BUREAU OF
RECLAMATION

Side Channel Evolution and Design: Achieving Sustainable Habitat for Aquatic Species Recovery

Science and Technology Program
Research and Development Office
Final Report No. ST-2022-19266-01

U.S. Department of the Interior

January 2023

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)* 13-01-2023	2. REPORT TYPE Research	3. DATES COVERED *(From - To)* 2019 – 2022

4. TITLE AND SUBTITLE Side Channel Evolution and Design: Achieving Sustainable Habitat for Aquatic Species Recovery	5a. CONTRACT NUMBER F007A
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Nathan Holste, Hydraulic Engineer, P.E., M.S. Aaron Hurst, Geomorphologist, Ph.D. Colin Byrne, Hydraulic Engineer, Ph.D.	5d. PROJECT NUMBER Final Report ST-2022-19266-01
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bureau of Reclamation Denver Federal Center PO Box 25007, Denver, CO 80225-0007	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2022-19266-01

12. DISTRIBUTION/AVAILABILITY STATEMENT

Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Side channels increase the hydraulic and geomorphic complexity of river systems, which provides aquatic habitat by reducing velocity and increasing shoreline length and cover. Constructed side channels are a common habitat restoration technique to improve ecological value, but design guidance is limited. This study analyzes naturally formed side channels to improve the efficacy of constructed projects. We used historical aerial imagery of the Middle Rio Grande, the Sacramento River, and the Trinity River to better understand how side channels form, how they evolve, and how long they persist. We identified and classified side channels between 1935 and 2012 with a time series of at least five different years for each river. Classification types consider if the side channel was likely created by erosion or deposition through processes such as lateral channel migration or channel avulsion. Evaluating spatial and temporal trends for each river highlights relationships between geomorphic processes and side channel abundance and longevity.

15. SUBJECT TERMS

side channels, habitat restoration, geomorphic evolution

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Nathan Holste
a. REPORT U	b. ABSTRACT U	THIS PAGE U			19b. TELEPHONE NUMBER *(Include area code)* 303-445-2507

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. Joel Sholtes developed the research proposal and has provided suggestions throughout the study. Melissa Shinbein and Brianna Herner assisted with digitizing side channels. David Gaeuman provided data for side channels on the Trinity River. Jonathan Pomeroy rectified aerial imagery for the Sacramento River.

Side Channel Evolution and Design: Achieving Sustainable Habitat for Aquatic Species Recovery

Final Report No. ST-2022-19266-01

prepared by

Technical Service Center
Sedimentation and River Hydraulics Group

Nathan Holste, Hydraulic Engineer, P.E., M.S.
Aaron Hurst, Geomorphologist, Ph.D.
Colin Byrne, Hydraulic Engineer, Ph.D.

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2022-19266-01

Side Channel Evolution and Design: Achieving Sustainable Habitat for Aquatic Species Recovery

NATHAN HOLSTE

Digitally signed by NATHAN HOLSTE
Date: 2023.01.09 13:07:59 -07'00'

Prepared by: Nathan Holste, P.E., M.S.
Hydraulic Engineer, Sedimentation and River Hydraulics Group

AARON HURST

Digitally signed by AARON HURST
Date: 2023.01.09 13:20:01 -07'00'

Prepared by: Aaron Hurst, Ph.D.
Geomorphologist, Sedimentation and River Hydraulics Group

COLIN BYRNE

Digitally signed by COLIN BYRNE
Date: 2023.01.09 13:16:35 -07'00'

Prepared by: Colin Byrne, Ph.D.
Hydraulic Engineer, Sedimentation and River Hydraulics Group

D. BRADLEY

Digitally signed by D. BRADLEY
Date: 2023.01.10 12:22:15 -08'00'

Peer Review by: D. Nathan Bradley, Ph.D.
Hydraulic Engineer, Sedimentation and River Hydraulics Group

This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation's determination or policy.

Acronyms and Abbreviations

CDF	Cumulative Distribution Function
cfs	cubic feet per second
ft	foot or feet
LiDAR	Light Detection and Ranging
Reclamation	Bureau of Reclamation
RM	River Mile
TRRP	Trinity River Restoration Program

Symbols

%	percent
D50	median grain size

Contents

Page

Page

Executive Summary

Channels and their floodplains have been negatively impacted by human alterations and suffer from the effects of higher velocity, higher stream power, decreased connectivity, and decreased off-channel habitats and refugia for aquatic species. Over the last twenty to thirty years, Reclamation has established species recovery programs to address the loss of geomorphic complexity and restore habitat in key river systems for threatened and endangered species. Constructed side channels are one restoration technique to provide suitable fish habitat and support various life stages where the main channel geometry is relatively uniform with high velocity and depth. Side channels are dynamic features that are created and maintained by fluvial processes and evolve, senesce, and eventually may be abandoned. Natural side channels provide a useful empirical reference for improving planning, resource allocation, and design methods for constructed side channels. Our study develops a process-based classification framework for natural side channels and then analyzes their morphology and abundance between the 1930s and 2010s. Understanding the formation, evolution, and persistence of natural side channels can improve implementation and develop realistic expectations for the performance of side channel restoration projects.

We identified and classified side channels on three river systems: the Middle Rio Grande, the Sacramento River, and the Trinity River. Repeat aerial imagery between 1935 and 2012 (Middle Rio Grande), 1938 and 2009 (Sacramento River), and 1944 and 2011 (Trinity River) provided time series to assess side channel formation, longevity, and persistence. The Middle Rio Grande evolved from a wide, braided river in the early 1900s to a channelized and stabilized river during the 1950s–1980s, to a narrower river with vegetated banks and more natural maintenance practices during the 1990s–present. The early 1900s had high peak flows and high total annual flow, the mid-1900s had infrequent peak flows with low total annual flow, the 1980s and 1990s had reduced peaks from upstream dams but high annual flow, and 2000 to the present has had an ongoing drought with low peak flows and low annual flow.

The Sacramento River has been affected by irrigation and diversions throughout the study period in addition to dams and other infrastructure installed between about 1940 and 1975. The early to mid-1900s had high peaks but below average total annual flow, the 1970s through about 2010 have had lower peaks, increased base flow, and above average total annual flow, while recent years have been in a drought. The Trinity River has been subject to geomorphic alteration since the late 1800s: primarily mining through about 1950, then industrial logging through about 1990, and more recently, river restoration and more natural river management. Trinity Dam and Lewiston Dam were constructed in the 1960s and altered the downstream hydrology and sediment supply. The early to mid-1900s had high peak flows and high average annual flows, flows were dramatically reduced by upstream dams from 1960 to 1998, and then since 1998 peak flow releases occur in May with slightly elevated base flows compared to historical conditions.

We digitized side channels on the three rivers and classified them based on erosional or depositional processes. The digitization and classification process also included recording attributes such as geometry (e.g., width, angle) and location relative to the channel planform and floodplain. We analyzed these attributes for each side channel type on each river to identify relationships between

morphology, evolution, and persistence while providing guidance for design. Erosional side channels form by large flow events scouring the banks, floodplain, or main channel point bars and include the following types: incised floodplains, incised bars, chutes, avulsions, anastomoses, obstructions, and sills. Depositional side channels occur when there is an increase in sediment supply or local reduction in transport capacity because of a reduction in slope or an increase in width. Depositional side channel types include medial bars, braided systems, diagonal bars, accreted bars, and backwater shoals.

Side channel abundance is presented as number of side channels per mile to facilitate comparison between different rivers and geomorphic reaches. Comparing each river's first year of aerial imagery between 1935 and 1944, the Sacramento River has the most side channels per mile and the Trinity River has the fewest. After about the early 1960s, the Sacramento River has the lowest side channel density, and the Trinity River has the greatest side channel density. The number of side channels on the Middle Rio Grande increased significantly after about 1992. Upstream reaches of the Middle Rio Grande have the greatest abundance of incised bars and diagonal bars, while downstream reaches have the greatest abundance of incised floodplain side channels. Side channels on the Middle Rio Grande were the most dynamic of the three rivers with sediment erosion, deposition, and bar evolution creating accreted bar side channels, diagonal bars, and incised bars. Differences in side channel types are primarily linked to differences in reach characteristics from upstream to downstream.

On the Sacramento River, the upstream reach is partially confined with bedrock sections that create obstructions and sills not found in other reaches. Downstream of Red Bluff, the river is unconfined with active lateral migration and meander dynamics that form chutes and meander cutoff side channels. Flows on the Sacramento River can be roughly an order of magnitude higher than both the Middle Rio Grande and Trinity River. Historically, this created a highly dynamic river and floodplain system that has stabilized in recent years. The Sacramento River showed larger differences in side channel metrics than the Rio Grande. Chutes and cutoff meanders had the most distinct characteristics and are remnant main channel flow paths. Chutes tended to have the greatest side channel top width and the lowest side channel-to-main channel length ratio, and conversely, that ratio is highest for cutoff meanders. Cutoff meanders represent the opposite transition as a chute and tend to have opposite characteristics.

The Trinity River has a diversity of side channel types in geomorphically-complex reaches and a higher proportion of sills and obstructions in confined bedrock-dominated reaches. Incised bars and medial bars are present in all reaches, suggesting that localized sediment dynamics are important for these features. Side channel attributes exhibit many common characteristics for all three rivers, such as chutes that have small length ratios and high width ratios for the side channel relative to the main channel. Inlet and outlet angles typically vary between 35 and 55 degrees for nearly all channel types.

The three rivers have different lateral migration rates and different geomorphic characteristics between reaches. All three rivers generally have the highest migration rates during the mid-1900s between the earliest periods of aerial imagery. Migration rates increased on the Trinity River after 2001. The number of side channels per mile increased in the four upstream Middle Rio Grande reaches, stayed consistent in the fifth and sixth reach, and decreased in the two downstream reaches. Analysis for the Sacramento River is complicated by inconsistent aerial imagery extents between years. The number of side channels decreased between 1938 and 1958 and then have remained mostly constant. Conversely, the number of Trinity River side channels increased between 1960 and

1980 and then have been consistent in recent years. The upstream three reaches were responsible for the increased abundance while the downstream reach has maintained the lowest number of side channels in nearly every year.

In addition to documenting the number of side channels by geomorphic reach and classification type, we examined channel lifespans by recording whether each side channel was newly formed, reoccupied, continued from the previous imagery year, or abandoned. The ratio of new to continued side channels was higher for earlier years of imagery. Many new side channels formed on the Middle Rio Grande in 1992 and 2002. 1992 was in the middle of a high flow period. High flows have the capacity to erode, transport, and deposit large volumes of sediment, which rearranges the channel and can create many new side channels. Starting around 2000 at the onset of the current drought for the Middle Rio Grande, a higher proportion of side channels were continued rather than newly formed. The lower flows during a drought after a long period of channel mobilization allows banks to vegetate and establishes bars that can then persist. The number of abandoned side channels is lower since 2000 and higher in the earlier years, peaking in 1962 during the channelization river maintenance period.

There is a similar trend on the Sacramento River where the number of new channels and abandoned channels is lower since about 2000 and the number of continued channels is higher. However, there is a larger ratio of new to continued side channels than the other rivers. Reaches with lower migration rates have fewer new side channels and a higher proportion of continued side channels. On the Trinity River, many new side channels formed between 1960 and 1980 when flow control from upstream dams and reduced mining impacts allowed bankline vegetation to establish and create more stable flow paths. After 1980, the quantity of newly formed side channels consistently decreased while persistent side channels that continued for multiple years became more prevalent. The total side channel abundance is consistent after 1980 because the number of abandoned channels is similar to the amount of new plus reoccupied channels. Side channel trends for the Trinity River and Middle Rio Grande indicate that wet periods create more side channels and subsequent dry periods favor continued side channels. Trends in new or continued side channels over time are likely partially influenced by the more frequent aerial images in later years, which provides greater temporal resolution.

We evaluated whether a side channel can change from one classification type to another by creating evolution diagrams to illustrate classification changes between consecutive years of aerial imagery. The results highlight that side channel type is typically stable through time, especially on the Trinity River. The Trinity River has almost no change in side channel type, which confirms the hypothesis that less mobile rivers will have more stable side channels that persist for longer. A side channel that evolves between types also has a greater opportunity to become abandoned. The Middle Rio Grande is the most dynamic river system and has many side channels that alternate between types. For example, bars can become accreted and then re-incised to join the main channel multiple times throughout a side-channel’s history. On both the Middle Rio Grande and Sacramento River, incised bars were relatively dynamic. Side channels are periodically reoccupied through a cycle of gradual abandonment during low flow periods and reactivation during high flows. On the Sacramento and Trinity rivers, side channels are typically more stable. For these two rivers, obstructions, sills, and medial bars are especially stable.

We quantified the longevity of side channels by going back in time for all side channels existing during the most recent year of imagery. The age of each side channel is how long it persisted between consecutive years of imagery. Many of the 2012 Middle Rio Grande side channels formed during the previous 4 years. Many side channels also persisted to the 1992 imagery but not the 1972 imagery, an age of 20 to 40 years. The largest proportion of side channels on the Sacramento River persisted to 1999 but not 1974, an age of 10 to 35 years. All reaches had side channels persisting 35 to 51 years (between 1974 and 1958) while the two upstream reaches had several side channels persisting 51 to 71 years (between 1958 and 1938). 1938 imagery was not available in the downstream reach. The Trinity River has the highest proportion of ages between 0 and 2 years, which are side channels newly formed or reoccupied between 2009 and 2011. Other age classes were broadly distributed until a decline in side channels persisting beyond 51 years (1960 or earlier).

The accreted bar has the shortest lifespan of any channel type on the Middle Rio Grande, which has almost no accreted bar channels older than 4 years. These are bars that attach to the outer bank and tend to become filled with sediment. Medial bars are short-lived features on the Sacramento and Trinity Rivers. Medial bars are also depositional features that exist where there is a local reduction in sediment transport capacity. Not all depositional side channel types have a short longevity. Diagonal bars are relatively long-lasting features on the Middle Rio Grande and Trinity River. Vegetation may help stabilize the diagonal bars and they also have a different shape with narrower channel threads and streamlines more parallel to the dominant flow direction. The side channel types with the longest persistence are the chute and sill. Sills have incised to bedrock, an inherently stable configuration, and tend to be wider because the bedrock prevents further bed erosion. On the Sacramento River, chutes have a relatively high longevity. Chutes typically have a larger relative width compared to the main channel and a shorter length on the inside of a meander bend.

The Middle Rio Grande has topographic change data available for constructed channels to further understand persistence, a dataset not available for the other rivers. Elevation comparisons for the period 2012 to 2018 showed that 14% of constructed sites had a median change above the deposition threshold. Quantile values corresponding to 75% and 90% non-exceedance had a larger percentage of sites above the deposition threshold, 29% and 48%, respectively. This illustrates that side channel deposition is spatially variable. An elevation change map demonstrates that most deposition occurs at the side channel inlet, with some deposition at the outlet. Therefore, suspended sediment deposition at the interface with the main river appears to be a common disconnection process for constructed side channels in some rivers or reaches.

Information from this empirical study of natural side channel classification, morphology, formation, evolution, and persistence can be applied to designing new side channels for habitat restoration. First, designers and planners should consider the geomorphic reach of the proposed project and the context of multiple geomorphic reaches within a river system. There is a balance between identifying reaches that may have a side channel deficit and understanding that certain reaches naturally do not support as many side channels. After identifying a reach for side channel implementation, the next step is to consider side channel types appropriate for that reach. The level of planning and design effort should be scaled to the expected persistence and life cycle benefit of a side channel. For example, medial bars on the Sacramento River have a short longevity while backwater shoals, chutes, obstructions, and sills may persist for much longer. Once a side channel type is selected for a general location, the geometric parameters compiled for this study can be applied to develop the design dimensions. Finally, after design and construction is complete, side channels should be monitored to track their evolution, geomorphic change, and ultimately, whether they are providing the expected habitat benefits.

1. Introduction

Rivers throughout the world have suffered from a loss of geomorphic complexity caused by land use changes, hydrologic modifications, flood control, channelization, and stabilization (Kondolf et al., 2006; Wohl, 2016). Channels and their floodplains are currently more confined than historical conditions with higher velocity, higher stream power, decreased connectivity, and decreased off-channel habitats and refugia for aquatic species (Wohl, 2018). These trends became significant in the western United States in watersheds within the Bureau of Reclamation's (Reclamation) regions during the mid to late-1800s, coinciding with the expansion of European settlers, and have continued to the present (Rowley, 2006). Urbanization and increasing water demands continue to affect aquatic and riparian ecosystems as society attempts to balance human and ecological needs. Over the last twenty to thirty years, Reclamation has established species recovery programs to restore habitat in key river systems for threatened and endangered species. These programs often focus on fishes that rely on slower moving water along channel margins, vegetated floodplains, and other areas beyond the main channel (U.S. DOI, 2000; Medley and Shirey, 2013; Tetra Tech, 2014; Mortensen et al. 2019). Common types of restoration features constructed by the recovery programs include side channels, backwaters, embayments or alcoves, and bank lowering (Holste et al., 2022).

This study focuses on side channels, which support various fish life stages such as egg retention for pelagic spawners, juvenile rearing, and adult refuge during high flow events (Barko and Herzong, 2003; Rosenfield, 2008; Medley and Shirey, 2013). Hydraulically, side channels provide suitable habitat because of a lower unit discharge, lower velocity, shallower depth, and roughened shoreline areas that create eddies and velocity gradients. These attributes are especially important in altered river systems where the main channel geometry is relatively uniform and disconnected from its floodplain. Constructed side channels attempt to mimic naturally formed side channels to achieve the same benefits for aquatic species (Tetra Tech, 2004). However, side channels are dynamic features that are created and maintained by fluvial processes and evolve, senesce, and eventually may be abandoned. Designing and constructing side channels requires investing resources, so it is important to consider the expected evolution and longevity as part of the project planning process. Additionally, side channel formation and evolution vary depending on the geomorphic setting; river channel characteristics influence the type of side channel and its persistence. Side channels fail to persist when all flow less than the bankfull discharge is captured by a single channel. This is typically caused by one of the following processes (Burge and Lapoint, 2005):

- Side channel fills with sediment and aggrades above connected level
- Main channel incises and degrades below connected level
- Main channel migrates away from side channel and loses surface-flow connection
- Main channel avulses into side channel and contains all flow

Understanding these processes will help designers create more sustainable side channels and develop realistic expectations for longevity of constructed projects. Furthermore, understanding how side channels are created will help develop geomorphically-compatible side channel designs where the type of side channel, its dimensions, and its location are consistent with naturally formed side channels. Side channel formation is dominated by one of two processes: erosion or deposition

(Nanson and Knighton, 1996; Carling et al., 2013). Erosion-based processes include the scouring of new channels into the floodplain or point bar, whereas deposition-based processes include the accretion of bars within the main channel that create islands or ridges that divide flow. Erosional channels are typically caused by scour during high flow events and depositional channels are typically caused by a channel expansion, slope reduction, or increased sediment supply. There are several morphological factors thought to be important for side channel formation and evolution (Kleinhans et al., 2013; van Dijk et al., 2014; van Denderen et al., 2016; Gaeuman and Stewart, 2017; van Denderen et al., 2019):

- Relative longitudinal slope of side channel to main channel
- Planview angle of side channel to main channel (bifurcation angle) or angle of streamlines at channel-forming discharge
- Transverse bed slope, helical flow, and location of side channel inlet relative to bend planform
- Bank erodibility and lateral migration
- Sediment size, transport capacity, and supply of bedload and suspended load
- Shear stress at bifurcation point generated by channel-forming discharge
- Partitioning of flow, shear stress, and sediment load between side channel and main channel
- Bed elevation of side channel inlet relative to main channel, which determines if sediment entering the side channel is predominantly bedload, suspended bed-material load, or wash load

Several papers examined during a literature review discuss the importance of sediment transport, asymmetric bed topography, and multi-dimensional hydraulics. However, we did not have consistent sediment data, channel surveys, or hydraulic models available for most of our side channel sites. Therefore, the scope of our study is limited to an empirical investigation of side channels using repeat aerial imagery. The aerial imagery includes at least six different years between 1935 and 2012 for three river systems with lengths between 40 and 200 miles. We selected the Middle Rio Grande, the Sacramento River, and the Trinity River because they each have significant species recovery programs and have a comprehensive database of aerial images. These rivers and time periods represent a range of hydrologic regimes, sediment supplies, and geomorphic characteristics.

Another study goal is to develop a classification framework and conceptual model of side channel formation and evolution. This analysis tracks naturally formed side channels over the period of record to provide realistic expectations for constructed side channels. There are relatively few constructed side channels on the three rivers, and they are more recent features, so including natural side channels provides a more comprehensive dataset. We also briefly evaluate geomorphic change within constructed side channels where elevation data are available. The final goal of this study is to provide design guidance for constructing geomorphically-compatible side channels that will provide habitat benefits over reasonable timescales given the dynamic nature of rivers. Comprehensive and quantitative design guidelines for side channels do not currently exist, and this study seeks to contribute to improved projects through a better understanding of the formation, evolution, and persistence of natural side channels.

2. Study Sites

2.1 Middle Rio Grande

2.1.1 River System Description

The Rio Grande is the fifth longest river in North America, forming the border between Texas and Mexico. It generally flows from north to south from its headwaters in the San Juan Mountains of Colorado through New Mexico and into the Gulf of Mexico. Its tributaries drain the Rocky Mountains and several steppes and plateaus through the desert of the southwestern US, serving as a major water source for agriculture throughout the region. The entire watershed area is about 180,000 square miles, of which approximately 89,000 square miles are in the United States and the remainder in Mexico (Wozniak, 1996). The Middle Rio Grande is the 270 miles of the river between Velarde and Caballo, New Mexico. The area of the Middle Rio Grande Basin above Elephant Butte is approximately 30,000 square miles and falls almost entirely within the Rio Grande Valley (Wozniak, 1996). The eastern boundary of the basin drains mountainous topography, and the western boundary drains isolated volcanic and granitic rocks.

The climate in the Middle Rio Grande basin ranges from arid to humid, but most of the basin possesses a semiarid climate (Bartolino and Cole, 2002). Most of the precipitation is derived from summer storms originating mainly from the Gulf of Mexico. July and August are typically the wettest months, with 45 to 62 percent of the annual precipitation falling between July and October. Average annual precipitation ranges from 7.6 inches in the valley lows to about 23 inches at the drainage crest with a mean of 10 inches or less. Precipitation can be extremely spatially and temporally variable. Peak streamflow is bimodal, with higher flows occurring during the spring snowmelt or summer monsoon. This region is characterized by periodic droughts with immediate effects on surface water and long-term effects on ground water recharge and use.

The Middle Rio Grande is evolving rapidly through incision and narrowing, with less flooding and aggradation than historical conditions. The watershed has been in an ongoing drought since 2000, except for infrequent high flow events such as the 2005 spring runoff or 2013 summer monsoon. This dry period caused the river to narrow. Areas of the river that promoted island stabilization and growth during the drought narrowed and deepened further. For example, the 2005 spring runoff event deposited sediment along the top of banks and floodplain. The main channel incised in the reach upstream of Elephant Butte Reservoir because the reservoir pool elevation had decreased about 100 feet since the late 1990s. Single-threaded channel reaches began to migrate. Throughout recent history, the bed material has been generally coarsening in most of the reaches. The major controlling processes at present are floodplain conversion to terraces, channel narrowing, loss of sand resulting in a gravel-dominated bed, and lateral channel migration (Martin et al., 2007).

Human interference began on the Middle Rio Grande as early as the 10th century with primitive irrigation systems. Since then, various groups have depended heavily on the river for irrigation to support agriculture. Irrigation diversions peaked in the late 1800s, during which the Rio Grande was dry downstream of Albuquerque for four months of the year (Wozniak, 1996). In 1915, Elephant Butte Reservoir was constructed. This reservoir sets the baselevel for the area of interest. In 1934, the Cochiti diversion dam was built at the upstream end of the study reach. The 1950s–1970s were dominated by multiple flood and sediment control dam installations on almost all the tributaries of the MRG. The Cochiti flood control dam replaced the diversion dam in 1973 and impounded water at the upstream end of the study area, regulating the flow for approximately 200 miles downstream. Throughout the 1990s there were various levee, drainage system, and river channelization projects. Prior to the mid-1980s, Middle Rio Grande maintenance plans were focused on controlling the location of the river. In the 1980s and 1990s, maintenance practices changed to allow for controlled river migration rather than complete channelization and stabilization.

The approximately 170 miles of the Middle Rio Grande between Cochiti Reservoir and Elephant Butte Reservoir were the focus of this side channel identification study. This stretch of river is split into eight geomorphic reaches from Makar and AuBuchon (2012) (Table 1). River Miles (RM) are based on the 2012 river planform geometry. Reach lengths ranged from 7.5 to 43.8 miles and averaged 23.5 miles.

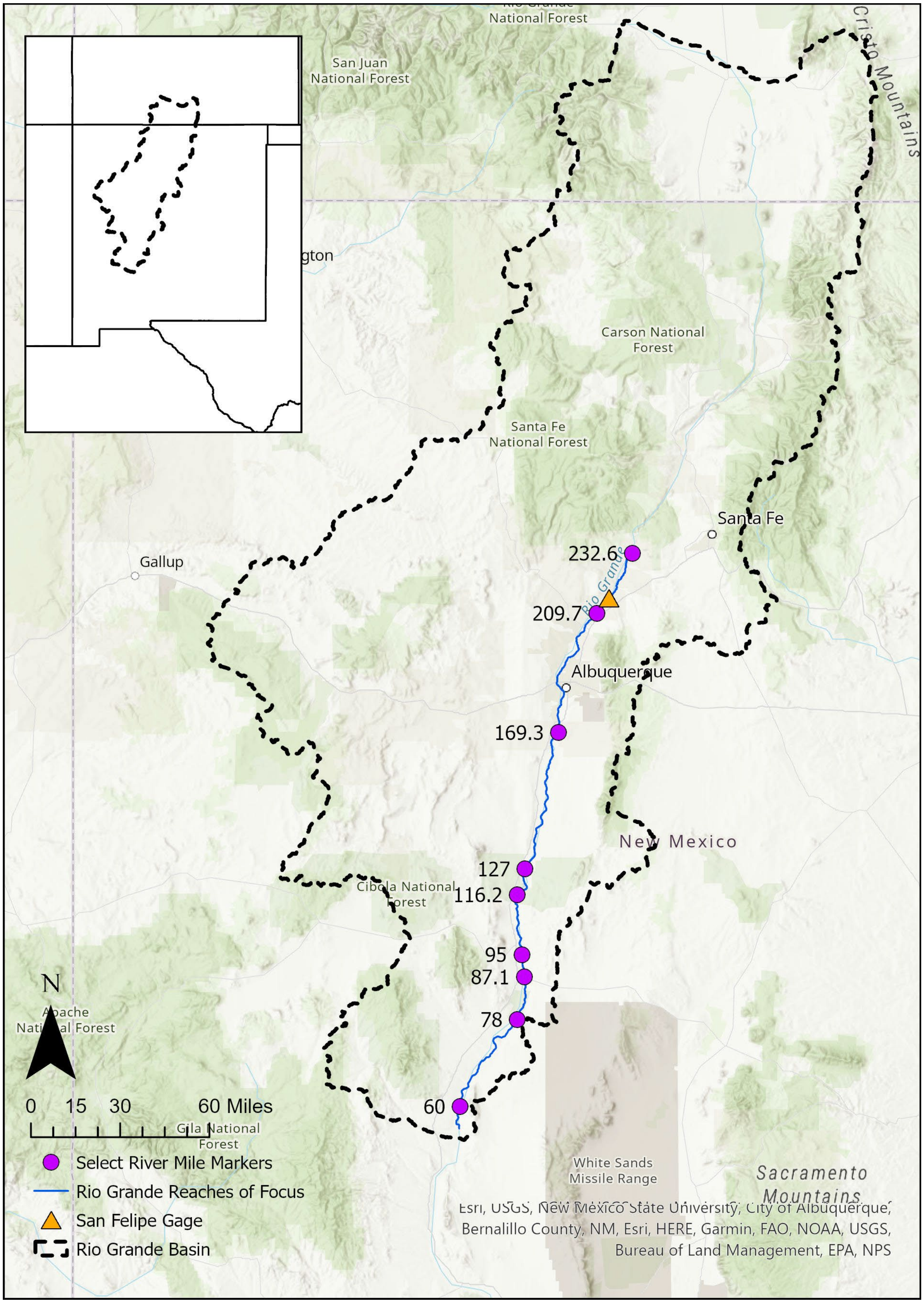


Figure 1. Rio Grande reaches of interest in this study. The Rio Grande Basin only shows the drainage area upstream of Elephant Butte Reservoir.

Table 1. Middle Rio Grande reach characteristics (adapted from Makar and AuBuchon, 2012 and Martin et al., 2007)

Reach	Name	River Miles	Planform	Slope	Sinuosity	Bed Material	Bed Elevation	Recent Trends
1	Cochiti Dam to Angostura Diversion Dam	RM 232.6 – RM 209.7	Moderate sinuosity, single channel, with islands	0.0012	1.12	Gravel & small cobble	Moderate incision, currently stable	Lateral erosion, several bankline erosion sites
2	Angostura Diversion Dam to Isleta Diversion Dam	RM 209.7 – RM 169.3	Transition from wide braided to single channel	0.0010	1.04	Bimodal gravel & sand	Moderate incision – greater upstream	Continued incision, narrowing, and coarsening
3	Isleta Diversion Dam to Rio Puerco	RM 169.3 – RM 127	Braided but narrowing	0.0008	1.04	Sand	Low incision, increasing to high downstream	Potential to become unstable
4	Rio Puerco to San Acacia Diversion Dam	RM 127 – RM 116.2	Single thread with few islands, narrowing	0.0008	1.09	Bimodal gravel & sand	Entrenched with low bank height	Potential for migration
5	San Acacia Diversion Dam to Arroyo de las Cañas	RM 116.2 – RM 95	Single channel – low to moderate sinuosity	0.0009	1.07	Bimodal gravel & sand	High incision, decreasing downstream	Large rapidly migrating bends
6	Arroyo de las Cañas to San Antonio Bridge	RM 95 – RM 87.1	Becoming single threaded	0.0007	1.05	Sand	No recent incision	Fairly stable
7	San Antonio Bridge to River Mile 78	RM 87.1 – RM 78	Braided but narrowing	0.0007	1.08	Sand	Slightly aggrading	Continued narrowing
8	River Mile 78 to Full Pool Reservoir	RM 78 – RM 60	Narrow single thread	0.0006	1.05	Sand	Generally aggrading, recent incision	Recent headcut and lateral migration

2.1.2 Imagery, Hydrology, and Sediment Data

Georeferenced aerial imagery was available for the years 1935, 1949, 1962, 1972, 1992, 2002, 2005, 2008, and 2012 (Table 2). Reach 8, the downstream-most reach, ends at the full pool elevation of Elephant Butte Reservoir (RM 60). Areas downstream of RM 60 were not consistently available for all years because of proximity to the reservoir pool.

Dams on the mainstem Middle Rio Grande and on the tributaries affect flows within our study area. Discharges are consistently higher in late spring to early summer with low flows typical in the late summer to early fall (Figure 2 and Figure 3). High flows may occur during spring snowmelt runoff from the Southern Rocky Mountains or flashy monsoon rain events. Cochiti is operated as a flood control dam and typically only affects downstream discharge during high flow events. This is evident in the reduction in peak discharges after 1973 (Figure 4). The river flow and geomorphology are heavily impacted by periods of drought (Figure 5). Irrigation in southern Colorado's San Juan Valley also reduces flow inputs to the Middle Rio Grande.

We obtained median bed material diameter data from Greimann and Holste (2020) for 1962, 1972, 1992, 2002, and 2012. We downloaded flow data from USGS gages at San Felipe (RM 216, Reach 1) and San Marcial (RM 68, Reach 8) and daily suspended sediment concentrations from the San Marcial gage. The median grain sizes (D50) on the Middle Rio Grande have generally increased through time due to Cochiti Dam trapping fine sediments upstream of the study reach. The D50 decreases from upstream to downstream, and the range in D50 values between the reaches has also increased through time (Figure 5). Sediment yields have been influenced by anthropogenic impacts such as agricultural practices and multiple diversion dam installations on the tributaries to the Middle Rio Grande. A notable decrease in suspended sediment began in the 1980s due to cumulative effects of land use, upstream dams, tributary controls, increased riparian vegetation, and river management. Suspended sediment yields are plotted with median bed material diameters in Figure 5.

The timeline depicted in Figure 5 summarizes the available data. The number of side channels per river mile through time is plotted on the top panel. We show side channel density for the entire river with the dashed black line and subdivide the results by reach in the blue dots. The bars below the side channel time series depict the dominant river management practice that affected channel and floodplain morphology. Agriculture and irrigation continue to have effects, but the period shown by the green bar is when most diversions were constructed before future periods of channelization, bank stabilization, and habitat restoration. We plot suspended sediment data from the San Felipe Gage (USGS 08319000) in the third panel with the solid black line (secondary y-axis) and D50 on the primary y-axis with the blue dots that correspond to geomorphic reaches. Hydrology data are in the bottom panel. The vertical black dashed lines correspond to the years that we have imagery data for.

Table 2. Available imagery for the Middle Rio Grande (each year includes all reaches spanning RM 232.6 to RM 60)

Year
1935
1949
1962
1972
1992
2002
2005
2008
2012

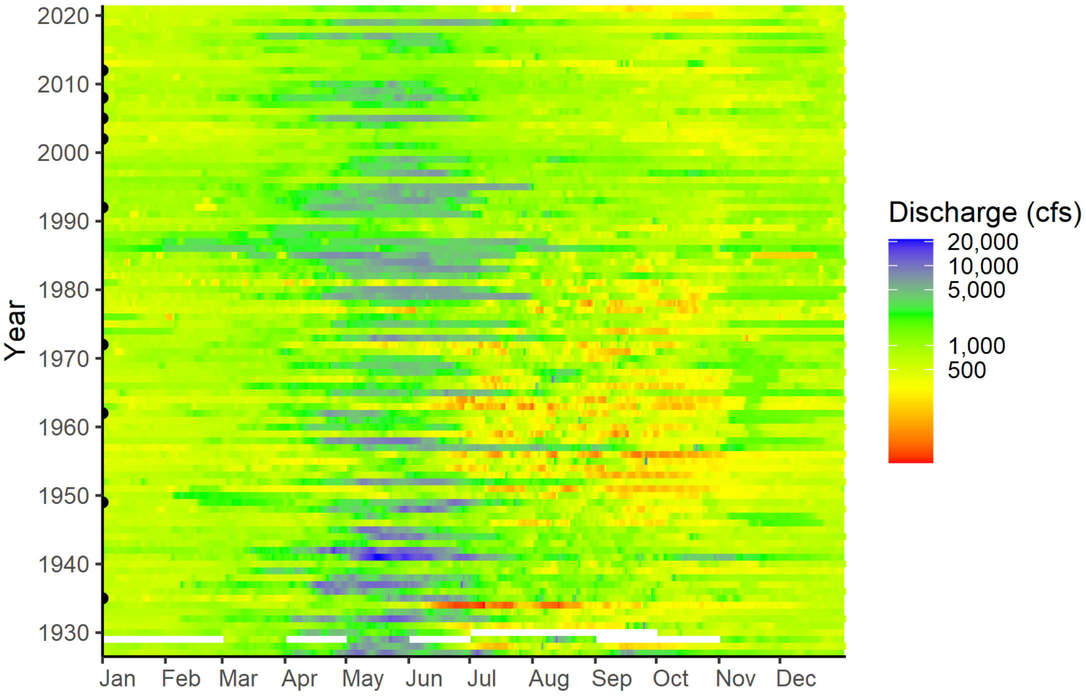


Figure 2. Mean daily flow at San Felipe between 1927 and 2022 (USGS Gage 08319000).

