IDENTIFYING AND UNDERSTANDING THE HISTORICAL EXTENT OF SIDE CHANNELS ON THE MISSOURI RIVER

by

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Abstract

The US Army Corps of Engineers (USACE) has begun side channel restoration projects on the Missouri River as part of the Missouri River Recovery Program. The USACE acquires land on the Missouri River needed to develop fish and wildlife habitat. There is a need to prioritize which land to purchase on the Missouri River. High priority land would be areas that had side channels and can be constructed to restore ecosystems to a more natural state. Much of the river has since been dammed, straightened, and channelized starting heavily in the mid 1890's, and historical side channels have been eliminated, leaving little information to guide USACE efforts to restore them. My thesis documents the historical distribution of side channels on the Missouri River between St. Louis and Kansas City and explores the relationships between side channel location and a variety of potential driving variables, including channel sinuosity, valley width, valley slope and the presence of large confluences. This is the first know study to document the historical extent of side channels on a major river system, and it is also the first to quantitatively explore driving variables of side channel formation. The historical analysis revealed abundant side channels in the late 1800's, with a dramatic decline into the early 1920's as engineering works on the river began in earnest. Results also show that high channel sinuosity and the presence of a large confluences are the two variables most correlated with side channel formation. Based on documented frequencies and locations of historical side channels, recommendations for specific side channel restoration opportunities are also highlighted.

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Dedication

A chance encounter at a K-State job fair brought me to Jason Sheeley. Mr. Sheeley being true purple blooded alumni gave me an unbelievable opportunity, an internship with the Army Corps of Engineers in Kansas City Missouri. To work with this great organization and be able to apply my studies on a daily basis was absolutely a dream come true. I thank him for all he has done for me and the experience I was given. In working at the Corps of Engineers I met a lot of memorable people but I would like to express my gratitude to Tracy Brown for giving me unquestionable support and I can't say enough to thank her for her sound advice and being a wonderful mentor.

Secondly, I would also like to express my gratitude to Professor Melinda Daniels. To describe advisor the Thesaurus uses words like, aide, authority, coach, confidant, consultant, director, expert, guide, mentor Professor Daniels has been all those. She has been an amazing force in pushing, prodding, and assisting me along the way to complete my research. She has not only guided me to complete my work, but also has helped me understand myself along the way. It is people like Professor Daniels that make K-State the exceptional place it is.

Lastly, I have to thank my family. Without their love, support and encouragement I would not have been able to make it through this experience.

Chapter 1 - Introduction

The Missouri River basin drains a land of over 1,372,700 km^2 covering approximately one-sixth of the continental United States (National Research Council, 2002). Near the end of the nineteenth century, the Missouri River's length was measured at 4,097 km from Three Forks, Montana to St. Louis, Missouri (Missouri River Commission, 1895). Historically the Missouri River was a meandering river with complex side channels. The historic river refers to the Missouri River before engineering efforts. Large, looping meanders of the main channel, some of which were nearly circular and that measured tens of miles in circumference, were prominent features of the river. However, beginning in the late 1880's, extensive engineering works have simplified and straightened the river, eliminating side channels and many meander bends. As a result, the Missouri River's length today is 3,767 km, a shortening of roughly 330 km (USACE, 2001). Today, the Missouri River is the subject of much concern regarding native species declines thought to be linked to the alteration of river habitats. In response, the United States Army Corps of Engineers (USACE) has been tasked with restoring river habitat features, including side channels.

This restoration task is complicated by an almost complete lack of knowledge regarding river side channel abundance or dynamics. For example, on the Missouri River, there is no numerical data regarding the historical abundance of side channels or where they may have been located in relation to the modern river channel. The modern river refers to the Missouri River after the efforts to stabilize the banks and engineer the river for better navigation. Despite this lack of information, the USACE has started restoration projects on the Missouri River as part of the Missouri River Recovery Program which enables the Corps acquires land on the Missouri River needed to develop fish and wildlife habitat. Initial side channel restoration projects have met with mixed results. To increase the likelihood of successful side channel restoration, the USACE would like guidance as to where side channels were historically present along the Missouri River as well as an increased understanding of the relative scale and persistence of these features. This information will be used to prioritize which land the USACE purchases for side channel restoration on the Missouri River.

The purpose of this thesis is to document the historical distribution of side channels along a 643.7 km section of the Missouri River between river miles 0 and 400 (St. Louis to Kansas City) and to evaluate potential driving forces of side channel formation and maintenance. My working hypothesis is that the distribution of side channels on the Missouri River was concentrated in reaches that were highly sinuous, had wide valley widths, low valley slopes and contained major confluences.

Thesis Structure

Chapter two reviews the rather limited literature on fluvial side channels, what we already know about the channel structure of the Missouri River, as well as the literature on fluvial applications of spatial decision support tools. Chapter three details the procedures followed for historical data collection and analysis, while Chapter four presents the results of the historical analysis of side channel abundance and presents analysis relating the measured abundances to reach-scale system variables. Chapter five presents discussion and conclusions.

Chapter 2 - Literature Review

2.1 Geomorphological and Ecological Significance of Side Channels

Studies of river systems have historically focused on the longitudinal patterns present along main channels (e.g. Vannote et al., 1980). However, more recently the river literature has broadened its focus to include lateral connectivity with floodplains (Stanford and Ward, 1993; Roach et al., 2008), yet there have been very few investigations of lateral fluvial channel features such as those formed when the main channel bifurcates into a large main channel and one or more smaller side channels that run parallel to the main channel for a distance and then rejoin the main channel downstream. The lack of research on these side channel features is likely due to their widespread scarcity on modern large rivers, which have been heavily engineered to support navigation, power generation, water supply and flood control uses.

One of the only published studies of side channels and their dynamics originated from a study of the Rhine River in the Netherlands (Barneveld, 1994). The study is largely conceptual, proposing the reopening of old side channels on the Rhine to improve the ecological value of the river and restore some of the lost riverine habitat diversity. A motivation in the Rhine's case is the need to meet requirements proposed by the World Wide Fund for Nature. These requirements include discharge through side channels, with mixtures of flowing and still water areas with velocities ranging from .20 to .80 ms^{-1}, snag and water plants on banks and bed, and a quasi-stable and controllable channel (Barnevald, 1994). Based on assumptions of discharge diversion through the side channels, Barneveld (1994) theorizes that the change hydrodynamics will alter sediment transport within the main channel and recommends that this should be taken into account when designing side channel restorations. Unfortunately, this study lacks enough field data to support more detailed recommendations or guidelines for side channel restorations.

The other published geomorphological study of a side channel focuses on a reach on the Missouri River called Lisbon Bottoms, located on the Missouri River near the town of Lisbon. In the flood of 1993, the Lisbon Bottom levee was breached and the floodplain was inundated from bluff to bluff. During this large over-bank flow event, a side channel formed as a chute cutoff (a channel that scours across the floodplain "cutting off" a meander bend, creating a shorter route in the downstream direction). After the 1993 flood receded, the levee breaks were not fixed, and the chute was allowed to evolve with minimal human interference until the 1996 flood which enlarged the side channel. After this, the USACE constructed control weirs to limit the discharge conveyance into the side channel while still permitting some connectivity. Monitoring of this side channel has revealed abundant shallow water and slow water habitat compared to main channel conditions, and fish, including the endangered pallid sturgeon, are utilizing the side channel habitat (Jacobson, 2001).

Relevant to the Lisbon Bottoms side channel case study are other studies of chute cutoff formation, which appears as though it may be a primary side channel formation mechanism. Unfortunately, studies of chute formation are also rare. In one of the most extensive studies, Hooke (2004) studied the occurrence and causes of multiple cutoffs on the meandering Bollin River located in the UK using 20 years of historical monitoring records. Her study concluded that the sinuosity of the River Bollin reached a critical value of 1.4,which then precipitated a cluster of chute cutoff formations from 2000-2001. Another study showed that meander cutoff and oxbow lake production was positively and exponentially related to sinuosity. The frequency of oxbow lakes showed to be higher with reaches that were highly sinuous (Constantine, 2008). It is important to note that the Lisbon Bottoms side channel formed in a highly sinuous reach of the Missouri River (Jacobson, 2001).

Sinuosity is an important value when looking at river formation. Sinuosity gives an impression of great activity and not being a favorable trait for today's modern structured river. A highly sinuosity channel can have conditions that are relatively stable (Schumm, 2005). A straight channel has a sinuosity of 1.0. If a channel has a sinuosity of 1.5 than the channel length is one-third longer than the valley distance (Schumm, 2005). Kiss et al. study of the lower Tisza River showed when cut offs declined due to regulation works the sinuosity and channel length declined while straight sections and the river slope doubled.

Studies of side channels have focused primarily on their role in providing unique fish habitat diversity. Historic large rivers channels are thought to have had 3 to 7 times more shallow water habitat (across all discharges ranges) than modern channels, regardless of flow regime. Side channels were likely a large source of this shallow water habitat and important features providing the habitat diversity to support high biological diversity. While shallow water habitat is present even in modern engineered rivers at low flow, when discharge increases these habitats are largely eliminated. However, side channels would have continued to provide shallow water and slow water habitat even at high discharges (Jacobson, 2004). Yet no studies have documented the historical extent of these side channel features.

2.2 The Missouri River

Historically the Missouri River was a shallow, wide braided river with side channels and backwaters. Side channels provided off-channel aquatic habitats and increase hydrologic connection of valley bottom to main channel (Jacobson, 2004). These side channels chutes provided increased areas of sandbars and shallow, slow water habitats thought to be substantially diminished in the modern Missouri River (Jacobson, 2004). Channel complexity tends to be reduced by the changes that channel bank infrastructure produces like loss of access to side channels (Florsheim, 2008). On the Lower Missouri River, changes in channel geometry and flow dynamics clearly coincided with the time of wing dam construction and other engineering activities (Pinter, 2005). A study for the Mississippi River stated structural modifications of the river mostly began in 1868 when the U.S. Corps of Engineers began removing snags and conducted dredging to improve steamboat navigation (Anfinson, 2003). Additional dredging and construction of wing dams and closing structures were authorized in 1878 to further deepen the navigation channel. These efforts continued into the early decades of the 20th century when by 1930 the river between Minneapolis and St. Louis was lined with wing dams, and closing dams blocked off most side channels (Anfinson, 2003). These river features provided unique habitats to native species that had evolved to only survive in these conditions. The lack of side channel habitats has lowered the number of sand bar areas that formerly provided nesting habitat for the threatened piping plover and endangered least tern (Poff, 1997). Egg numbers in nests that fish species produce become sensitive to decline when water circulation changes under inflated flow regimes (Carlisle, 2010). Many avian species have evolved to take advantage of the exposure of the surfaces of low bars and floodplains for nesting purposes, migration stopovers, or forage (Graf, 2006).

2.3 River Restoration Decision Support Tools

There has been a big push to recreate side channels to restore the loss of off-channel habitats. Off-channel aquatic habitats restorations should reverse the engineered simplification of the channel and thereby provide greater channel complexity. The degree to which streamflows are controlled in many river systems and the pervasiveness of streamflow alteration across the US suggest that a national priority of restoring natural streamflow magnitudes could be broadly implemented and would produce widespread and measurable ecological dividends (Postel and

Richter 2003). In addition, it has been recognized that engineering the Lower Missouri River channel increased current velocities and depths at the expense of slow, shallow water important for survival of young and juvenile native fish. Efforts have focused on recreating side channel chutes and increasing channel top width to increase habitat diversity and provide slower, shallow water (Jacobson, 2004). Process-based restoration promotes floodplain functions such as inclusion of secondary channels that rely on connectivity (Florsheim, 2008).

The loss of native species and their habitat has prompted restoration efforts on the Missouri River. Collectively, Missouri River basin development has contributed to listing as endangered, threatened, or rare by state or federal agencies seven species of plants, six insects, two mussels, 16 fishes, four reptiles, 14 birds and three mammals (Galat, 2000). The conservation organization, American Rivers, listed the Missouri River as North America's most endangered river in 1997 (American Rivers, 1997). It is only within the last half century that social opinion and cultural perspectives have changed from viewing rivers as mere transportation routes or sources of commodity water to seeing them as landscapes, hydrosystems, and ecosystems worthy of preservation and restoration (Graf, 2001). River restoration is returning a river ecosystem to a close approximation of a condition that existed prior to Euro American alteration (Sparks, 1998). The guiding principle of most restoration projects is to change existing degraded conditions into ones that are more natural. Massive public investments in restoration now face the primary questions: what is natural for any particular stream, and given the pervasive effects of dams, what are realistic restoration goals? (Graf, 2001). Sparks et al. (1998) demonstrated that simply looking at pre-1900 maps of the Illinois and upper Mississippi Rivers reveals much about the design and functioning of the pre-dam rivers that could be applied to river restoration today. For example backwaters and floodplain lakes were historically much smaller during the low-flow season than they are today because the modern navigation dams do not allow the river to drop as low as it once did naturally. The floodplain lakes previously had winds that would blow over large expanses of water and build large waves that resuspended sediments. Because the permanent aquatic areas were much smaller, more of the floodplain was occupied by trees and other terrestrial plants that served as windbreaks and anchored the soil during spring floods. Therefore, even though the water surface area expanded during the flood, waves were not as severe a problem as they are now (Sparks, 1998). The same type of historical analysis can be done for the Missouri River and can help guide current Missouri River management and restoration efforts.

