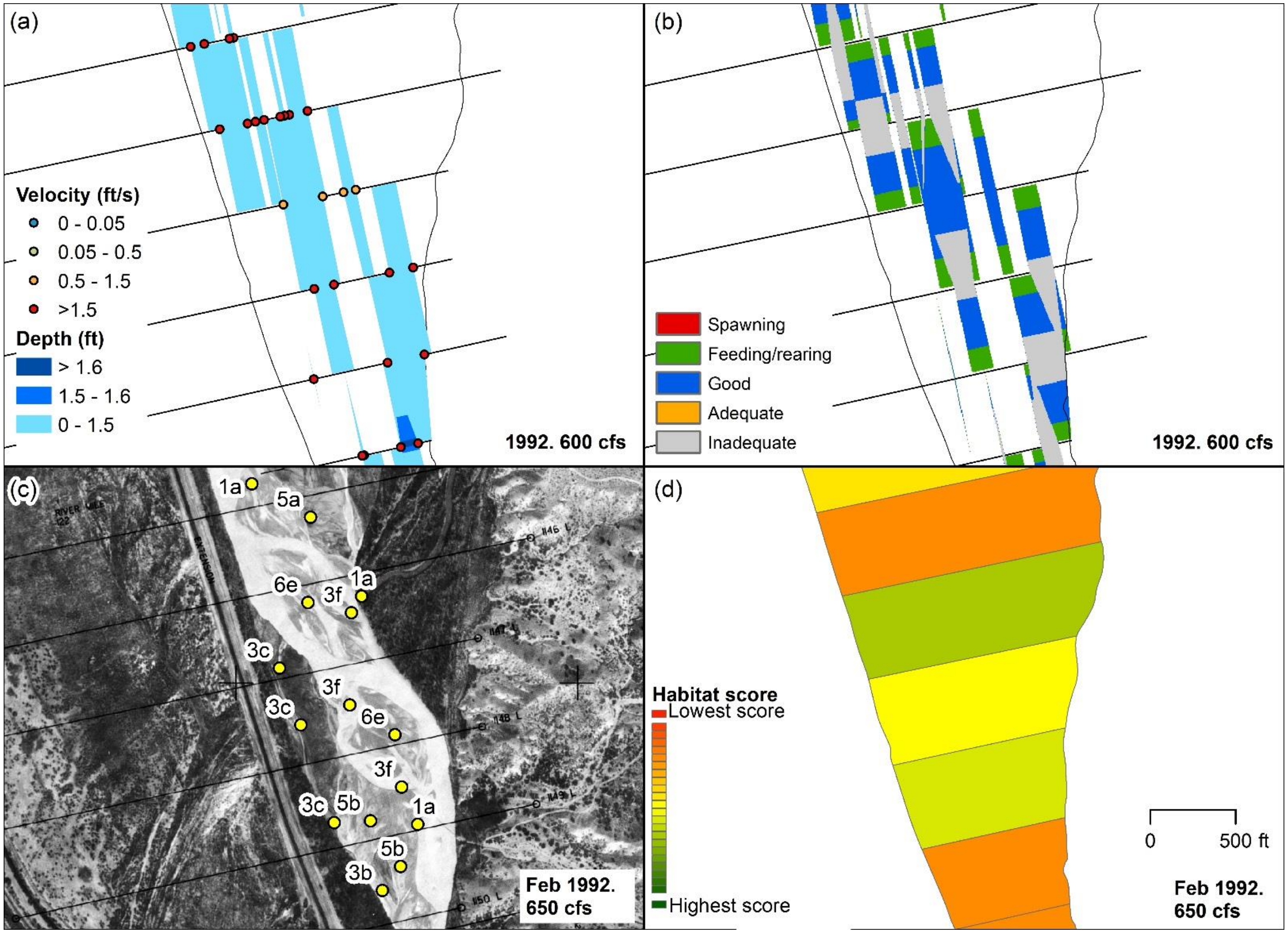


Habitat Score by Agg/Deg Polygons
Subreach Delineation
Lowest Score
Highest Score
1992
650 cfs
2002
600 cfs
2006
580 cfs
2012
740 cfs