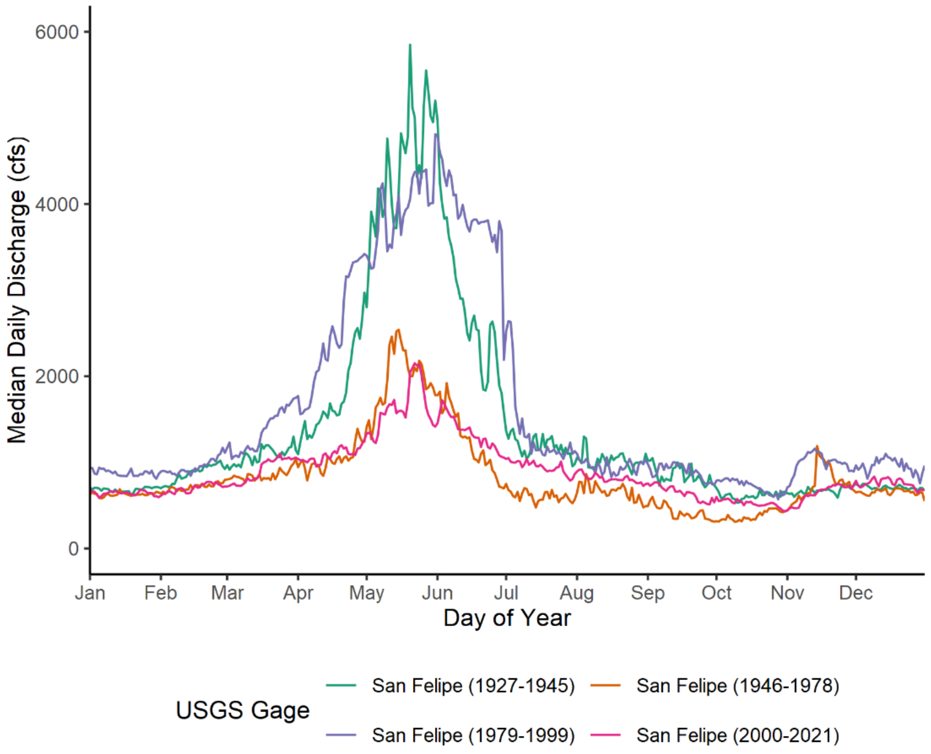


Figure 3. Comparison of median daily discharge during dry and wet periods along the Rio Grande at San Felipe (USGS Gage 08319000).

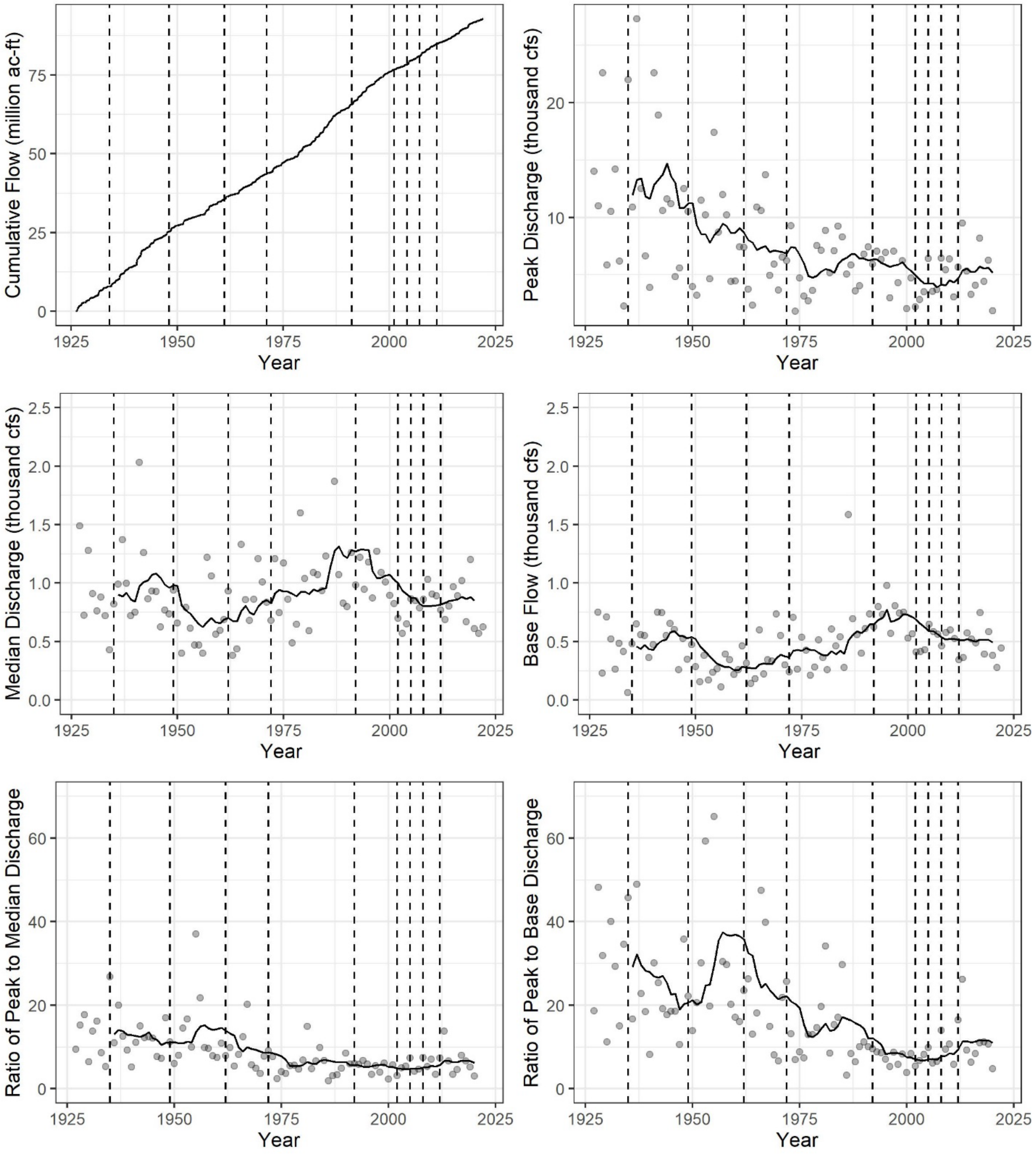


Figure 4. Cumulative and annual discharge parameters for the Rio Grande at San Felipe (USGS Gage 08319000). Gray circles represent annual values, solid black lines represent the 10-year moving average, and dashed vertical lines depict the dates of aerial imagery.

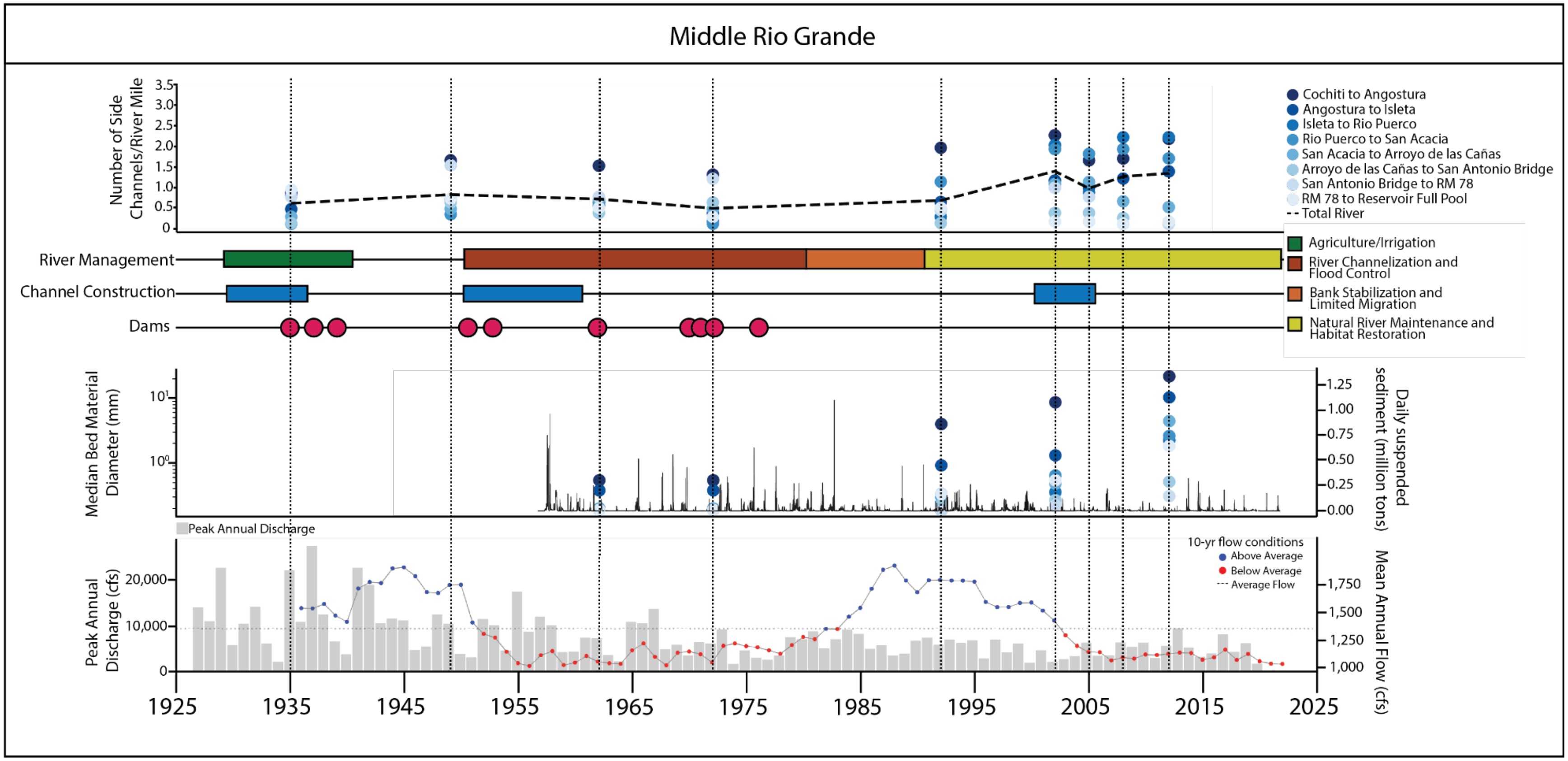


Figure 5. Timeline figure for the Middle Rio Grande. The top panel shows number of side channels normalized by river mile subdivided by reach (blue dots) and for the entire river (dashed black line). The second section highlights periods of anthropogenic modification. The third panel shows sediment data with the median bed material diameter (D50) illustrated by reach (blue dots; left y-axis) and the daily suspended sediment load in millions of tons (solid black line; right y-axis). The bottom panel plots hydrology data where mean annual flow is represented as a 10-year moving average in the red and blue dots on the right y-axis. Flows above the average of the period of record are blue and flows below the average are red. The gray bars depict the peak annual discharge (cubic feet per second) on the left y-axis. Vertical dashed lines represent the years where we have aerial imagery.

2.2 Sacramento River

2.2.1 River System Description

The Sacramento River is the second largest river on the west coast of the contiguous United States and drains an approximate area of 27,850 square miles (Figure 6). The mainstem Sacramento flows generally north to south from the headwaters in the southern extent of the Cascade Mountains through the Central Valley to the Sacramento-San Joaquin Delta and San Francisco Bay. Major tributaries also drain portions of the Modoc Plateau in southern Oregon and northeastern California, the Sierra Nevada mountain range on the eastern side of the basin, and the eastern slopes of the Coastal Ranges of California on the western side of the Sacramento River basin.

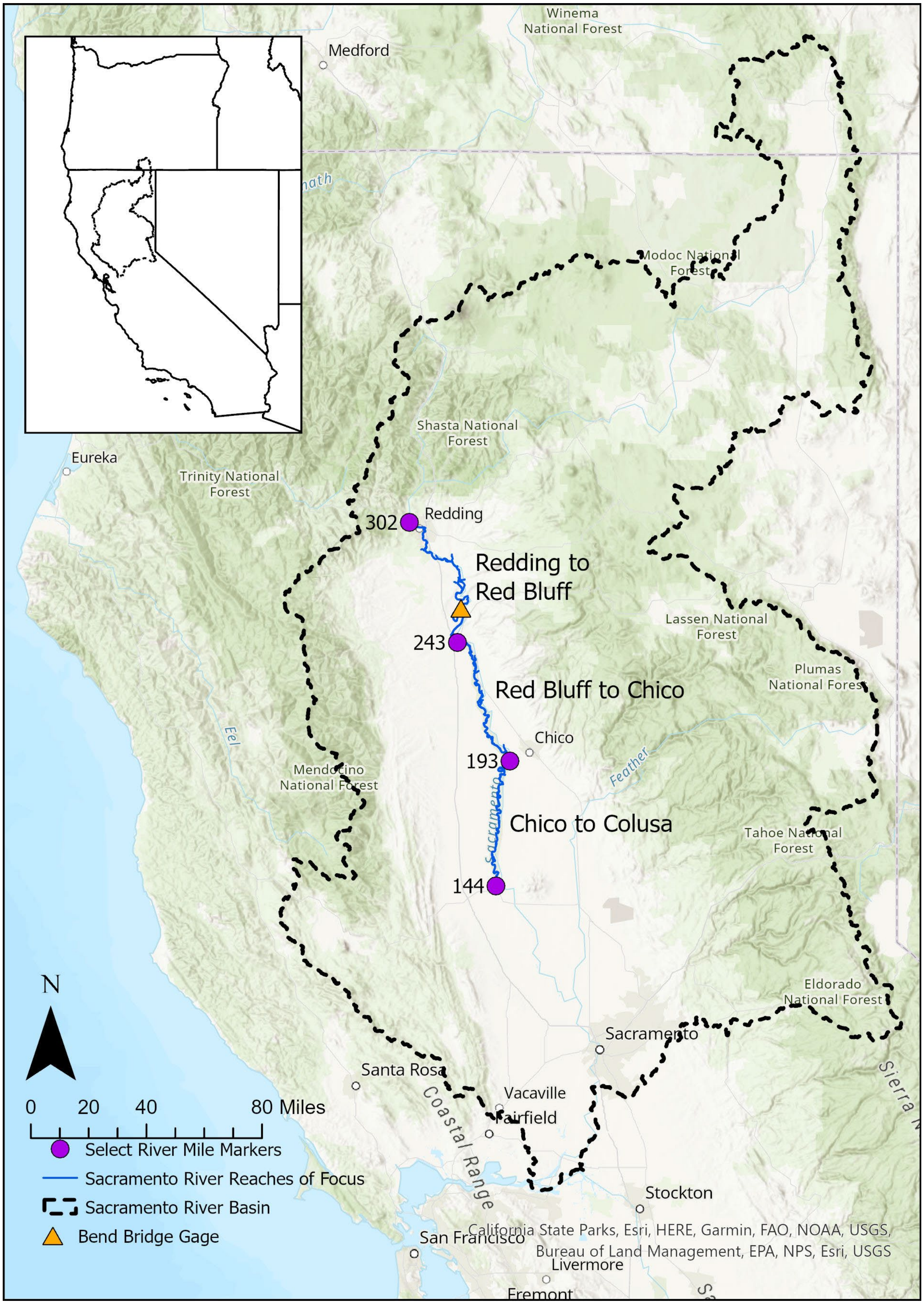


Figure 6. Sacramento River reaches of interest for this study.

The Sacramento River is subject to a Mediterranean climate with hot, dry summers and cool, wet winters. Mean annual precipitation can be an order of magnitude different across the basin, ranging from approximately 11 to 113 inches (PRISM, 2020). Hydrology of the western tributaries of the Coastal Range is generally defined by winter rainfall patterns, while the eastern tributaries of the Sierra Nevada are snowmelt dominated (Lane et al. 2018). On the volcanically influenced Modoc Plateau in the northeastern portion of the basin, ground water is highly influential, which results in more consistent hydrology.

The Sacramento River basin has been subjected to extreme anthropogenic influences since the late 19th century. Construction of large dams has hydrologically altered many of the major tributaries of the Sacramento River, including the mainstem Sacramento upstream of Redding, CA. These dams were constructed for the purpose of flood control, hydropower generation, water storage, and water delivery. In addition, dams trap sediments from higher in the watersheds. A large proportion of Sacramento River basin water is used for agricultural practices. Much of the alluvial Central Valley has been converted from wetlands and riparian forests to agricultural land use on an industrial scale (Mount, 1995). Several other land use practices, including logging and mining, have also influenced the hydrology and sediment characteristics of the mainstem Sacramento River. Hydraulic mining is perhaps the most notable of these and was responsible for extreme sediment loading to the Sacramento River basin in the 19th century (Gilbert, 1917).

Approximately 150 river miles of the Sacramento River between Redding and Colusa, CA were the focus of side channel identification and delineation (Table 3). This stretch of river has been split into three main reaches: Redding to Red Bluff, Red Bluff to Chico, and Chico to Colusa, CA, which extend from river miles 298 to 243, 243 to 193, and 193 to 144, respectively.

Table 3. Sacramento River reach delineation and characteristics

Reach	Name	River Miles	Planform	Slope	Sinuosity	Bed Material
1	Redding to Red Bluff	RM 298 – RM 243	Partially confined meandering, transitioning to confined single thread river	0.0007	1.30	Cobble, gravels
2	Red Bluff to Chico	RM 243 – RM 193	Partially to unconfined with moderate sinuosity	0.0006	1.32	Cobble, gravel transitioning to bimodal gravel/sand
3	Chico to Colusa	RM 193 – RM 144	High sinuosity channel in Central Valley alluvium	0.0003	1.52	Bimodal gravel/sand transitioning to sand

2.2.2 Imagery, Hydrology, and Sediment Data

Aerial imagery was available for the years 1938, 1958, 1974, 1999, 2004, and 2009. Some years did not include the full study area, so Table 4 documents the specific river miles and reaches in each year. To be consistent in the analysis of side channel abundance between 1974 and 2009, we truncated results from 1974, 1999, and 2004 to the imagery extents available in 2009 (RM 278–172). We kept all the data for all other results.

Table 4. Available imagery for the Sacramento River

Year	River Miles	Reaches
1938	RM 207–178	Red Bluff to Chico (partial); Chico to Colusa (partial)
1958	RM 276–204	Redding to Red Bluff (partial); Red Bluff to Chico (partial)
1974	RM 298–144	All
1999	RM 298–144	All
2004	RM 298–144	All
2009	RM 278–172	All (Redding to Red Bluff partial; Red Bluff to Chico all; Chico to Colusa partial)

Dams and other river infrastructure on the Sacramento River impact flows in the mainstem. Flow volumes and seasonal patterns can vary greatly along the Sacramento River. At the Keswick gage (USGS 11370500) upstream of Redding, CA (near RM 302 in Figure 6), flows are most greatly impacted by Shasta and Keswick Dams, which were completed in 1945 and 1950, respectively. At the Keswick gage, flows can be highly variable during winter and early spring, but median flows are consistently higher during the summer (Figure 7 and Figure 8). In comparison, at a downstream gage at Bend Bridge near Red Bluff, CA (USGS 11377100), variability also remains greatest during the winter and spring months. However, those months are also associated with the greatest median daily flows and several tributaries contribute to greater discharges at the Bend Bridge gage as compared to the Keswick gage (Figure 8 and Figure 9).

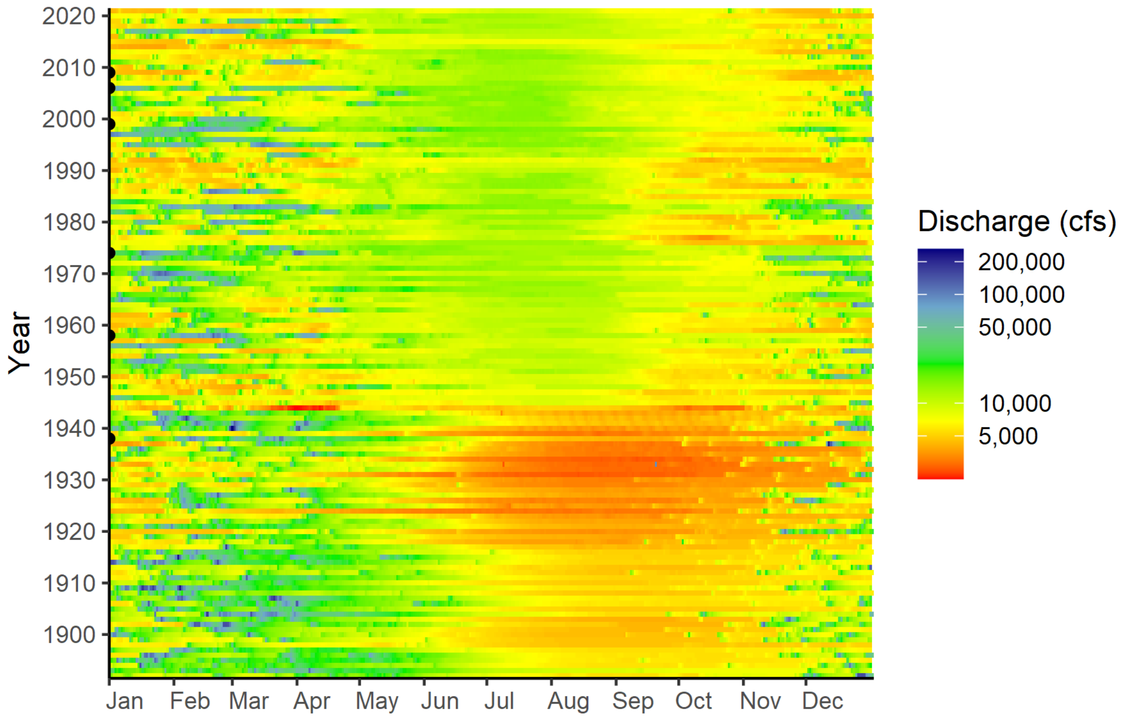


Figure 7. Mean daily flow at Bend Bridge, CA between 1891 and 2022 (USGS 11377100).

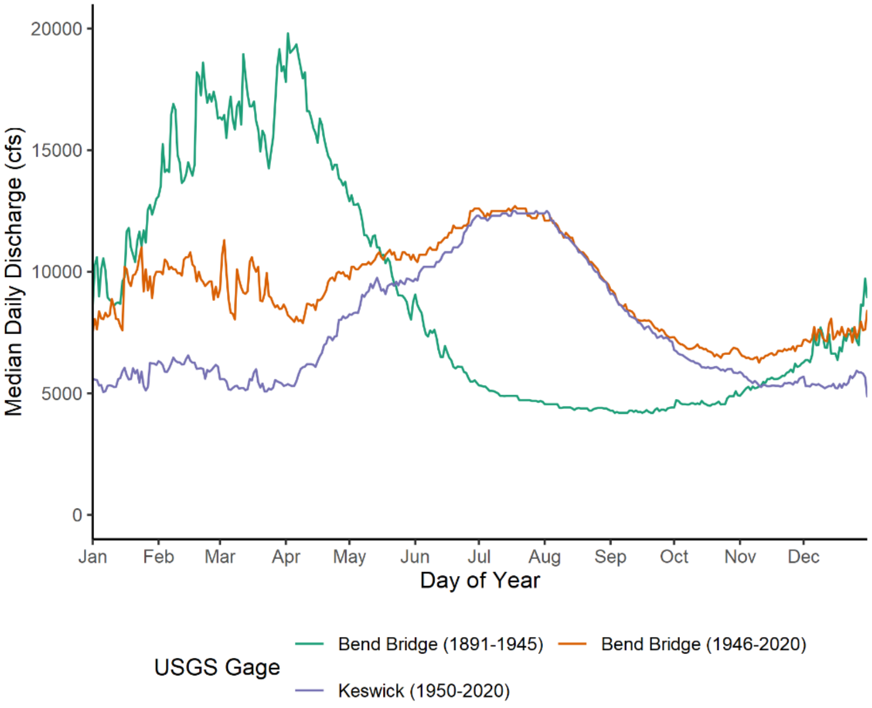


Figure 8. Comparison of flow conditions at Keswick and Bend Bridge gages. Bend Bridge gage data shown for years before upstream dam construction and after.

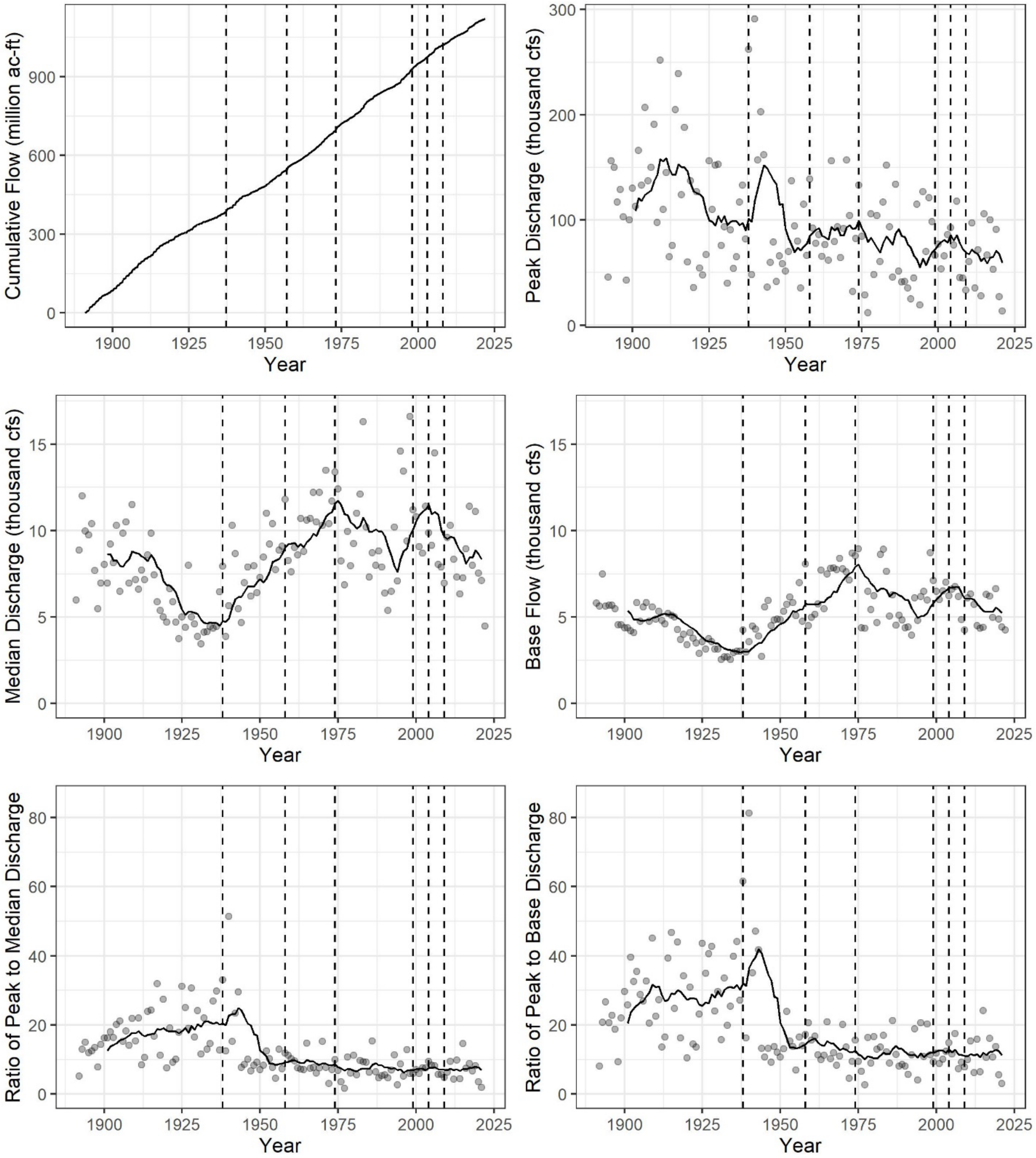


Figure 9. Cumulative and annual discharge parameters for the Sacramento River at Bend Bridge (USGS Gage 11377100). Gray circles represent annual values, solid black lines represent the 10-year moving average, and dashed vertical lines depict the dates of aerial imagery.

Over the course of its lower 300 miles, the mainstem Sacramento River exits a confined, mountain region, flows through partly-confined and confined areas between Redding and Red Bluff, and then progressively becomes an unconfined, sinuous river in the Central Valley. Median grain sizes (D50) also transition from predominantly cobbles and gravels at the upper end of the study extent near Redding, CA to almost entirely sand by the time the river reaches Colusa, CA (Singer, 2008). This fining is a gradual process and is not heavily influenced by the numerous tributaries emptying into the Sacramento River from the Sierra Nevada and Coast mountain ranges (Singer, 2008). It is estimated that during the 19th century, hydraulic mining in the basin may have increased sediment loads to tributaries by an order of magnitude. Dams constructed on major tributaries during the 20th century are now trapping upstream sediments and leading to a decline in sediment yield (Gilbert, 1917; Wright and Schoellhamer, 2004). Suspended sediment yields measured at the downstream extent of the study reach are depicted in Figure 10.

Figure 10 provides a timeline of the available data and the relationship between side channels, river management, sediment, and flow. The number of side channels normalized by river mile is plotted on the top panel through time. We show side channels per river mile for the entire study length with the dashed black line and subdivide the results by reach in the blue dots. The bars below the side channel time series depict the dominant river management practices, channel construction (i.e., levees), and dam building. We plot the daily suspended sediment data from the Bend Bridge Gage (USGS 11377100) in the third panel. Hydrology data are in the bottom panel. The vertical black dashed lines correspond to the years that we have imagery data for.

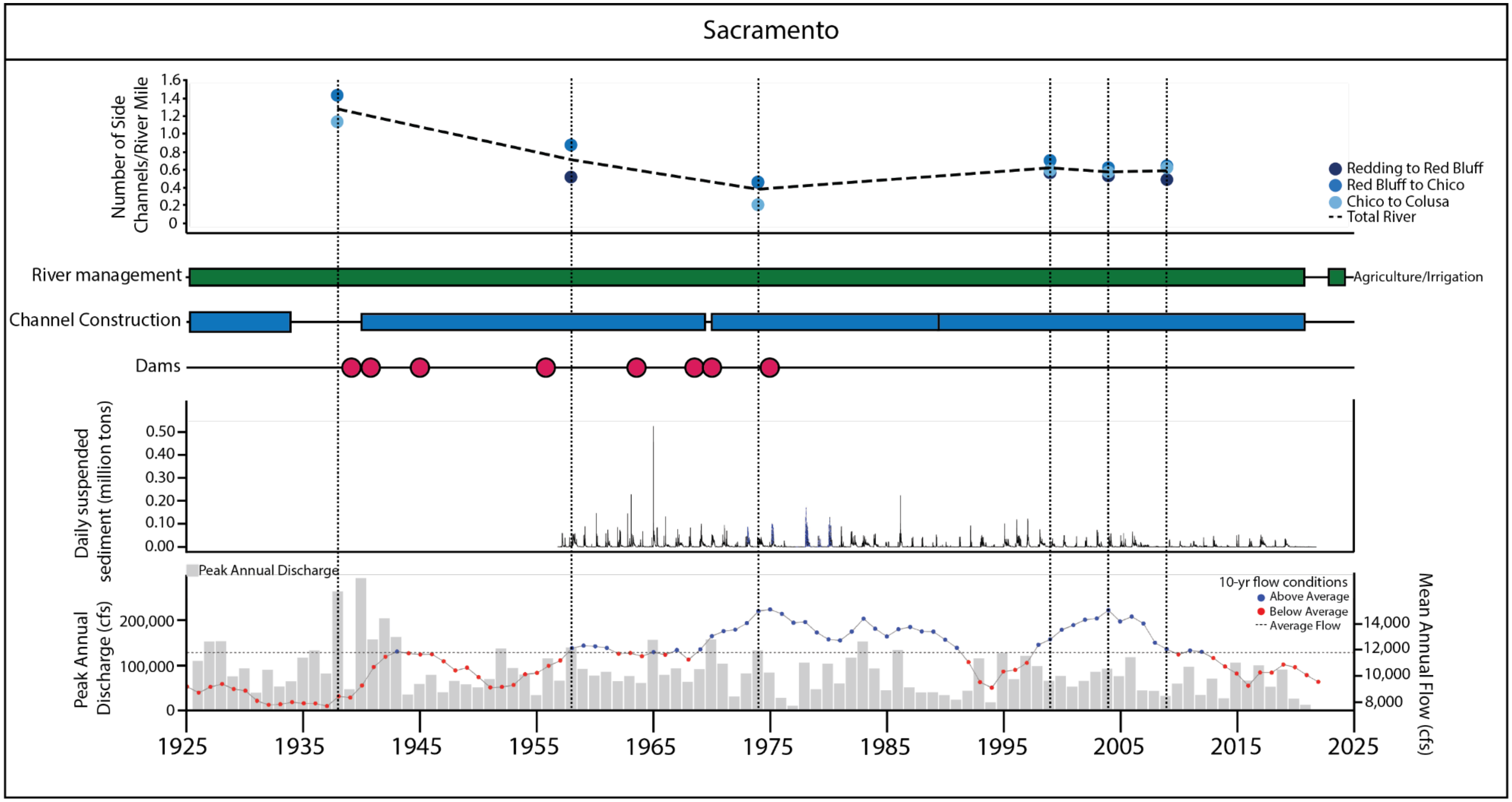


Figure 10. Timeline figure for the Sacramento River. The top panel shows number of side channels normalized by river mile subdivided by reach (blue dots) and for the entire river (dashed black line). The second section highlights periods of irrigation, channel construction, and dam construction (including tributary dams). The third panel shows sediment data with daily suspended sediment in millions of tons (solid black line). The bottom panel plots hydrology data with flow plotted as a 10-year moving average in the red and blue dots on the right y-axis. Blue colors represent flows above the average of the period of record and red colors represent flows below the average. The gray bars show the peak annual discharge (cubic feet per second) on the left y-axis. Vertical dashed lines represent the years where we have aerial imagery.

2.3 Trinity River

2.3.1 River System Description

The Trinity River is a tributary of the Klamath River located in northwestern California (Figure 11). The Trinity River watershed has a drainage area of 2,970 square miles. The Trinity River begins in the southern Cascade Mountains and flows southwest around the Trinity Alps before flowing northwest to its confluence with the Klamath River in the coastal ranges of California. The climate in this portion of California, like much of the state, is Mediterranean. However, winter rain and snow events can be significant and sometimes cause extreme flood events. Historically, the Trinity River was an important salmon fishery and in 1981 the river was designated as a Wild and Scenic River.

Figure 11. Trinity River area of interest for this study.

The construction of dams has hydrologically altered the Trinity River. Two major dams were constructed on the Trinity River in the early 1960s. Trinity Dam was completed in 1962 and forms Trinity Lake with a storage capacity of 2,448,000 acre-feet. Trinity Powerplant produces hydropower at Trinity Dam. Lewiston Dam is approximately 8 miles downstream of Trinity Dam and serves as an afterbay to the Trinity Powerplant to regulate releases to the Trinity River. Lewiston Powerplant at Lewiston Dam also produces hydropower. Within Lewiston Lake, the upstream reservoir of Lewiston Dam, Clear Creek Tunnel diverts up to 3,200 cubic feet per second (cfs) to Whiskeytown Lake and the Sacramento River basin.

The Trinity River has also been subjected to geomorphic alteration since the late 1800s. After the discovery of gold, some of the largest gold mines in the state were established in the Trinity River watershed (AECOM, 2013). Hydraulic and dredge mining practices resulted in extreme changes to sediment loads and floodplain conditions along the river (Krause 2012). Although the mining era eventually ended, these altered conditions persist in many locations along the Trinity River. Logging practices in the upland areas of the watershed have also contributed fine sediments that are detrimental to salmon redds (AECOM, 2013). These geomorphic issues are compounded by the afore-mentioned hydrologic changes to the system.

More recently, a partnership between government agencies and native tribes has led to the creation of the Trinity River Restoration Program (TRRP), which was created after a 2000 Record of Decision for the restoration of the Trinity River mainstem fishery. The TRRP focuses on restoring fisheries that were detrimentally impacted by the construction of the dams on the Trinity River and the cross-basin transfer of water from the Trinity River to the Central Valley Project. The TRRP focuses its efforts on the approximate 40 river mile (RM) section of river from downstream of Lewiston Dam to the confluence with the North Fork Trinity River.

Approximately 40 river miles of the Trinity River were the focus of side channel identification and delineation between Lewiston Dam (RM 40) and the confluence of the North Fork Trinity River at Helena, CA (RM 0). The Trinity River segment of interest was split into four geomorphic reaches designated by the TRRP and are described in Table 5.