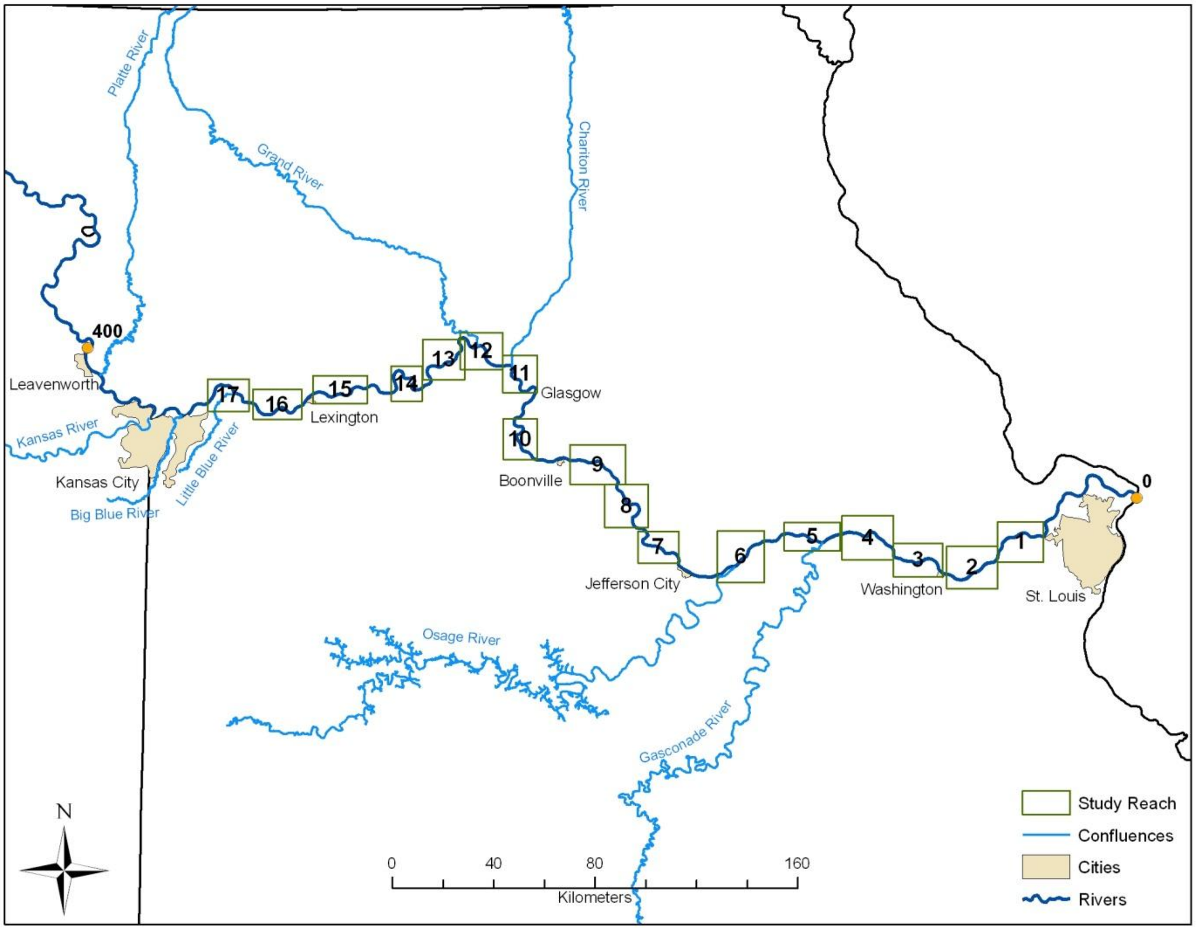
Graf (2001) proposes using locational probability maps to help gain insight on restoration and other management projects. A locational probability map based on observations of past conditions provides a statistical view of the geography of the river that reflects its most likely arrangements (Graf, 2001). Using this approach will provide historical information about the spatial characteristics of fluvial systems that will afford insight into probable patterns of behavior. Graf (2001) states historical data can define other spatial aspects of the river reach such as the most locations for bars, islands, and meanders. Aerial photos provide useful historical data that can be used to explore geomorphic change, including the dynamics of fluvial landforms (Trimble, 1991). Micheli and Larsen (2011) used field survey and aerial photography to measure patterns of river channel migration and cutoff between 1904 and 1997. Using these data sources they were able to look at a span of 93 years and process new data. Looking at different time-series of the river system can show the evolution of the river channel (e.g. Tiegs, 2005; Hooke, 2008; Funk, 1974). Tiegs and Pohl (2005) used a channel probability map to study channel change and areas modified by varying degrees by flood flows to the lower Colorado River. These studies highlight past research that looks at fluvial dynamics to predict how to modify river conditions now.

Chapter 3 - Methods

3.1 Study Area

The study area is the 400 mile reach of the Missouri River between St. Louis, Missouri and Kansas City, Kansas. Urbanized stretches of the river were excluded from the study area because they are more heavily engineered and would not be able to have restoration areas. This section of the river was chosen because it is on the Missouri River in the Kansas City district of the US Army Corps of Engineers which has the least number of USACE owned side channel mitigation sites. Examining the historical distribution of side channels in this area will help evaluate which floodplain sections should be purchased and engineered for side channel restoration purposes. Seventeen study sub-reaches, each 15 river miles in length, were demarcated within the larger study area (Figure 3.1). Study reaches break the study area into sections that exclude river segments with urban areas. River confluences were included within study sub-reaches.

Figure 3.1 Study Reaches for Missouri River Miles 0 to 400



3.2 Data Sets

This study analyzes three different temporal data sets to identify where the historical side channels were located and distributed with the study sub-reaches. These data sets were the 1879 and 1894 Missouri River Commission Surveys and a 1928 USACE commissioned series of aerial photographs.

The Missouri River Commission conducted land cover surveys along the river and identified water features in 1879 and 1894 (Figure 3.2 and 3.3). The Corps digitized and georeferenced these paper land surveys for each year. These maps were originally at a scale of

1:63,360 with a scanned pixel resolution in ArcGIS of 4.6 m. Original maps were in latitude-longitude, and scanned georeferenced images were in the Albers projection. The 1879 historic map series had 14 sheets to display the river from St. Louis to Kansas City. A process to digitize the land cover was broken down to analyze each sheet. Polylines circled the map sheet illustration to separate each land cover category. The polylines were converted to polygons of each category. Data information was inserted in the attribute table to label all the land cover classifications. Each land cover classification was symbolized as a different color. All classes in the project fit into one of three categories: aquatic, wetland, or upland. The mitigation restoration project uses a combination of two classification systems: The National Wetlands Inventory system (NWI) and the National Land Cover Data Set (NLCD). The aquatic and wetland portions of this guide borrow for the NWI system and the upland features are taken from the NLCD system. The NWI was developed by US Fish and Wildlife Service and wetland ecologists. This system can be used for delineating wetlands based on plants, soils, and water conditions. The NLCD set was created by many different agencies for decisions related to managing natural resources. NLCD is a modified system from the Anderson system, which has eight main classes with 21 sub-classes. Anderson system classes are derived from aerial photography which makes it different to derive classes from Landsat data. So, some of the Anderson level classes were consolidated into a single NLCD class. The codes from the mitigation recovery program are: 11 Main Channel of the Missouri River, 12 Side Channel of the Missouri River, 13 Side Channels and Tributaries, 14 Shallow Water, Chutes, and Channels, 15 Lakes, Ponds, and Scour Holes, 30 Barren, 40 Deciduous Forests, 50 Shrubland, 70 Grassland, 80 Cultivated, 91 Forested Wetland, 92 Emergent Wetland, 93 Scrub Scrub Wetland. The 14 sheet shapefiles were merged into a single shapefile that represented the river from St. Louis to Kansas City. The land cover polygons were reviewed and corrected by Corps GIS personal. Topology was run on the shapefile to ensure the data has no topological errors or gaps. Topology is important for the accuracy of the area calculations. The same process was applied to the 15 1894 historic map series sheets. Since the classification codes are identified, the analysis queried and assessed the side channels codes for both data sets. The information was copied into a new shapefile named 1879_sidechannels.shp and 1894_sidechannels.shp.

Figure 3.2 Example of Commission Survey 1879 (Study Reach 9)

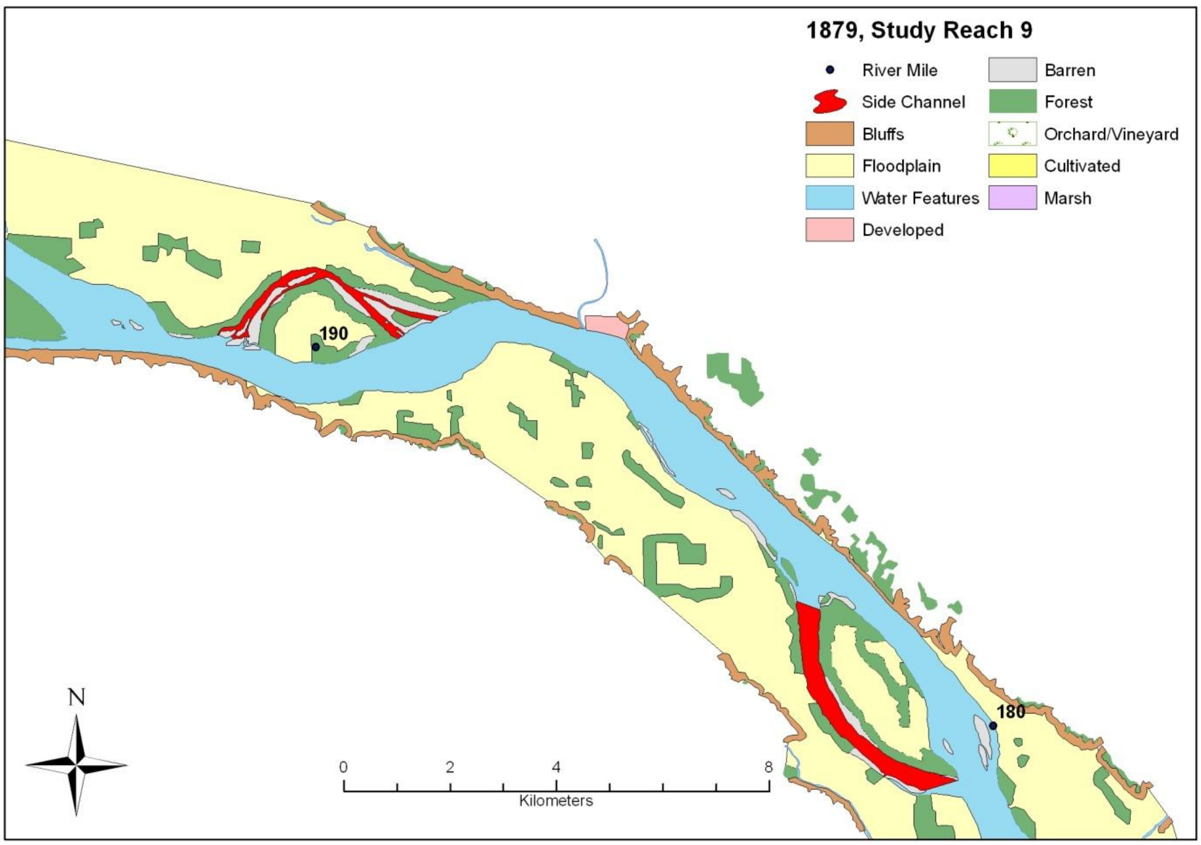
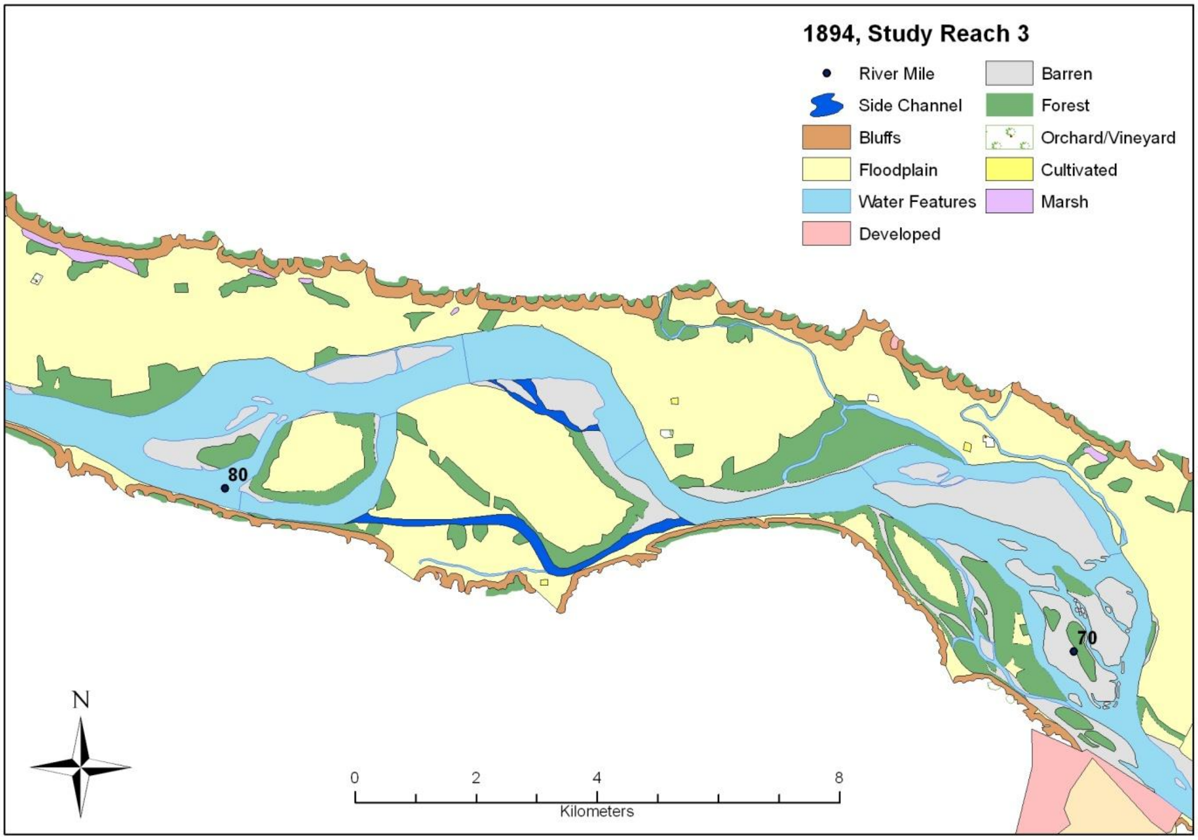
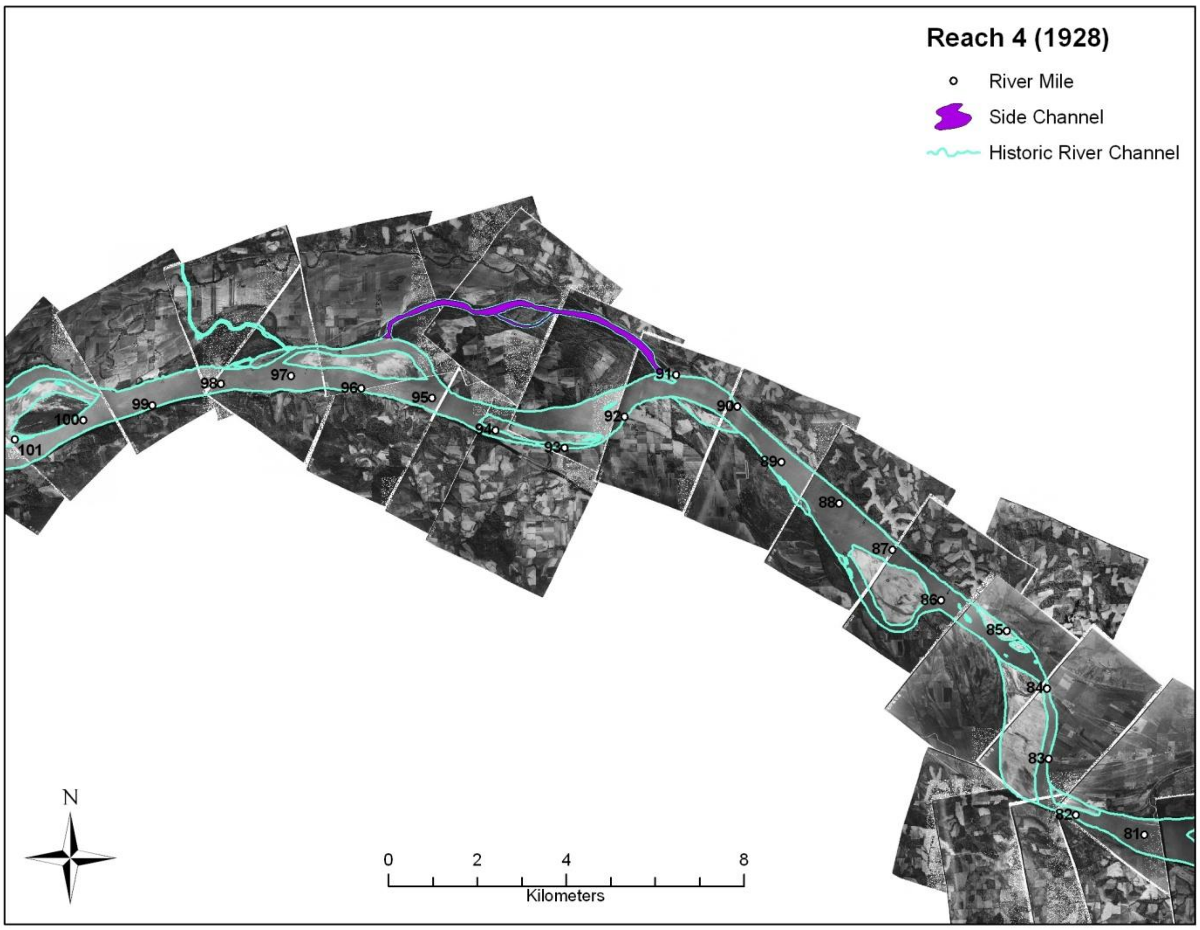