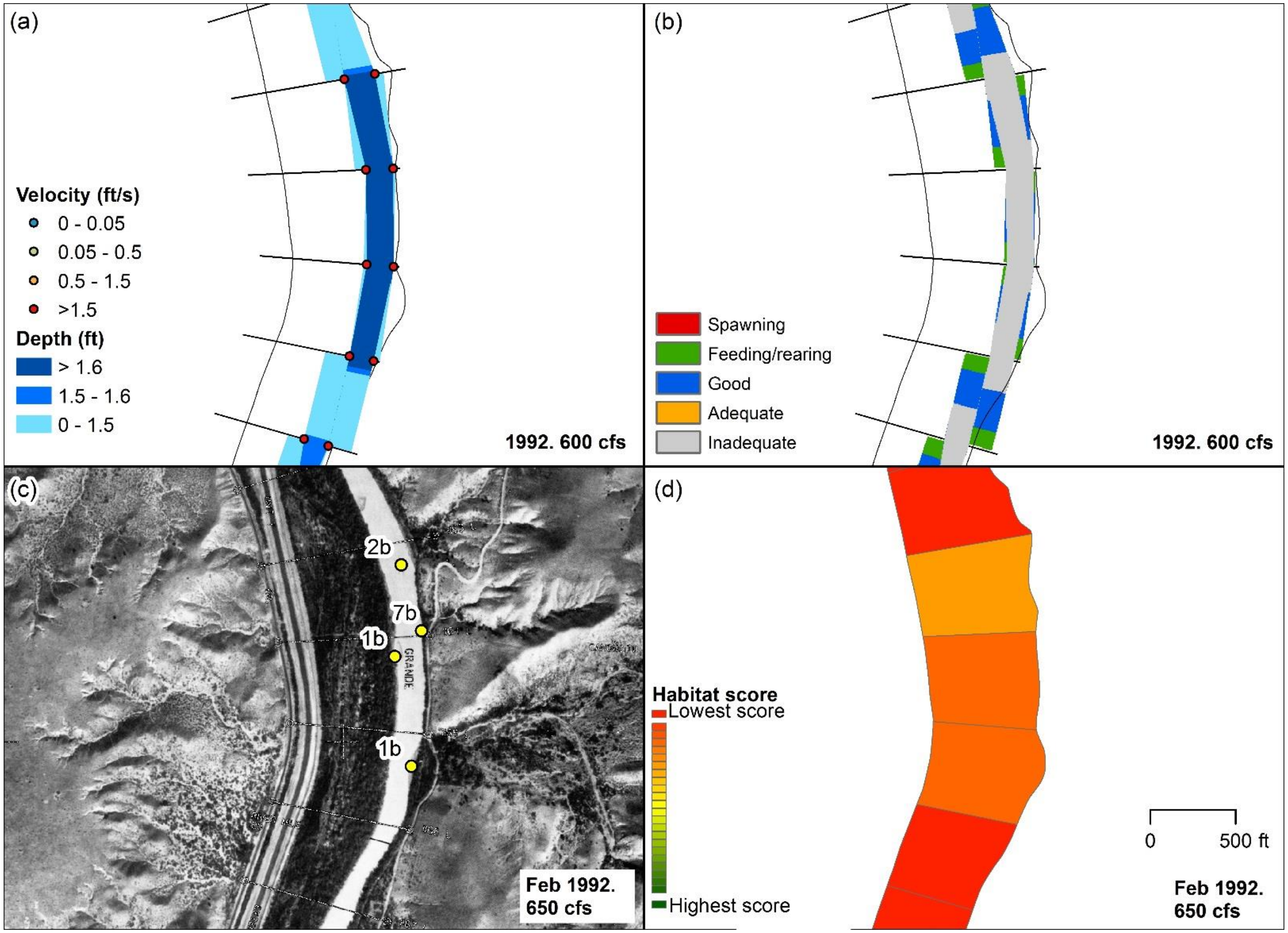
P5



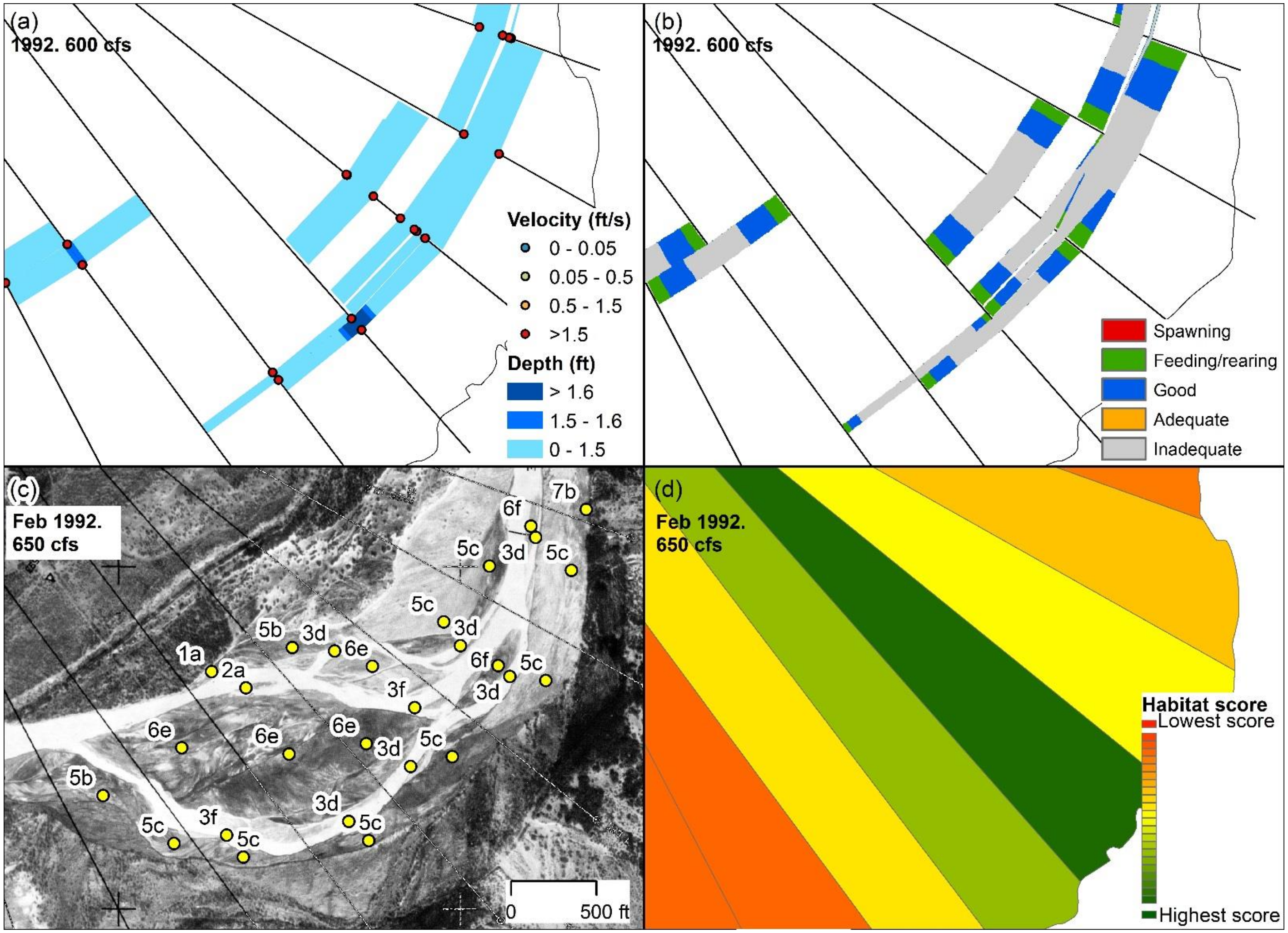
Summary of HEC-RAS and GIS habitat at subreach P1, agg/deg 1115 to 1121. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. (d) Habitat color scheme based on habitat features.