Table 5. Trinity River reach characteristics between Lewiston Dam and the confluence with the North Fork Trinity River

Reach	Name	River Miles	Planform	Slope	Sinuosity
1	Lewiston to Indian Creek	40 to 23	Variable morphology, relatively wide alluvial valleys separated by short, confined sections and relatively low sediment supply	0.0022	1.11
2	Indian Creek to Reading Creek	23 to 21	Similar morphology to the Lewiston to Indian Creek reach, with increased sediment supply from Indian Creek	0.0013	1.05
3	Reading Creek to Dutch Creek (Canyon)	21 to 14	Termed the "Canyon" reach as the river is predominantly confined by bedrock walls apart from a smaller alluvial flat	0.0020	1.06
4	Dutch Creek to North Fork Trinity (Junction City)	14 to 0	Wider alluvial valleys, but often confined where the river has incised in mining debris. This reach was heavily altered by hydraulic mining on hillsides and dredge mining on the valley floors.	0.0022	1.22

2.3.2 Imagery, Hydrology, and Sediment Data

Aerial imagery was available for the years 1944, 1960, 1971, 1980, 1997, 2001, 2006, 2009, and 2011. All years of available data encompassed the entire study reach (Table 6). Although more recent aerial imagery exists for the Trinity River, only imagery until 2011 was used to have similar final imagery years for each of the three rivers.

Table 6. Available imagery for the Trinity River (each year includes all reaches spanning RM 40 to 0)

Year
1944
1960
1971
1980
1997
2001
2006
2009
2011

The upstream Trinity and Lewiston Dams have substantially altered the hydrologic regime along the Trinity River between Lewiston Dam and the confluence with the North Fork Trinity River. Prior to 1960, the Trinity River was defined by extreme seasonal variation (Figure 12 and Figure 13). Pre-dam mean daily discharge were characterized by gradually increasing discharge during the winter months and intermittent extreme high flow due to heavy rainfall events common in the coastal mountains of California. Pre-dam flows typically peaked in May at about 4,500 cfs with contributions from snow melt at higher elevations. Flows in the river then dropped through June and July to extremely low flows that were often less than 100 cfs. River flows remained low during the dry California summer and early fall before winter rains returned to the region.

There have been three eras with distinct hydrology during and after dam construction on the Trinity River (Figure 13 and Figure 14). From approximately 1960 to 1979, which would include dam construction and reservoir pool filling, flows below Lewiston Dam were consistently low and only exceeded 500 cfs on a few occasions, likely during winter storms. From 1979 to 1998, flows were increased, but remained below 500 cfs for much of the year. Since 1998, a consistent flow peak once again exists in May. However, flows remain lower than during the pre-dam era. In addition, there is little variation in flow outside of the late spring-early summer rainfall-snowmelt hydrograph. Because of the upstream dam, the reach of interest only acquires sediment from the alluvial bed, contributing tributaries, and gravel augmentation conducted to make up for upstream deficits.

Figure 15 provides a timeline of the available data and the relationship between side channels, river management, sediment, and flow. The number of side channels per river mile through time is plotted on the top panel. We show side channel density for the entire river with the dashed black line and subdivide the results by reach in the blue dots. The bars below the side channel time series depict the dominant river management practices, channel construction (i.e., levees), and dam building. We plot the daily suspended sediment data obtained from the Lewiston Gage (USGS Gage 11525500) in the third panel. The suspended sediment record is sparse on the Trinity River. Hydrology data are in the bottom panel. The vertical black dashed lines correspond to the years that we have imagery data for.

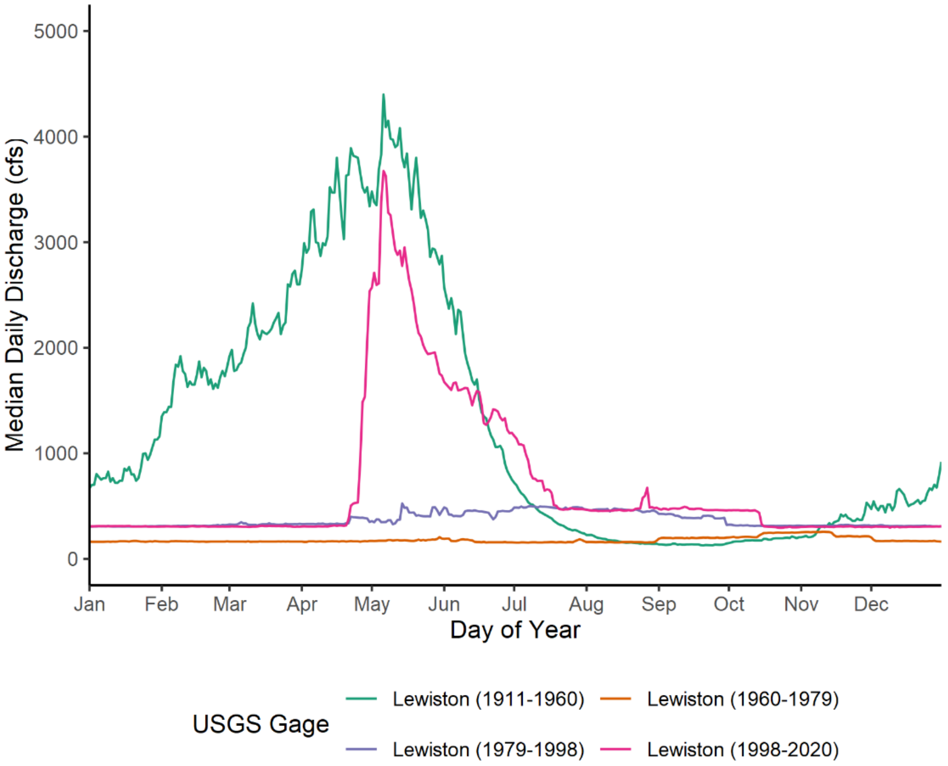


Figure 12. Mean daily flow of the Trinity River at Lewiston California at Lewiston (USGS Gage 11525500).

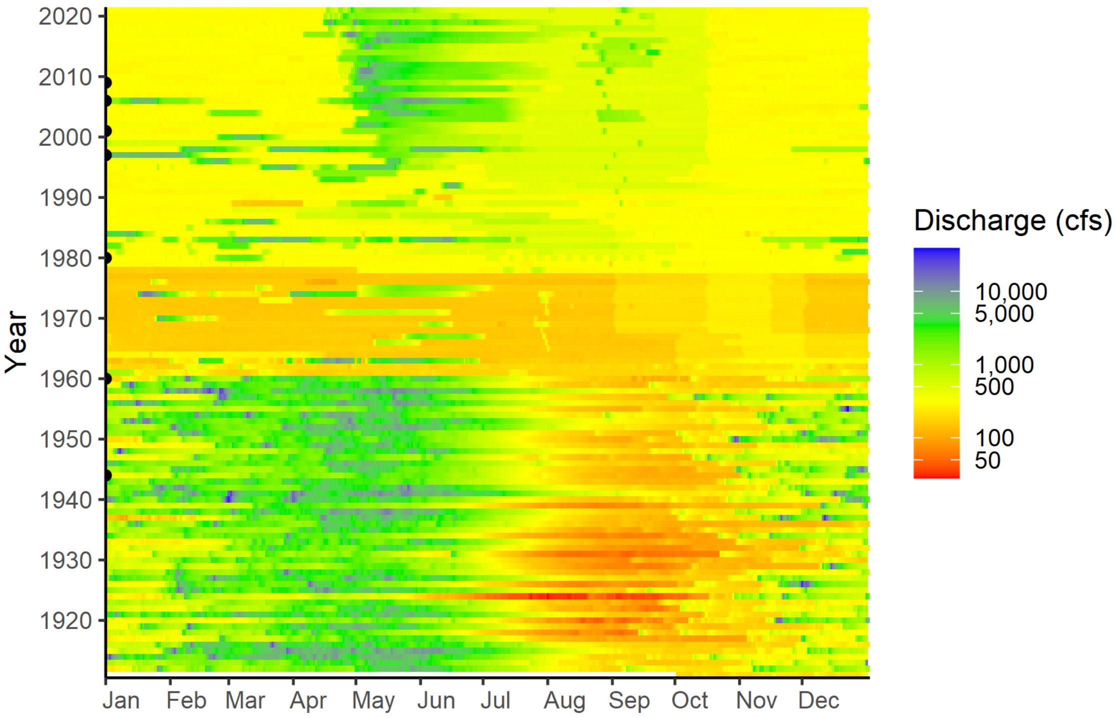


Figure 13. Comparison of hydrologic periods for the Trinity River at Lewiston (USGS Gage 11525500).

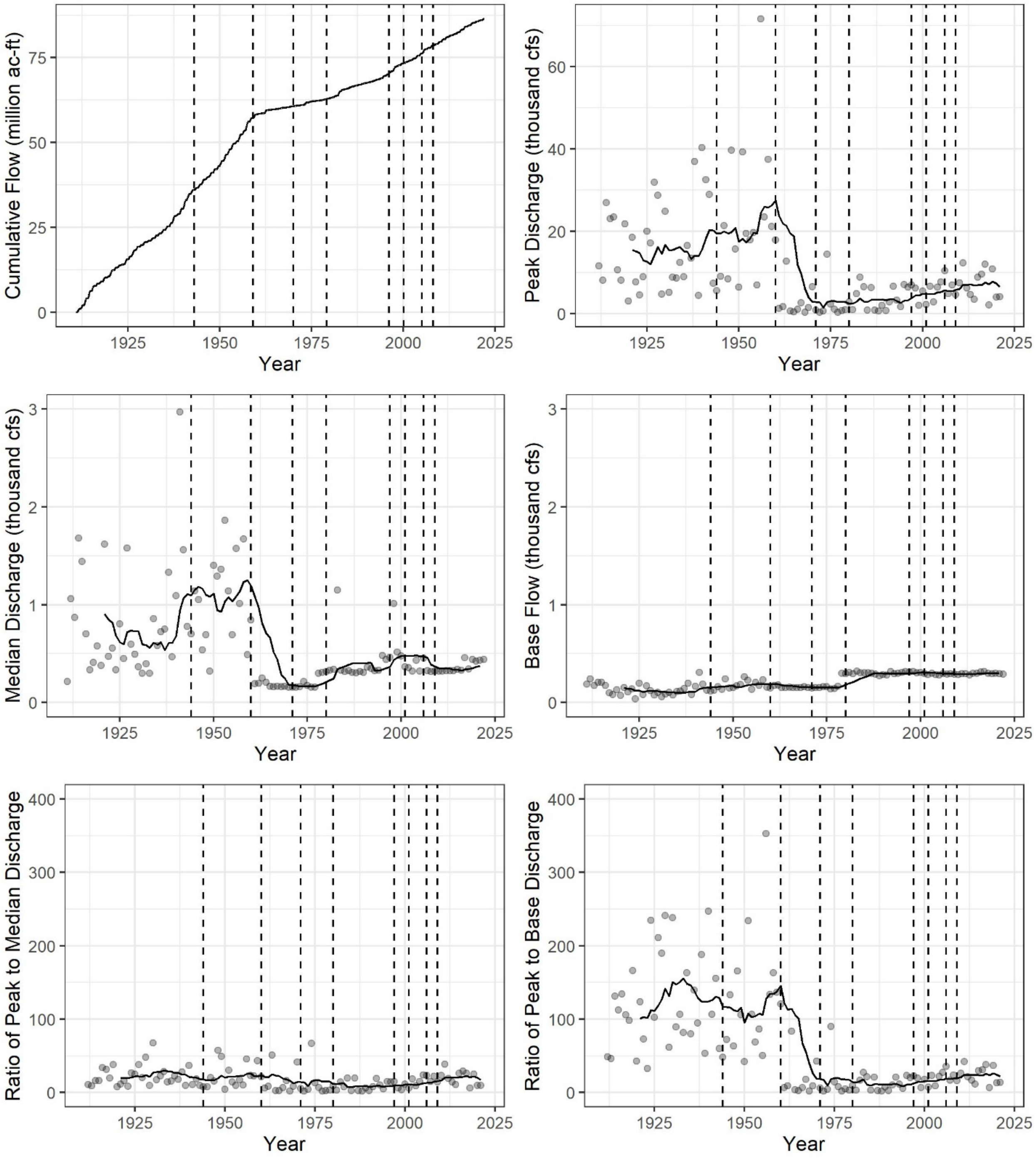


Figure 14. Cumulative and annual discharge parameters for the Trinity River at Lewiston (USGS Gage 11525500). Gray circles represent annual values, solid black lines represent the 10-year moving average, and dashed vertical lines depict the dates of aerial imagery.

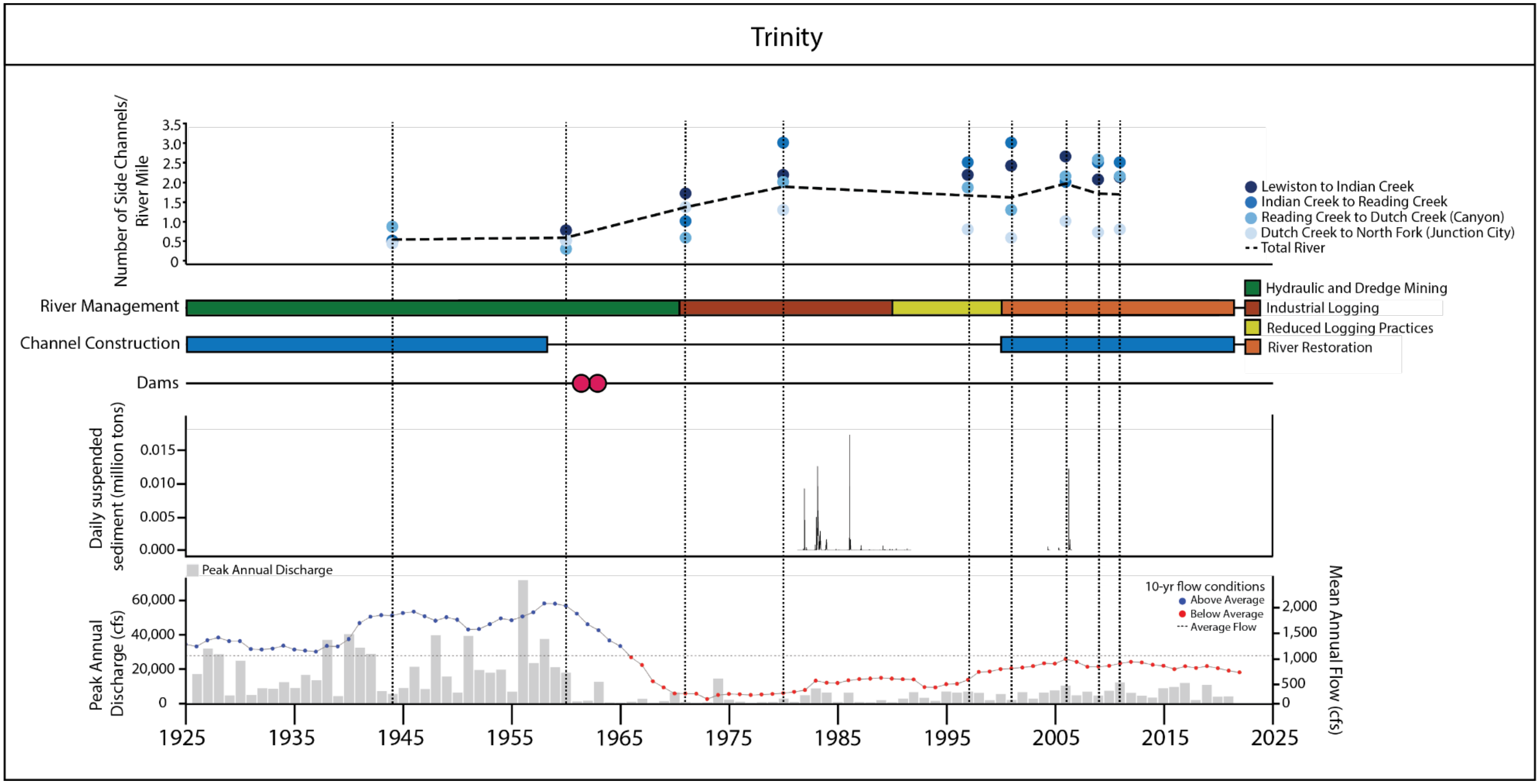


Figure 15. Timeline figure for the Trinity River. The top panel shows number of side channels normalized by river mile subdivided by reach (blue dots) and for the entire river (dashed black line). The second section highlights periods of different river management practices, channel construction, and dam construction. The third panel shows sediment data with daily suspended sediment in millions of tons (solid black line). The bottom panel plots hydrology data with flow plotted as a 10-year moving average in the red and blue dots on the right y-axis. Blue colors represent flows above the average of the period of record and red colors represent flows below the average. The gray bars show the peak annual discharge (cubic feet per second) on the left y-axis. Vertical dashed lines represent the years where we have aerial imagery.

3. Methods

3.1 Side Channel Delineation

Side channels were identified for all three rivers in locations where historical aerial imagery was available. We defined a side channel as a flow path connected to the main channel at one or both ends where the total discharge within that flow path is less than half the bankfull flow.

When selecting side channels, off channel flow paths were digitized when the flow path was inundated or a distinct flow path could be discerned from unvegetated sediments (e.g., sand, gravel, etc.). Channels around vegetated islands within the main channel were digitized as side channels if the flow path diverted less than half of the flow. Unvegetated main channel bars and the split flow around those bars were not included as side channels because it is likely that the bars are at low enough elevations to be scoured frequently and can be considered part of the main channel. The exception to this was if a later side channel form was clearly present as a sand bar or braided channel in a prior year of aerial imager; then we counted that sand bar or braided section as a side channel. If a vegetated flow path on the floodplain was identified as having clear directional flow, it was also considered a side channel. We excluded side channels with clear anthropogenic influences, such as bridges, canals, or channelization efforts.

Three shapefiles were required for automated calculation of side channel attributes across all aerial imagery years and rivers: a main channel centerline, side channel centerlines, and main channel polygons. Each shapefile was manually digitized. Main channel centerlines were digitized as a single line for the entire aerial imagery extent for all years. The main channel centerline was digitized as the center of the dominant flow path within the main river channel. Main channel polygons were digitized for the inundated extent of the dominant main channel flow path. While main channel polygons did not need to extend over the entire reach, the polygons extended upstream and downstream of any side channel by at least a length equal to the length of the side channel. The main channel centerlines and polygons focused on the portion of the channel that visually appeared to transport most of the flow to include baseflow side channels in the analysis.

Side channels were digitized from an intersection point with the main channel centerline, through the mouth and center of the side channel, and reconnected with the main channel centerline downstream of the side channel. The inlet and outlet angles were calculated at the intersection of the side channel centerline and main channel centerline. Each side channel was assigned a river mile based on commonly available river mile markers. Although an individual side channel’s inlet location often changed slightly between aerial imagery years, river mile identification was held constant for the same side channels. This allowed for investigation of side channel dynamics and longevity. Figure 16 provides an example of the main channel centerline, side channel centerline, and main channel polygon.

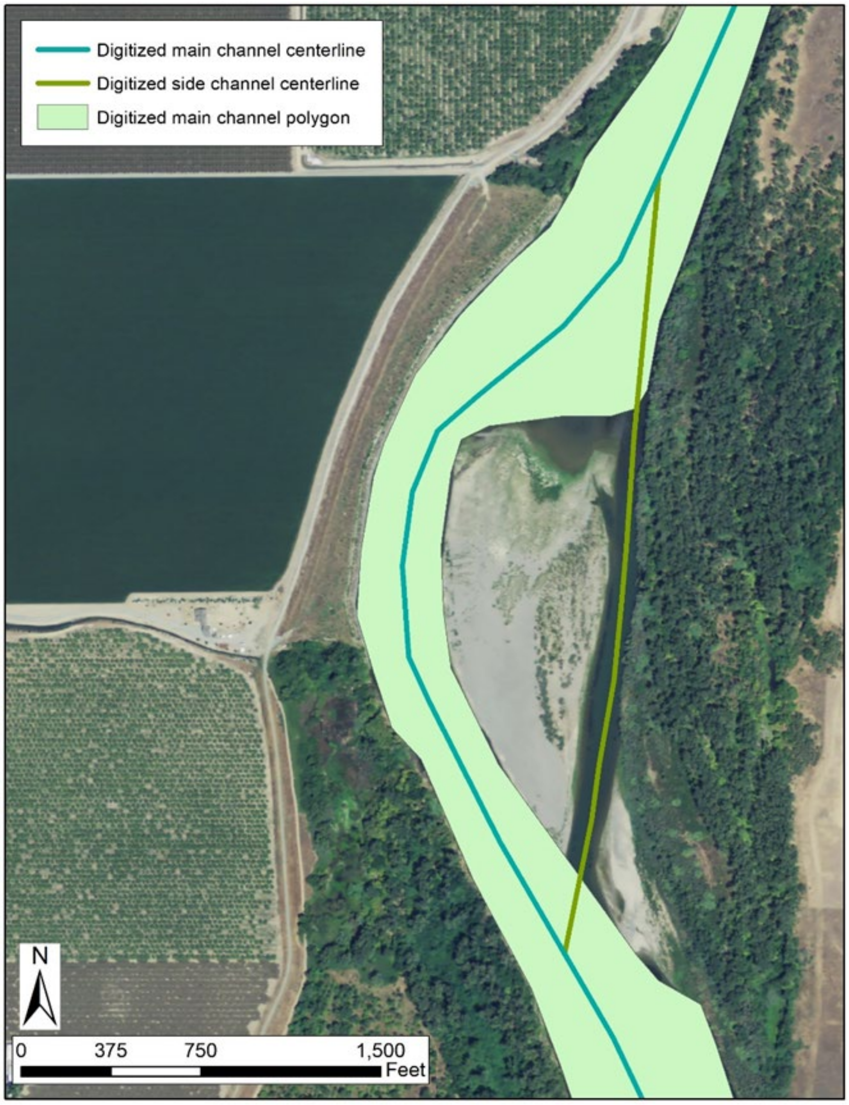


Figure 16. Example of digitized main channel centerline, side channel centerline, and main channel polygon.

3.2 Side Channel and Main Channel Attributes

Prior to any analysis and comparison of side channels, we calculated or assigned various characteristics to each side channel. All dimensional attributes were measured or calculated in ArcMap or ArcGIS Pro. Based on the digitization of the shapefiles described above, many characteristics could be calculated through a scripted ArcPy automation process. However, other characteristics could not be easily calculated or were dependent on expert opinion. Those side channel characteristics were entered manually.

We used the main channel centerline, side channel centerline, and main channel polygon shapefiles described above to automate the calculation of many of the side channel attributes. In total, we automated calculation of seven attributes to include in further analysis: latitude, longitude, main channel top width, main channel length, side channel inlet angle, side channel outlet angle, side channel length, and the ratio of side channel to main channel length. Appendix A provides more detail about the step-by-step geospatial workflow and calculation of automated attributes.

We manually measured two further attributes and defined six more qualitative attributes. First, side channel width was measured as a representative width near the mid-point of the side channel length. We used this to calculate the ratio of side channel to main channel width. Qualitative attributes were also defined based on expert opinion and are summarized in Table 7. Side channel classification is perhaps the most notable of these attributes. Side channel types were adapted from previously documented side channel types (Gaeuman and Stewart, 2017).

Table 7. Qualitative side channel characteristics

Side Channel Attribute	Definition	List of Values
Cause of formation	Was the side channel likely formed by erosional or depositional processes?	• Erosion • Deposition
Classification	Side channel type based on geomorphic characteristics of the reach and local observable channel characteristics	• Incised floodplain • Incised bar • Chute • Cutoff meander • Obstruction • Medial Bar • Diagonal Bar • Backwater Shoal • Sill • Accreted bar • Braided • Anastomose • Avulsion
Planform location	Side channel location in relation to main channel banks	• Active Channel • Floodplain
Inundation frequency*	Flow stage at which the side channel is inundated	• Base flow • Intermittent • High flow
Life cycle stage*	Level of connection; side channels evolve through a range of conditions based upon age and main channel connectivity	• Flow through (most connected) • Backwater • Terrestrial (least connected)
Inlet location	Main channel planform at the side channel inlet	• Inside meander • Inside-to-outside meander • Outside meander • Straight

*Not analyzed in this report, but recorded for potential future analysis

River migration metrics were calculated using a geospatial approach based on digitized river channel centerlines. An ArcPy script was developed to analyze migration distance and rates. The ArcPy tool compares river channel centerlines for subsequent years of aerial imagery. The tool converts the area between centerlines to polygons, calculates the area of each polygon, and estimates the mean downstream length of the polygon based on the mean of each bounding main channel length from the two years. It then calculates migration distance for each polygon as the polygon area divided by mean downstream length. The migration rate for each polygon is then calculated by dividing migration rate by the time span between main channel centerline years. For analysis in this report, several more metrics were calculated to better understand river migration between years and to compare across reaches and rivers (Table 8). Because the years between aerial imagery datasets were not always equal, we also included normalized migration rates.

Table 8. Lateral migration metrics calculated for the main channel. Each metric is calculated between subsequent years of aerial imagery for each reach

Migration metric	Definition
Total Migration Distance*	Sum of migration distance across all imagery years
Normalized Migration Distance	Sum of length-weighted migration distances of all polygons. Length-weighted meaning how long the polygon is divided by the total river length.
Maximum Migration Rate*	Maximum migration value from all migration polygons
Mean Migration Rate*	Average migration value calculated from all migration polygons
Normalized Migration Rate	Sum of length-weighted migration rates of all polygons. Length-weighted meaning how long the polygon is divided by the total river length.
Migration Rate per Year*	Migration value between two years of aerial imagery.

*Not analyzed in this report, but recorded for potential future analysis

3.3 Side Channel Classification

We classified side channels into different types based on observations of Gaeuman and Stewart (2017) and additional types from our own observations. The side channel types were grouped into erosional side channels and depositional side channels to establish links between geomorphic processes and the cause of formation.

3.3.1 Erosional Side Channels

Erosional side channels form by large flow events triggering erosion into the banks of the main channel. Figure 17 illustrates the common types of erosional side channels, which are incised floodplains, incised bars, chutes, avulsions, anastomoses, obstructions, and sills.

Incised Floodplain

Erosion into the floodplain forms a side channel.

Incised Bar

Erosion into the outer bank forms a bar along the channel edge.

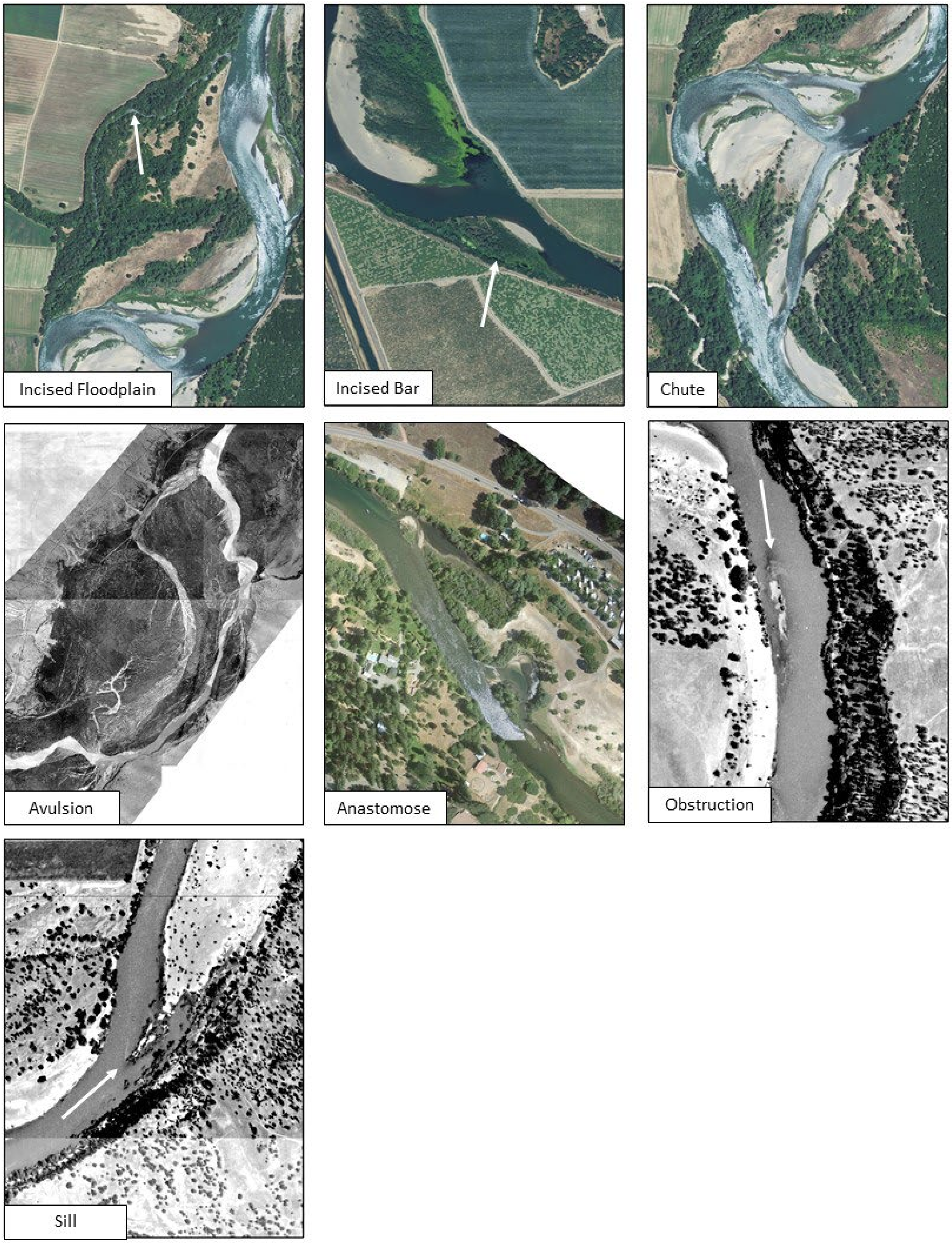
Chute
Point bar formation within the main channel causes erosion of an inside meander bend. This allows for the continued transport of sediment through the meander. If the chute side channel continues to erode, it may become the main channel, which would likely lead to a cutoff meander side channel.

Avulsion
If the main channel is extremely active, avulsions can result in hundreds of side channels connecting the prior and new channel locations.

Anastomose
Erosion at a bifurcation is not from any observable hydraulic control.

Obstruction
Gaeuman and Stewart (2017) note that obstructions can force incision into the local overbank area, again forming a side channel. Obstructions can also create erosional side channel formation within the broader active channel, which sustains a flow split and associated side channel.

Sill
Gaeuman and Stewart (2017) note that a channel-spanning bedrock sill can spread flow over a wider area producing separate flow paths and thus a side channel.



Incised Floodplain

Incised Bar

Chute

Avulsion

Anastomose

Obstruction

Sill

Figure 17. Examples of erosional side channel types. White arrows point to side channel feature.

3.3.2 Depositional Side Channels

Depositional side channels occur when hydraulic conditions, changes in river geometry, or flow obstructions trigger depositional events within the main channel that bifurcates the flow. This begins as deposition of sediment that through time can become vegetated and stabilized. Figure 18 illustrates the common types of depositional side channels, which are, medial bars, braided systems, diagonal bars, cutoff meanders, backwater shoals, and accreted bars.

Medial Bar

Medial bars form when flow expansion downstream of a constriction causes mid-channel bar deposition. The abrupt expansion reduces the transport capacity of the flow and results in sedimentary deposits in the channel. Gaeuman and Stewart (2017) differentiate medial bar and incised bar depending on whether the bar is within the inner or outer channel banks and the presence of riffle controls. This bar initially is bare sediment but may eventually become vegetated.

Braided System

A decrease in sediment transport capacity or increase in sediment supply causes sections of the river to become braided. These braided sections have multiple intersecting side channels within sedimentary deposits. These side channels are often temporary and are erased when the river's capacity to transport sediment exceeds the load again. Other outcomes for this system are that the braided islands become vegetated and form a diagonal bar or merge into a single bar that later can become vegetated.

Diagonal Bar

A diagonal bar is a vegetated and strongly diagonal bar system intersected by multiple thalwegs. The longitudinal shape of these bars is due to transverse flow splits. From observation on the Middle Rio Grande, these bars start as braided systems that become vegetated and elongated. Wheaton et al. (2015) describe a second mode of formation where diagonal bars attach to the bank on the inside bend and then become detached through chute cutoff. This progression is from chute to diagonal bar rather than braided system to diagonal bar.

Accreted Bar

As the mainstem river migrates or flow conditions change, bars accrete to the bank of the river. Often, additional flow paths fill in with sediment and only the outermost channel remains open. This channel can change length depending on which (if any) flow path is used as the outlet channel that reconnects the side channel to the mainstem flow.

Backwater Shoal

Gaeuman and Stewart (2017) note that shoaling is caused by "sharp curvature of the valley that creates backwater conditions during floods." Shoaling due to sharp curvature in the Sacramento River is likely caused by both natural (e.g., bedrock) and engineered valley constraints (e.g., levees, reinforced banks).

Cutoff Meander

A cutoff meander is the opposite of a chute. In the development of a cutoff meander, transport capacity through the meander decreases within the meander and the main flow path takes a shortened, steeper path downstream. While the chute is actively eroding, the meander is likely depositional as it becomes more separated from the main channel.

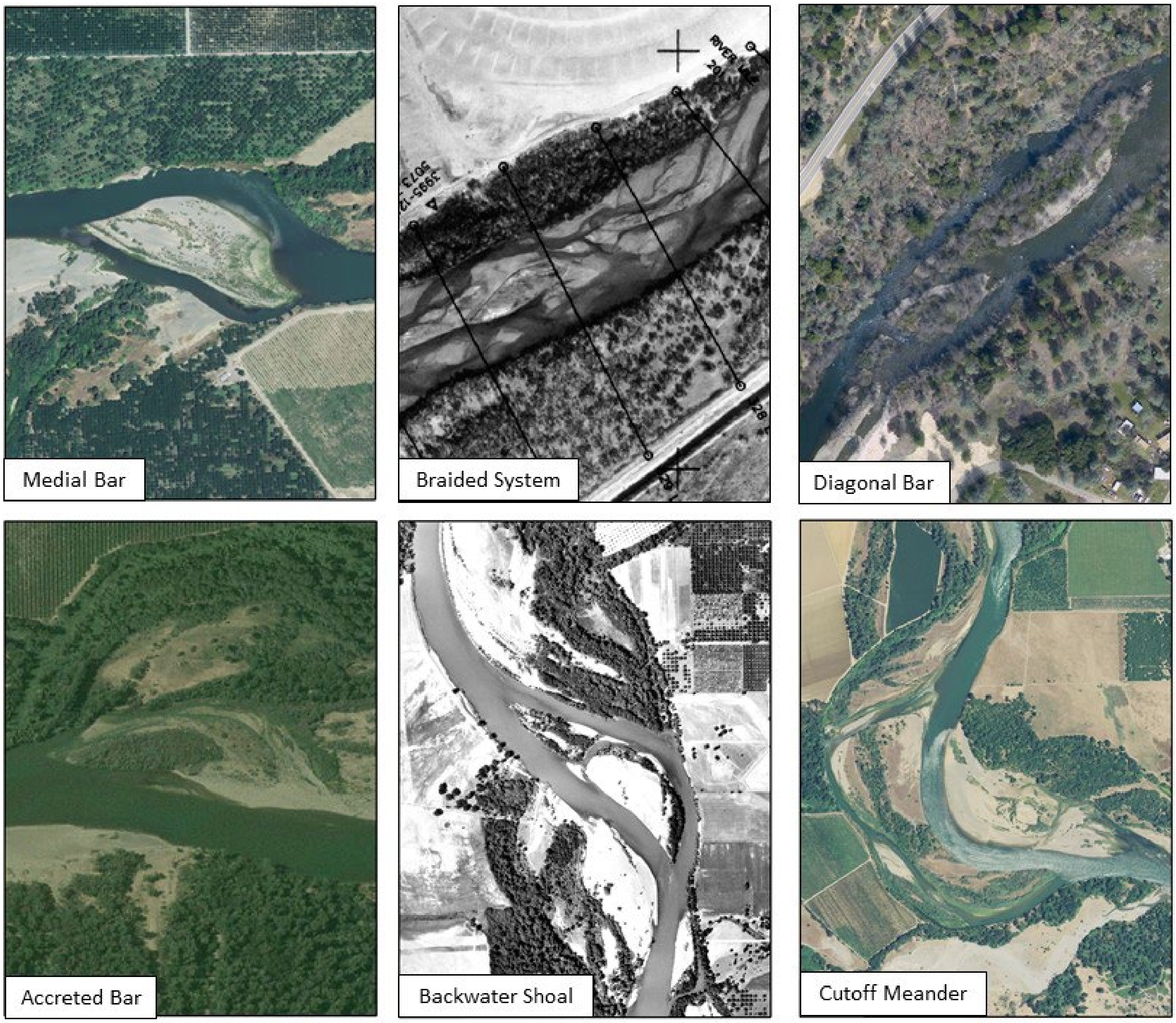


Figure 18. Examples of depositional side channels.