Figure 3.3 Example of Commission Survey 1894 (Study Reach 3)



The other data set used for this thesis consists of the aerial photos (black and white) taken in 1928 for the US Army Corps of Engineers (Figure 3.4). This photo series represents the most recent available data set prior to major engineering works and channel alternation. The Corps scanned and georeferenced the 496 separate orthophotos using the North American Datum 1983 Universal Transverse Mercator coordinate system. The channel banks and sand bars were digitized to create a historic river channel shapefile. To determine side channels locations in these photos, I visually interpret water that branched off the main channel using heads-up on-screen digitizing. Side channels were delineated as the stream channel segments that departed from the main channel but fully reconnected further downstream. Other criteria to delineate side channels used was branches had to be no wider then 25% of the main channel width. Side channels were identified to have visible shrubbery between the feature and main channel. The study will also identify areas with meander scrolls. A shapefile named 1928_sidechannels.shp was digitized to display the side channel areas in 1928.

Figure 3.4 Sample of Side Channel Delineation on Missouri River 1928 orthophoto series (Study Reach 4)



3.3 Analytical Procedures

3.3.1 Derivation of Variables

Main channel variables calculated for each study sub-reach include side channel frequency, side channel area, total channel area, side channel density, and main channel length. Side channel frequency identified how many side channels are present in each reach by each data set year. Side channels had to be completely in the study reach boundaries to be counted. Internal operations within ArcGIS permitted the measurement of total area for each side channel polygon. The sum of all side channel areas was calculated in each sub-reach for 1879, 1894, and 1928 data sets separately. Total channel area was also calculated using ArcGIS operations which included both main river channel area and side channel areas. Side channel density is calculated as the total area of side channels divided by the total channel area. Channel length is the centerline of the channel area polygon for each year measured between the study reach boundaries.

The river valley variables for this study are average valley width, valley length, sinuosity, and average valley slope. All river valley variables are calculated using the current conditions of the Missouri River. The measuring tool in ArcGIS was used to measure the width of the Missouri River from bluff to bluff each river mile in each 15-mile study sub-reach, producing valley width that is an average of 15 measurements within each study sub-reach. Valley length was calculated by using the midpoint tool under the editor toolbar in ArcGIS. The midpoint tool created a point mid way between the valley bluff to bluff layer. A midpoint was calculated every river mile in the study sub-reach. A line connecting all the midpoints represents the valley length for the study sub-reach. Sinuosity was calculated using the channel length values divided by the valley length values. To produce the valley slope variable, a raster dataset of the elevation profile of the Missouri River area was extracted by mask to the bluff to bluff shapefile. The contour tool was run in ArcGIS with the raster dataset as its input. The contour tool created a shapefile with contour lines every 1.524 meters on the floodplain. The river bank elevation was recorded every river mile. The bluff elevation was recorded for the same area. The elevation change is the river bank elevation value subtracted by the bluff elevation value. The valley slope is an average of the 15 measures of elevation change in each study sub-reach. Side channel metrics were then regressed against river, valley and network metrics.

To determine any statistical relationship between side channel locations and stream confluences, a spatial autocorrelation test was performed using the ArcGIS Moran's I tool. Spatial autocorrelation tests allow one to evaluate the general statistical properties of data variables in geographic space (Legendre, 1993). First, a major tributary layer was created by querying the 2007 ESRI major rivers dataset. Tributaries over 115 km in length were considered the major tributaries. The confluence point is where the major tributary meets the Missouri River. The distance between the midpoint of each side channel to the closest confluence point was calculated in kilometers. In the attribute table the calculate geometry feature calculated the length of the polyline distance in kilometers. Once the distance was known for every side channel to the nearest confluence the Moran's I tool was run. A shapefile with all the side channel properties was the input feature class and the distance was the input field. The Moran's I tool was run using inverse distance for the conceptualization of spatial relationships. Euclidean was the distance method used which specifies how distances are calculated when measuring spatial autocorrelation. The Moran's I tool runs and returns results in the tool window. Negative (positive) values indicate negative (positive) spatial autocorrelation. Values range from −1 (indicating perfect dispersion) to +1 (perfect correlation). A zero value indicates a random spatial pattern. To test statistical significance, the Moran's I values are transformed by the ArcGIS tool to Z-scores. Moran's I z-scores than 1.96 or smaller than −1.96 indicate significance at the 95% confidence level (Moran, 1950).

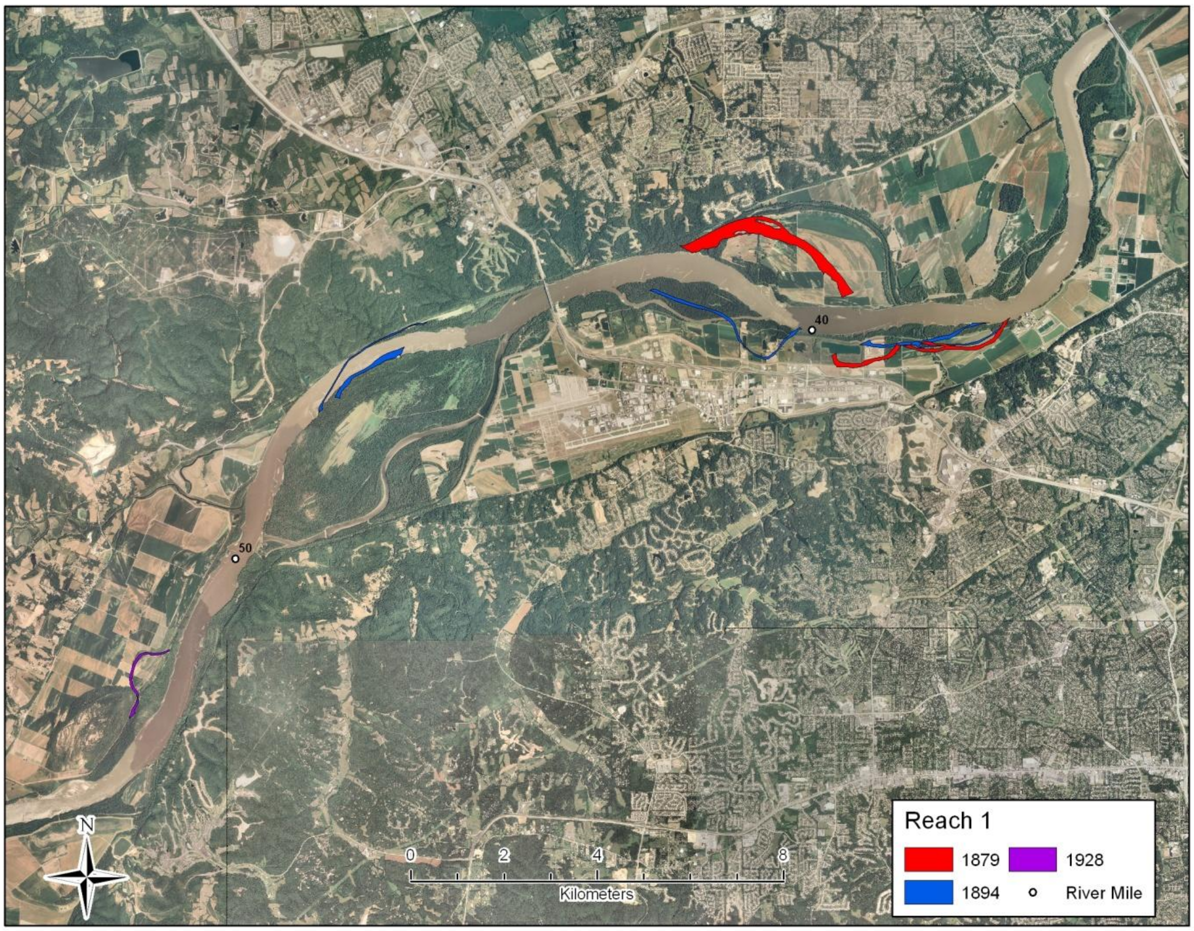
Chapter 4 - Results

4.1 Historical Extent of Side Channels

The 1879 Missouri River Commission Survey indicated that there were 56 side channels with a total side channel area of 17,468,344.69 m^2. The number decreases to 37 side channels in 1894 with a total side channel area of 12,878,819.25 m^2. Aerial photos in 1928 display the locations of 28 side channels with the total area of 6,392,955.93 m^2. The river was broken into sub-reaches to analyze the data in longitudinal sections. For each sub-reach, the channel configuration was mapped using ArcGIS to illustrate the locations of the side channels through the entire study period (1879-1928). The polygons represent side channels that were present in 1879 (red), 1894 (blue), and 1928 (purple). The aerial imagery in the background is derived from the 2007 National Agriculture Imagery Program (NAIP) imagery.

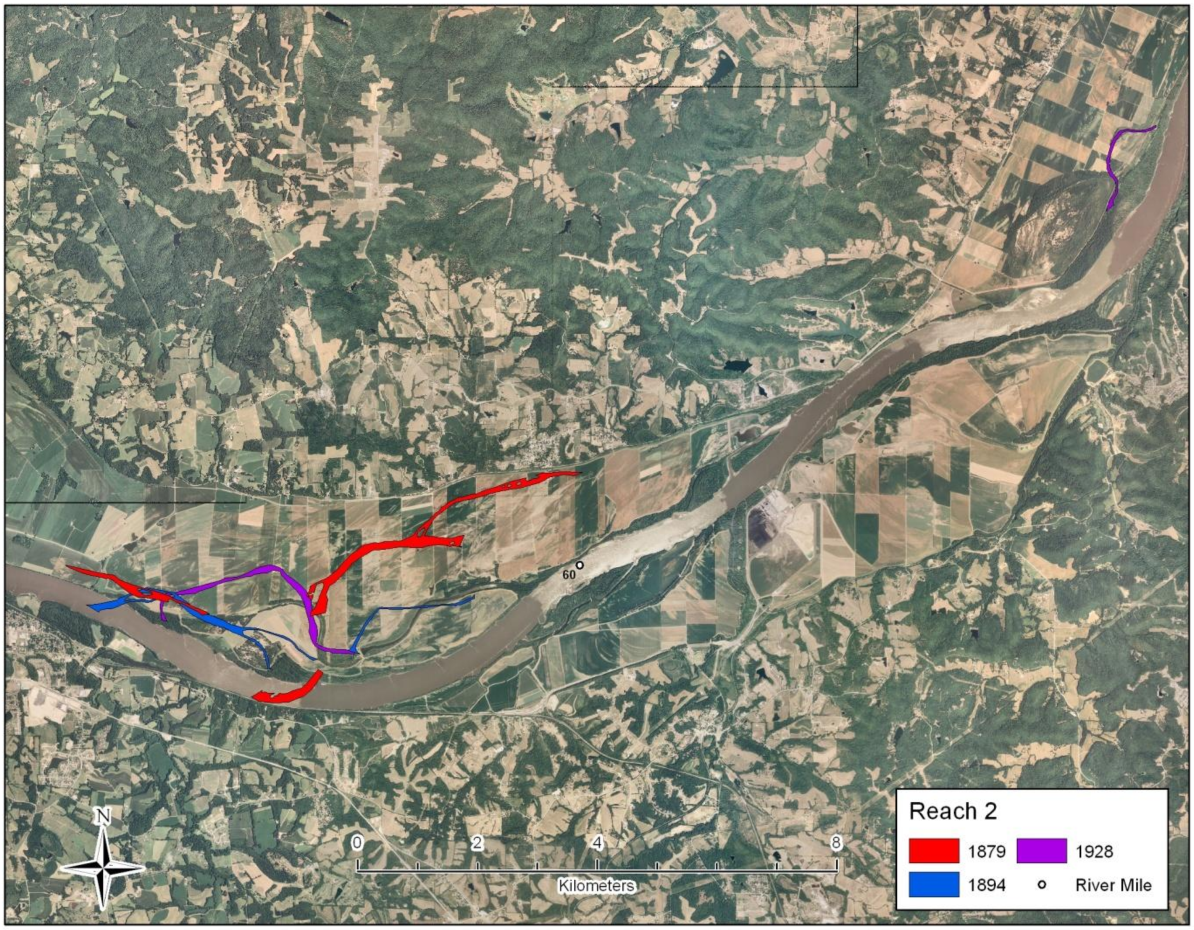
The first sub-reach is the closet to the confluence of the Missouri River and the Mississippi River and is located at river miles 37 to 52 (Figure 4.1). Reach 1 contained 7 side channels which were all close to the current river channel. In 1879, 3 side channels were located relatively close to each other. Side channel frequency increased by 1894, with 4 side channels but then declined to zero by 1928.