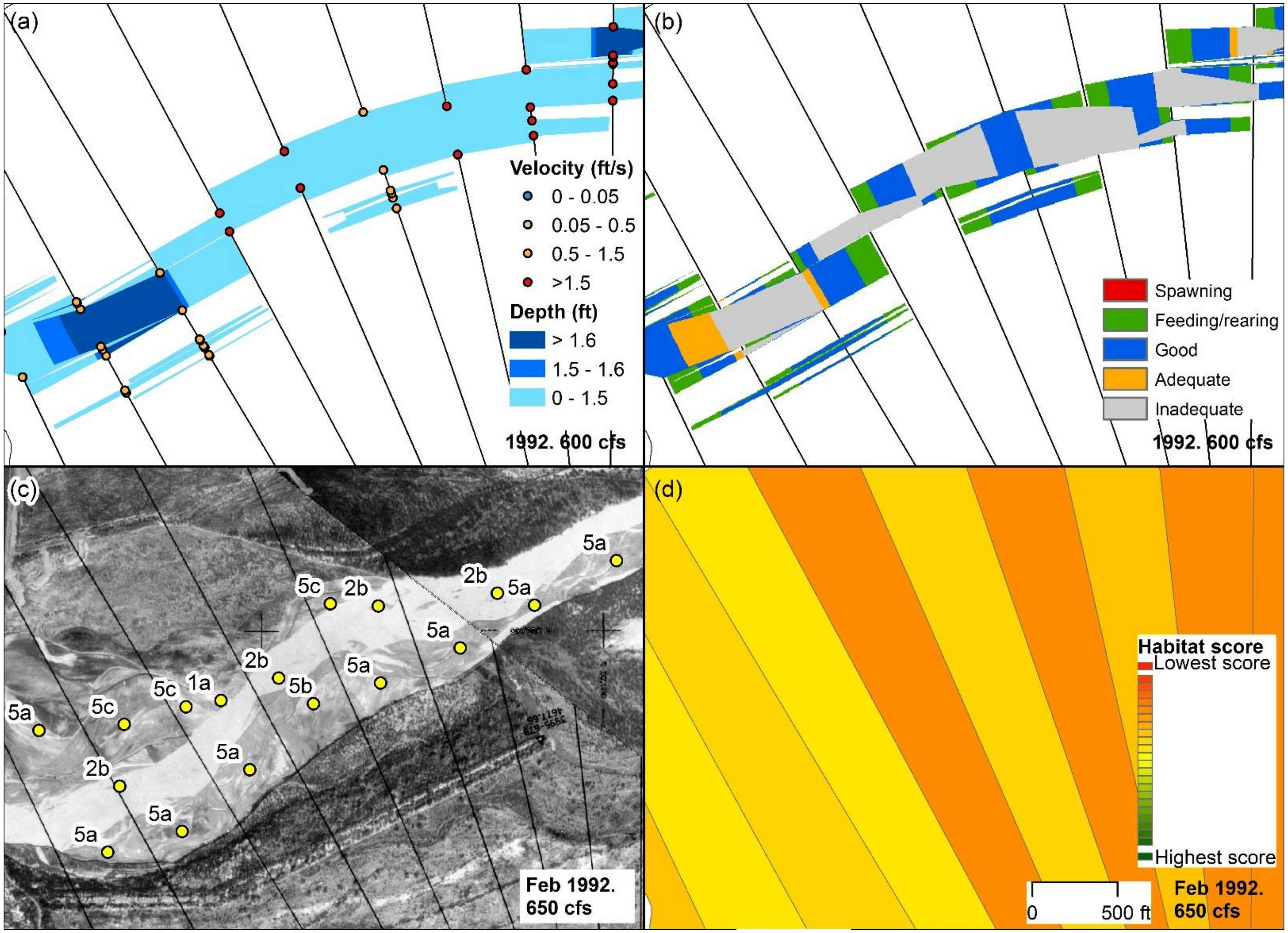
Summary of HEC-RAS and GIS habitat at subreach P2, agg/deg 1145 to 1150. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. (d) Habitat color scheme based on habitat features.