3.4 Side Channel Analyses

The results of the side channel digitization and classification were analyzed in several ways to compare side channel types, side channels by river reach, and side channels by river. The analyses focused on number of side channels per mile (defined as abundance or density), the attributes of side channel types, the longevity and persistence of side channels, and side channel evolution (e.g., if a side channel changes from one type to another). Analyses in Sections 4.1 through 4.3 were conducted in R-Studio using the R programming language (R Core Team, 2020).

4. Results

We analyzed results for the three river systems to compare side channel classification and morphology, formation and evolution, and persistence. Figure 19 summarizes the number of side channels over time, normalized by the length of each river. The number of side channels increased for the Middle Rio Grande after 1992 and increased for the Trinity River after 1960. Conversely, side channel quantities for the Sacramento River decreased between 1938 and 1974 and then remained relatively constant in later years. The Trinity River has the greatest number of side channels per mile in recent years while the Sacramento River has the fewest.

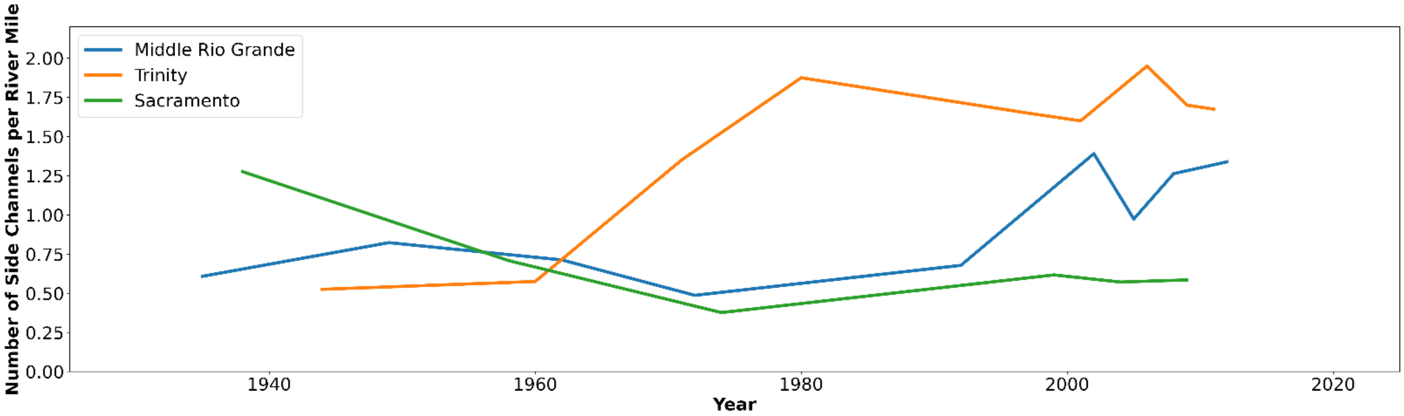


Figure 19. Comparison of normalized side channel quantities over time for the Middle Rio Grande, Sacramento River, and Trinity River.

4.1 Side Channel Classification and Morphology

On the Middle Rio Grande, the reaches upstream of San Acacia Diversion Dam are characterized by a high proportion of incised bars and diagonal bars. Most of the side channels in the reaches downstream of San Antonio Bridge are classified as incised floodplain. All the reaches have accreted bars in similar proportions. The side channel types associated with high migration rates and meanders (chutes, backwater shoals, and cutoff meanders) are concentrated in the Cochiti to Angostura reach (Figure 20). Many of the depositional side channel types (medial bars, diagonal bars, braided channels, and accreted bars) are concentrated in the Isleta to Rio Puerco reach. This reach has relatively low incision compared to the adjacent reaches.

The Sacramento River reach between Redding and Red Bluff transitions between segments that are relatively unconfined, partly confined, and confined by bedrock valley walls. In comparison to downstream reaches that are unconfined, the presence of bedrock along the reach produces two side channel types unique to this northern reach: bedrock obstruction and sill side channels (Figure 21). Both side channel types are erosional features in that the river has eroded down to the bedrock surface. This reach has no cutoff meanders and is largely dominated by erosional side channels. The other seven side channel types are present in all three reaches.

In unconfined reaches of the Sacramento River downstream of Red Bluff, meander dynamics are responsible for the many side channels. Related channel types of meander cutoffs and chutes are common. Apart from side channels related to meander dynamics, the downstream reaches on the Sacramento River contain a similar distribution of the other side channel types (Figure 21).

Reach confinement generally informs the distribution of side channel types across each of the Trinity River reaches. The longest and most geomorphically diverse reach, Lewiston to Indian Creek, includes all side channel types (Figure 22). In this reach, the river alternates between wider alluvial valleys and more confined canyons. Therefore, it is logical that all side channel types are represented. In comparison, the Dutch Creek to North Fork (Junction City) reach is predominantly located in wide alluvial valleys with minimal confinement. In this reach, obstructions and sills are absent because bedrock walls are further from the main river channel. Bedrock-related side channels are most prevalent in the middle two reaches (Indian Creek to Reading Creek and Reading Creek to Dutch Creek). Meanwhile, incised bar and medial bar side channel types exist across all reaches. This suggests that erosional and depositional processes associated with incised and medial bars, respectively, are localized processes based upon sediment transport dynamics. Finally, anastomosed and diagonal bar side channel types only exist in one reach. It may be that these side channel types are also dependent on local conditions or river dynamics that are not common within this segment of the Trinity River. However, because the Trinity River has been heavily impacted historically by mining efforts, the frequency of side channel types prior to human alteration may have been quite different.

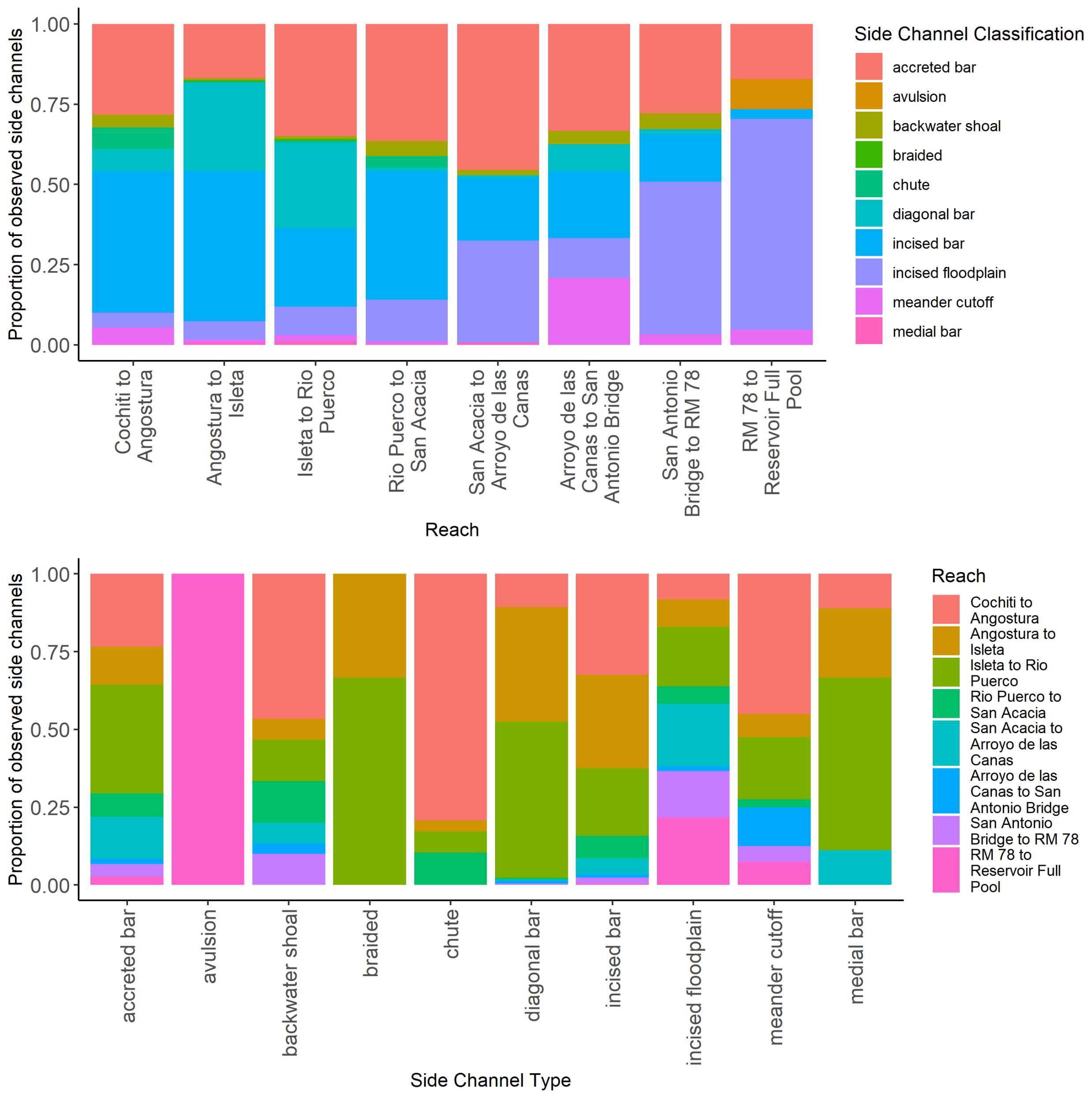


Figure 20. Middle Rio Grande side channel distribution by geomorphic reach and classification type. Top panel: for all side channels in a reach, y-axis is the fraction of each channel type. Bottom panel: for all side channels of a given type, y-axis is the fraction located within each reach.

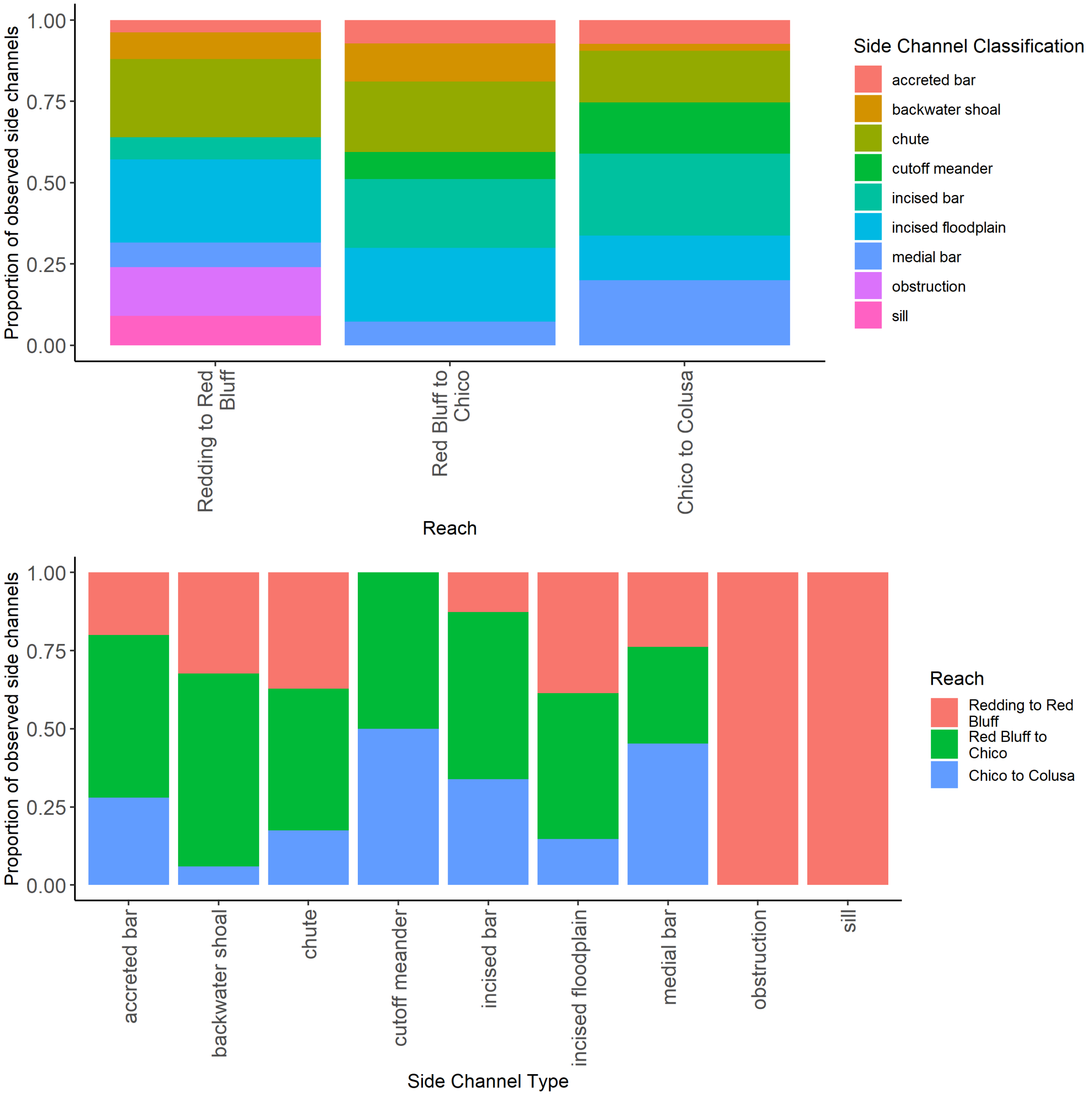


Figure 21. Proportion of side channel types within each of the three reaches of the Sacramento River. Top panel: for all side channels in a reach, y-axis is the fraction of each channel type. Bottom panel: for all side channels of a given type, y-axis is the fraction located within each reach.

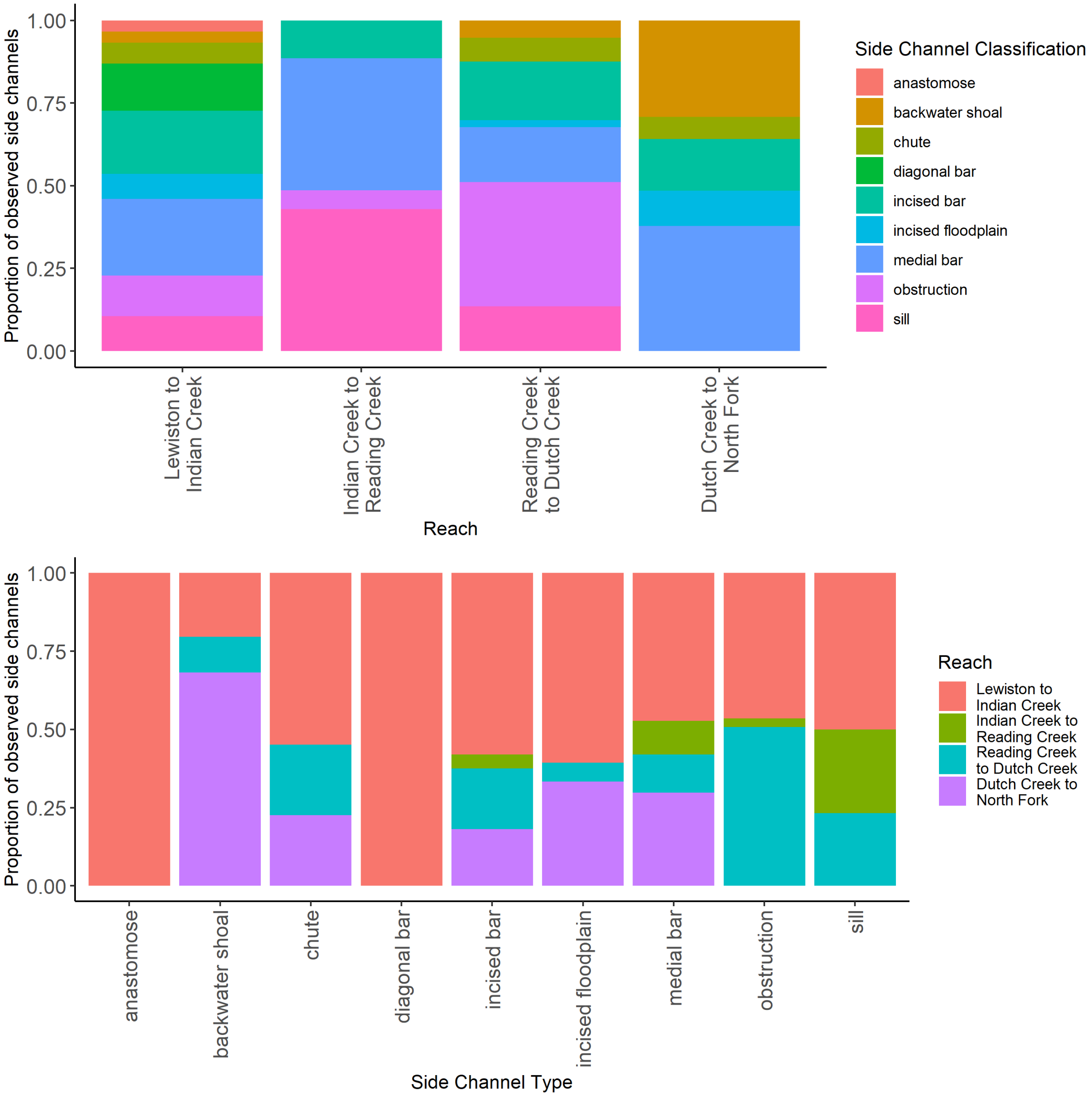


Figure 22. Proportion of side channel types within each of the four reaches of the Trinity River. Top panel: for all side channels in a reach, y-axis is the fraction of each channel type. Bottom panel: for all side channels of a given type, y-axis is the fraction located within each reach.

Figure 23 through Figure 25 are box-and-whisker plots of side channel attributes across all aerial imagery years. Median attribute values are depicted by the black line within a box, the box represents the 25 to 75% confidence intervals, the lines represent the 5 to 95% confidence intervals, and black dots are outlier values. Some common characteristics between side channel types exist across all three rivers. Chutes consistently exhibit low side channel to main channel length ratios and on the Trinity and Sacramento have high side channel top widths. Inlet and outlet angles are not significantly different between side channel types except for avulsions on the Middle Rio Grande, which have much higher inlet angles than other types. Typical inlet angles for all non-avulsion side channels range from 35 to 50 degrees, and outlet angles range from 35 to 55 degrees. Medial bars have a slightly higher side channel to main channel width ratio. On the Sacramento and Trinity, incised bars and accreted bars typically occur where the main channel is relatively wide while obstructions and sills occur where it is narrow. Cutoff meanders and incised floodplains are typically longer than other side channel types on all three rivers, and on the Middle Rio Grande, avulsions are orders of magnitude longer than other side channel types (Figure 23 through Figure 25). Overall, there is not much difference between geometric attributes for the different side channel classification types. This suggests that side channel form is similar for different geomorphic settings and processes and that plan view variability is subtle. Elevation data such as local side channel slope, inlet elevation relative to main channel thalweg, and cross-sectional area would likely provide additional insight that cannot be discerned from aerial imagery.

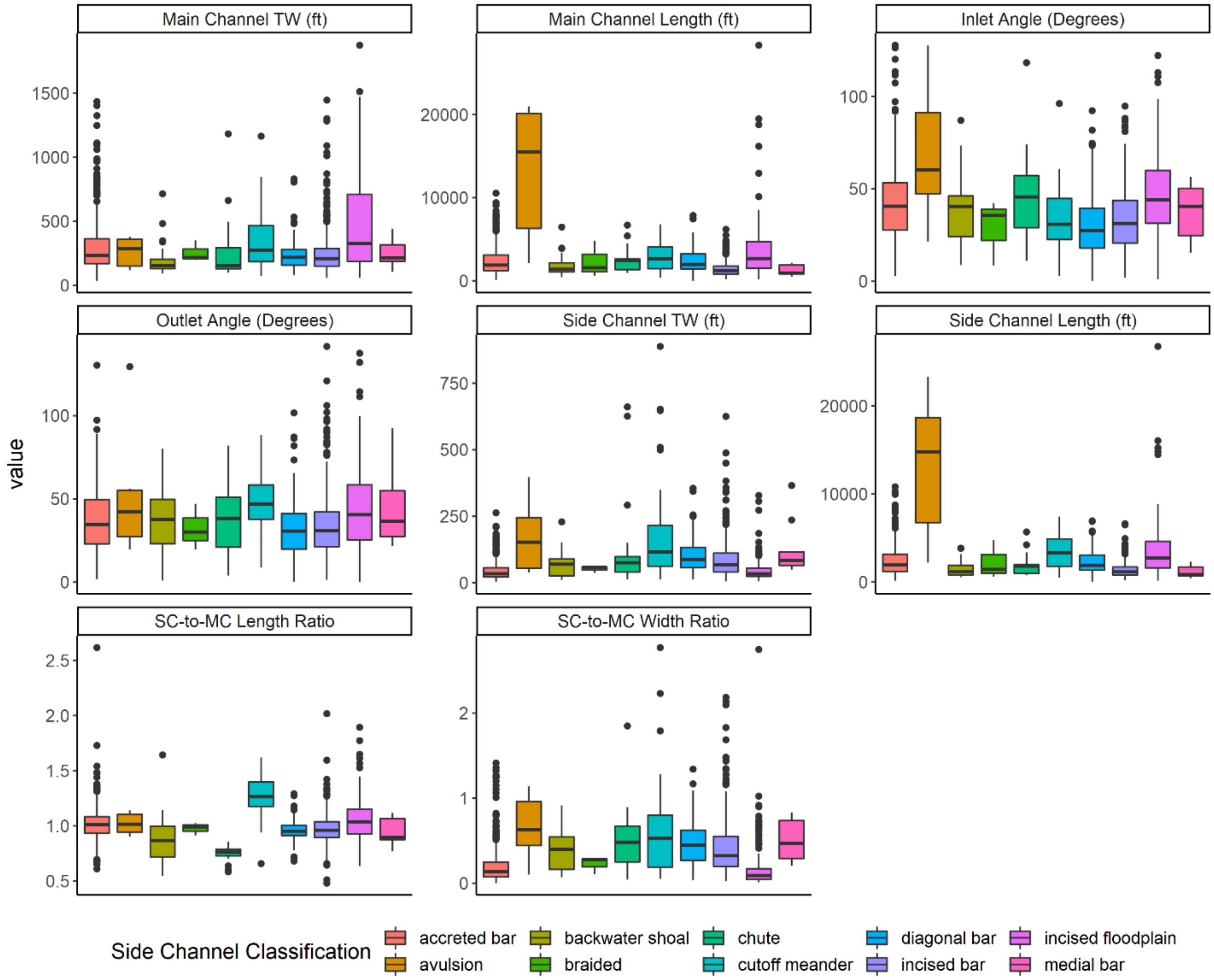


Figure 23. Box-and-whisker plots of side channel characteristics grouped by side channel type for the Middle Rio Grande.

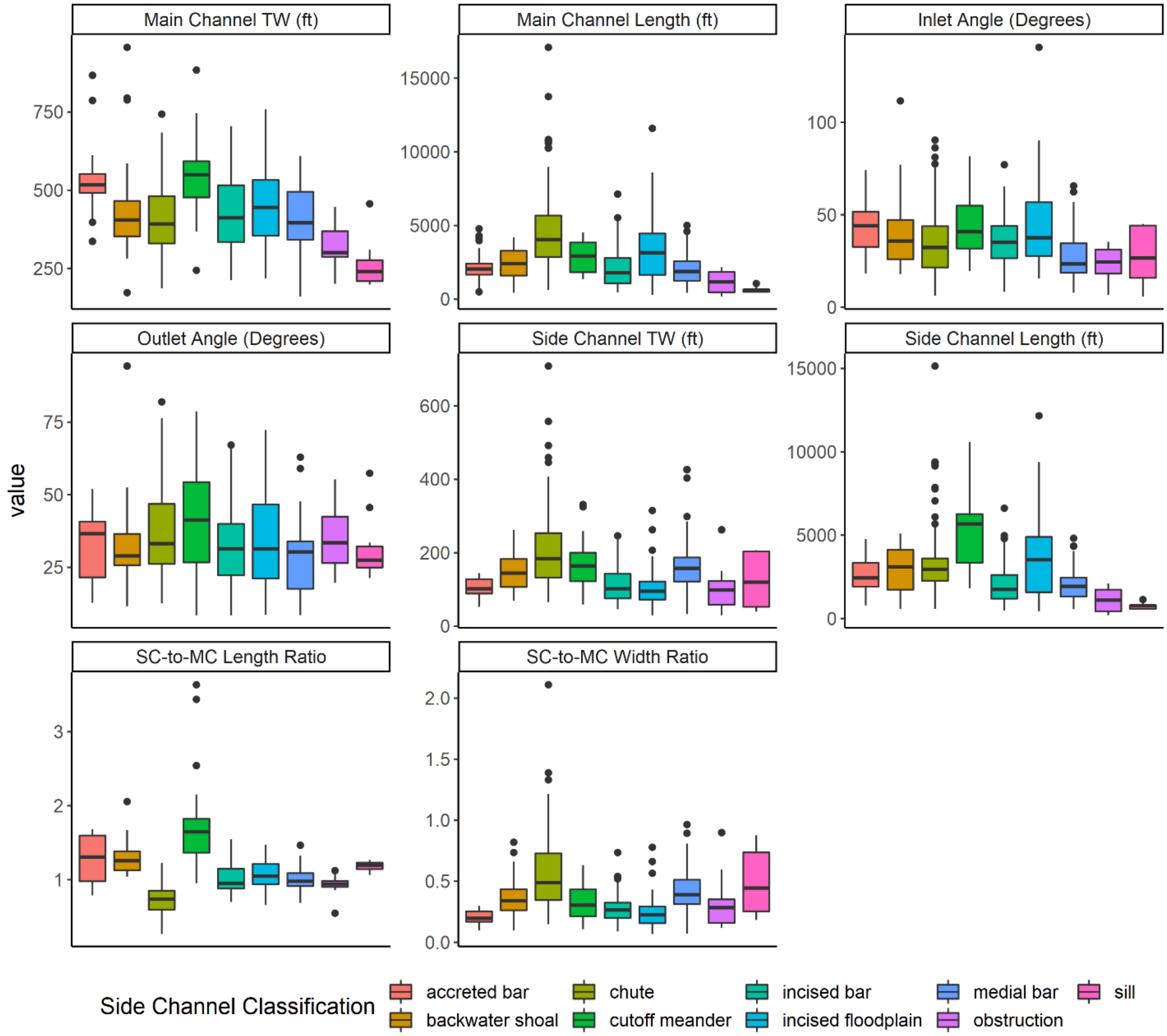


Figure 24. Box-and-whisker plots of side channel characteristics grouped by side channel type for the Sacramento River.

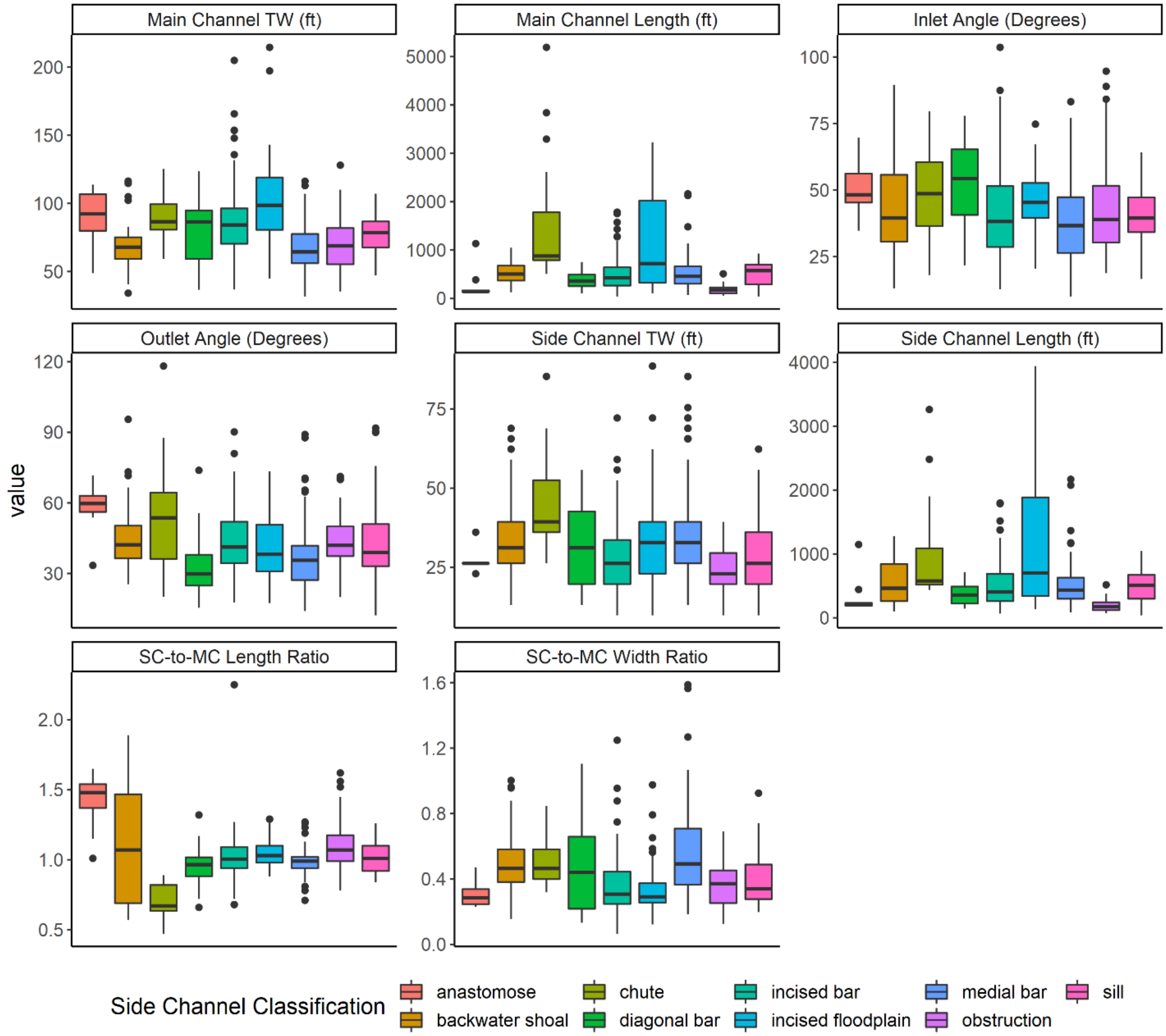


Figure 25. Box-and-whisker plots of side channel characteristics grouped by side channel type for the Trinity River.

4.2 Side Channel Formation and Evolution

This section focuses on river migration, how side channel abundance has changed through time, and the evolution patterns between side channel types. The three rivers we looked at for this study have different levels of geomorphic activity and diversity, even for different reaches of the same river. This is highlighted by analyzing migration variables for the three rivers.

4.2.1 Channel Migration

Migration rates on the Middle Rio Grande have generally decreased from the mid-1900s until the most recent aerial imagery except for an increase in rates between 2002 and 2005 (Figure 26). The largest channel migration rates were between 1949 and 1962 within the two southernmost reaches:

San Antonio Bridge to RM 78 and RM 78 to Reservoir Full Pool. These extremely high migration rates are the result of human alteration to the system because the Rio Grande was moved to the opposite side of the valley during the 1950s channel reconstruction. Migration rates at all other times were generally between 0 and 40 ft/yr. Of the remaining reaches, normalized migration rates and distances were greatest in the Rio Puerco to San Acacia and San Acacia to Arroyo de las Cañas reaches.

Results from the Sacramento River migration analysis illustrate the importance of valley setting in meandering dynamics. Although limited overlapping aerial imagery in early years prevented a full comparison of migration rates across all reaches, migration rates have decreased in all reaches from 1999 to 2009 (Figure 27). Migration rates in the Redding to Red Bluff reach have been relatively low over time, which is logical as the northernmost reach is also the most confined with a portion of the reach within a canyon.

The Trinity River migration rates decreased for all reaches until the late 1990s when the migration rates began to increase again for all reaches (Figure 28). The most downstream reach, Dutch Creek to North Fork, has the greatest migration rates and distances, which also makes logical sense as it is the least confined of the four Trinity River reaches. The most confined reach, Reading Creek to Dutch Creek, displays the lowest migration rates and in conjunction smallest migration distances. The upper reaches have more moderate migration characteristics.

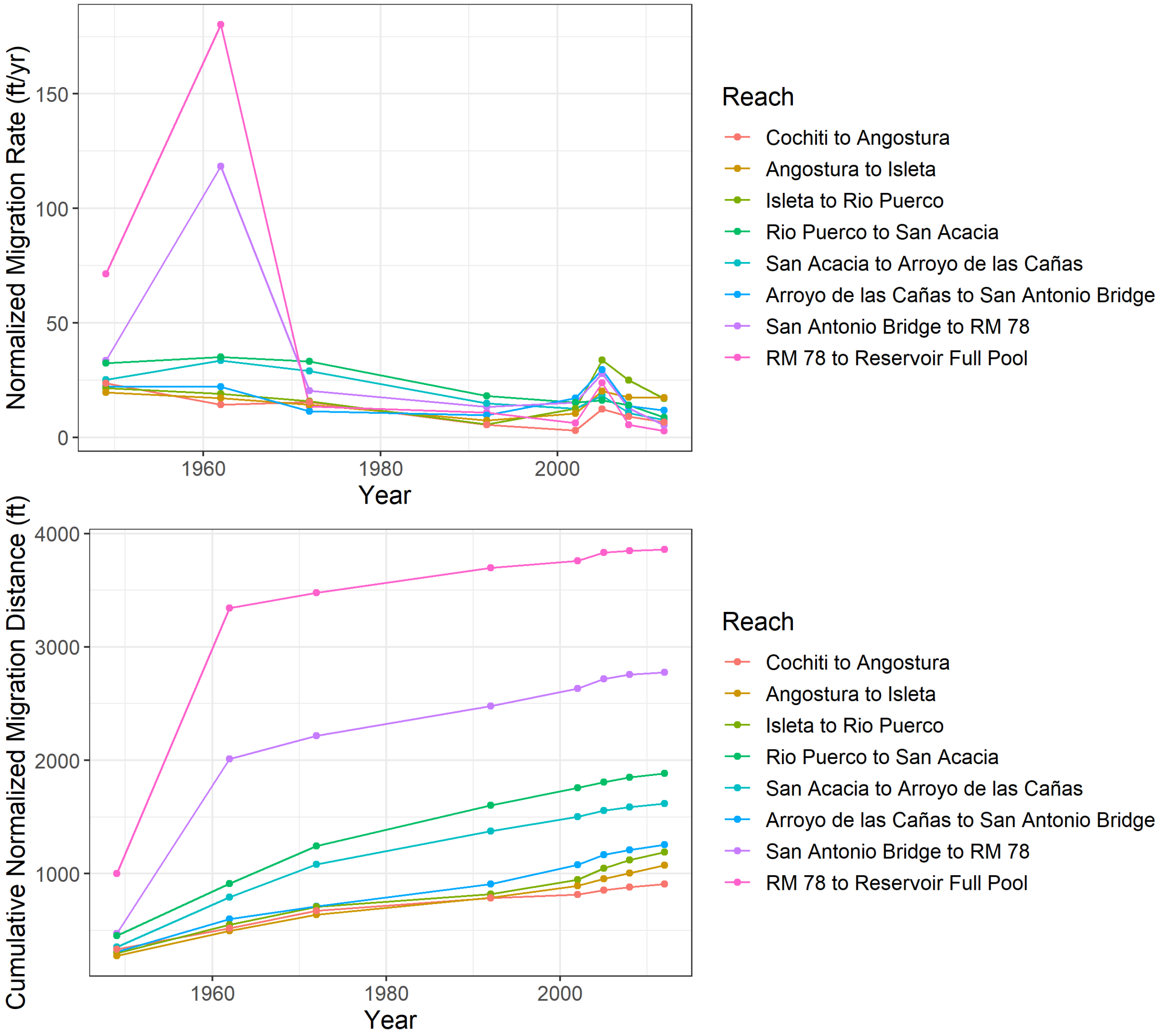


Figure 26. Rio Grande reach migration rates and distance. Rates and distances are normalized by reach length.