Figure 4.1 Distribution of Historical Side Channels on Missouri River Study Reach 1



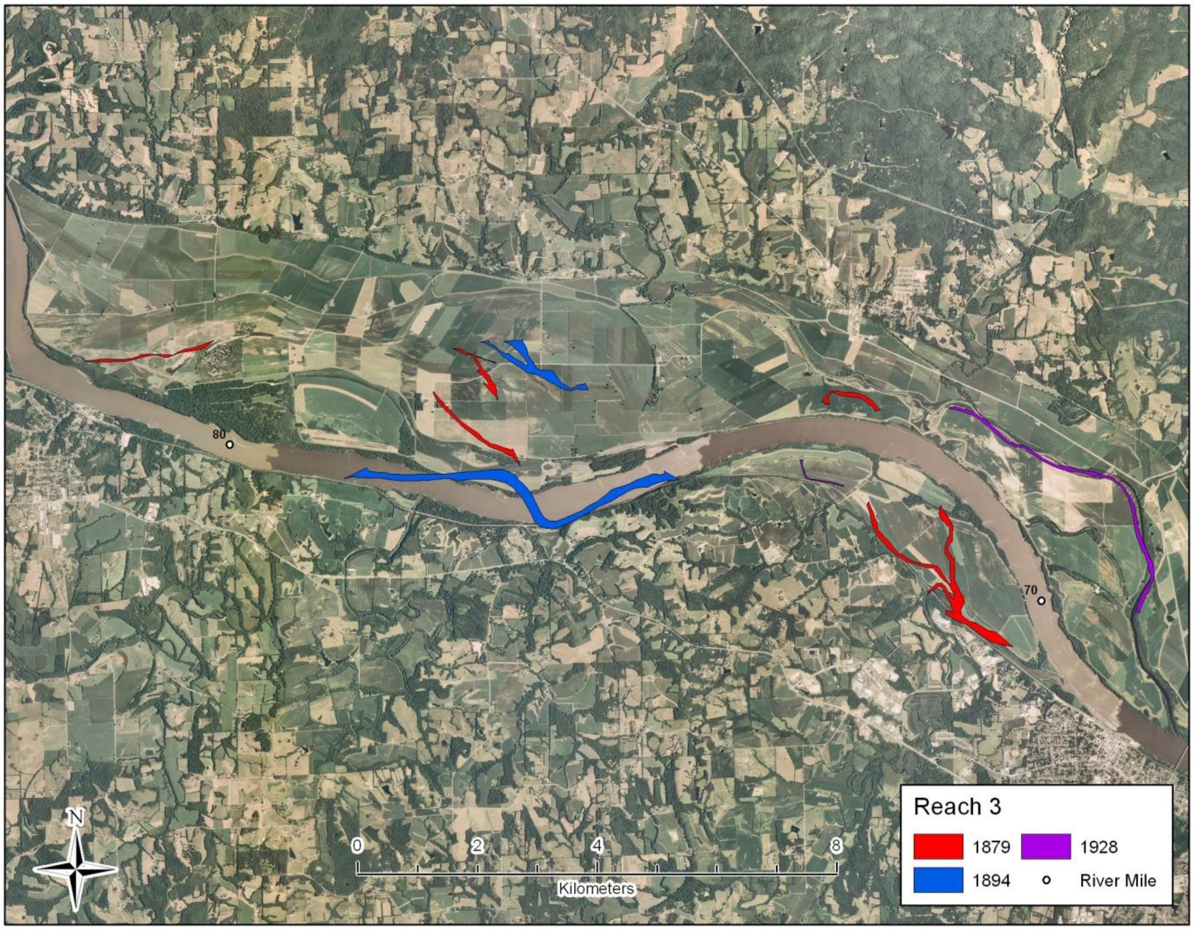
Reach 2 is located between river miles 52 and 67 and contained 7 separate side channels within the study period (Figure 4.2). All but one of the side channels in this reach are overlapping in space, with only one of the historical side channels in 1879 far removed from the current river channel location.

Figure 4.2 Distribution of Historical Side Channels on Missouri River Study Reach 2



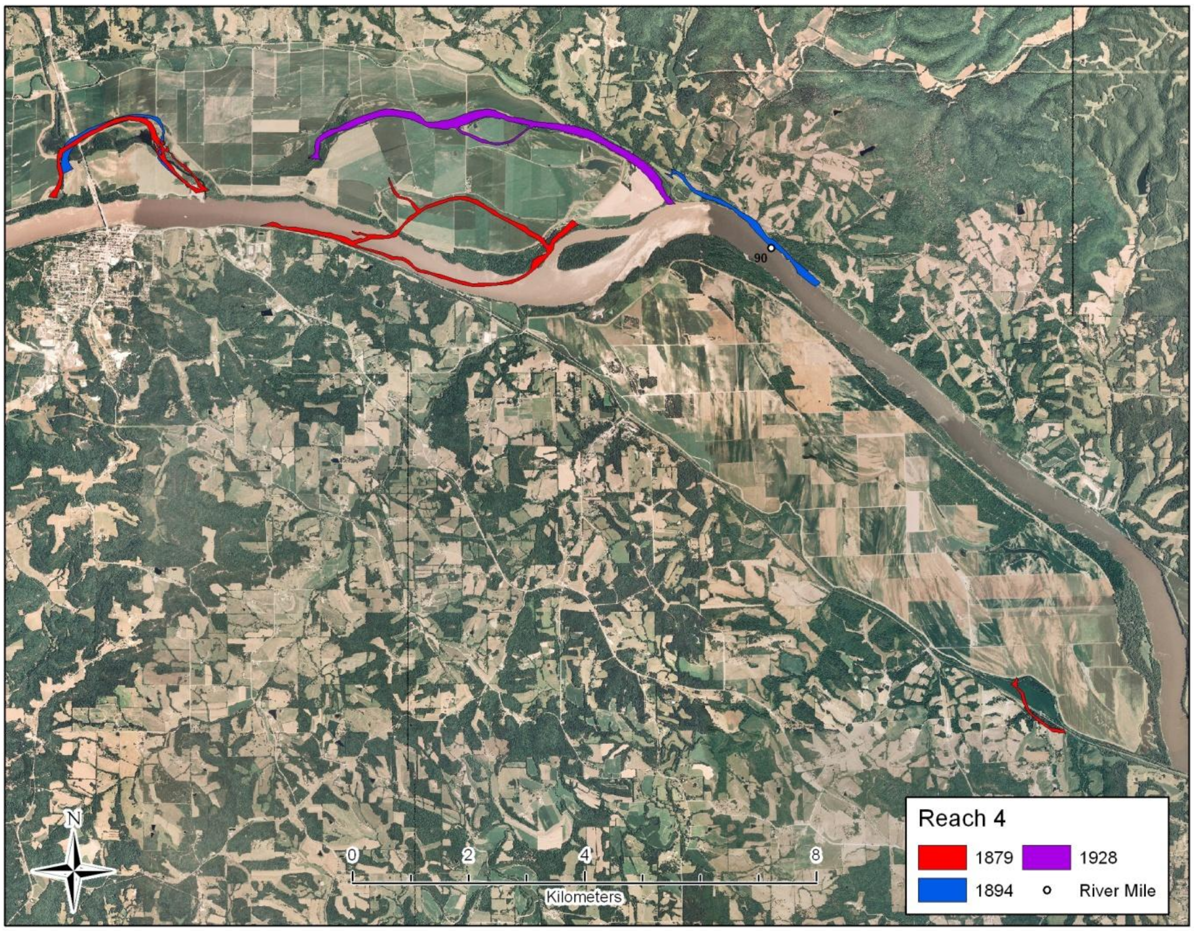
Reach 3 runs from river mile 68 to 83 and contained 9 different historical side channels with a peak of 5 in 1879. Most of the historical side channels in reach 3 were widely distributed and not located near the current river channel (Figure 4.3). However, in 1894 there was a large side channel that was located where the river in currently located. However, in the Eastern extremity of this reach there is a large 1928 side channel that appears to now be occupied by a tributary to the Missouri River.

Figure 4.3 Distribution of Historical Side Channels on Missouri River Study Reach 3



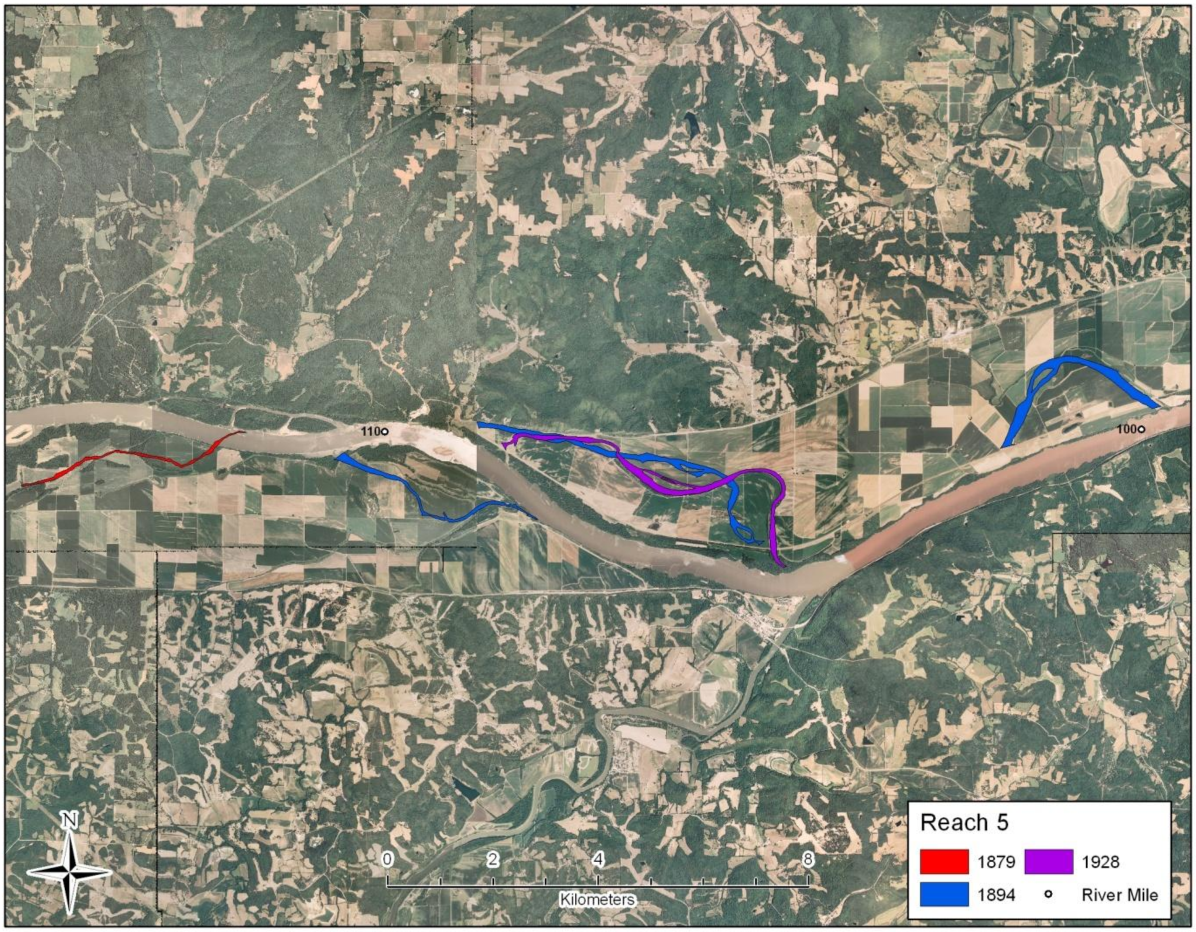
Reach 4 extends from river mile 84 to 99 and contained 2 side channels in 1879, 2 in 1894, and 1 in 1928 (Figure 4.4). While two side channels were located where the modern river now flows, the 1879 and 1894 maps show several sides channels persisting in the same location that branch off and connect to the current river location. In addition, a very large 1928 side channel location also connects well with the modern river channel.

Figure 4.4 Distribution of Historical Side Channels on Missouri River Study Reach 4



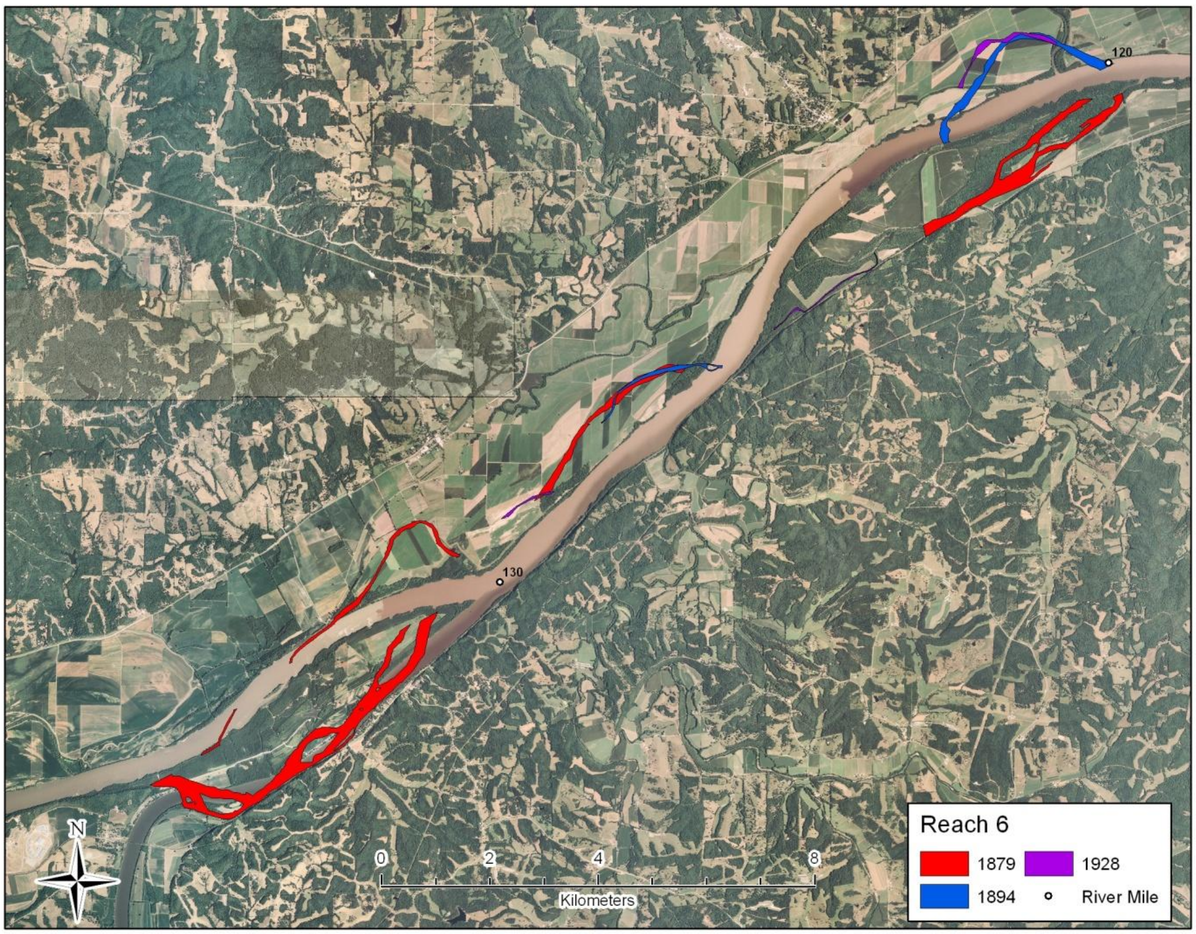
Reach 5 shows 5 extends for river mile 99.5 to 114.5 and contained 5 long and narrow side channels, with the highest density in 1894 (Figure 4.5). The historical locations of all of these side channels are very close to the current river channel, and one appears to have persisted from 1894 to 1928 with some planform adjustments.