Summary of HEC-RAS and GIS habitat at subreach P3, agg/deg 1162 to 1167. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. (d) Habitat color scheme based on habitat features.



Summary of HEC-RAS and GIS habitat at subreach P4, agg/deg 1187 to 1193. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. (d) Habitat color scheme based on habitat features.



Summary of HEC-RAS and GIS habitat at subreach P5, agg/deg 1196 to 1204. (a) Velocity and depth of the simulation. (b) Habitat criteria mapped based on velocity and depth. (c) Habitat features mapped out by points and letters. (d) Habitat color scheme based on habitat features.

Appendix H - Division of Labor

Division of Labor			Kristin LaForge		Chun-Yao Yang	
Sections and Subsections:			Writing	Analysis	Writing	Analysis
Abstract			x			
Introduction (1)	Literature Review (1.1)	Middle Rio Grande History (1.1.1)	x			
		Silvery Minnows- An Endangered Species (1.1.2)	x			
		Silvery Minnows and the River (1.1.3)	x			
	Site Description and Background (1.2)	Rio Puerco History (1.2.1)	x			
		Rio Puerco Reach Description and Subreach Delineation (1.2.2)			x	x
Flow and Sediment Discharge Analysis (2)	Discharge (2.1)				x	x
		Single Mass Curves (2.1.1)			x	x
		Recurence Interval (2.1.2)	x		x	x
		Relation between flow and population of RGSM (2.1.3)			x	x
	Precipitation (2.2)		x			
	Suspended Sediment (2.3)		x		x	x
	Double Mass Curves (2.4)		x			
	Total Load (2.5)		x			
Geomporhpic and River Characteristics (3)	Sinuosity (3.1)		x	x	x	x
	Width (3.2)		x		x	x
	Braiding (3.3)		x		x	x
	Bed Elevation (3.4)				x	x
	Volume Change (3.5)				x	x
	Bed Material (3.6)				x	x
	Flow Depth, Velocity, Width, Wetted Perimeter and Slope (3.7)		x		x	x
	Geomorphic Conceptual Model (3.8)		x	x		
HEC-RAS Silvery Minnow Hydraulic Modeling (4)	Habitat Criteria (4.1)		x		x	x
	Method (4.2)		x		x	x
	Results and Discusison (4.3)				x	x
Silvery Minnow Habitat Criteria (5)	Introduction (5.1)		x			
	Methods (5.2)	Data Use/Aerial Photography (5.2.1)	x	x		
		Criteria Development (5.2.2)	x			
		General Guidelines for Scoring and Mapping (5.2.3)	x	x		
		Methods of Analysis (5.2.4)	x	x		
	Results (5.3)	Overall Habitat Score (5.3.1)	x	x		
		Subreach Delineation (5.3.2)	x	x		
		Agg/Deg Line Delineation (5.3.3)	x	x		
	Discussion (5.4)		x			
Shoreline Complexity (6)	Methods (6.1)		x	x		
	Results (6.2)		x	x		
	Discussion (6.3)		x			
Summary of HEC-RAS and GIS Habitat Analysis (7)			x		x	x
Conclusion (8)	Future Research (8.1)		x			
References (9)					x	
Appendices	Appendix A- Habitat Criteria		x	x		
	Appendix B- HEC-RAS				x	x
	Appendix C- Habitat Counts (Years with flows around 650 cfs)		x	x		
	Appendix D- Shoreline Complexity		x	x		
	Appendix E- Habitat Score by Subreach (All Years)		x	x		
	Appendix F- Habitat Score by Subreach (Years with flows around 650 cfs)		x	x		
	Appendix G- Summary of HEC-RAS and GIS habitat				x	x

Edits on each section were made by each author (not stated in table because they were done throughout the entire document). An x indicates who did a majority of the “writing” or “analysis”. The division of labor was done because two reach reports (Rio Puerco and Isleta) were written for USBR. Another set of edits were made solely by Kristin LaForge for the technical report which only comprises one of the two reports (Rio Puerco Reach).