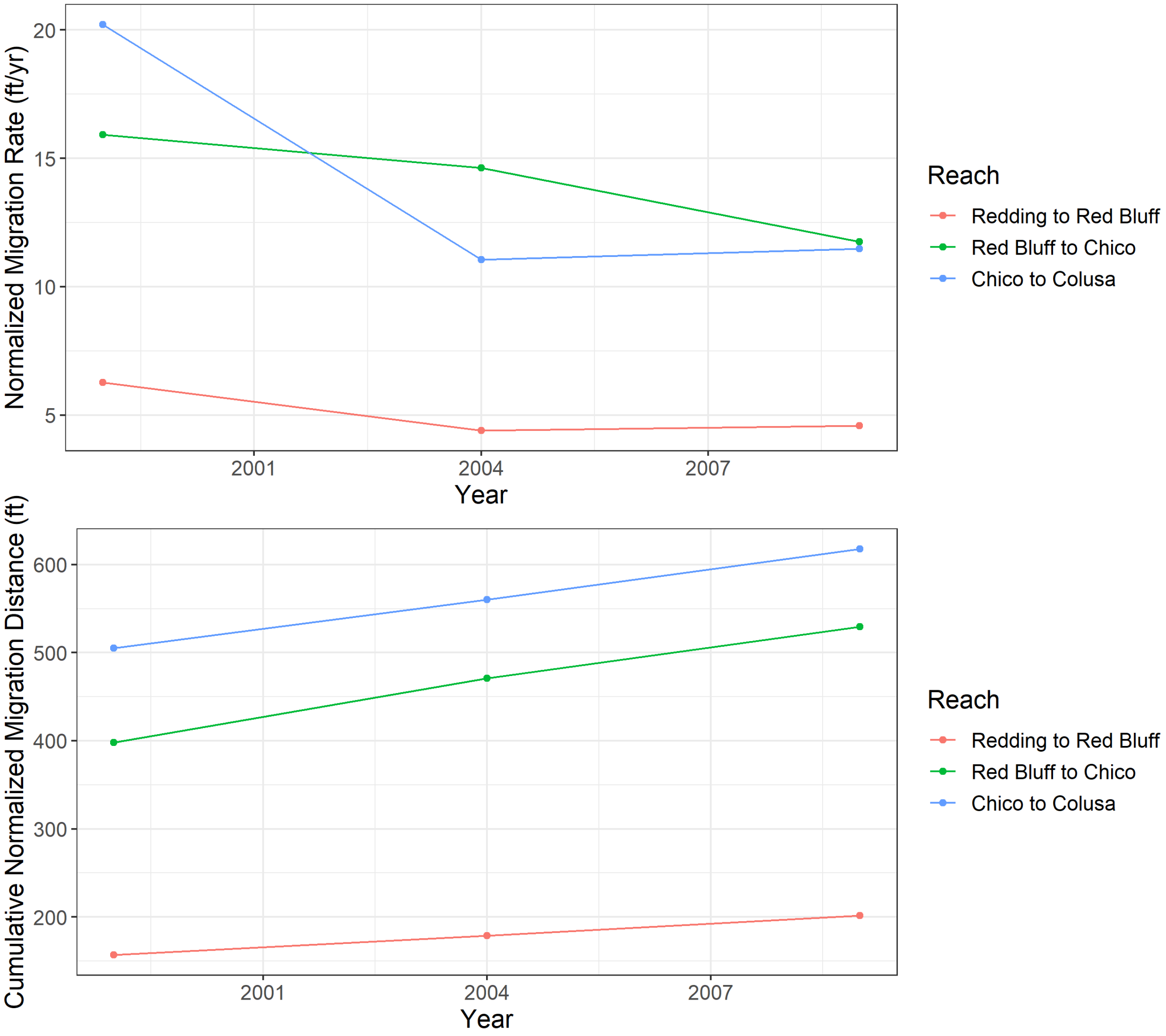


Figure 27. Sacramento River reach migration rates and distance. Rates and distances are normalized by reach length.

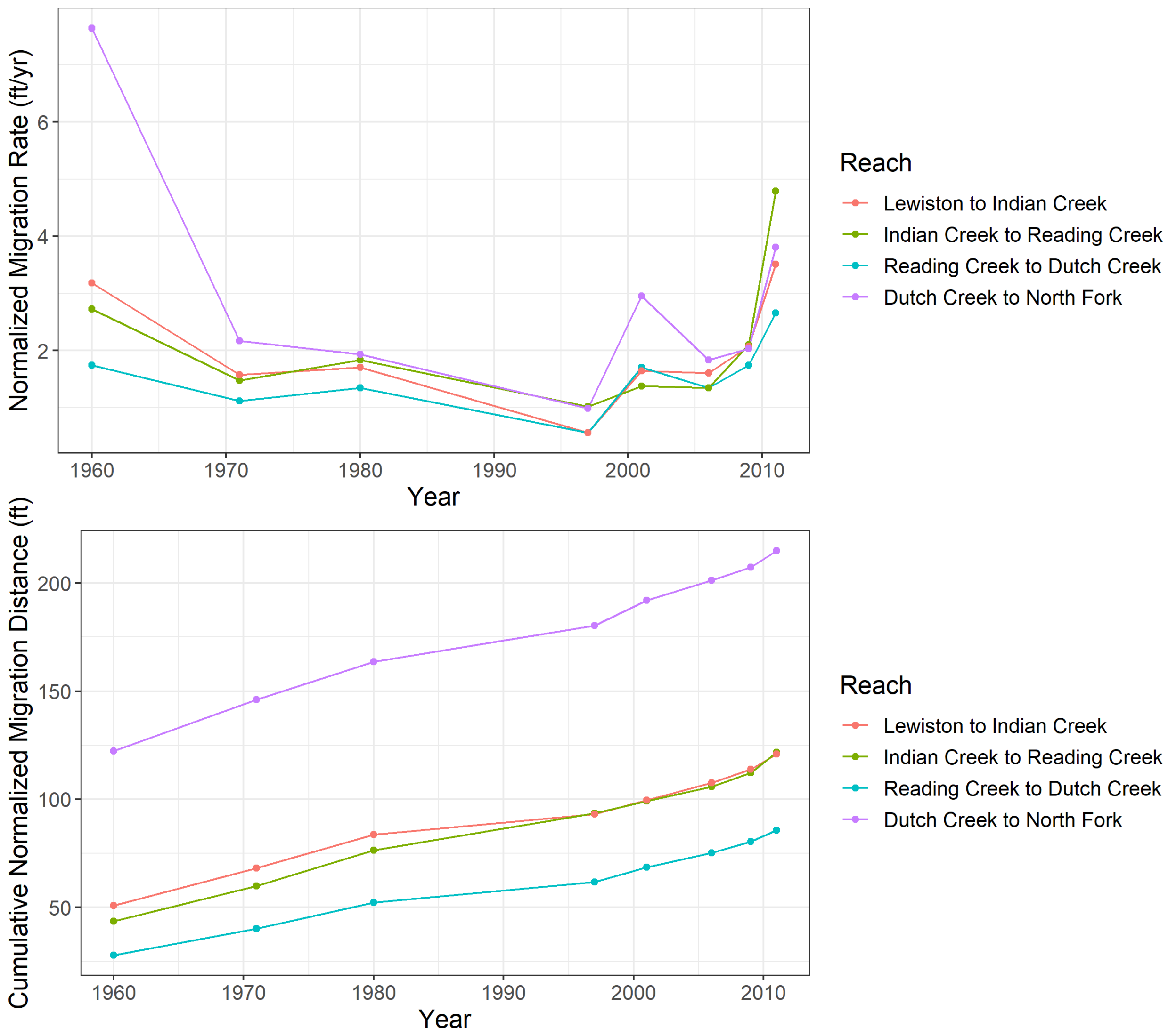


Figure 28. Trinity River reach migration rates and distance. Rates and distances are normalized by reach length.

4.2.2 Temporal Changes in Side Channel Abundance

On the Middle Rio Grande, the number of side channels per mile has generally decreased through time in the San Antonio Bridge to River Mile 78 and River Mile 78 to Reservoir Full Pool reaches, stayed consistent in the San Acacia to Arroyo de las Cañas and Arroyo de las Cañas to San Antonio Bridge reaches, and increased in the most upstream four reaches (Figure 29). The number of depositional side channels per mile increased greatly in 1992, while the number of erosional side channels per mile has more gradually increased throughout the period of study. The normalized number of floodplain side channels has remained relatively constant excepting a large increase in 2012, but the normalized number of side channels within the active channel began increasing in

1992. There was a large increase in diagonal bars in 2002 that slowly declined until 2012. The number of incised bars also increased in 1992 and stayed high through 2012. Bars began to accrete to the banks at a higher rate in 2002. The number of medial bars decreased through time.

On the Sacramento River, the normalized number of side channels has been relatively constant through time after 1958 (Figure 30). When viewing information by reach, it is important to consider that 1938, 1958, and 2009 did not have complete aerial imagery for the entire river. This number is consistent for all reaches where we have data. The normalized number of erosional side channels has decreased through time, with large decreases in 1958 and 1974 and then relatively stable numbers after that. The normalized number of depositional side channels has remained relatively constant through time. There has also been a decrease in the normalized number of active channel side channels after 1938, but little change in the normalized number of side channels located within the floodplain. There was a decreased in the number of incised bars and chutes after 1938, but all other side channel types stayed relatively constant through time. Incised bars are observed to recover in number after 1974, but not to the point of early years, which could be a result of river management impacts.

On the Trinity River, the normalized number of side channels has increased through time (Figure 31). The normalized number of side channels on the Dutch Creek to North Fork reach has remained constant through time, but the normalized number of side channels has increased in the other three reaches, especially beginning in 1980. The Trinity River has maintained consistent numbers of erosional versus depositional side channels through time, with both types increasing around 1971 and staying high throughout the remaining years of aerial imagery. Most side channels are located within the active channel of the main river. The normalized number of floodplain side channels has remained constant through time. The normalized number of medial bars began to increase in 1971 and has stayed high. Obstructions, sills, and incised bars increased in 1980 and stayed high. Other side channel types have been constant through time. It is likely that both the increase in total side channels and observation of bedrock related features in later years may be explained by the combination of lower quality imagery and a highly altered channel-floodplain system (e.g., mining) in early years. This combination of factors may have led to difficulty in identifying side channels. In addition, mining impacts to the active channel area and minimal vegetation growth limited the demarcation of side channels from the active channel, which was a requirement for defining a side channel in this study. As the Trinity River was cut off from scouring flows after the upstream dams were constructed, vegetation growth expanded to produce more identifiable side channels.

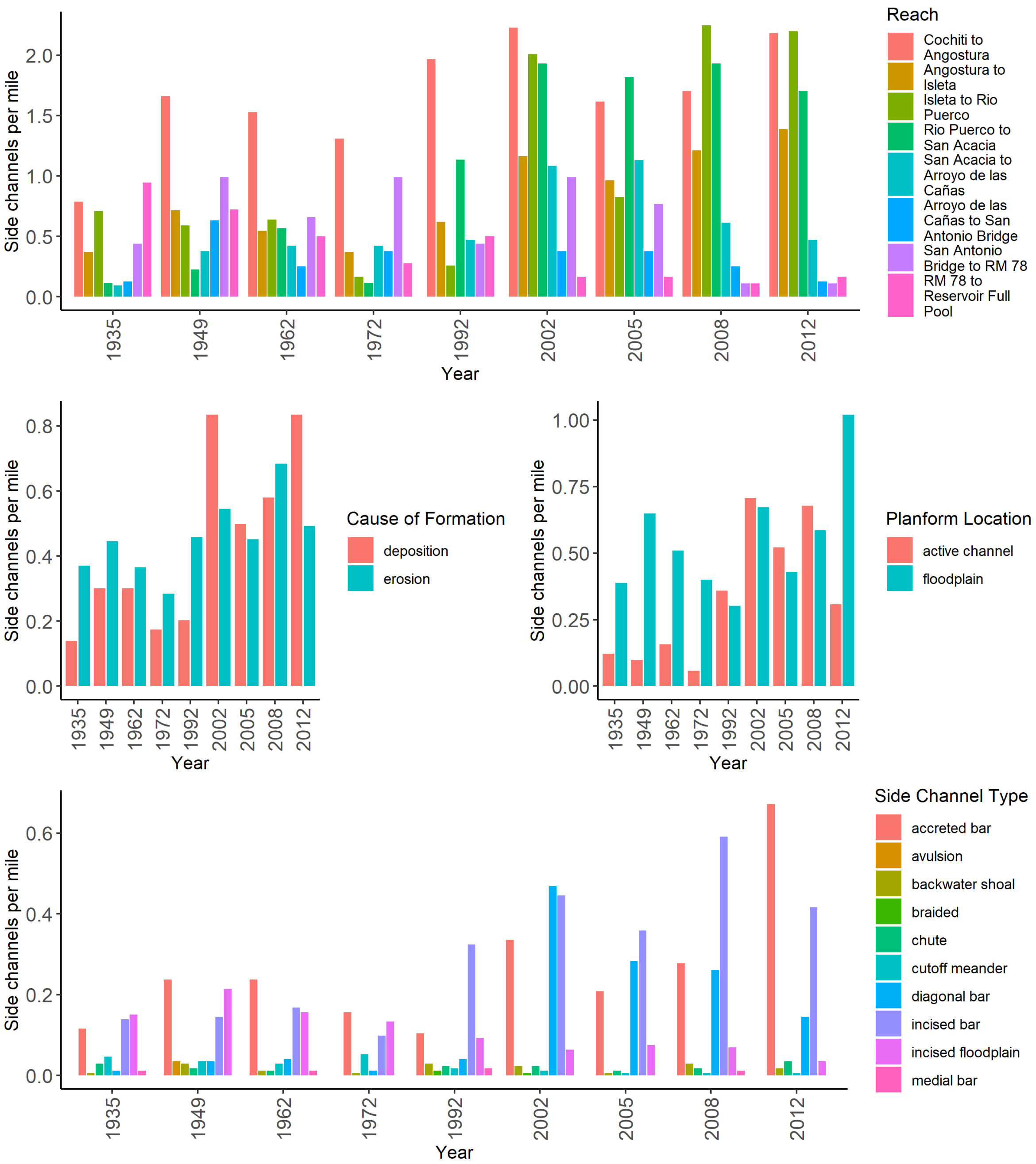


Figure 29. Side channels per river mile for each reach, formational mechanism, side channel type, planform location, and estimated inundation frequency on the Middle Rio Grande.

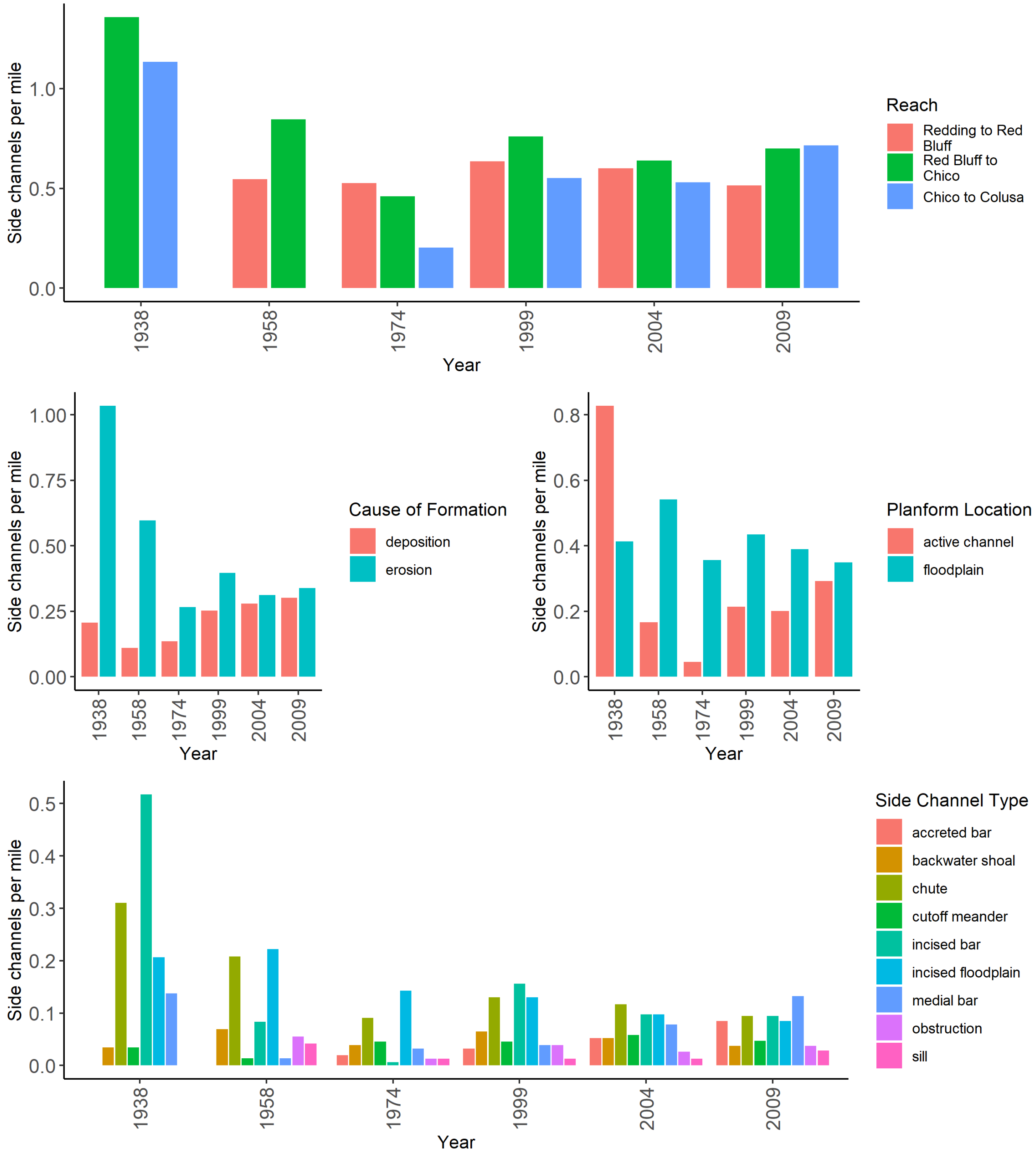


Figure 30. Side channels per river mile for each reach, formational mechanism, side channel type, planform location, and estimated inundation frequency on the Sacramento River.

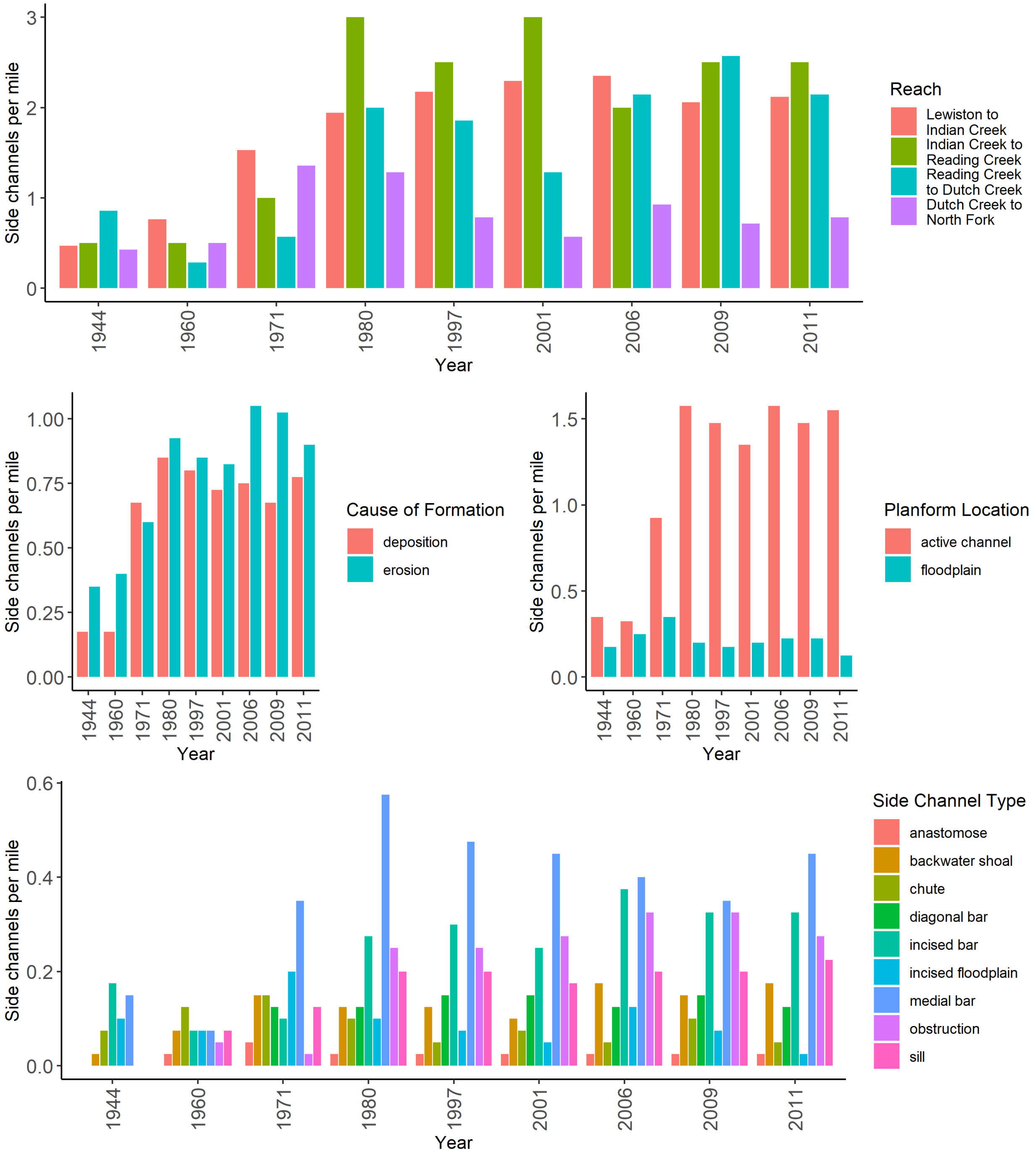


Figure 31. Side channels per river mile for each reach, formational mechanism, side channel type, planform location, and estimated inundation frequency on the Trinity River.

4.2.3 Side Channel Persistence

Figure 32 through Figure 34 show side channel abandonment, persistence, reoccupation, and new formation through time. Each channel was assigned "continued" if the channel existed in the previous aerial image, "reoccupied" if the channel existed previously but not in the prior aerial photograph, "new" if the channel was observed for the first time, and "abandoned" if the channel existed in the previous aerial photograph but was not found in the current images. In the plots below, the number of "abandoned" side channels are represented by a negative number indicating that disconnection or abandonment reduces the overall side channel abundance. The plots were then normalized by total channel length to produce the number of side channels per mile.

On the Middle Rio Grande, there was a relatively similar proportion of continued side channels until 1992. Continued side channels become much more common starting in 2002, which may be due to the increasing frequency of aerial imagery. The number of continued side channels from 2005 through 2012 have remained consistent. Reoccupied side channels are the lowest proportion of side channels in all years with most observed in the recent years of aerial imagery.

On the Sacramento River, approximately 25% of all side channels in 1974 continued in 1999. There were larger numbers of side channels per mile in 1999 compared to 2004 and 2009, but this is likely due to the longer period between aerials. The number of new and continued side channels were relatively similar between 2004 and 2009. The Sacramento River does not have any reoccupations of pre-existing side channels.

On the Trinity River, the number of new side channels peaked in 1980 and decreased in recent years, although a slight increase in new side channels was observed between 2009 and 2011. The number of continued and reoccupied side channels has increased, and the number of abandoned side channels increased (i.e., more negative values) through 1997 and then predominantly decreased again.

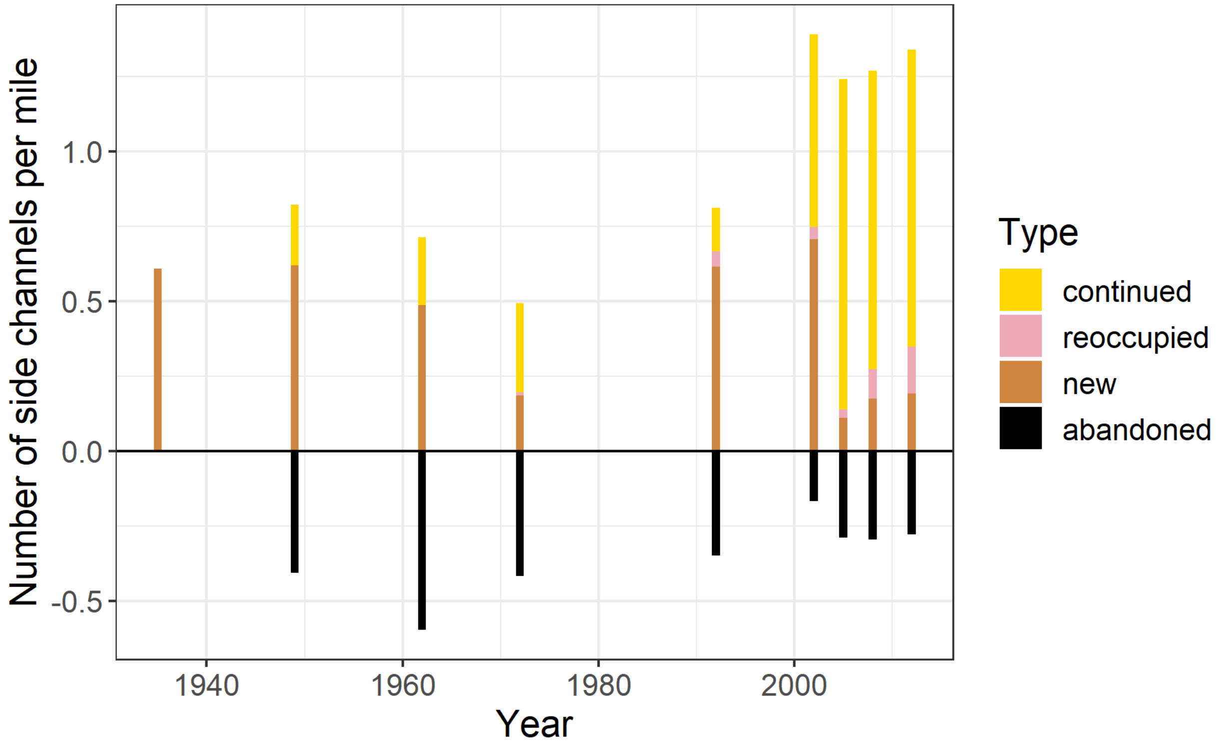


Figure 32. Normalized side channel persistence on the Middle Rio Grande.

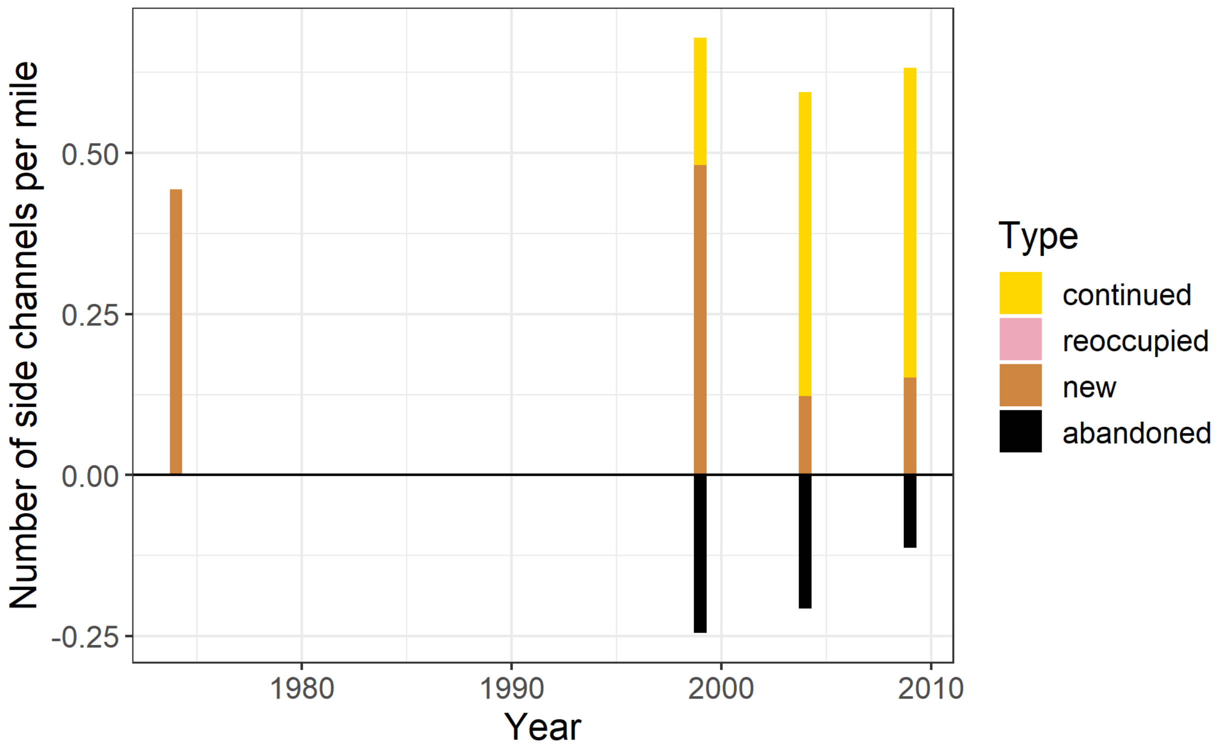


Figure 33. Normalized side channel persistence on the Sacramento River. The Sacramento River side channel persistence plot was only calculated between RM 172 and 278 between 1974 and 2009 due to limited overlapping datasets in other years.

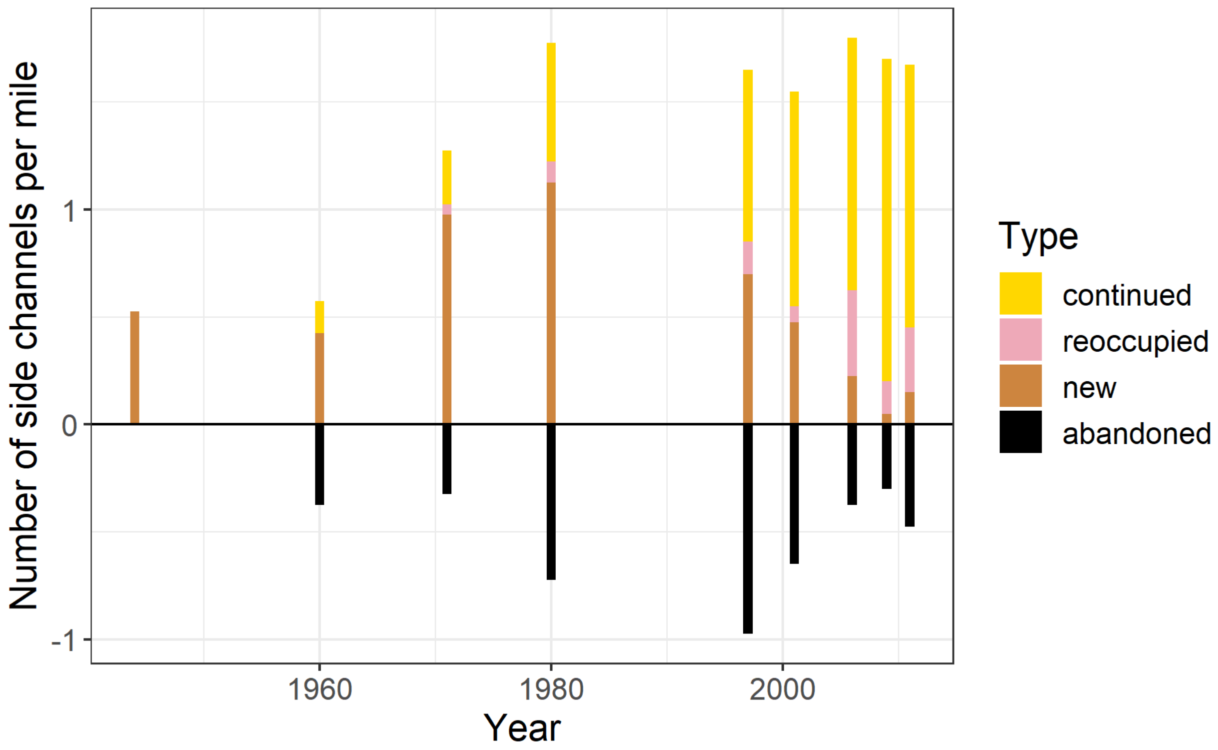


Figure 34. Normalized side channel persistence on the Trinity River.

4.2.4 Side Channel Life Cycle

The Sankey diagrams in Figure 35 through Figure 37 show whether a side channel type changes from one year of aerial imagery to the subsequent year of aerial imagery. The size of line connecting the left and right sides of the figure represents the quantity of channels that either stay the same or evolve into a different side channel type. The results highlight that side channel type is dependent on the starting type and river. Rio Grande side channel types were the most dynamic, while Trinity River side channel types were quite stable through time. On both the Middle Rio Grande and Sacramento River, incised bars were relatively dynamic. The typical evolution for incised bars on both rivers is transition to an accreted bar, but they can also become diagonal bars on the Middle Rio Grande. In contrast, medial bars often evolved into a different side channel type on the Middle Rio Grande but were much more stable as a side channel type on the Sacramento River. On the Middle Rio Grande, medial bars transitioned to accreted bars or diagonal bars. On the Middle Rio Grande, backwater shoal and braided channel types largely evolved into different side channel types over time. The Middle Rio Grande is a generally more dynamic river system than the other two, with side channel types often fluctuating back and forth. For example, bars can become accreted and then re-incised to join the main channel again multiple times throughout a side-channel's history. On the Sacramento and Trinity rivers, side channels are typically more stable. On both rivers, obstructions, sills, and medial bars are especially stable. Accreted bars are stable on the Middle Rio Grande and Sacramento, and incised floodplain side channels are stable on all three rivers.

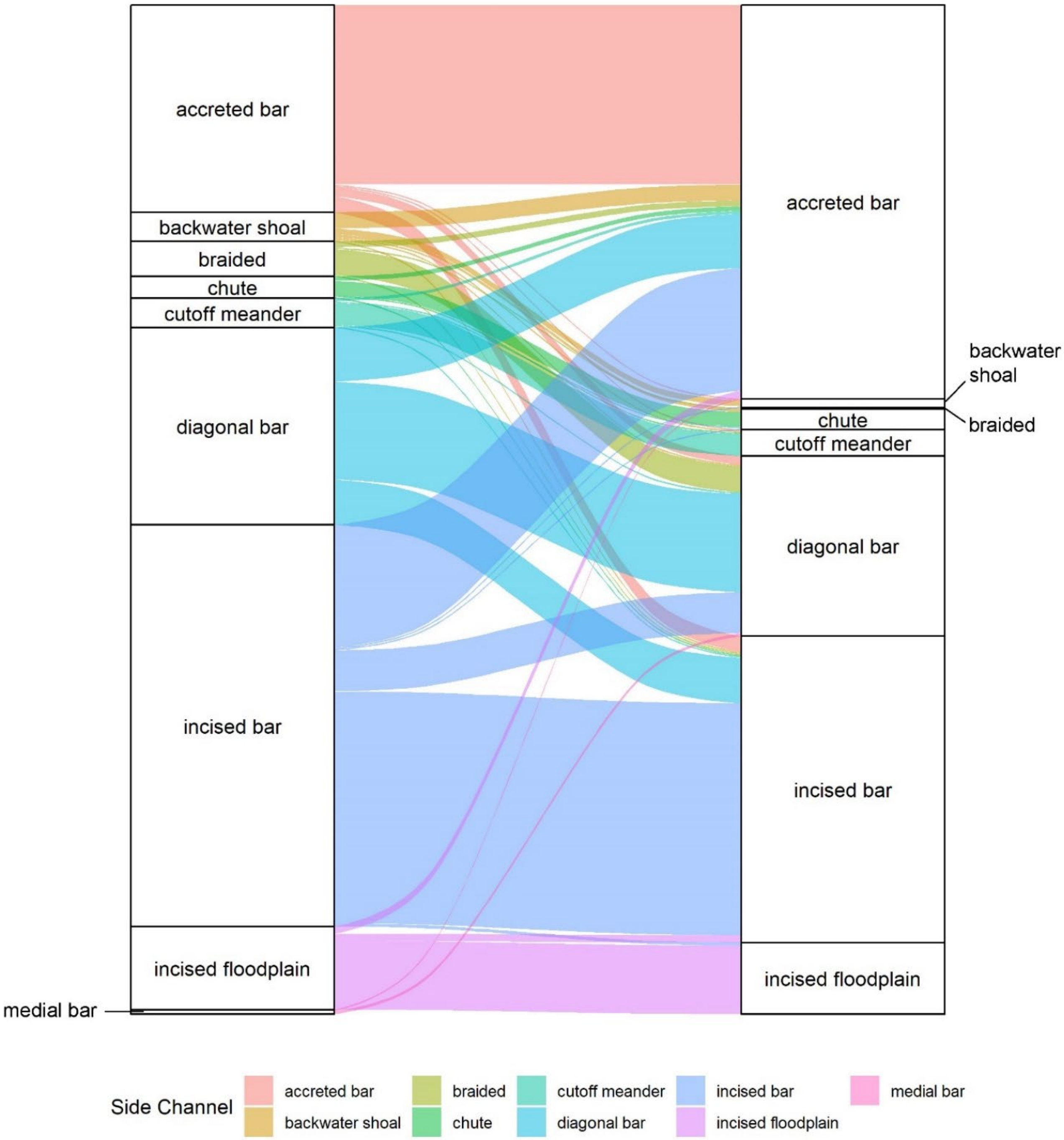


Figure 35. Side channel evolution along the Middle Rio Grande.