Figure 4.5 Distribution of Historical Side Channels on Missouri River Study Reach 5



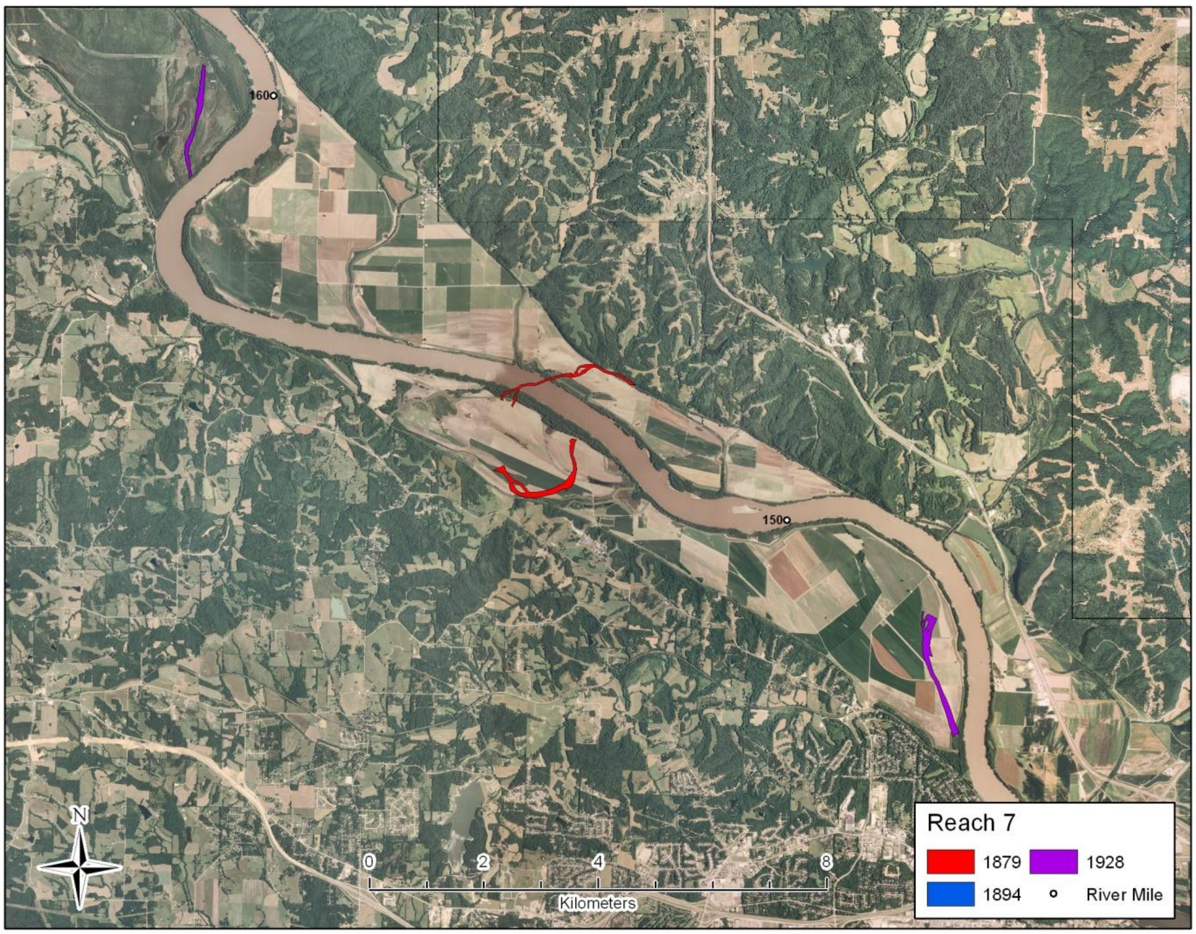
Reach 6 extends from river mile 120 to 135 and contained a total of 10 side channels with 5 in 1879, 2 in 1894, and 3 in 1928 (Figure 4.6). As in Reach 5, most of Reach 6's historical side channel locations are in good alignment with the modern river channel, with only one (the 1879 side channel at the Eastern extremity of the reach) not connected at both ends. Two of these side channels also appear to have persisted through time, with slightly different planforms revealed in sequential data layers.

Figure 4.6 Distribution of Historical Side Channels on Missouri River Study Reach 6



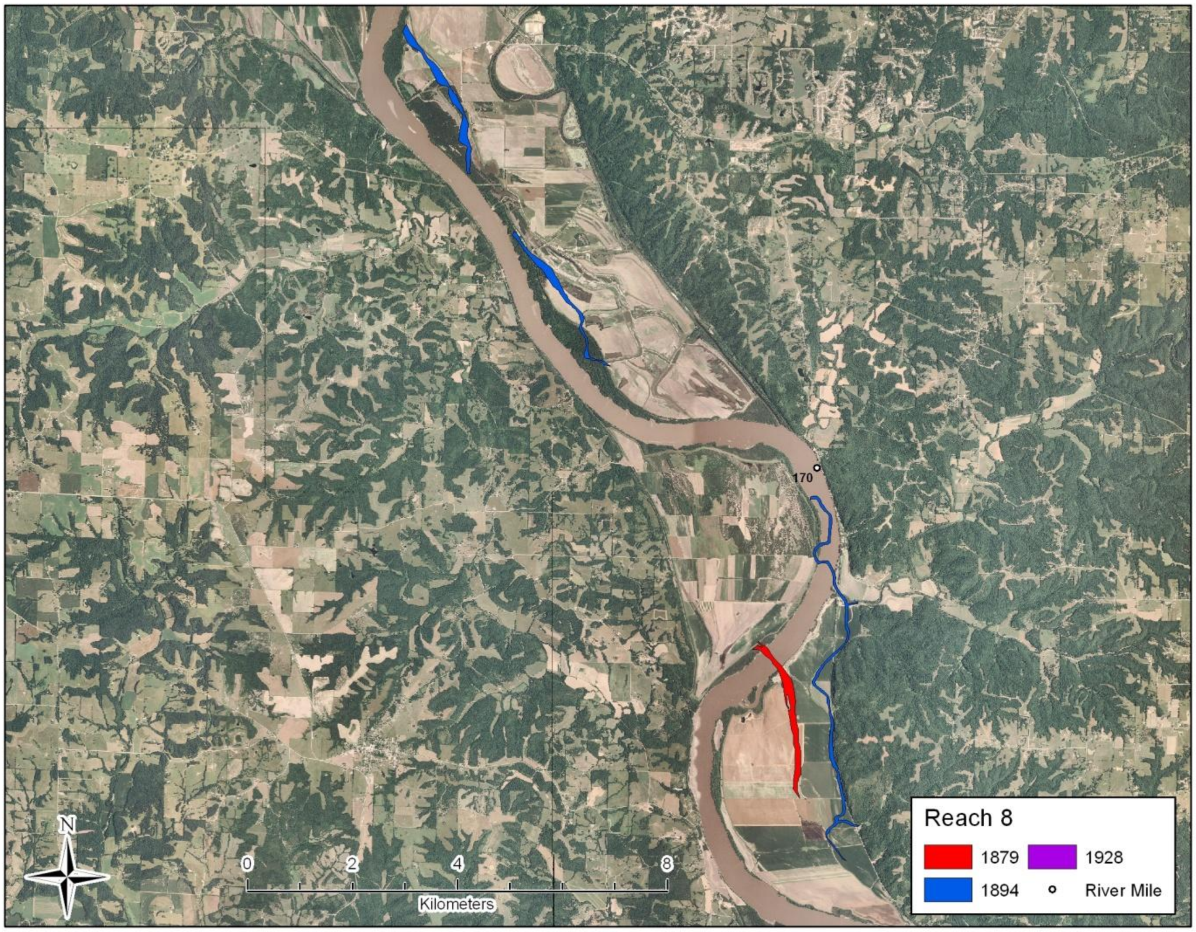
Reach 7 extends from river miles 146 to 161 and contained a total of 4 side channels (Figure 4.7). The two side channels present in 1928 were distantly located from one another, but in 1879 the side channels were located immediately opposite of one another along the main river channel. There were no side channels present in 1894. Total side channel area is the lowest of all reaches (680,482.88 m^2).

Figure 4.7 Distribution of Historical Side Channels on Missouri River Study Reach 7



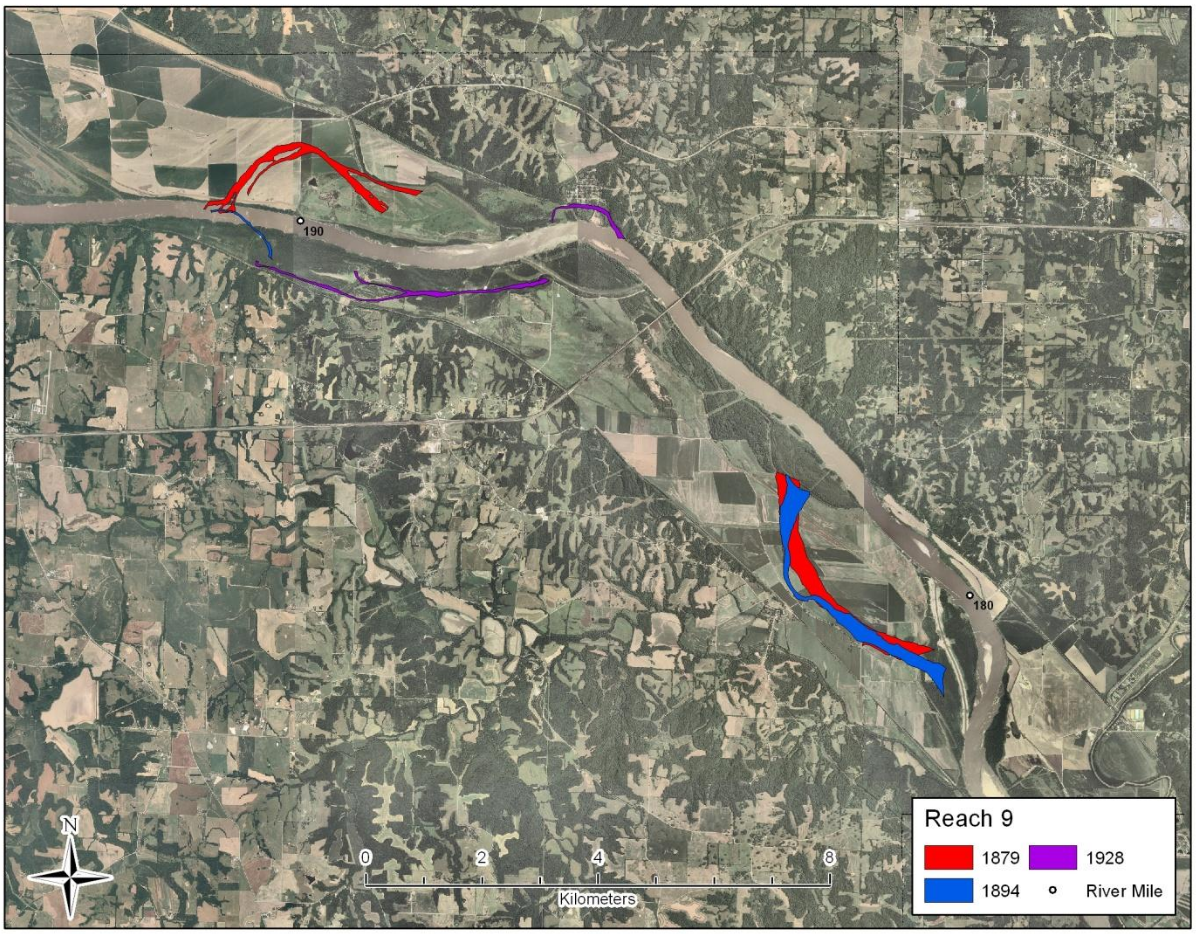
Reach 8 extends from river mile 163.5 to 178.5 and contained three side channels in1894 that branch off and connect close back to the current river conditions as well as 1 less closely situated side channel in 1879 and none in 1928. (Figure 4.8).

Figure 4.8 Distribution of Historical Side Channels on Missouri River Study Reach 8



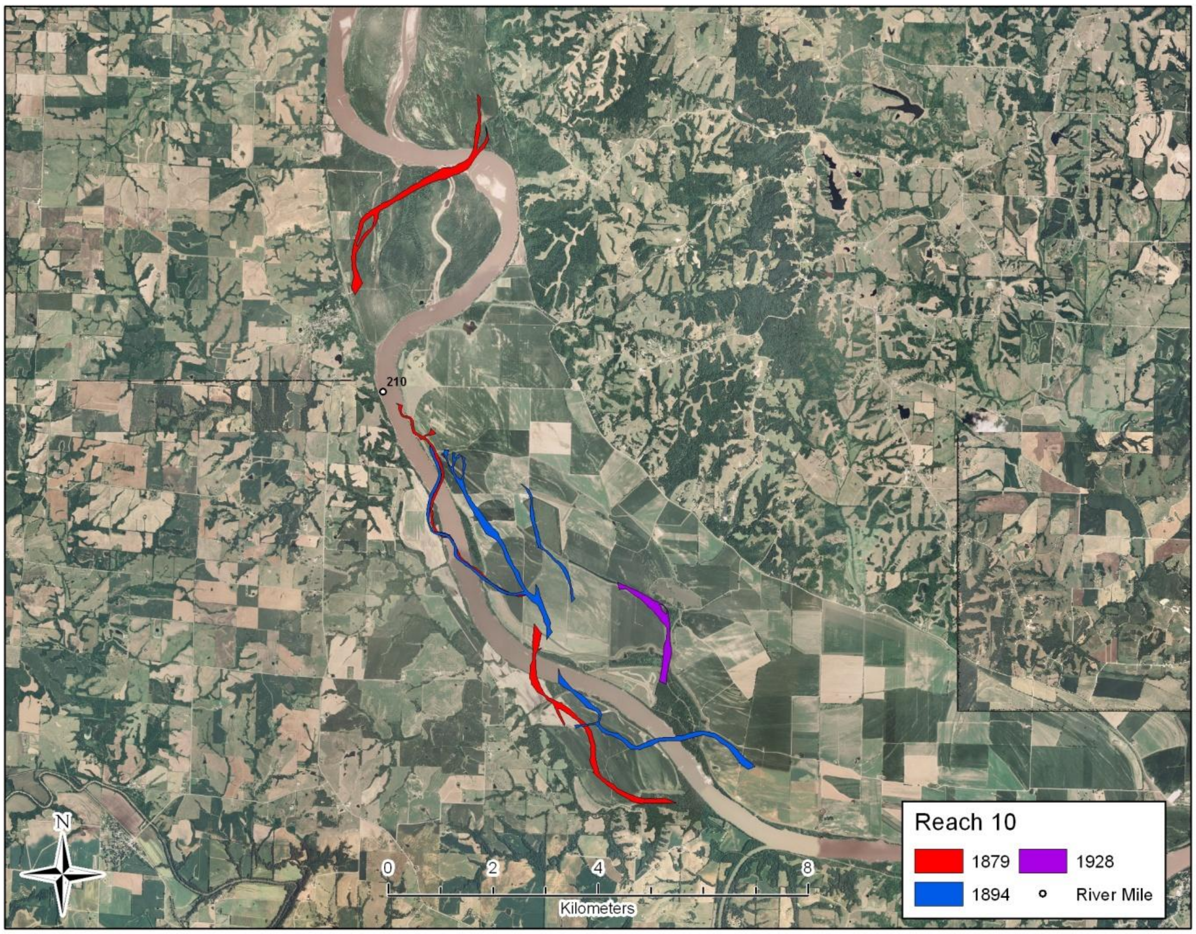
Reach 9 extends from river mile 178.5 to 193.5 and contained a total of six side channels, two in each study year in each study year (Figure 4.9). Two large side channels persist from 1879 to 1894 in the same area with minor planform changes. All historical side channels in this reach are close to the current river channel, though not as well connected to the main river channel as those in Reaches 5 and 6. This reach also contains a modern side channel mitigation side (near river mile 180) that overlaps spatially with two historical side channels.