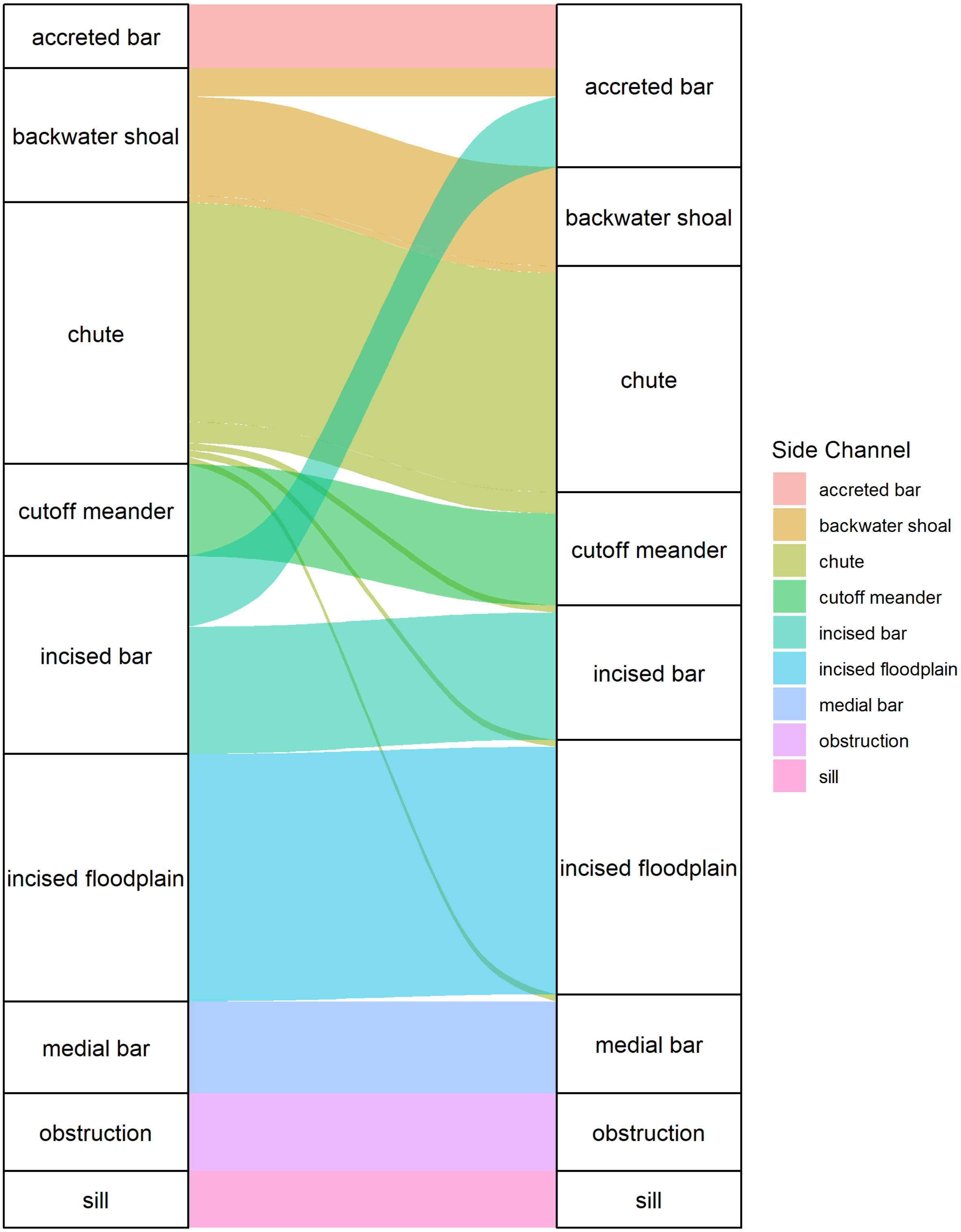


Figure 36. Side channel evolution along the Sacramento River.

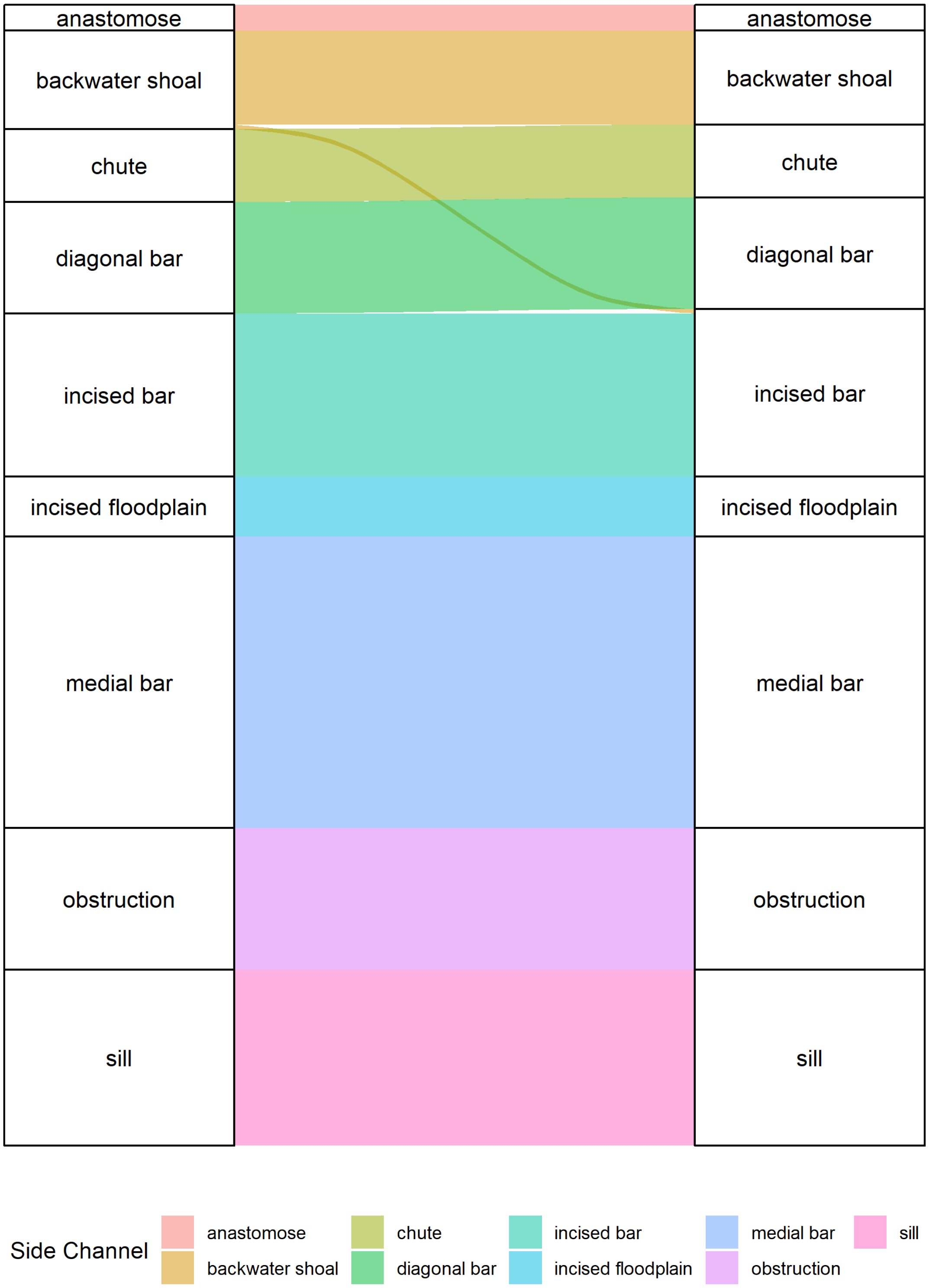


Figure 37. Side channel evolution along the Trinity River.

4.3 Side Channel Longevity

To quantify the longevity of side channels, all side channels in the last year of aerial imagery were assessed to see how long each has been in existence. On the Rio Grande, many side channels have only been around 0 to 4 years, however, a large proportion have existed for up to 40 years (Figure 38). The low number of channels existing for 7-10 years is the result of 2005 imagery being flown during a high flow event, which meant many channels were not observable due to inundation. Most side channels observed in 2012 were in the most upstream three reaches from Cochiti to the Rio Puerco and all three have side channels that persist for up to 40 years. The Cochiti to Angostura reach has most of the side channels greater than 40 years old. In terms of side channel types, most accreted bars have been in existence for relatively short periods of time. Incised bars can either be short lived or exist for an extended period. In addition to incised bars, braided channels had the second greatest number of channels to have been in existence for at least 20 years. Maximum possible years in existence was also calculated and plotted for all side channel types, planform locations, and formational process. On the Rio Grande, braided channels had the greatest median time in existence, while diagonal bars persisted for the shortest amount of time (Figure 39).

On the Sacramento River, all reaches had side channels that persisted for up to 51 years (Figure 40). Because of a lack of overlapping data beyond 51 years, no side channels could be observed in the Chico to Colusa reach, but the other reaches had a combined 13 side channels that persisted for up to 71 years. The largest proportion of side channels on the Sacramento River have been in existence for between 10 and 35 years. Medial bars were found to last the shortest amount of time both in terms of the most recent side channels and maximum years in existence for all side channels (Figure 41). Incised bars represent a channel type with a moderate time in existence. Chutes can be short lived, but also make up the largest proportion of channels that have persisted for 51 to 71 years. Backwater shoals, obstructions, and sills have the highest median time in existence with sills lasting the longest periods. In terms of planform location, side channels located on the upstream end of meanders (inside-to-outside meander) tended to last the longest.

On the Trinity River, recent side channels have a gradual decline in age, with the largest proportion of side channels only having been in existence for 0 to 2 years (Figure 42). The low number of side channels in the 2-to-5-year age class complements Figure 34 by showing that relatively few new side channels were created between 2006 and 2009. Most channels that persisted for at least 2 years have been on the landscape for 14 years or more. Generally, of the side channels existing in the 2011 imagery, side channel types had a broad distribution of ages. When looking at all side channels in terms of maximum possible years of existence, diagonal bars and sills were observed to persist the longest (Figure 43). The remaining side channel types had similar maximum existence periods.

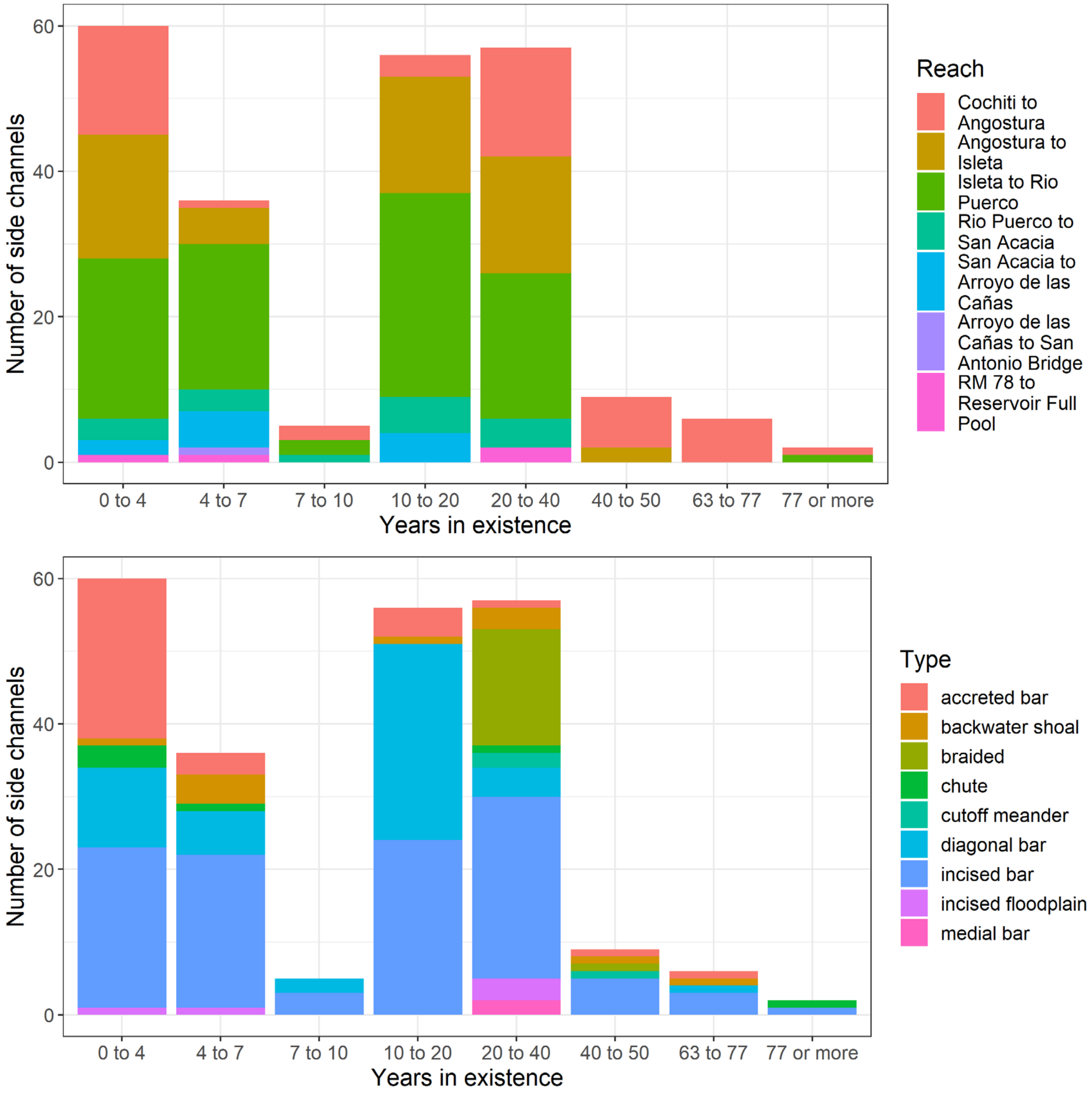


Figure 38. Middle Rio Grande longevity for side channels existing during 2012 imagery.

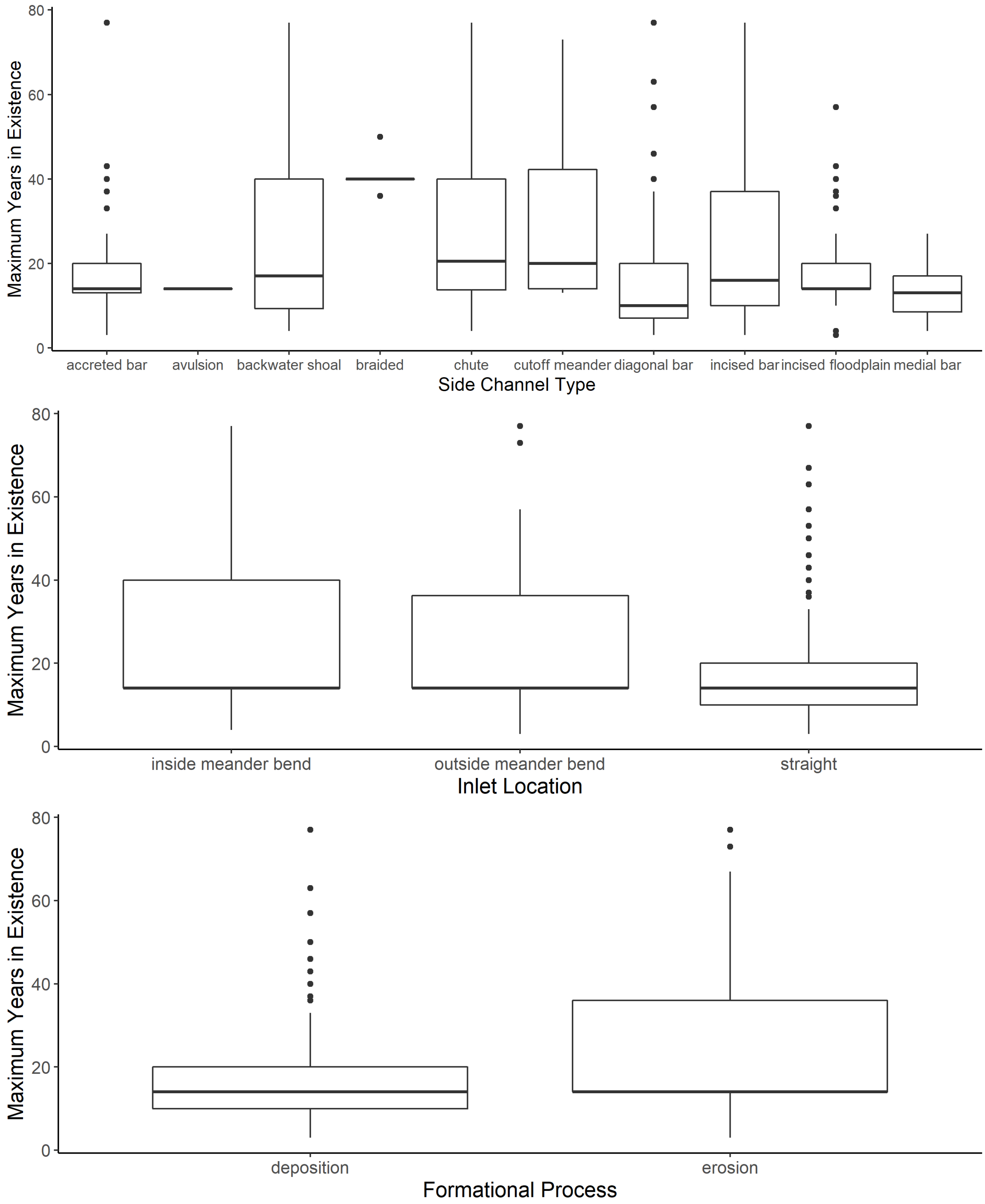


Figure 39. Longevity of side channels along the Middle Rio Grande by side channel type, planform location, and formational process.

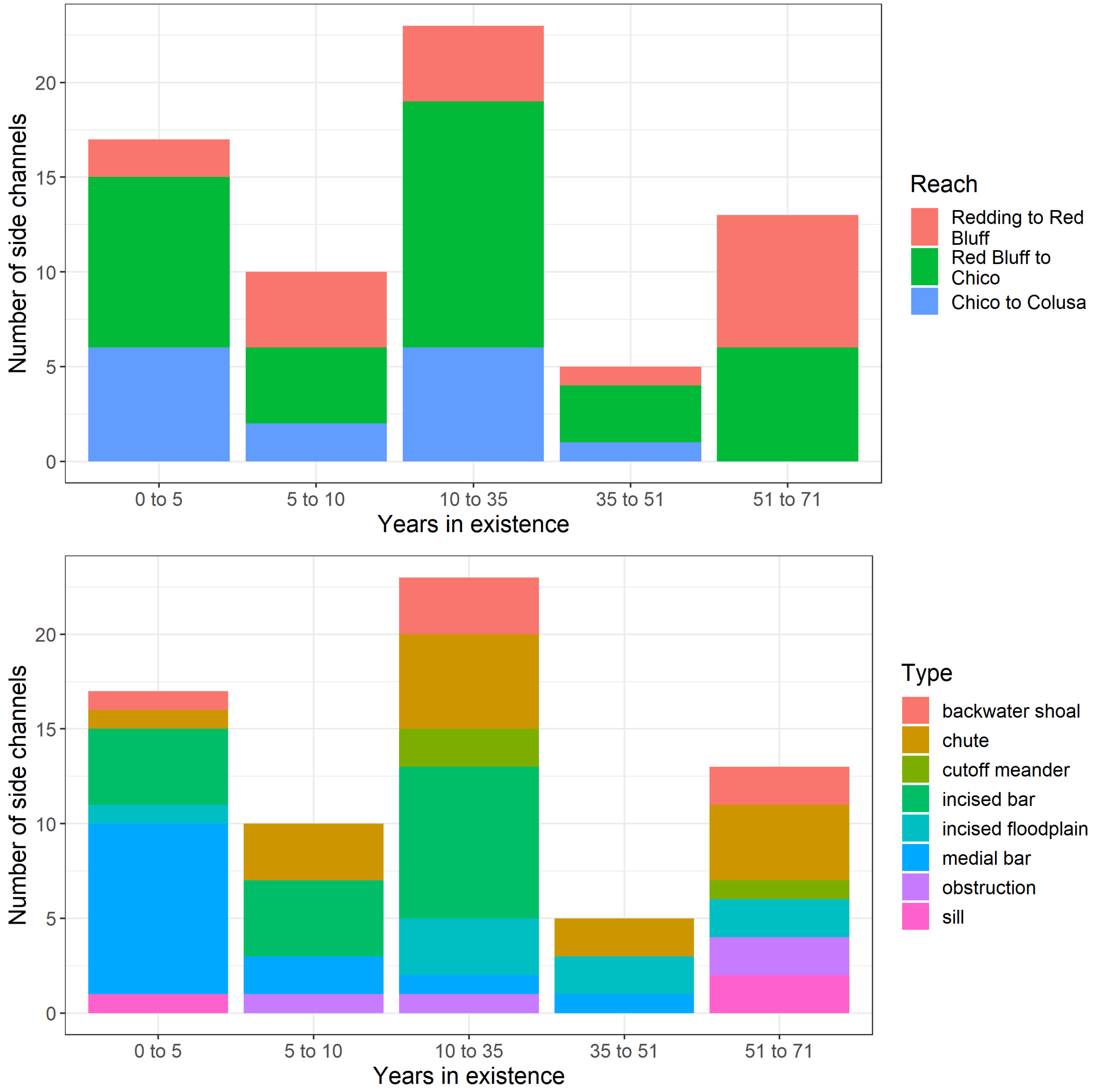


Figure 40. Sacramento River longevity for side channels existing during 2009 imagery.

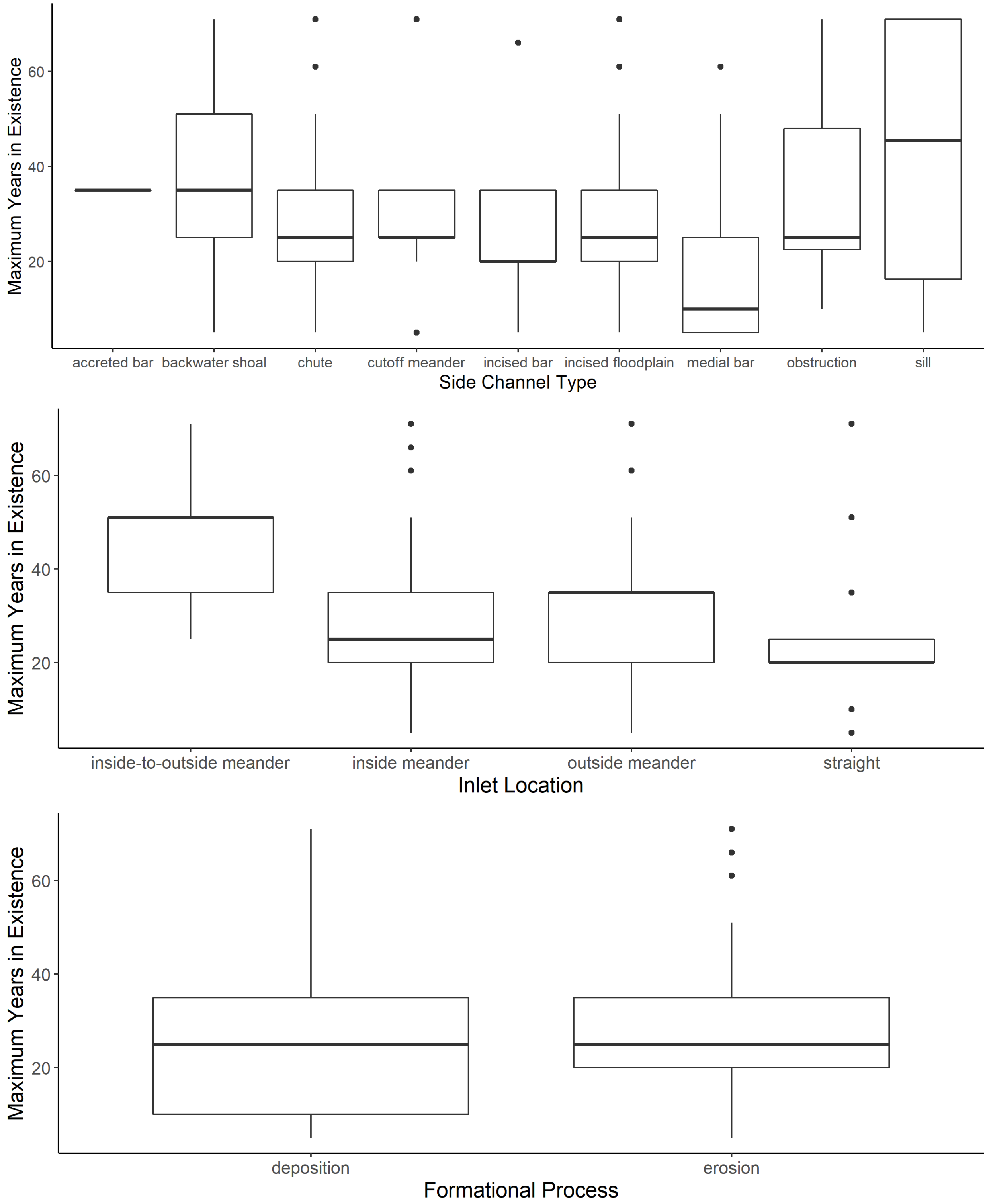


Figure 41. Longevity of side channels along the Sacramento River by side channel type, planform location, and formational process.

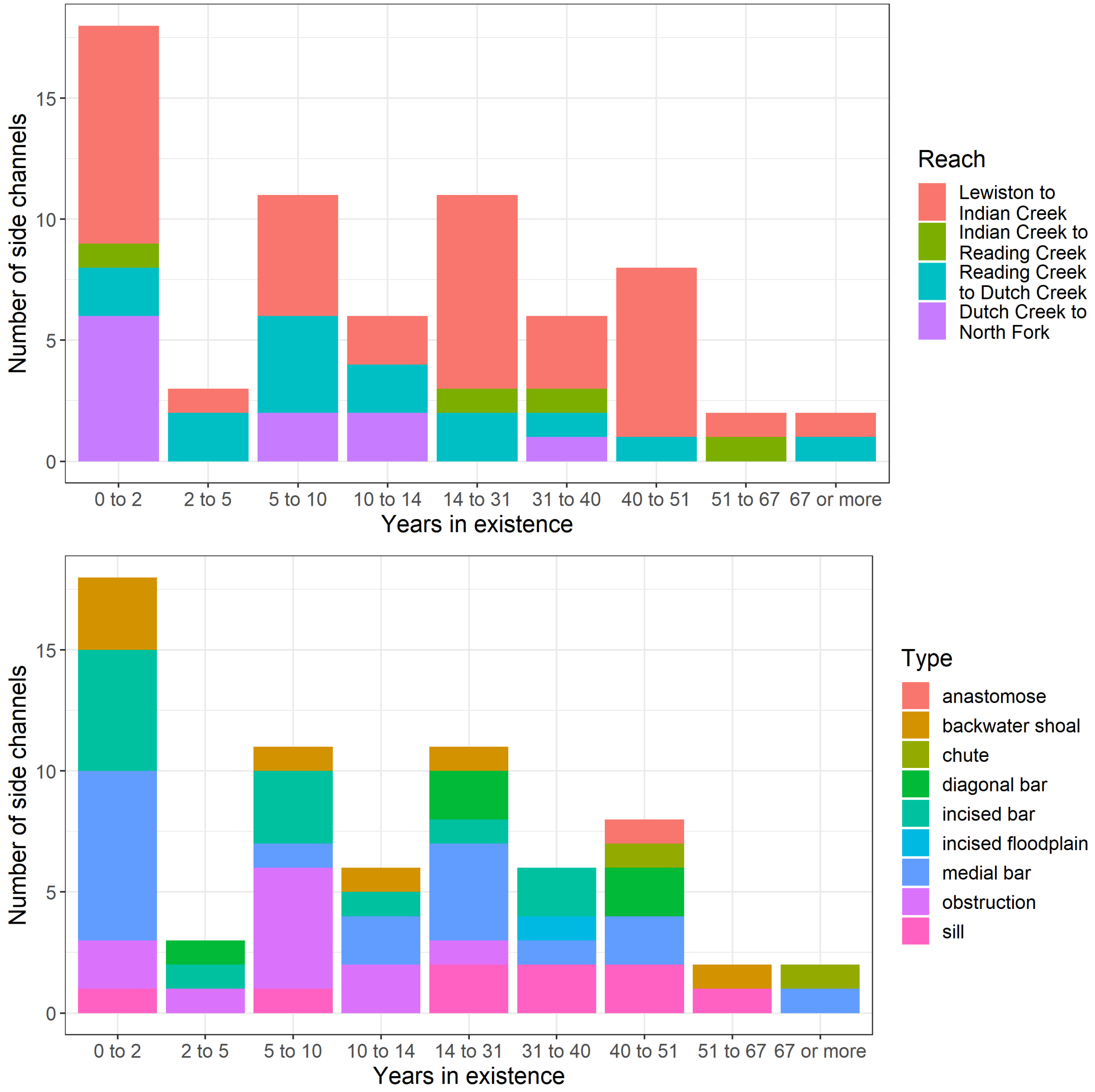


Figure 42. Trinity River longevity for side channels existing during 2011 imagery.

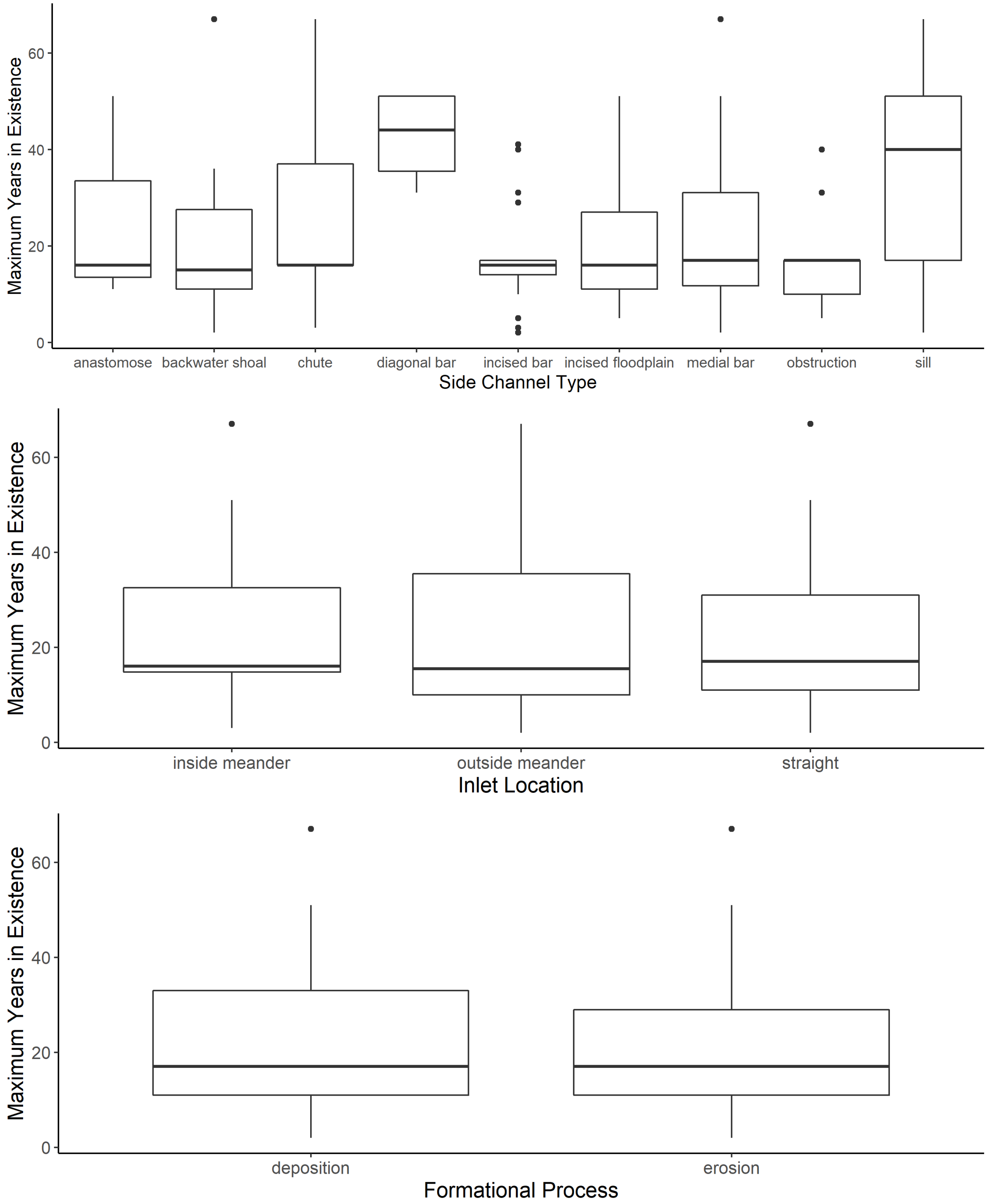


Figure 43. Longevity of side channels along the Trinity River by side channel type, planform location, and formational process.

4.4 Constructed Side Channel Geomorphic Change

Recent Light Detection and Ranging (LiDAR) data available for the Middle Rio Grande provide additional insights about side channel evolution and persistence. In a companion study to this project, Holste et al. (2022) evaluated topographic change at 42 side channel sites constructed between 2006 and 2011. They used four sets of LiDAR (2010, 2012, 2017, and 2018) to calculate erosion and deposition between each time interval. Most of the side channel sites were designed to flow intermittently, activating at moderate to high discharges. Flows were relatively low during the study period, except for larger spring runoff events in 2010 and 2017, moderate spring runoff in 2015 and 2016, and large monsoon events in 2013 and 2017.

Holste et al. (2022) developed Cumulative Distribution Functions (CDFs) for elevation change within each side channel site (Table 9). CDF percentiles are non-exceedance values that correspond to elevation change relative to other points within a site boundary. The median values (50% CDF) were typically within the erosion and deposition detection limits, indicating that the elevation change was not statistically different from elevation change measured at stable sites such as roads and parking lots. Between 2012 and 2018, only 14% of the sites had median values above the deposition detection limit. However, larger CDF values of 75% and 90% had deposition at 29% and 48% of the sites, respectively. Median values do not provide a complete representation of elevation change because local deposition at inlets or outlets to the main channel may cause a side channel to become disconnected. There were very few side channels with any measurable erosion.

Table 9. Number of Middle Rio Grande side channel restoration sites constructed before various LiDAR periods with deposition above detection limit

LiDAR Interval	Number of Sites Analyzed	Deposition Detection Limit (ft)**	Depositional Sites for 50% CDF [Number (%)]***	Depositional Sites for 75% CDF [Number (%)]***	Depositional Sites for 90% CDF [Number (%)]***
2010–2012	24	1.04	0 (0%)	5 (21%)	12 (50%)
2010–2017*	14	1.12	6 (43%)	11 (79%)	14 (100%)
2010–2018	24	1.27	9 (38%)	13 (54%)	22 (92%)
2012–2017*	17	0.26	12 (71%)	14 (82%)	17 (100%)
2012–2018	42	0.96	6 (14%)	12 (29%)	20 (48%)
2017*–2018	22	0.27	3 (14%)	6 (27%)	12 (55%)

*Intervals that include 2017 have fewer sites because the LiDAR does not extend downstream of Reach 2

**Calculated from analysis of stable surfaces (e.g., parking lots) to determine statistically significant elevation change thresholds

***CDF percentiles (50%, 75%, 90%) are calculated from spatial distribution of elevation change within each site polygon boundary

Figure 44 plots CDFs for elevation change during the 2012 to 2018 LiDAR period. There are three curves: low, median, and high. The low curves are the average of five sites with the least deposition, the median curves are the average of five sites nearest to the middle deposition value, and the high curves are the average of five sites with the most deposition. There is typically 1 to 2 ft of elevation change difference within a site and about 2 ft of elevation change difference between sites with the least and most deposition. Sites with the lowest and median deposition were within the detection limits and sites with the most deposition were above the detection limit at nearly all CDF values. Differences between sites may be the result of different design techniques, desired inundation frequency, planform location, or geomorphic reach.

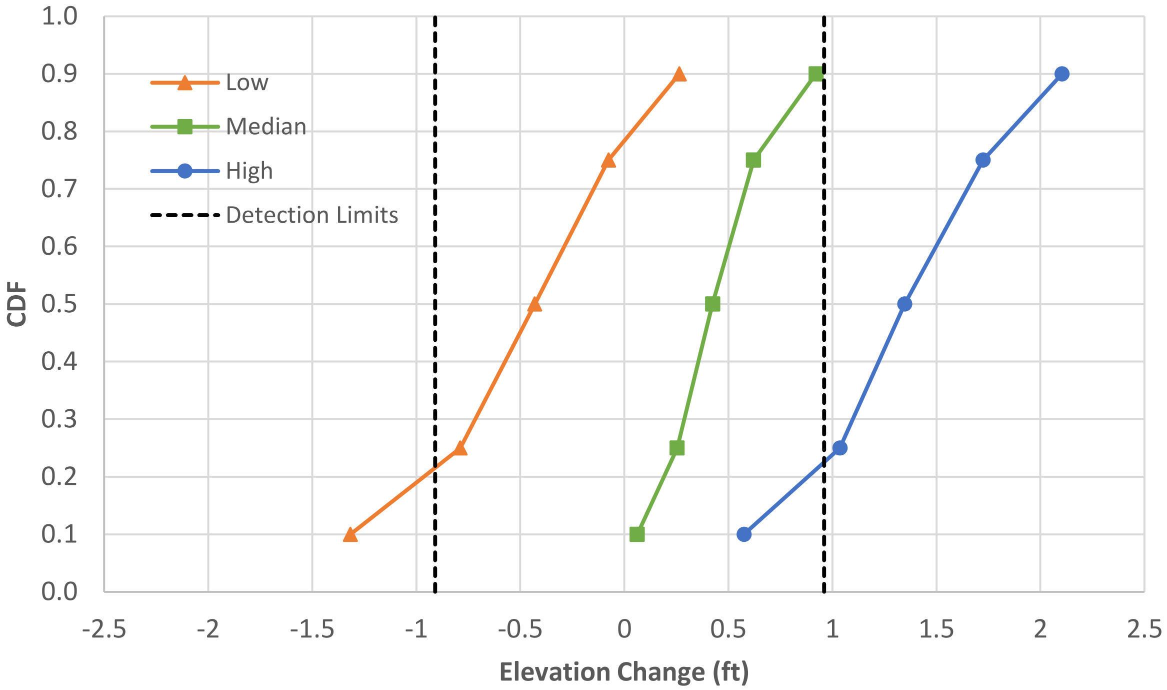


Figure 44. Elevation change (2018 minus 2012) for 42 side channels constructed between 2006 and 2011. Low, Median, and High are the average of five sites with the least, middle, and most deposition, respectively.

The variability between different CDF values demonstrates that there is a spatial gradient of deposition within many side channels. This spatial gradient requires further analysis relative to the connectivity and function of constructed restoration sites. Figure 45 is an elevation change map for a side channel within the Angostura Diversion Dam to Isleta Diversion Dam Reach (Reach 2). There is preferential deposition near the inlet and deposition progressively decreases downstream until reaching the detection limit about midway through the channel. Elevation change remains constant until deposition increases within about 200 ft of the outlet. The inundation boundary shows that the full length of the channel was wet during the 2017 spring runoff recession (3400 cfs), although the inlet is nearly disconnected. Deposition has mostly blocked the original inlet location but there are narrow flow paths slightly upstream and downstream that allow water to flow into the site. Shortly after construction in 2009, the channel was perennially connected at base flows near 500 cfs. Elevation change from the LiDAR also indicates that there are a few areas of localized bank erosion within the side channel. Inundation extents generally match these erosional areas near the outside of bends. The channel was constructed as a relatively uniform trapezoid, which demonstrates that post-construction geomorphic change can increase planform and bed profile variability.

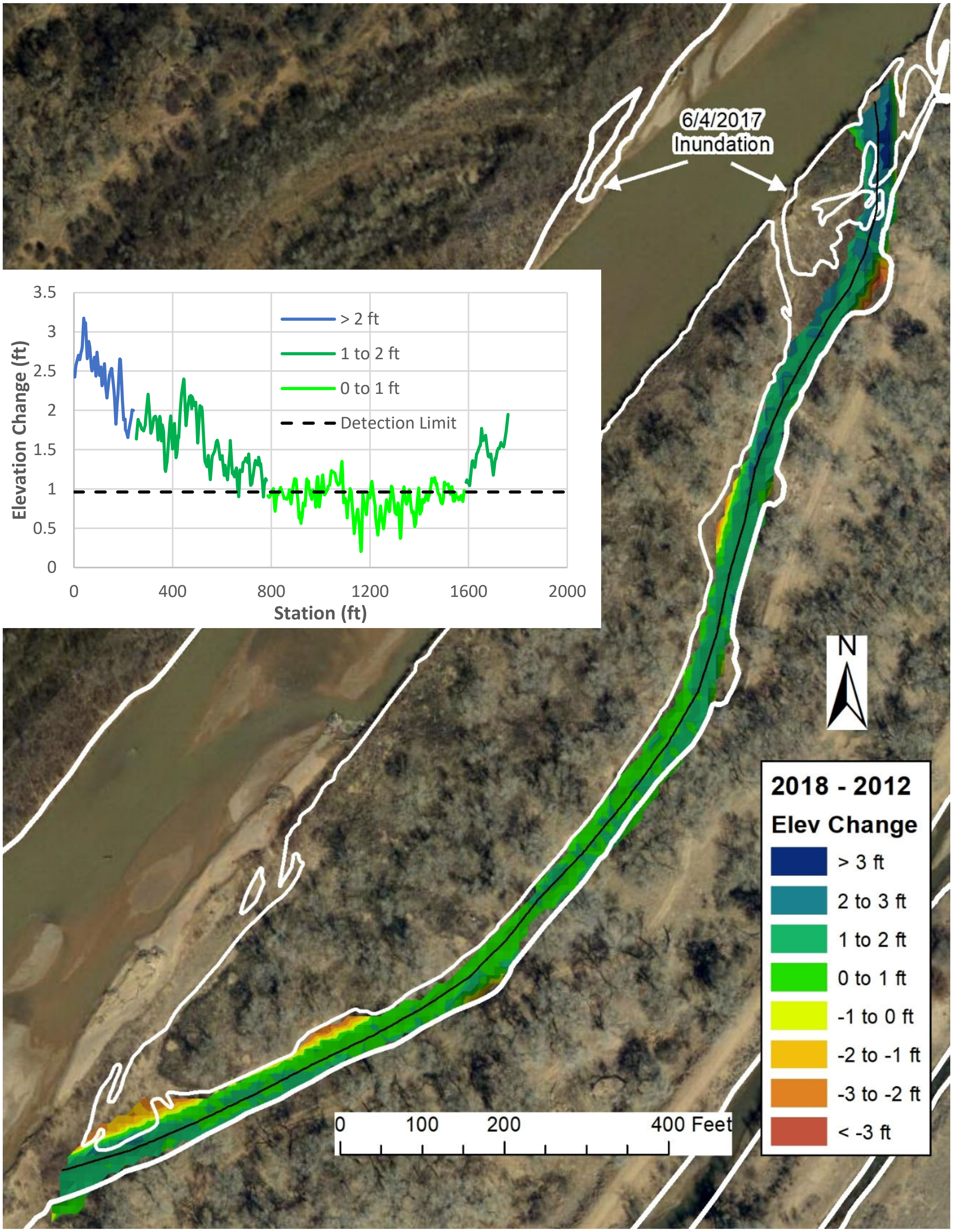


Figure 45. Elevation change (2018 minus 2012) for side channel site constructed in 2009. Inundation boundary (white line) is during high flow spring runoff at 3400 cfs. Inset profile graph shows elevation change along the centerline, from upstream (northeast) to downstream (southwest).

5. Discussion

5.1 Side Channel Classification and Morphology

We observed a wide variety of side channel types across three considerably different rivers. Each river had unique characteristics in terms of side channel types and formational processes due to differences in hydrology, sediment, valley confinement, and human alteration.

The Rio Grande, largely a sand bed river, displayed more dynamics in terms of side channel types and evolution of those types. As would be expected in a sand bed river, sediment erosion and deposition in the form of bar dynamics lead to large proportions of accreted bars, diagonal bars, and incised bars. This is especially true in the upstream reaches of the Rio Grande. In the downstream reaches of the Rio Grande, incised floodplains become much more common. Unlike the confined portions of the Trinity and Sacramento Rivers, the Middle Rio Grande largely exists within alluvial material, thus obstructions and sills are absent from the side channel types observed along the river. Differences in side channel types are likely because of differences in reach characteristics. For example, the downstream reach has the lowest slope of any of the reaches. This reach contains a larger number of incised floodplain channels and is the only reach where an avulsion was observed.

Side channel types are likely influenced by human alteration of the Rio Grande. Upstream, Cochiti Dam has created a coarsened channel bed throughout the Cochiti to Angostura reach and a portion of the Angostura to Isleta Reach. Angostura, Isleta, and San Acacia Diversion dams also create differences within each reach with sedimentation occurring upstream of the dams and incision downstream of the dams, especially at San Acacia. Finally, Elephant Butte Reservoir historically provided the downstream hydraulic control of the RM 78 to Full Pool reach, but in more recent years the channel has incised as reservoir pool elevation has dropped. Differences in side channel metrics between side channel types were minor except for avulsions, which is not surprising given the new side channel is a remnant main channel. The lack of differences in bar-type side channels may be due to the sand bed system and a historically braided and dynamic river.

The Sacramento River is subjected to considerably different geomorphic influences than the Rio Grande. Flows on the Sacramento River can be roughly an order of magnitude higher than both the Rio Grande and Trinity River. Historically, this likely created a highly dynamic river and floodplain system. The three reaches studied here vary in geomorphic setting. Redding to Red Bluff is the most variable with large portions being confined and smaller lengths in alluvial settings. Downstream of Red Bluff there is less confinement, before being completely unconfined within the Central Valley of California. Generally, the river fines from upstream to downstream from cobbles near Redding to sand near Colusa. These differences in geomorphic setting create differences in side channel types. Redding to Red Bluff is the only reach to have obstructions and sills, which are more characteristic of bedrock influence on the river. In contrast, cutoff meanders were found only in the lower two reaches where the river meanders within alluvial material. Meander dynamics clearly play a role in the creation of side channels along the Sacramento River as chutes are also a large proportion of side channels in all three reaches. Backwater shoals are also a product of meandering or forced bends in the river and are observed most often in the upstream reaches. Although meandering clearly drives creation of some types of side channels, bar dynamics are also important. As the river transitions downstream into unconfined, alluvial areas, incised and medial bars are increasingly common. Finally, incised floodplain side channels are observed throughout the river.

The Sacramento River showed larger differences in side channel metrics than the Rio Grande. Chutes and cutoff meanders had the most identifying characteristics. Similar to avulsions on the Rio Grande, both types of side channels are remnant main channel flow paths. Chutes tended to have the greatest side channel top width and the lowest side channel-to-main channel length ratio, and conversely, that ratio is highest for cutoff meanders. Cutoff meanders represent the opposite transition as compared to a chute, so cutoff meanders tend to have opposite characteristics with the exception that similarly cutoff meanders are wide. In contrast to the Rio Grande where bar-type side channels had relatively similar attributes, there are notable differences between incised and medial bars. Medial bars tended to have smaller inlet angles, but greater top widths. This is likely a product of more flow being routed through a medial bar side channel as opposed to an incised bar which is often bank attached.

The Trinity River has been subjected to a complicated geomorphic history including extreme flow manipulation, increased sediment loading and floodplain dredging from mining practices, and an organized restoration effort. This has led to a changing river environment over the past two centuries. Even with the human impacts, geomorphic reach characteristics are apparent in the distribution of side channel types. All side channel types were observed in the diverse Lewiston to Indian Creek reach. While the Indian to Reading Creek reach is short, it was dominated by sills and medial bars. Reading to Dutch Creek is a confined reach of the Trinity River and shows many sills and obstructions, which are the result of bedrock influence on the channel. The Dutch Creek to North Fork reach exhibits more bar dynamics similar to more unconfined reaches of the Rio Grande and Sacramento River. Medial bars, incised bars, and backwater shoals are all common within this reach while obstructions and sills are non-existent.

5.2 Side Channel Formation and Evolution

5.2.1 Temporal Changes in Side Channel Abundance

On the Middle Rio Grande, the number of side channels per river mile increased after 1992 from 0.5 to 1.25. This increase is likely a combination of better image quality in later years and a shift in the maintenance strategy for the river that allowed for more channel migration than in the 1960s and 1970s. In Figure 32, many side channels are abandoned in 1962 after maintenance strategies shifted focus to channelization and controlling the migration of the river. This served to immobilize the channel banks, but also excluded any side channels that were affected by the channelization. Many new side channels appeared in 1992 and 2002. 1992 was in the middle of a high flow period. The high flow has the capacity to transport a lot of sediment, which rearranges the channel and can create a lot of new side channels. 2002 was the start of a drought after a long period of above-average flows. The lower flows during a drought after a long period of channel mobilization allows banks to vegetate and establishes bars that can then persist. After 2002, Figure 32 shows an increased number of continued side channels, which confirms this. A further reason for increased new side channels in 1992 is that in the late 1980s, maintenance practices changed to reduce emphasis on channelizing and stabilizing the river, which allowed for more geomorphic diversity.

If the drought period continues, fewer new side channels will be created and there will be a higher proportion of persistent side channels. Eventually, channel paths will stay disconnected from the main channel for long enough that they will fill in and become abandoned.

In recent years on the Middle Rio Grande, the upstream reaches (1–3) have more side channels than the downstream reaches. These reaches are characterized by active incision, lateral erosion, and low bank heights. They also have coarser bedload sediment than the downstream reaches. The side channels within these reaches are incised bars and chutes, which are erosional features. The number of incised bars has increased through time, which aligns with the recent erosion in these upstream reaches. These reaches also contained the highest proportion of accreted bars. As the river incises, less flow will be diverted to side channels along the banks, which can cause the bars to accrete. This will eventually lead to channel abandonment if the incisional trend continues and side channel inlets become disconnected from the mainstem. These reaches also had a higher total migration distance throughout their existence, but the migration rates were consistent with other reaches. This indicates that on the Middle Rio Grande, migration rate is not important for number of side channels but having space available to migrate allows channels to form without being immediately reoccupied by the main channel. Active erosion and a coarser bedload encourage more side channels. The reach with the maximum migration rate was the RM 78 to Reservoir Full Pool Reach, which also contained all the avulsion side channels. Higher migration rates lead to more channel avulsions.

On the Sacramento River, the number of side channels steadily decreased through 1974, gradually increased until 1999, and then has remained relatively constant. Limited years of aerial imagery data make it difficult to conduct much conclusive analysis on the Sacramento. It is possible that levees and bank hardening have limited the channel migration rate, resulting in a decreasing number of side channels. The Sacramento River also has a higher ratio of new to continued side channels in more recent years than the other two rivers, with a lower proportion of continued side channels and no reoccupation channels (Figure 33). The above average flow in recent years supports trends seen on the Middle Rio Grande of wet years rearranging the channel and creating new side channels.

Side channels in the Chico to Colusa reach on the Sacramento River don’t persist as long as side channels in the other two reaches, but this reach also has fewer side channels in general. This is likely because this is the most unconfined stretch of the river, and in the case of the Sacramento, as the channel migrates, side channels become frequently disconnected from the main channel. Most of the side channels are located within the Red Bluff to Chico reach. The Chico to Colusa reach and Redding to Red Bluff reach had data gaps in the early years and in 2009, so this could affect the number of side channels and their longevity. The Redding to Red Bluff reach has low migration rates, which results in fewer new side channels and more continued side channels. The side channels in this reach are largely incised floodplain, chutes, sills, and obstructions. All these side channel types tend to persist for a long time.

On the Trinity River, the number of side channels increased through time, with a large spike in the late 1990s. This increase in side channels came as higher flows were restored after the very low flow period of 1960 to 1998. The low flow period allowed for vegetation encroachment to stabilize banks. The focus of the TRRP could also be playing a role in the increasing number of side channels. Figure 34 shows that many side channels were abandoned after the de-watering, but this imagery year was after a relatively large gap in time, so there are also many new side channels in this year. Throughout the imagery years following 1998, few new side channels are established, and a higher proportion are continued. The flow in these years is below the average, where the average is strongly influenced by the early years of record. This again confirms the trend from the Middle Rio Grande that a dry period after a wet period favors continued side channels over new side channels.

In recent years on the Trinity River, the Dutch Creek to North Fork reach has had fewer side channels than the three upstream reaches. Most of the side channels in this reach are medial bars and backwater shoals. This reach has wider alluvial valleys but is locally confined by mining debris. Reading Creek to Dutch Creek is confined in bedrock canyons, but still has many side channels comparable to the two upstream reaches. Over 50% of the side channels in this reach are sills or obstructions, which aligns with bedrock sills spreading out flow and narrow canyons allowing for obstructions. On the Trinity, the number of medial bars and incised bars have increased through time.

In general, the trends in the rivers show that in a system with available floodplain, above-average flows are conducive to new side channel formation and fewer continued side channels. Below-average flows tend to support more continued side channels and fewer new ones. More dynamic systems like the Middle Rio Grande have more side channels that don’t persist, and less dynamic systems like the Trinity River have fewer new side channels that persist for longer.

5.2.1 Side Channel Life Cycle

Almost all side channel types are stable throughout their existence; side channels usually stay the same type until they are abandoned. The Trinity River has almost no change in side channel types. This confirms the hypothesis that less mobile rivers will have more stable side channels that persist for longer. Two particularly stable types on the Sacramento and Trinity are obstructions and sills. Although these features originally form from erosion around and above more resistant bedrock features, once established these features persist for decades. Some erosion likely continues on the bedrock surface, but at a much slower pace than the surrounding terrain.

Incised bars and diagonal bars change types the most frequently. On the Middle Rio Grande, incised bars and diagonal bars can switch between each other. Both types can also become accreted bars. A typical life cycle on the Middle Rio Grande and Sacramento River is that an incised bar becomes accreted to the bank as either the mainstem flow decreases or the inlet becomes filled with sediment. On the Middle Rio Grande, accreted bars can revert to incised bars again depending on the flow conditions. This cycle can continue until eventually the accreted bar is disconnected from the main channel and abandoned.

On the Middle Rio Grande, another common side channel life cycle is the transition from a braided system to a diagonal bar, and finally to an accreted bar (Figure 46). The accreted bar can again revert to a diagonal bar or can become an incised bar if the internal flow paths are no longer open. On all three river systems, incised bars also often remain incised bars throughout the side channel’s life cycle.

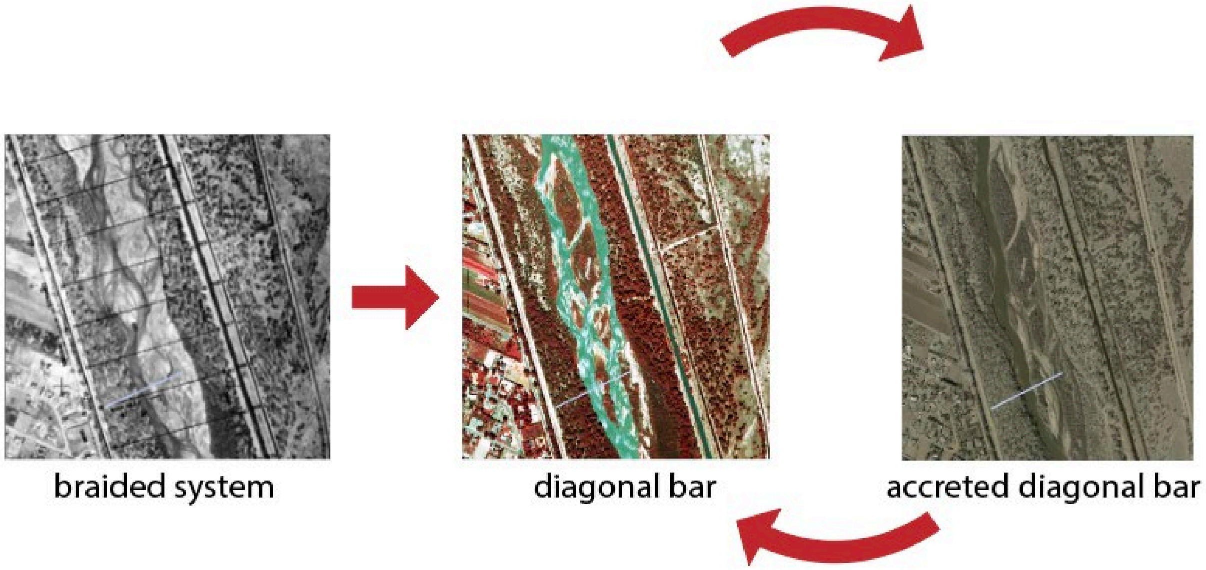


Figure 46. On the Middle Rio Grande braided systems transition to diagonal bars. Diagonal bars then become accreted bars. The accreted bars can revert to diagonal bars. This cycle continues until the side channel is abandoned or it remains an accreted bar.

Medial bars on the Middle Rio Grande also typically evolve into other side channel types. Medial bars usually begin as a sand bar deposition within the channel. Through time, they can elongate and begin to vegetate. Once fully vegetated and accreted to the bank of the main channel, the accreted bar tends to mimic an incised floodplain side channel. Through time, the side channel fills with sediment and becomes vegetated, at which point it is abandoned (Figure 47). In later years, the side channel can become reoccupied at high enough flows.

Reoccupation channels occur for two noted reasons on the Middle Rio Grande. The first is when the main channel of the river has avulsed, leaving behind an abandoned channel. During high flow events, the bank of the new main channel can erode. This reconnects the abandoned main channel to the new main channel. Depending on how the flow is partitioned, the re-occupied main channel can fluctuate between being the side or main channel of the flow.

The second reason for a reoccupation channel is when low flow conditions cause a pre-existing side channel to be abandoned for multiple years. In later high flow years, the channel can become re-activated as an active side channel.

Both channel reoccupation scenarios have a continuum of connectivity. The initial condition for reoccupation is a dry channel that is no longer connected to the main channel. Once the inlet to the side channel has been eroded enough to allow for flow, the outlet can remain plugged for some time. The final, fully active reoccupation channel has flow through the entire channel where both the inlet and outlet are connected to the main channel.

Meandering in two of the three reaches of the Sacramento River is a primary mechanism for side channel creation. Neck cutoffs appear to be rare, which would involve the river meandering until an upstream channel erodes the banks and connects with a downstream meander (although one observed location is likely in the future). More commonly, meanders are cutoff from flow through the development of chutes or partially cutoff across point bars. Both processes involve the creation of an initial side channel in the form of a chute or incised bar. The new side channel then continues to enlarge until the chute or incised bar become large enough to contain most of the flow. During this process, erosion forms the initial side channel and subjects the main channel to deposition. Ultimately if the chute or incised bar side channel becomes the main channel, a new side channel will often remain in the form of a cutoff meander side channel (Figure 48). It appears that deposition continues in these cutoff meander systems, often leading to upstream disconnection except for during high flows. Once a chute forms, it will likely remain a chute and persists for 20 to 40 years for all three river systems.

Another common type of transition on the Sacramento River is from a backwater shoal to an accreted bar. In this type of side channel evolution, a backwater shoal side channel is developed at a relatively sharp bend in the river (Figure 49). The backwater shoal creates a side channel on the outside bend of the river. Over time the river can move toward the inside bend channel and vegetation can grow on the backwater shoal bar. As the bar becomes more terrestrial and the flow becomes directed more toward the inside bend channel, the backwater shoal bar will become attached to the floodplain and transition to an accreted bar side channel. In the example in Figure 49, the accreted bar side channel is a backwater at low flow but at slightly higher flows will become a flow through channel.

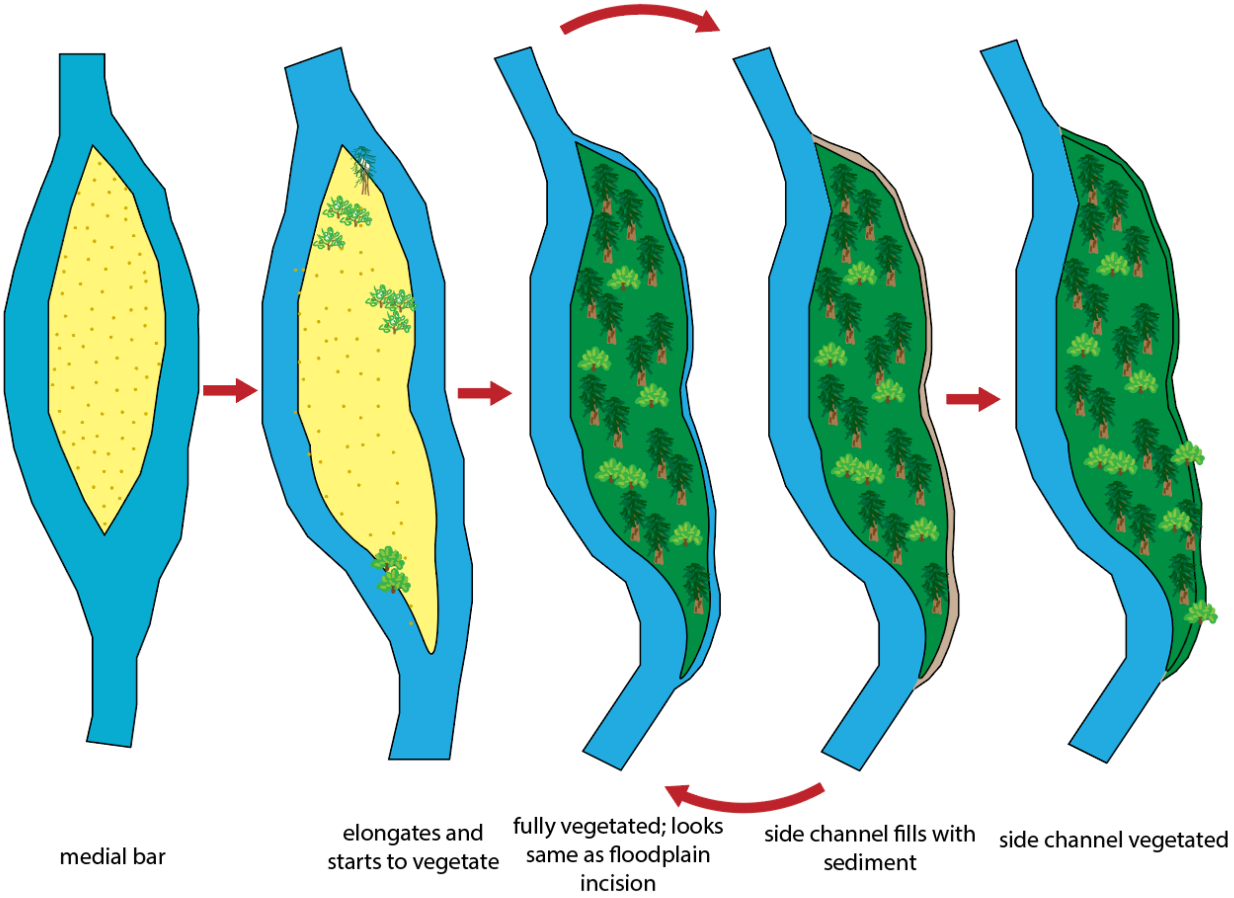


Figure 47. Bars in the channel elongate and become vegetated. Through time the side channel can accrete to the bank of the main channel and fill in with sediment before becoming vegetated and abandoned.

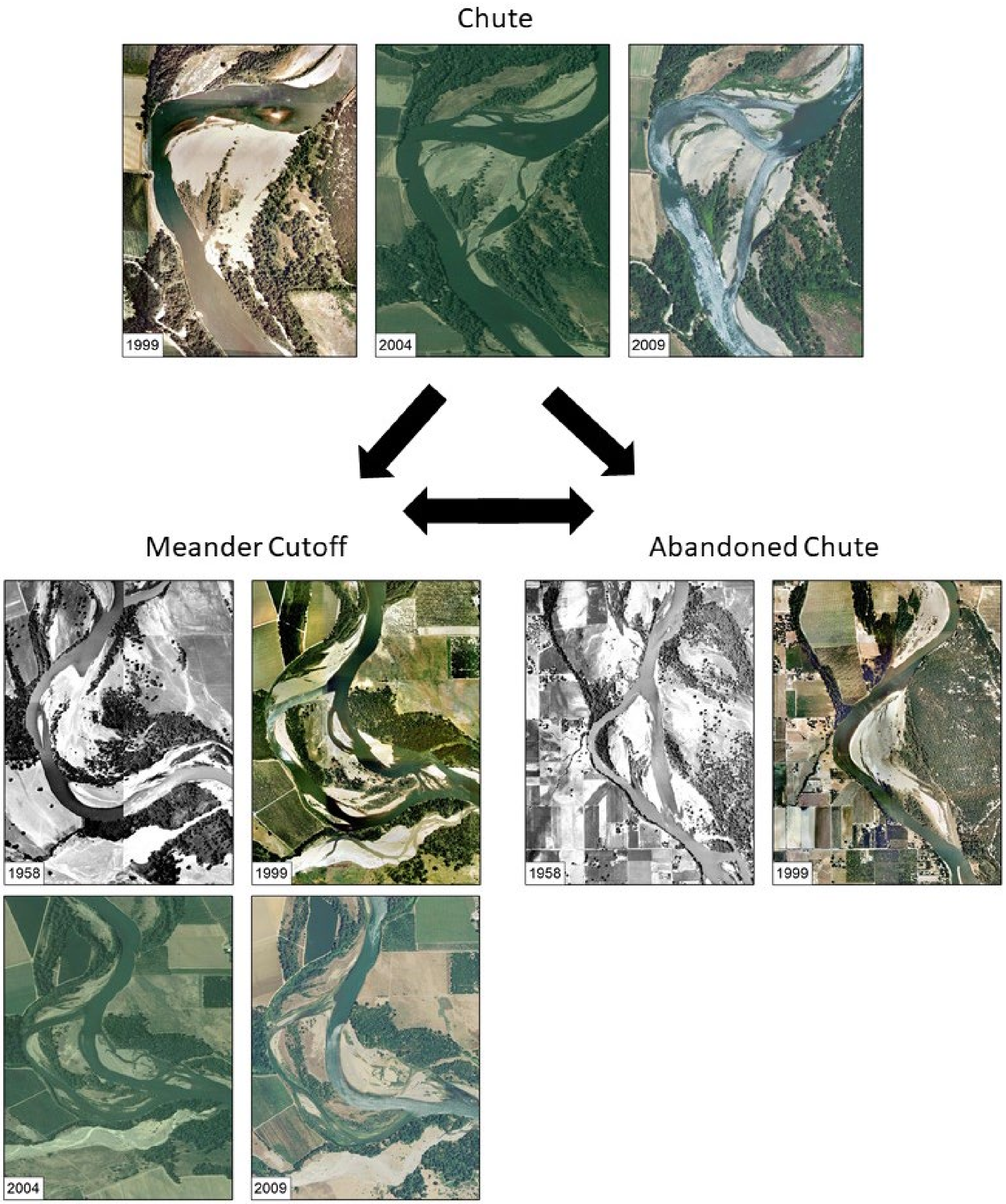


Figure 48. After creation of meander bends and chutes, river channels can fluctuate between either type as the main channel. This example from the Sacramento River highlights the transience of these stages.

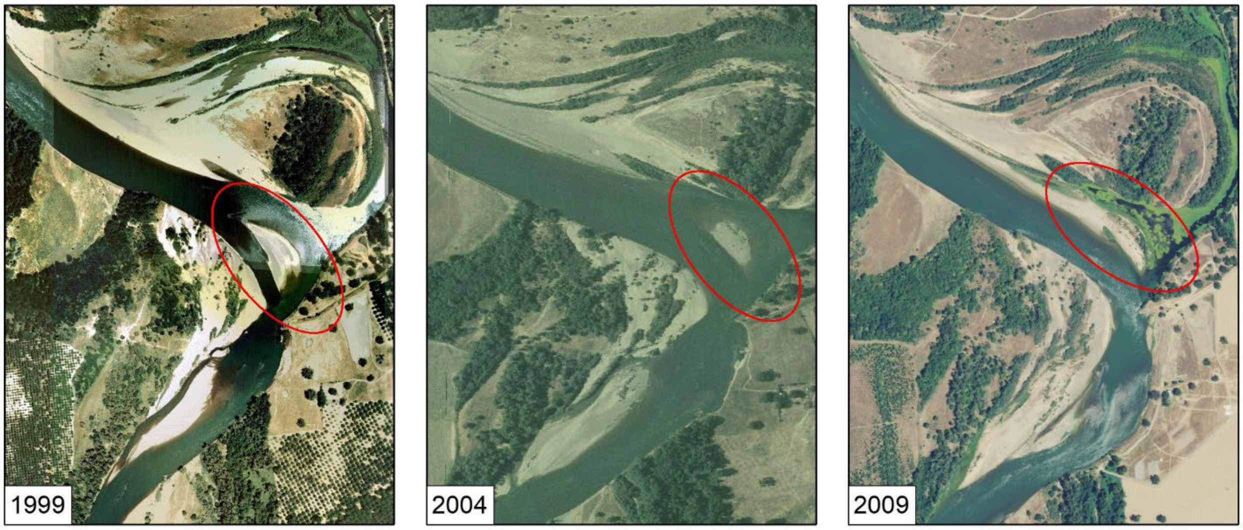


Figure 49. Backwater shoal bar and associated side channel becomes bank attached and transitions to an accreted bar side channel type. Flow is from the top to the bottom of the image.

5.3 Side Channel Longevity

Longevity and persistence analyses demonstrate that side channels are dynamic features in the landscape. The side channel age class distribution indicates that young side channels are the most common. That is, more side channels existing during the last year were newly formed or reoccupied during the most recent imagery period. Older time intervals had a larger number of total new side channels, but many of these were abandoned and did not persist until the last imagery year. When more recent time intervals are combined to account for the increased frequency of images, side channels with a longevity between 0 and 10 years are more common than any other age class. However, side channels persisting between 10 and 40 years are also relatively common. There are very few side channels still in existence that have persisted for 40 years or longer. For a generic side channel on the studied river systems, the median age is about 10 to 20 years. The median longevity increases to 20 to 30 years when considering the total maximum time in existence rather than only analyzing side channels existing during the last year of imagery.

Comparing rivers and side channel types provides more detailed information. The accreted bar has the shortest lifespan of any channel type on the Middle Rio Grande, which has almost no accreted bars older than 4 years. These are bars that attach to the outer bank and tend to become filled with sediment. Medial bars are short-lived features on the Sacramento (0 to 5 years, formed or reoccupied 2004 to 2009) and Trinity (0 to 2 years, formed or reoccupied 2009 to 2011). The most recent image interval contains the highest proportion of these side channel types relative to percentages for other age classes. Medial bars are also depositional features that exist where there is a local reduction in sediment transport capacity. Not all depositional side channel types are short-lived. Diagonal bars are relatively long-lasting features on the Middle Rio Grande (10 to 20 years, formed or reoccupied 1992 to 2002) and Trinity (commonly 14 to 51 years, formed or reoccupied 1960 to 1997). Vegetation may help stabilize the diagonal bars. They also have a different shape from other side channel types with narrower channel threads and streamlines more parallel to the dominant flow direction.