Figure 4.9 Distribution of Historical Side Channels on Missouri River Study Reach 9



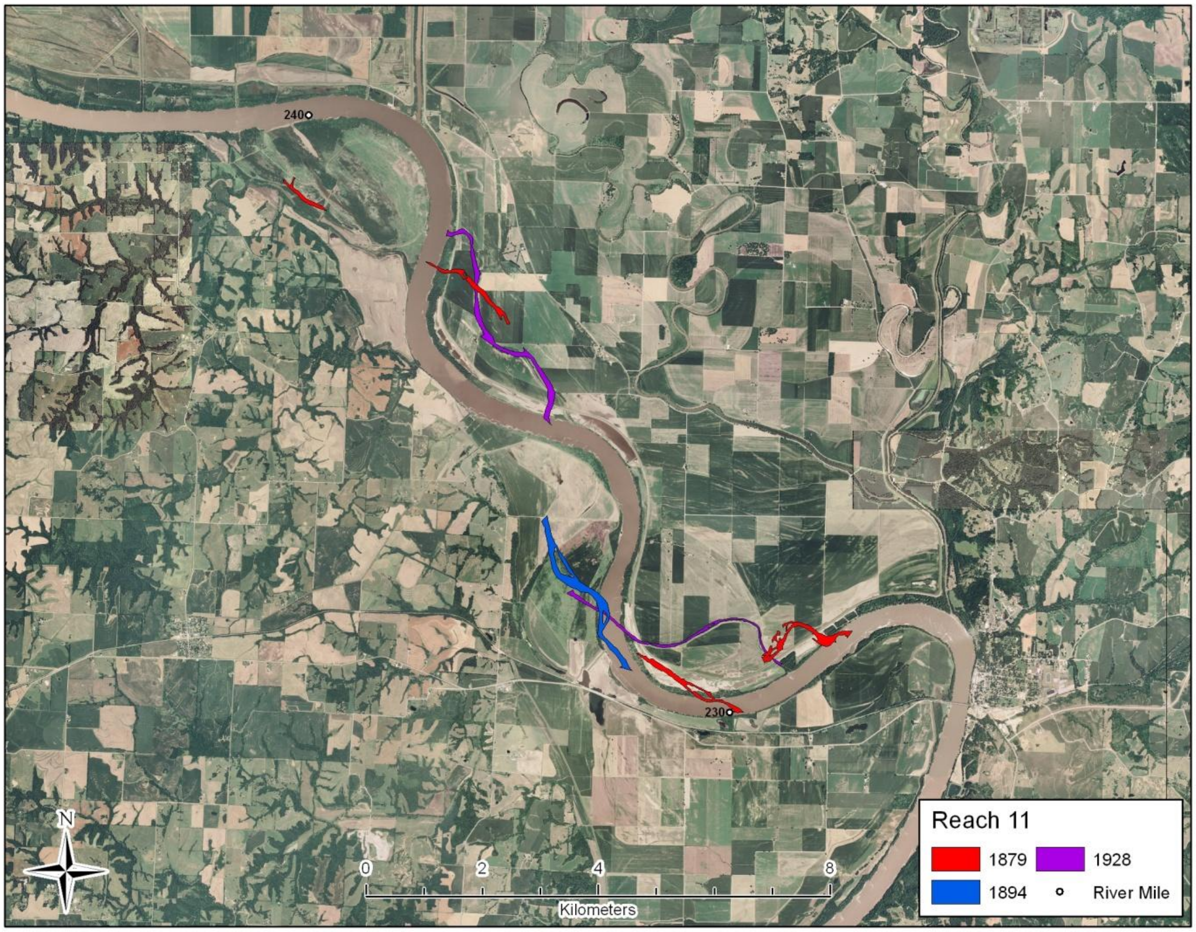
Reach 10 extends from river mile 202 to 217 and contained 7 historical side channels (Figure 4.10). Historical side channels were well distributed throughout Reach 10, with almost the entire modern river course connected to former side channel locations. One side channel displays persistence from 1879 to 1894 but is located in the modern river channel location. The one 1928 side channel is located far from the current river channel. The northern extremity of this reach also contains two modern side channel mitigation sites, the northernmost one of which formed naturally during the 1993 and 1996 flood events on the Missouri River.

Figure 4.10 Distribution of Historical Side Channels on Missouri River Study Reach 10



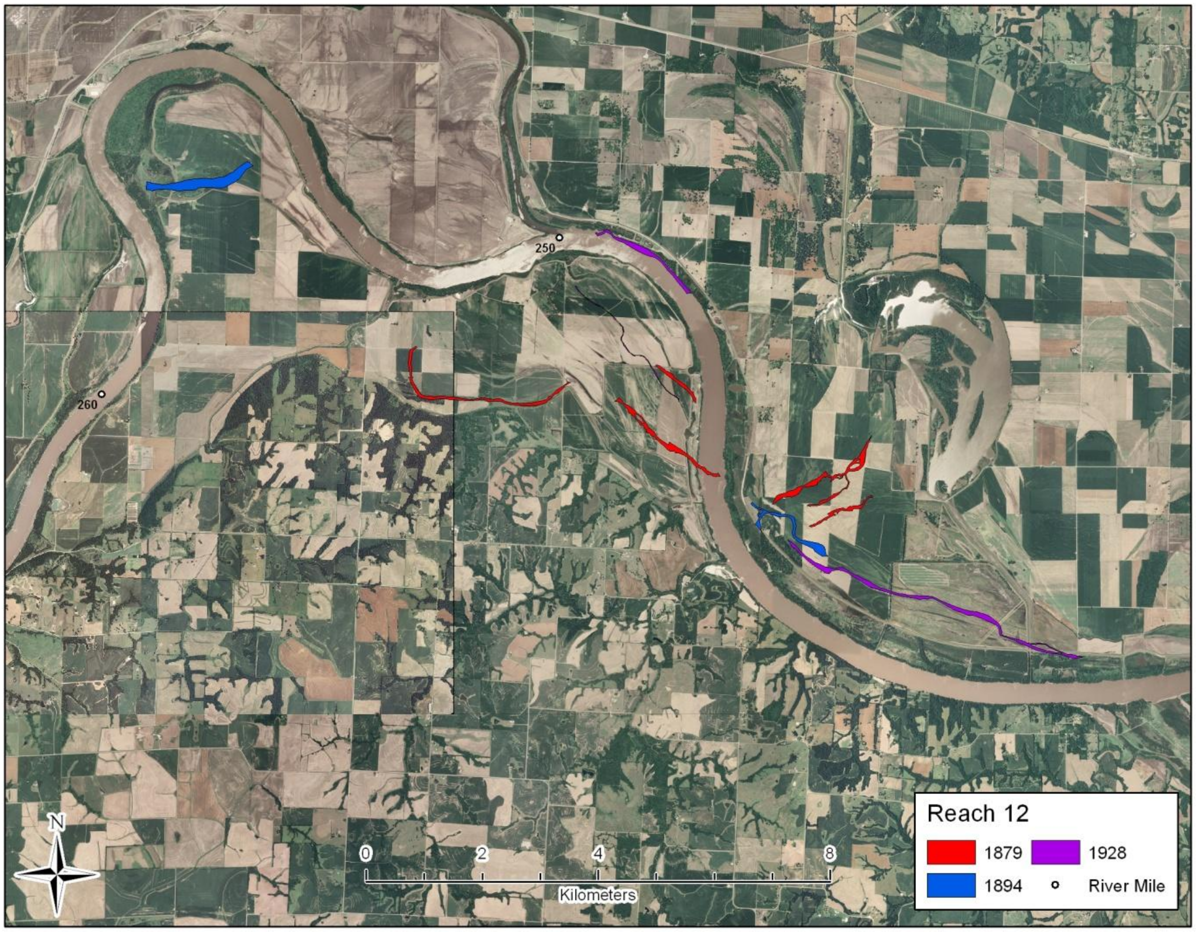
Reach 11 extends from river mile 226 to 241 and contained 7 historical side channels (Figure 4.11). With one exception, all historical side channel locations are near the modern river channel locations. However, no side channels display any persistence of location through time.

Figure 4.11 Distribution of Historical Side Channels on Missouri River Study Reach 11



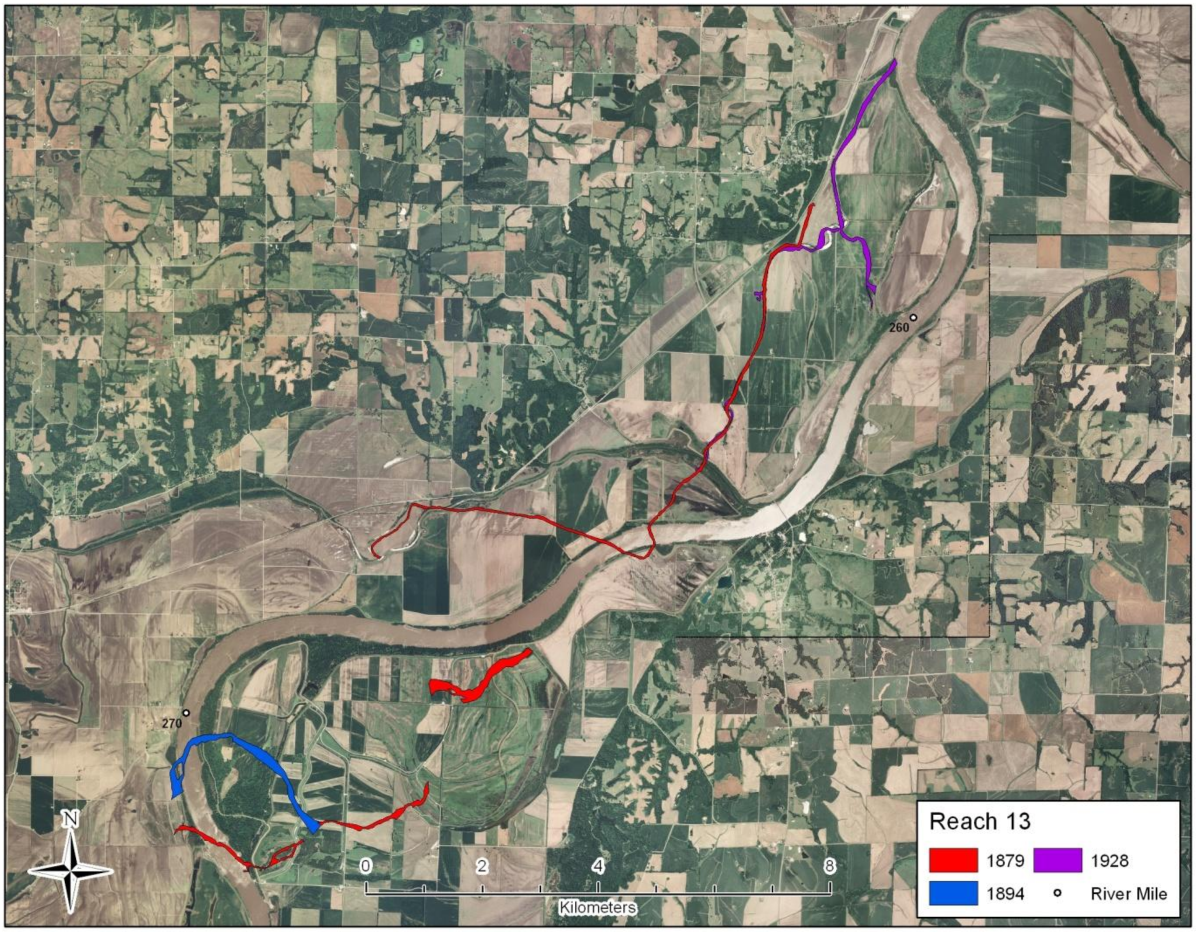
Reach 12 extends from miles 241 to 256 and contained 10 side channels (Figure 4.12). Even though there is a large frequency of side channels in reach 12, only half of these were located close to the current river channel. One 1928 side channel was located where the main channel is located today.