The chute and sill side channel types persist longer than other types. On the Trinity River, sills have a relatively high proportion for age classes between 14 and 51 years (formed or reoccupied 1960 to 1997). Upstream dams that reduced sediment supply may have caused channel bed lowering that exposed bedrock ledges. Sills have incised to bedrock, an inherently stable configuration, and tend to be wider because the bedrock prevents further bed erosion. On the Sacramento River, chutes have a relatively high proportion for age classes of 10 to 35 years (formed or reoccupied 1974 to 1999) and 51 to 71 years (formed or reoccupied 1938 to 1958). Chutes typically are wider and shorter relative to the main channel compared to other side channel types. Chutes also form on the inside of a meander bend. Similarly, incised bars persist relatively long on the Sacramento River (10 to 35 years, formed or reoccupied 1974 to 1999). Incised bars are also an erosional process, but form on the outside of a bend rather than the inside of a bend, which indicates that perhaps planform location does not drive channel persistence.

The Middle Rio Grande and Sacramento River side channels persist longer when the inlet is on the inside of a meander bend rather than the outside. These rivers have high lateral migration rates so locations along the outer bend are likely to be eroded. The Trinity River is more stable and has little difference in persistence between the inside or outside of a bend. Erosional channels last longer on the Middle Rio Grande, but there is little difference in persistence for the Sacramento or Trinity Rivers between erosional or depositional side channels. The Middle Rio Grande has a high suspended sediment load, so side channels in a depositional environment are more likely to be quickly filled in with sediment. Side channels on the Middle Rio Grande typically have the shortest longevity of the three rivers. A combination of high sediment loads, lateral migration, and high flow years in the 1980s and 1990s resulted in shorter persistence for many Middle Rio Grande side channels.

There is not a clear difference in side channel age between the Sacramento River and the Trinity River, although the Sacramento River has a greater proportion of side channels persisting for more than 51 years (formed prior to 1958). This difference in older side channels is likely caused by the Trinity River having few side channels before 1971. During the earliest years of Trinity River aerial imagery (1944 and 1960), the entire system was heavily disrupted and there were many ephemeral flow paths through sediment-laden areas with little riparian vegetation to produce stable side channels. The Trinity River has coarser bed material, less suspended sediment, and lower migration rates that contribute to longer persisting side channels after the anthropogenic impacts were reduced. The Trinity River also has the greatest number of side channels per mile in recent years, indicating different geomorphic processes for that river system. The Middle Rio Grande and Sacramento River both follow the expected trend where there is an inverse relationship between side channel quantity and persistence. The Middle Rio Grande has a greater number of shorter lasting side channels, while the Sacramento River has a lower quantity of longer lasting side channels.

5.4 Side Channel Design Application

Information from this empirical study of natural side channel classification, morphology, formation, evolution, and persistence can be applied to designing new side channels for habitat restoration. Designers should also complete modeling and topographic analysis beyond the scope of our study, but the results presented herein provide a framework for planning-level design and site selection. First, designers and planners should consider the geomorphic reach of the proposed project and the context of multiple geomorphic reaches within a river system. A habitat analysis of existing conditions will help identify reaches or characteristics that may be limiting factors or areas that have the highest potential for restoration. There is a balance between identifying reaches that may have a side channel deficit and understanding that certain reaches naturally do not support as many side channels (see Figure 29 – Figure 31 and Figure 38 – Figure 42).

After identifying a reach for side channel implementation, the next step is to consider side channel types appropriate for that reach (see Figure 20 – Figure 22). Increasing geomorphic complexity and habitat diversity is one goal of side channel restoration, so river managers should implement a mix of side channel types rather than a single "optimum" type. The level of planning and design effort should be scaled to the expected persistence and life cycle benefit of a side channel. For example, medial bars on the Sacramento River have a short longevity while backwater shoals, chutes, obstructions, and sills may persist for much longer. In the most recent year of imagery (2009), medial bars are the most common, there are a moderate number of chutes, and a small number of obstructions and sills. Therefore, medial bars may be useful features if multiple sites can be constructed efficiently, while obstructions and sills may warrant a larger investment for a single site. Chutes are an appealing side channel type for new projects because they are common throughout the river and have a longer persistence than many other classification types. Topographic analysis such as relative elevation mapping should be applied to identify suitable locations for side channels, especially for floodplain areas, to use existing low elevation areas and minimize excavation during construction.

Once a side channel type is selected for a general location, the geometric parameters compiled for this study can be applied to develop the design dimensions (see Figure 23 – Figure 25). The box plots provide a range of values for side channel length, width, and plan view angle. Site specific conditions will dictate if the design channel dimensions should be near the upper or lower bounds of the natural range, or closer to the median value. Finally, after design and construction is complete, side channels should be monitored to track their evolution (see Figure 35 – Figure 37), geomorphic change (see Figure 44 and Figure 45), and ultimately, whether they are providing the expected habitat benefits. Project planning should include adaptive management to decide if a constructed side channel will be periodically maintained or allowed to evolve naturally through its full lifecycle.

6. Conclusions

We identified and classified side channels on three river systems: the Middle Rio Grande, the Sacramento River, and the Trinity River. Repeat aerial imagery between 1935 and 2012 (Middle Rio Grande), 1938 and 2009 (Sacramento River), and 1944 and 2011 (Trinity River) provided time series to assess side channel formation, longevity, and persistence. Erosional side channels form by large flow events scouring the banks, floodplain, or main channel point bars and include the following types: incised floodplains, incised bars, chutes, avulsions, anastomoses, obstructions, and sills.

Depositional side channels occur when there is an increase in sediment supply or local reduction in transport capacity because of a reduction in slope or an increase in width. Depositional side channel types include medial bars, braided systems, diagonal bars, accreted bars, and backwater shoals.

Comparing each river's first year of aerial imagery between 1935 and 1944, the Sacramento River has the most side channels per mile, and the Trinity River has the fewest. After about the early 1960s, the Sacramento River has the lowest side channel density, and the Trinity River has the greatest side channel density. The number of side channels on the Middle Rio Grande increased significantly after about 1992. Side channels on the Middle Rio Grande were the most dynamic of the three rivers with sediment erosion, deposition, and bar evolution creating accreted bar side channels, diagonal bars, and incised bars. Differences in side channel types are primarily linked to differences in reach characteristics from upstream to downstream.

The three rivers have different lateral migration rates and different geomorphic characteristics between reaches. All three rivers generally have the highest migration rates during the mid-1900s between the earliest periods of aerial imagery. Migration rates increased on the Trinity River after 2001. The number of side channels per mile increased in the four upstream Middle Rio Grande reaches, stayed consistent in the fifth and sixth reach, and decreased in the two downstream reaches. Analysis for the Sacramento River is complicated by inconsistent aerial imagery extents between years. The number of side channels decreased between 1938 and 1958 and then remained mostly constant. Conversely, the number of Trinity River side channels increased between 1960 and 1980 and has been consistent in recent years. The upstream three reaches were responsible for the increased abundance while the downstream reach has maintained the lowest number of side channels in nearly every year.

The ratio of new to continued side channels was higher for earlier years of imagery. High flows have the capacity to erode, transport, and deposit large volumes of sediment, which rearranges the channel and can create many new side channels. Low flows during a drought after a long period of channel mobilization allows banks to vegetate and establish bars that can then persist. Reaches with lower migration rates have fewer new side channels and a higher proportion of continued side channels. Trends in new or continued side channels over time are likely partially influenced by the more frequent aerial images in later years, which provides greater temporal resolution.

Side channel evolution diagrams show whether a side channel type changes from one year of aerial imagery to the subsequent year of aerial imagery. The results highlight that side channel type is typically stable through time, especially on the Trinity River. The Trinity River has almost no change in side channel type, which confirms the hypothesis that less mobile rivers will have more stable side channels that persist for longer. A side channel that evolves between types also has a greater opportunity to become abandoned. The Middle Rio Grande is the most dynamic river system and has many side channels that alternate between types. For example, bars can become accreted and then re-incised to join the main channel multiple times throughout a side-channel's history. On both the Middle Rio Grande and Sacramento River, incised bars were relatively dynamic. Side channels are periodically reoccupied through a cycle of gradual abandonment during low flow periods and reactivation during high flows. On the Sacramento and Trinity rivers, side channels are typically more stable. For these two rivers, obstructions, sills, and medial bars are especially stable.

The Middle Rio Grande and Sacramento River side channels persist longer when the inlet is on the inside of a meander bend rather than the outside. These rivers have high lateral migration rates so locations along the outer bend are likely to be eroded. The Trinity River is more stable and has little difference in persistence or longevity between the inside or outside of a bend. Erosional channels last longer on the Middle Rio Grande, but there is little difference in persistence for the Sacramento or Trinity Rivers between erosional or depositional side channels. The Middle Rio Grande has a high suspended sediment load, so side channels in a depositional environment are more likely to be filled in with sediment. Side channels on the Middle Rio Grande typically have the shortest lifespan of the three rivers. A combination of high sediment loads, lateral migration, and high flow years in the 1980s and 1990s results in shorter persistence for many current Middle Rio Grande side channels. A companion study (Holste et al., 2022) analyzed constructed side channels and found their depositional patterns to be spatially variable. Elevation change mapping demonstrates that most deposition occurs at the side channel inlet, with some deposition at the outlet. Therefore, suspended sediment deposition at the interface with the main river appears to be a common disconnection process for constructed side channels in some rivers or reaches.

Information from this empirical study of natural side channel classification, morphology, formation, evolution, and persistence can be applied to designing new side channels for habitat restoration. First, designers and planners should consider the geomorphic reach of the proposed project and the context of multiple geomorphic reaches within a river system. There is a balance between identifying reaches that may have a side channel deficit and understanding that certain reaches naturally do not support as many side channels. After identifying a reach for side channel implementation, the next step is to consider side channel types appropriate for that reach. The level of planning and design effort should be scaled to the expected persistence and life cycle benefit of a side channel. For example, medial bars on the Sacramento River have a short longevity while backwater shoals, chutes, obstructions, and sills may persist for much longer. Once a side channel type is selected for a general location, the geometric parameters compiled for this study can be applied to develop the design dimensions. Finally, after design and construction is complete, side channels should be monitored to track their evolution, geomorphic change, and ultimately, whether they are providing the expected habitat benefits.

References

AECOM. (2013). Historic Context for Mining along the Trinity River. Prepared for U.S. Department of Interior, Bureau of Reclamation and Bureau of Land Management. Sacramento, CA.

Barko, V. A., & Herzog, D. P. (2003). Relationship among side channels, fish assemblages, and environmental gradients in the unimpounded Upper Mississippi River. *Journal of Freshwater Ecology*, *18*(3), 377–382. https://doi.org/10.1080/02705060.2003.9663973

Bartolino, J. R., & Cole, J. C. (2002). *Ground-water resources of the middle Rio Grande basin, New Mexico* (Vol. 1222). US Department of the Interior, US Geological Survey.

Carling, P., Jansen, J., & Meshkova, L. (2013). Multichannel rivers: Their definition and classification. *Earth Surface Processes and Landforms*, *39*(1), 26–37. https://doi.org/10.1002/esp.3419

Gilbert, G. K. (1917). Hydraulic-mining debris in the Sierra Nevada. United State Geological Survey Professional Paper No. 105. US Government Printing Office.

Gaeuman, D., & Stewart, R. (2017). Conditions favoring the persistence of secondary channel bifurcations: A multi-dimensional problem [Poster session]. American Geophysical Union Fall Meeting, December 11–15, New Orleans, LA.

Greimann, B., & Holste, N. (2018). *Analysis and Design Recommendations of Rio Grande Width* (Technical Report No. SRH-2018-24). U.S. Department of Interior, Bureau of Reclamation, Technical Service Center.

Holste, N., Bradley, D.N., & Byrne, C. (2022). *Geomorphic change of Middle Rio Grande restoration sites* (Technical Report No. ENV-2022-57). U.S. Department of Interior, Bureau of Reclamation, Technical Service Center.

Kleinhans, M. G., Ferguson, R. I., Lane, S. N., & Hardy, R. J. (2012). Splitting rivers at their seams: Bifurcations and avulsion. *Earth Surface Processes and Landforms*, 38(1), 47–61. https://doi.org/10.1002/esp.3268

Kondolf, G. M., Boulton, A. J., O'Daniel, S., Poole, G. C., Rahel, F. J., Stanley, E. H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C., Huber, H., Koljonen, S., Louhi, P., & Nakamura, K. (2006). Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecology and Society*, *11*(2). https://doi.org/10.5751/es-01747-110205

Krause, A. F. 2012. History of Mechanical Sediment Augmentation and Extraction on the Trinity River, California, 1912 – 2011. Technical Report TR-TRRP-2012-2 (Revised). Bureau of Reclamation. Trinity River Restoration Program. Weaverville, California.

Lane, B. A., Sandoval-Solis, S., Stein, E. D., Yarnell, S. M., Pasternack, G. B., & Dahlke, H. E. (2018). Beyond metrics? The role of hydrologic baseline archetypes in environmental water management. *Environmental Management*, 62, 678–693. https://doi.org/10.1007/s00267-018-1077-7

Makar, P. W., & AuBuchon, J. (2012). Channel Changes on the Middle Rio Grande. In *World Environmental and Water Resources Congress 2012: Crossing Boundaries,* 2556-2569.

Martin, K., Padilla, R., Nemeth, M., Donnelly, C., Terauds, V., Massong, T., Doster, R., Porter, M., Ford, C., Makar, P., & Baird, D. (2007). *Middle Rio Grande River Maintenance Plan Part 1 Report.* U.S. Department of Interior, Bureau of Reclamation, Middle Rio Grande Project, NM, Upper Colorado Region.

Medley, C. N., & Shirey, P. D. (2013). Review and reinterpretation of Rio Grande silvery minnow reproductive ecology using egg biology, life history, hydrology, and geomorphology information. *Ecohydrology*, *6*(3), 491–505. https://doi.org/10.1002/eco.1373

Mortensen, J., Dudley, R., Platania, S., & Turner, T. (2019). *Rio Grande Silvery Minnow biology and habitat synthesis.* American Southwest Icthyological Researchers, LLC and University of New Mexico.

Mount, J. F. (1995). California Rivers and Streams: The conflict between fluvial process and land use. University of California Press. Berkeley, CA.

Nanson, G. C., & Knighton, A. D. (1996). Anabranching rivers: Their cause, character and classification. *Earth Surface Processes and Landforms*, *21*(3), 217–239. https://doi.org/10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 4 Feb 2014, accessed 18 Oct 2020.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rosenfeld, J. S., Raeburn, E., Carrier, P. C., & Johnson, R. (2008). Effects of side channel structure on productivity of floodplain habitats for juvenile coho salmon. *North American Journal of Fisheries Management*, *28*(4), 1108–1119. https://doi.org/10.1577/m07-027.1

Rowley, W. D. (2006), *The Bureau of Reclamation: Origins and Growth to 1945, Volume 1.* U.S. Department of Interior, Bureau of Reclamation, Technical Service Center.

Singer, M.B. (2008). Downstream patterns of bed material grain size in a large, lowland alluvial river subject to low sediment supply. *Water Resources Research*, *44*, W12202, https://doi.org/10.1029/2008WR007183

Tetra Tech. (2004). *Habitat restoration plan for the Middle Rio Grande.* Prepared for Middle Rio Grande Endangered Species Act Collaborative Program Habitat Restoration Subcommittee.

Tetra Tech. (2014). *Ecohydrological relationships along the Middle Rio Grande of New Mexico for the endangered Rio Grande Silvery Minnow.* Prepared for U.S. Army Corps of Engineers, Albuquerque District.

U.S. Department of Interior (DOI). (2000). Record of decision, Trinity River mainstem fishery restoration final environmental impact statement/environmental impact report. Decision by the U.S. Department of Interior.

van Denderen, R. P, Schielen, R. M. J., Blom, A., Kleinhans, M. G., & Hulscher, S. J. M. H. (2016). Characteristics of side channels in the River Ain, France. In G. Constantinescu, M. Garcia, & D. Hanes (Eds.), *Proceedings of the International Conference on Fluvial Hydraulics (River Flow 2016)*, 220–228. CRC Press, Taylor & Francis Group.

van Denderen, R. P., Schielen, R. M., Straatsma, M. W., Kleinhans, M. G., & Hulscher, S. J. M. H. (2019). A characterization of side channel development. *River Research and Applications*, *35*(9), 1597–1603. https://doi.org/10.1002/rra.3462

van Dijk, W. M., Schuurman, F., van de Lageweg, W. I., & Kleinhans, M. G. (2014). Bifurcation instability and chute cutoff development in meandering gravel-bed rivers. *Geomorphology*, *213*, 277–291. https://doi.org/10.1016/j.geomorph.2014.01.018

Wheaton, J. M., Fryirs, K. A., Brierley, G., Bangen, S. G., Bouwes, N., and O'Brien, G. (2015). Geomorphic mapping and taxonomy of fluvial landforms. *Geomorphology*, *248*, 273-295.

Wohl, E. (2016). Spatial heterogeneity as a component of river geomorphic complexity. *Progress in Physical Geography: Earth and Environment*, *40*(4), 598–615. https://doi.org/10.1177/0309133316658615

Wohl, E. (2018). *Sustaining river ecosystems and water resources.* Springer. DOI 10.1007/978-3-319-65124-8_1

Wozniak, Frank E. (1996). Human impacts on riparian ecosystems of the Middle Rio Grande Valley during historic times. *Desired future conditions for southwestern riparian ecosystems—Bringing interests and concerns together: US Department of Agriculture, Forest Service General Technical Report RM–GTR–272,* 33-43.

Wright SA, Schoellhamer DH. (2004). Trends in the sediment yield of the Sacramento River, California, 1957-2001. *San Francisco Estuary and Watershed Science [online serial]*. Vol. 2, Issue 2 (May 2004), Article 2.

Appendix A

Description of ArcPy Automation for Calculation of Side Channel Attributes
Colin Byrne
September 24, 2020

Purpose
The Science & Technology funded study entitled "Side channel evolution and design: achieving sustainable habitat for aquatic species recovery" involved the identification of side channels in different years for several rivers. River lengths used for side channel identification were on the order of 100's of miles. Various attributes of the side channels were identified that may be influential in side channel evolution. Given the length of river and the large number of identified side channels across multiple rivers and years, calculation of numerous dimensional side and main channel attributes would likely take a substantial amount of time. Therefore, an automated workflow was determined to be the most efficient methodology for calculating many of the attributes that would otherwise need to be measured by digitization. The workflow was coded in python using ArcPy functions and the pandas library was used to calculate the output attributes. The toolbox that contains the resulting tool is entitled Side Channel Attribute Calculation (*SideChannelAttributeCalculation.tbx*). The script tool is titled Side Channel Attribute Automation. This document describes the inputs needed to run the tool and the resulting CSV file. The resulting CSV file includes the calculated attributes, which are also explained in detail here. Finally, the step-by-step documentation of the tool is included with each of the ArcPy functions called within the tool.

Tool Inputs

- Side channel centerline (Fig. 1) – each side channel should be labeled with a user defined river mile, name this attribute "RM"
- Main channel centerline (Fig. 1)
- Main channel polygon (Fig. 1)
- Output folder location
- Attribute that defines the starting location of your main channel centerline (Used to change the main channel into a route). There are four options:
    - UPPER_LEFT
    - UPPER_RIGHT
    - LOWER_LEFT
    - LOWER_RIGHT

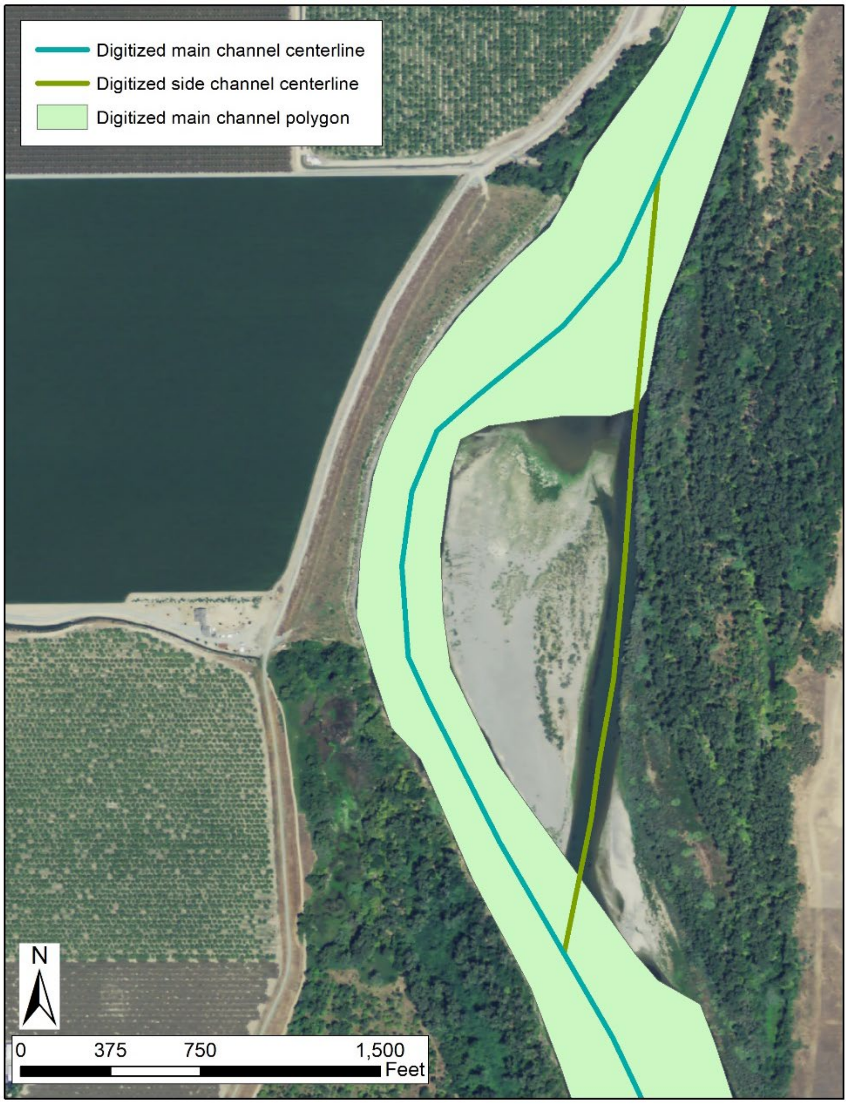


Figure 1. Example of the necessary input shapefiles for the Side Channel Attribute Automation tool.

Tool Output

Several shapefiles and three CSV files are output to the selected output folder while the tool is running. However, the CSV files named *sideChannelAttributes.csv* is the output of most interest and includes the following side channel attributes (further descriptions later in the document):

- River Mile ID
- Easting
- Northing
- Main channel mean top width
- Main channel inlet width
- Main channel outlet width
- Main channel length
- Main channel valley length (straight line distance)
- Inlet Angle (incorporates "ComputeSideChannelAngle" tool into larger tool)
- Outlet Angle (incorporates "ComputeSideChannelAngle" tool into larger tool)
- Side channel length
- Side channel valley length
- Side channel length to main channel length ratio

Calculation of Side Channel Attributes

Below is a description of how each final side channel attribute is derived. All reference to lines and polygons relates to Figure 2.

- RM ID – value retrieved from "RM" field of shapefile digitized from A to A'
- Easting – x-coordinate in the projection of the input shapefiles at point C
- Northing – y-coordinate in the projection of the input shapefiles at point C
- Main channel mean top width – area of main channel polygon divided by the main channel length from B to B'
- Main channel inlet width – length of cross-section that begins at point C
- Main channel outlet width – length of cross-section that begins at point C'
- Main channel length – length of main channel between points B and B'
- Main channel valley length – straight line distance between points B and B'
- Inlet Angle (incorporates "ComputeSideChannelAngle" tool into larger tool) – angle 'd' in degrees
- Outlet Angle (incorporates "ComputeSideChannelAngle" tool into larger tool) – angle 'e' in degrees
- Side channel length – length of side channel from point C to C'
- Side channel valley length – straight line distance between points C and C'
- Side channel length to main channel length ratio – ratio between the main channel length from B to B' and the side channel length from C to C'

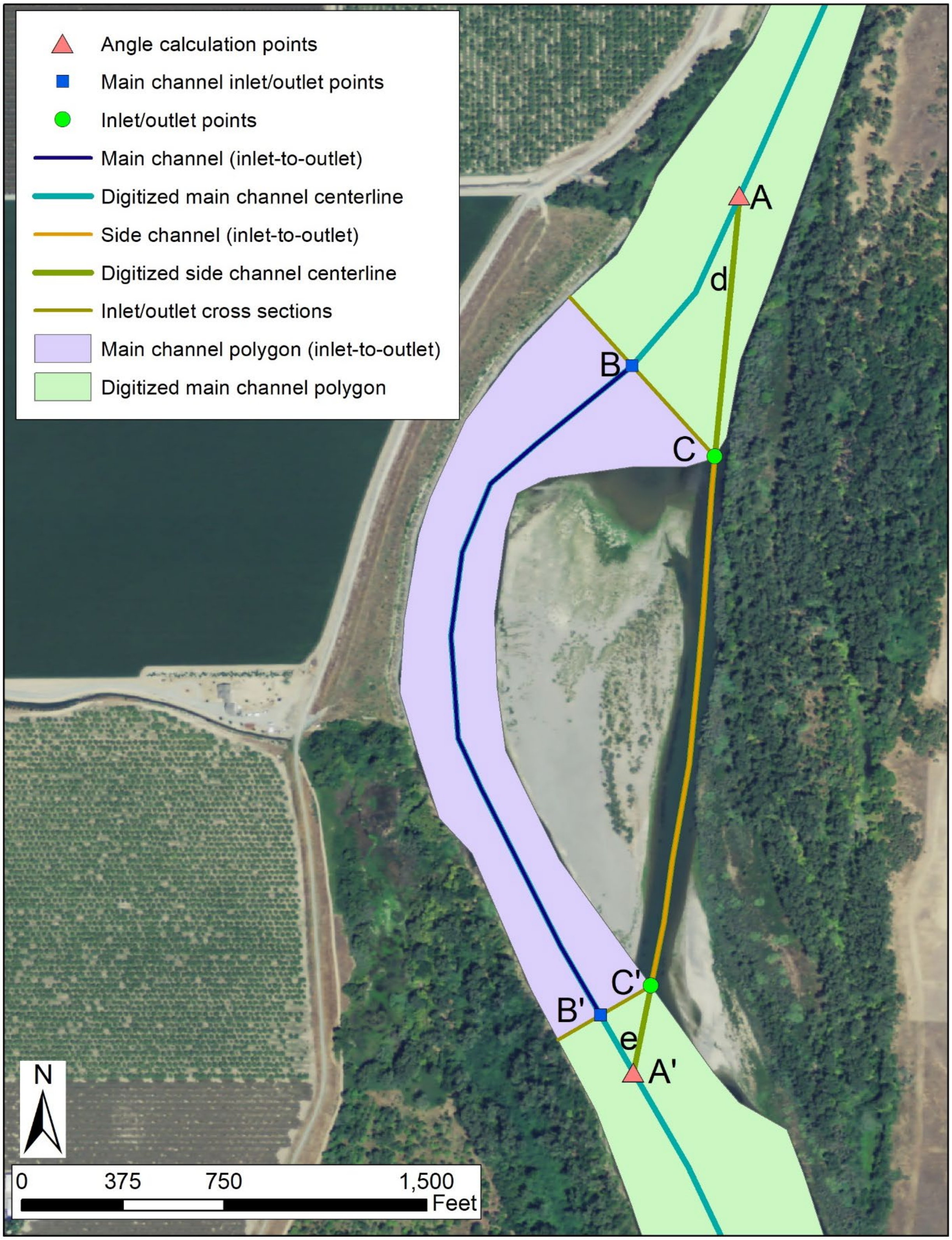


Figure 2. Key shapefiles created in the Side Channel Attribute Automation tool and subsequent used in the calculation of side channel attributes.

Assumptions and Tips

- Input shapefiles are in the projected coordinate system appropriate for calculation of lengths, widths, and areas
- Resulting length and width dimensions will be in feet or meters depending on the projection. This is important to keep in mind for analysis.
- The main channel centerline should be a single line digitized from upstream to downstream.
- The main channel centerline will follow the wider flow path in split channel flow situations if flow is likely not equal on alternate sides of mid-channel vegetated island.
- The side channels should all be labeled by an approximate river mile identifier. This river mile ID should be the same in different years if the same channel persists. The river mile identifier field should be named "RM". The RM field can be of any format.
- The main channel polygon can be many separate polygons if there are large lengths of river between side channels. However, if several main channel polygons are digitized, each polygon should extend in the upstream and downstream direction at least the length of the main channel centerline between the inlet and outlet of the side channel. In other words, the main channel polygon should be approximately 3 times the length the main channel adjacent to the side channel (1/3 upstream, 1/3 adjacent, 1/3 downstream of side channel).
- The angle calculation function was written by Nate Bradley.

Known Issues (should be double-checked after running tool)

- Angle calculation – if side channel intersects main channel at a main channel line vertex, the tool will not run properly. For now, a work around has been coded, so that outputs at these locations are documented as "NA" instead of an angle value. This allows for easy identification of problem side channel-main channel connections. Simply editing the side channel by moving the vertex of the side channel off the vertex of the main channel will solve the problem and the tool can be rerun to retrieve those values.
- When running the tool in ArcMap, input shapefiles cannot be dragged from the ArcMap window to the tool input box. However, if the same shapefile is selected from the appropriate file path method, the tool will run fine. Input shapefiles can be dragged from ArcCatalog to the tool input boxes.

ArcGIS/ArcPy Workflow

1) Digitize main channel centerline and determine which corner of the map is closest to the start of the main channel centerline
2) Digitize main channel polygon
3) Digitize side channel centerline
4) ID each side channel under an attribute named "RM" which stands for river mile – the river mile ID does not need to be exact. The main purpose is to label the same side channels with the same RM throughout the years

5) Call the Side Channel Attribute Automation script tool from the SideChannelAttributeCalculation toolbox, which will use the following steps to make calculations:
    a. Create Routes – change the main channel centerline to a route which will add distances along the centerline
        i. Inputs:
            1. Main channel centerline
            2. Corner of window closest to main channel starting point (e.g., UPPER_LEFT)
    b. Calculate side channel angles shapefiles – this gives you a multipoint shapefile with points aggregated by side channel ID
        i. Connection of side channel with main channel cannot be located at a vertex of the main channel line. The tool does not know how to deal with this situation because it extracts the vertices of the line segment of the main channel to calculate the angle.
        ii. Inputs:
            1. Main channel route
            2. Side channel centerline
    c. Add XY – This tool will add x-, y-coordinates of points where angles were calculated in addition to the m-value (distance along route) (OUTPUT in r)
    d. Convert the table containing angles to CSV file
        i. Inputs:
            1. Table of shapefile created in step c
        ii. OUTPUT – a CSV file with the following attributes:
            1. Inlet angle
            2. Outlet angle
    e. Erase tool – erase portions of side channel lines within the main channel polygon, leaving only the side channel segment outside of the main channel
        i. Inputs:
            1. Main channel polygon
            2. Side channel centerline
    f. Add Geometry Attributes (LENGTH, LINE_START_MID_END) – add attributes to side channel line
        i. Inputs:
            1. Side channels with main channel segments erased (output of step b)
    g. Feature vertices to points – extract the start and end points of the erased side channel lines (output of step c/d)
        i. Inputs:
            1. Side channels with main channel segments erased (output of step c) now with lengths associated (output of step f)
    h. Add XY – add coordinates to the endpoints of the side channels, these points are located at the inlet and outlet of the side channel
        i. Inputs:
            1. Feature vertices points created in step g

i. Near – locates the closest points of the main channel from the inlet and outlets of the side channels
    i. Inputs:
        1. Feature vertices points with XY coordinates created in step h
        2. Main channel route created in step a

j. Make XY Event Layer – Create temporary points at the nearest main channel location
    i. Inputs
        1. the points created in step i
        2. Use current map projection

k. Feature to Point – make the event layer a point file
    i. Inputs
        1. the points created in step j

l. Add Field – Add field columns that are named Tval, FAR_X, FAR_Y
    i. This adds fields to then calculate a point to extend line to
    ii. Inputs:
        1. Main channel center points created in step k
        2. Tval can be float
        3. FAR_X and FAR_Y should be double

m. Field Calculator (Calculate Field) - Calculate the three fields above, to create cross-sections that extend 1000 m (this just ensures that all cross-sections reach the far side of the channel
    i. Tval = (!NEAR_DIST! + 1000) / math.sqrt((!NEAR_X! – !POINT_X!) ** 2 + (!NEAR_Y! – !POINT_Y!) ** 2)
    ii. FAR_X = !POINT_X! + !Tval! * (!NEAR_X! – !POINT_X!)
    iii. FAR_Y = !POINT_Y! + !Tval! * (!NEAR_Y! – !POINT_Y!)

n. XY to line – creates the new 1000+ unit long lines based on the calculations in step m
    i. Inputs:
        1. Main channel center points created above with new values as of step m

o. Add field – Convert RM to a text attribute to make selectable by attribute
    i. Inputs:
        1. Main channel center points output from step q
        2. Field name - RMtxt

p. Calculate field – Convert the float label to a string
    i. RMtxt = str(!RM!)

q. Points to line – Create lines that connect the inlet cross-section to the outlet-cross-section
    i. Inputs:
        1. Table from main channel using RMtxt as Line Field

r. Spatial join – give cross-section lines the same RMtxt values as the center points they cross (opposite direction of above step q)
    i. Inputs
        1. Cross-section lines last used in p (and joined to points in q)
        2. Cross-section channel center points
        3. Try to only include RMtxt
s. Add field – add Area field to center point table
    i. Inputs:
        1. Center point shapefile
t. Loop through center point table using cursor with the input being the main channel center point shapefile table
    i. Retrieve RMtxt value from row in table
    ii. Use RMtxt value to output selected cross-sections with same RMtxt value
        1. Feature to feature
            a. Output are cross-sections for specific side channel
    iii. Feature to Polygon - Split main channel polygon
        1. Inputs:
            a. Main channel polygon
            b. Cross-section lines with selected cross-sections corresponding to the correct RMtxt
        2. Split channels that are within the main channel are filtered to use subsequently to avoid issues if long inlet and outlet cross-sections intersect due to a meander bend.
    iv. Output select RM connection lines to use in the loop using the RMtxt value to select appropriate connection lines
    v. Find centroids of split polygons
    vi. Find centroids of cross-section connection lines
    vii. Calculate distances of split polygon centroid points from the connection line centroid point (which is closest to the side channel) – Near tool
    viii. Retrieve value of the Near FID of the closest polygon
    ix. Export the centroid point that is closest to the connection line centroid
    x. Select polygon that contains the nearest centroid point
    xi. Output selected polygon to new shapefile
    xii. Add geometry - Calculate area of polygon
    xiii. Retrieve value of area for the selected polygon
    xiv. Clip and merge – clip the long cross-sections to within the main channel area and combine those with other side channel cross-sections already created
        1. Inputs:
            a. Lines created in step n
            b. Main channel polygon
    xv. Write area value to the Center point table
u. Add geometry (LENGTH) to the cross-section shapefile created in the loop above
    i. Inputs:
        1. Clipped lines created in step t

v. Spatial join to XS points
    i. Inputs:
        1. Main channel center points last used in m
        2. Clipped cross-sections create in t
w. Locate features along routes to create a table with distances along main channel route and all other attributes
    i. Inputs:
        1. Point features created in step j
        2. Main channel route created in step a
        3. Search distance must be set to 1
    ii. OUTPUT – a CSV file with attributes necessary to calculate the following attributes:
        1. Inlet x-coordinate
        2. Inlet y-coordinate
        3. Main channel length
        4. Side channel length
        5. Side channel valley length
x. Using the two tables created up to this point (steps d and w), use pandas to calculate the final necessary outputs and extract to final CSV for copying and pasting to main Excel spreadsheet.