Figure 4.12 Distribution of Historical Side Channels on Missouri River Study Reach 12



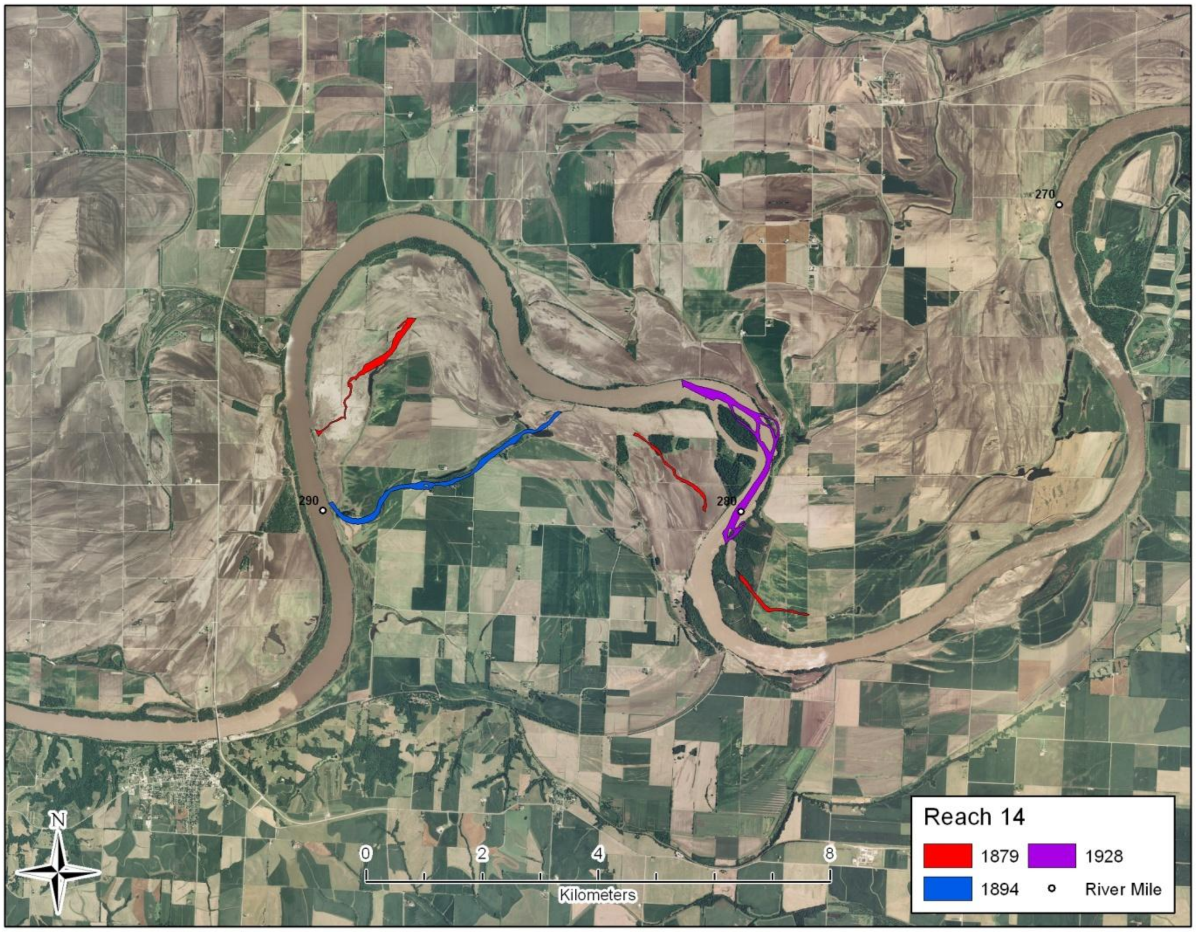
Reach 13 extends from river mile 257 to 272 and contained a total of 6 historical side channels (Figure 3.13). Most of these were present in 1879, including an exceptionally long side channel to the north of the modern river channel. The 1928 side channel is the most connected to the modern river channel location.

Figure 4.13 Distribution of Historical Side Channels on Missouri River Study Reach 13



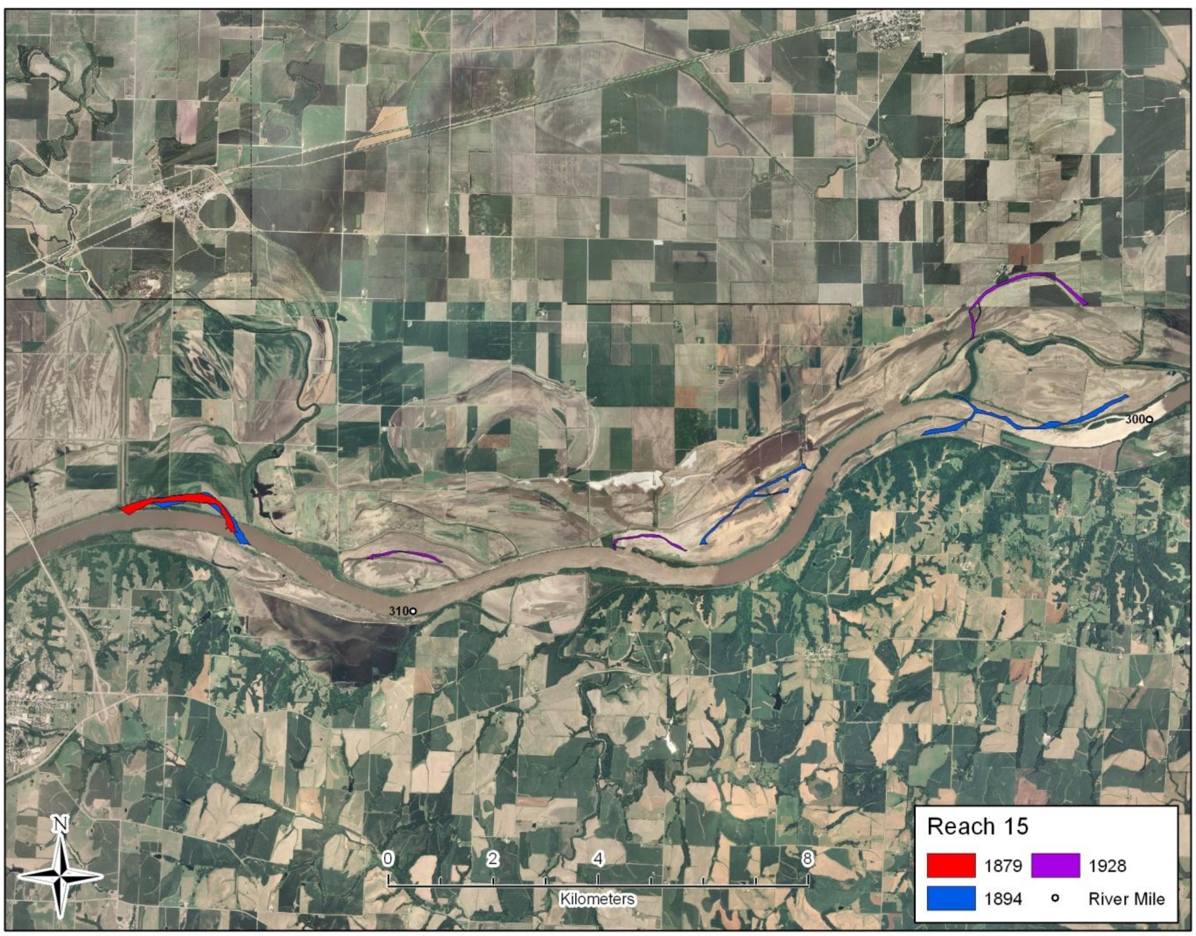
Reach 14 extends from river mile 278 to 293 and contained 5 historical side channels, with 3 in 1879, 1 in 1894, and 1 in 1928 (Figure 4.14). The 1928 side channel was located in the modern river channel location. The one 1894 side channel is in an almost perfectly connected configuration with the main channel, connecting as a chute cutoff in a large bend. All other side channels are located relatively close to the modern channel.

Figure 4.14 Distribution of Historical Side Channels on Missouri River Study Reach 14



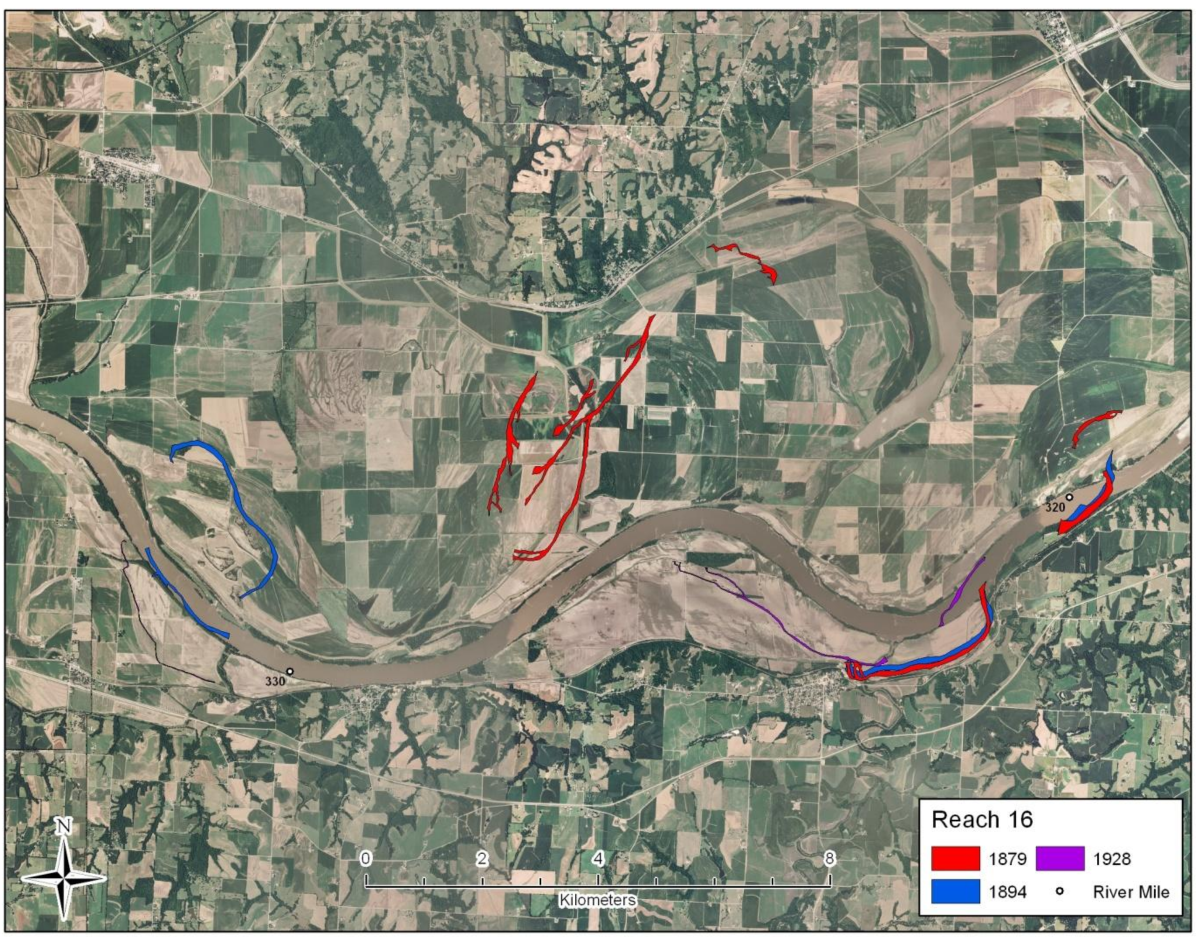
Reach 15 extends from river mile 300 to 315 and contained 7 side channels (Figure 4.15). All the historical side channels were located north of the modern river. In the westernmost section of this reach, a side channel persisted from 1879 to 1894 with very minor planform adjustments over time. This particular historical side channel is also very well connected to the main channel location. Through the middle section of this reach, there are several other very well connected reaches to the modern channel location. However, in the eastern part of the reach, there is one side channel located far to the north of the modern channel and the other one substantially overlaps with modern channel location.

Figure 4.15 Distribution of Historical Side Channels on Missouri River Study Reach 15



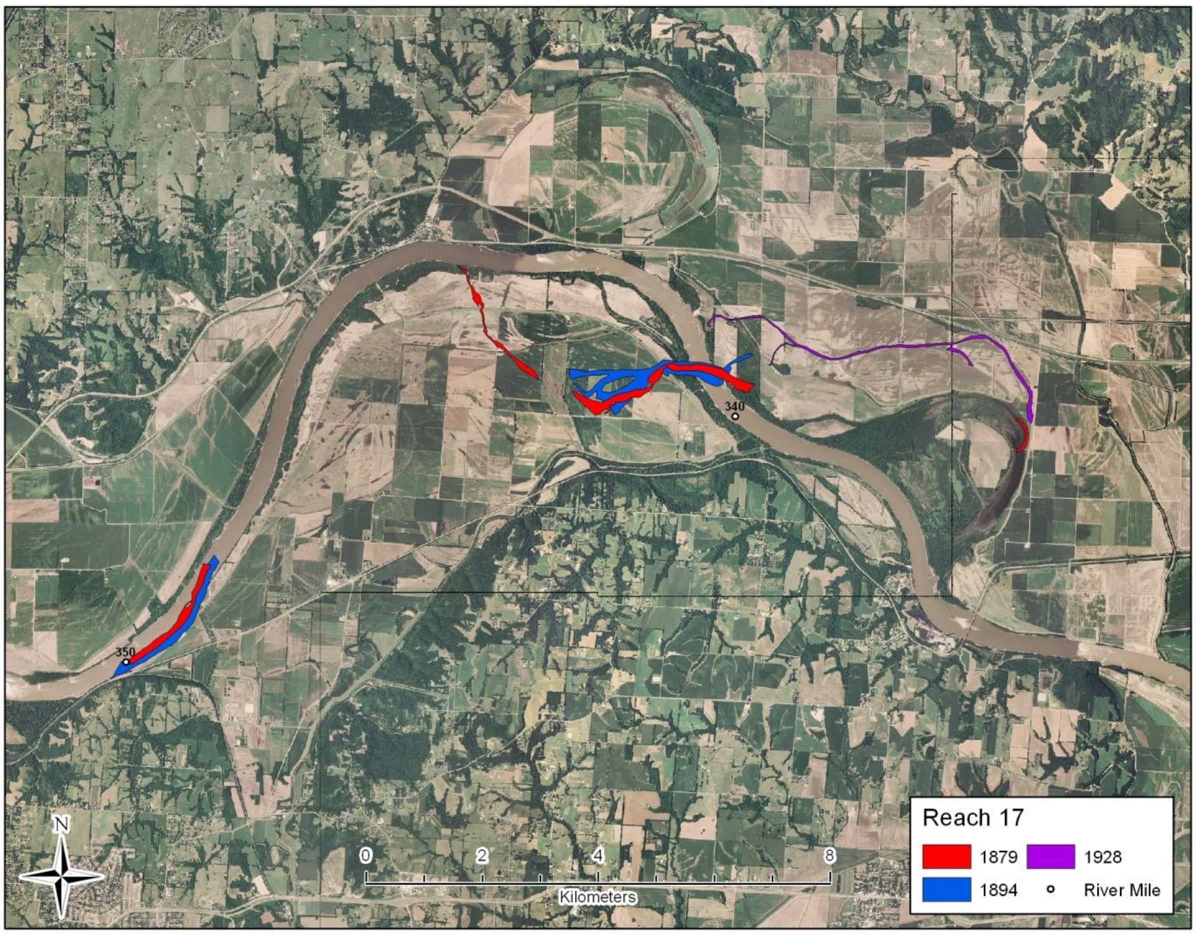
Reach 16 extends from river mile 319 to 334 and contained a total of 14 historical side channels (Figure 4.16). While this reach contained the highest frequency of side channels in each of the study years, it is only ranked fifth in highest total side channel area. The frequency of side channels in Reach 16 declined through time. In 1879 there were 7 side channels however, 5 of these were clustered in a location removed from the current river channel location. The other two 1879 side channels are well connected to the modern channel and also persisted in the same location at least until 1894 with very minor planform adjustments. One of the 1894 side channels were located where the modern river now flows. The 1928 side channels are narrow in width and long in length.

Figure 4.16 Distribution of Historical Side Channels on Missouri River Study Reach 16



Reach 17 is the farthest upstream and closest to Kansas City, extending from river mile 335 to 350 (Figure 4.17). As in Reach 16, the frequency of side channels in this reach declines through time with 4 in 1879, 2 in 1894, and 1 in 1928. The 1928 side channel begins near the modern channel but ends at a substantial distance away. Two side channels persist from 1879 to 1894 with minor planform changes, but these both overlap substantially with the modern river location.

Figure 4.17 Distribution of Historical Side Channels on Missouri River Study Reach 17



4.2 Relationship Between Side Channel Characteristics and River Variables

For each study reach, the side channel frequency (number of side channels) and side channel density (ratio of side channel area to main channel area) were quantified (Table 4.1). Eight of the 17 study reaches had the highest side channel frequencies in the 1879 sample year (Figure 4.18). Seven study reaches show a decline in side channel frequency through the progression of time. The same trend can be seen in the side channel density metric (Figure 4.19). To seek explanation for observed side channel variables, they were compared to main river variables including sinuosity, valley width, valley slope, and the location of major tributary junctions.

Table 4.1 Data of Reach Number and Side Channel Variables

	Side Channel Frequency				Side Channel Area (Sq Meters)			Side Channel Density		
Reach Number	1879	1894	1928	Total	1879	1894	1928	1879	1894	1928
1	3	4	0	7	1364671.64	672863.09	0	0.00360791	0.00221628	0
2	3	2	2	7	1102203.9	471333.36	456520.69	0.002914	0.00155248	0.00123937
3	5	2	2	9	843643.46	1066764.06	324572.62	0.00223042	0.00351372	0.000881155
4	3	2	1	6	1063398.67	575080.67	882483.6	0.00281141	0.00189421	0.002395781
5	1	3	1	5	197305.2	1635891.17	700713.33	0.00052163	0.00538832	0.001902308
6	5	2	3	10	3676640.34	671470.69	248648.13	0.00972028	0.0022117	0.000675034
7	2	0	2	4	325115.12	0	355367.76	0.00085954	0	0.000964758
8	1	3	0	4	389840.89	964764.84	0	0.00103066	0.00317775	0
9	2	2	2	6	2273265.76	1193688.49	426948.97	0.00601004	0.00393179	0.001159088
10	3	3	1	7	1273210.72	1139044.05	281698.88	0.00336611	0.0037518	0.000764761
11	4	1	2	7	501186.12	377252.93	489381.49	0.00132503	0.0012426	0.001328581
12	5	2	3	10	550057.1	398045.29	420131.87	0.00145424	0.00131109	0.001140581
13	4	1	1	6	1101158.27	465509.47	514163.61	0.00291123	0.0015333	0.00139586
14	3	1	1	5	353617.73	365163.53	502294.9	0.00093489	0.00120278	0.001363638
15	1	3	3	7	286651.79	752988.9	269820.4	0.00075785	0.0024802	0.000732513
16	7	4	3	14	1331976.64	902068.53	217860.5	0.00352147	0.00297124	0.000591451
17	4	2	1	7	834401.34	1226890.18	302349.19	0.00220598	0.00404115	0.000820822

Figure 4.18 Frequency of Side Channels in Each Reach

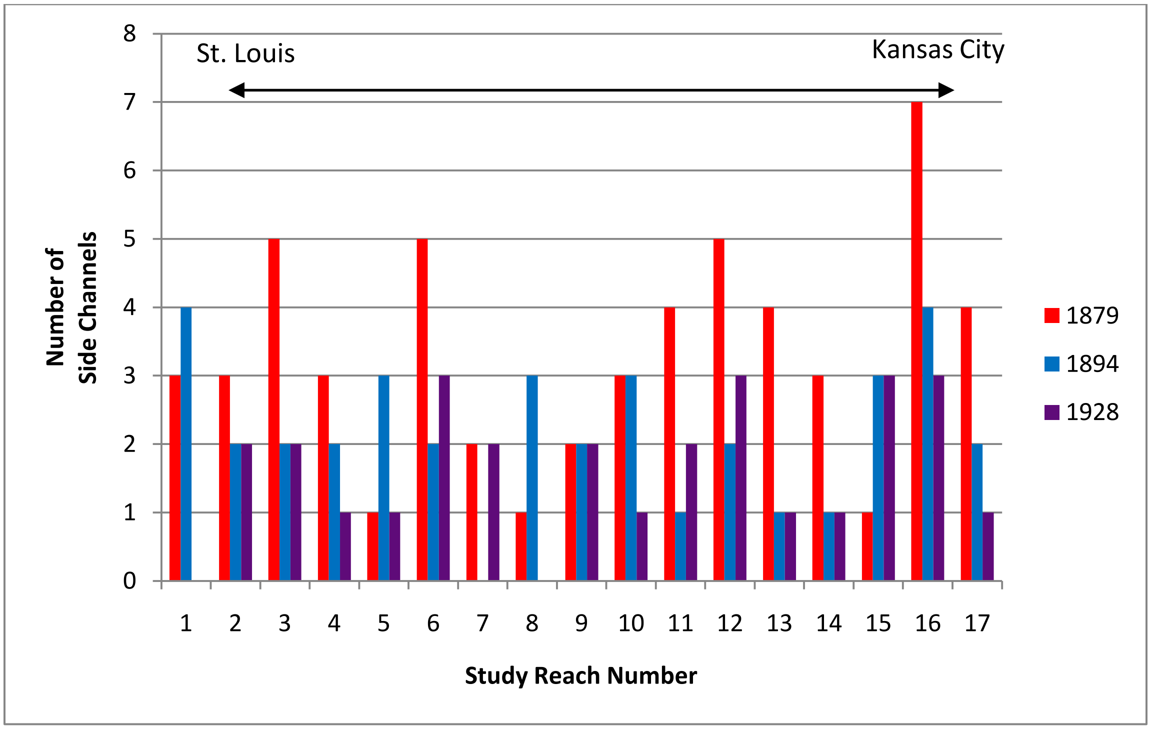
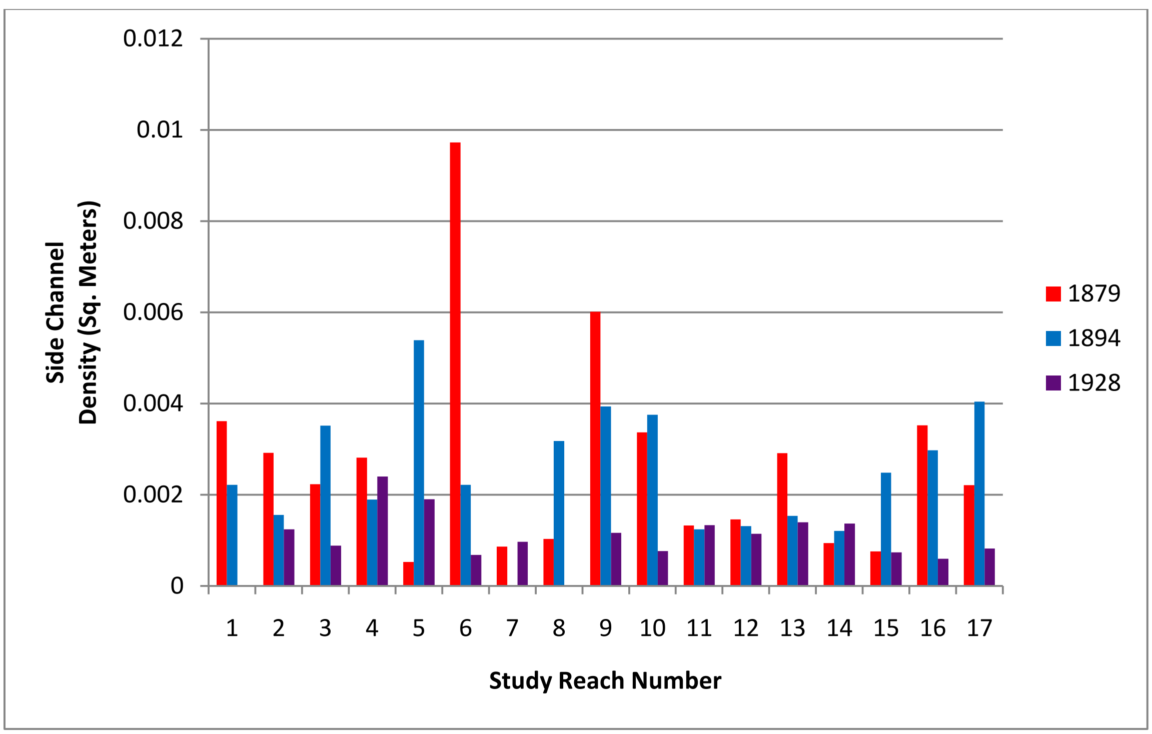


Figure 4.19 Side Channel Density in Each Reach



Sinuosity was measured for the main channel in each of the study years by study reach (Figure 4.20). Sinuosity measurements in reaches 1-6 were remarkably consistent through space and time. However, beginning at Reach 7 there is an increasing trend in sinuosity that is uniform across the sample time periods until a maximum is reached in Reach 14, upstream of which sinuosity declines again. Scatter plots of side channel metrics against a temporally averaged reach sinuosity value (Figure 4.21) shows a pattern 51% of which can be explained by a third-order polynomial function, with side channel frequency declining as sinuosity increases from 1.0 to ~1.2 and then increasing to sinuosity of ~ 1.6 at which point it declines again. However, when the data is parsed out by individual sample years, there is no consistent pattern relating side channel frequency to reach sinuosity (Figure 4.22).

Figure 4.20 Reach Sinuosity

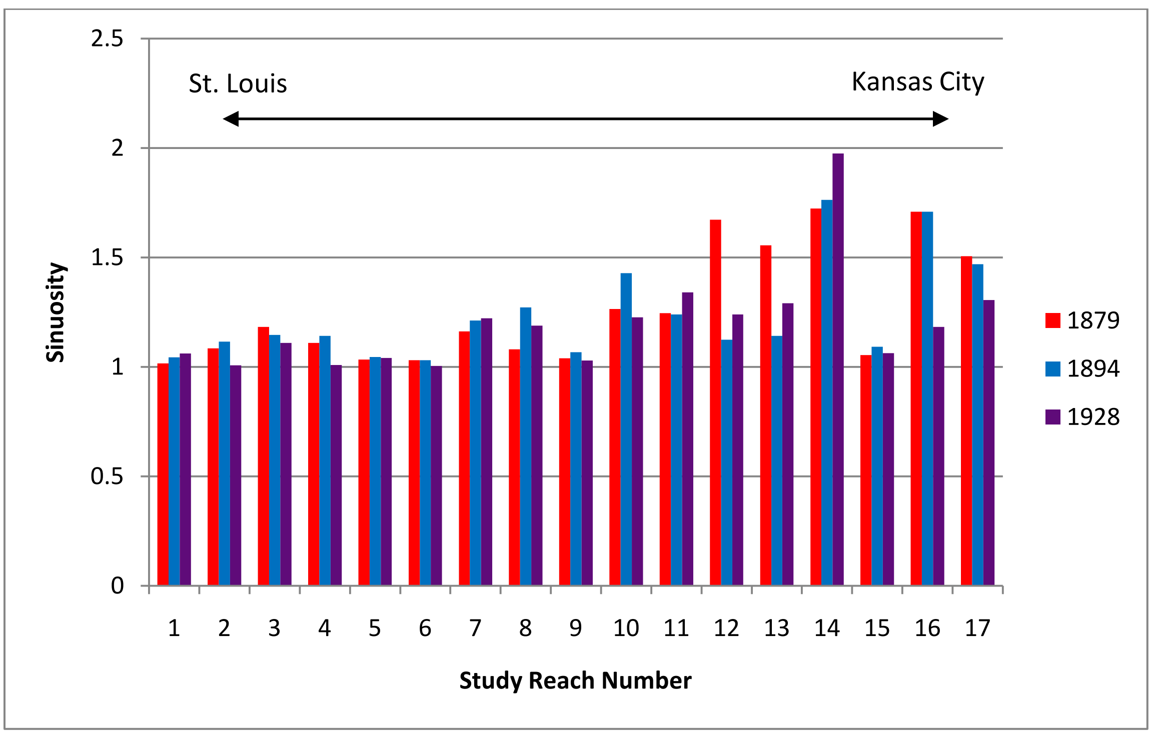


Figure 4.21 Relationship between Average Side Channel Frequency and Average Reach Sinuosity

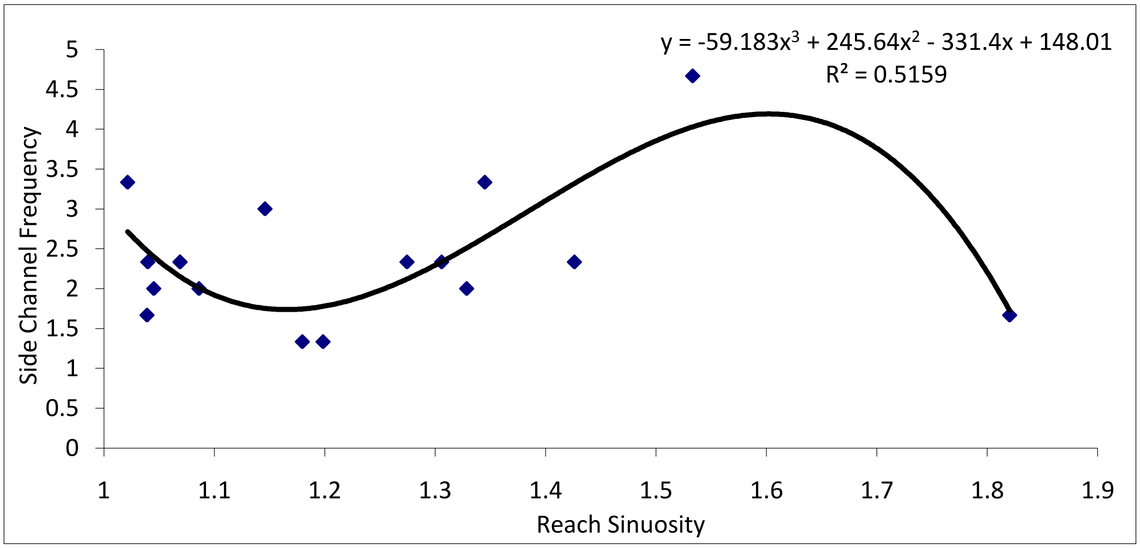
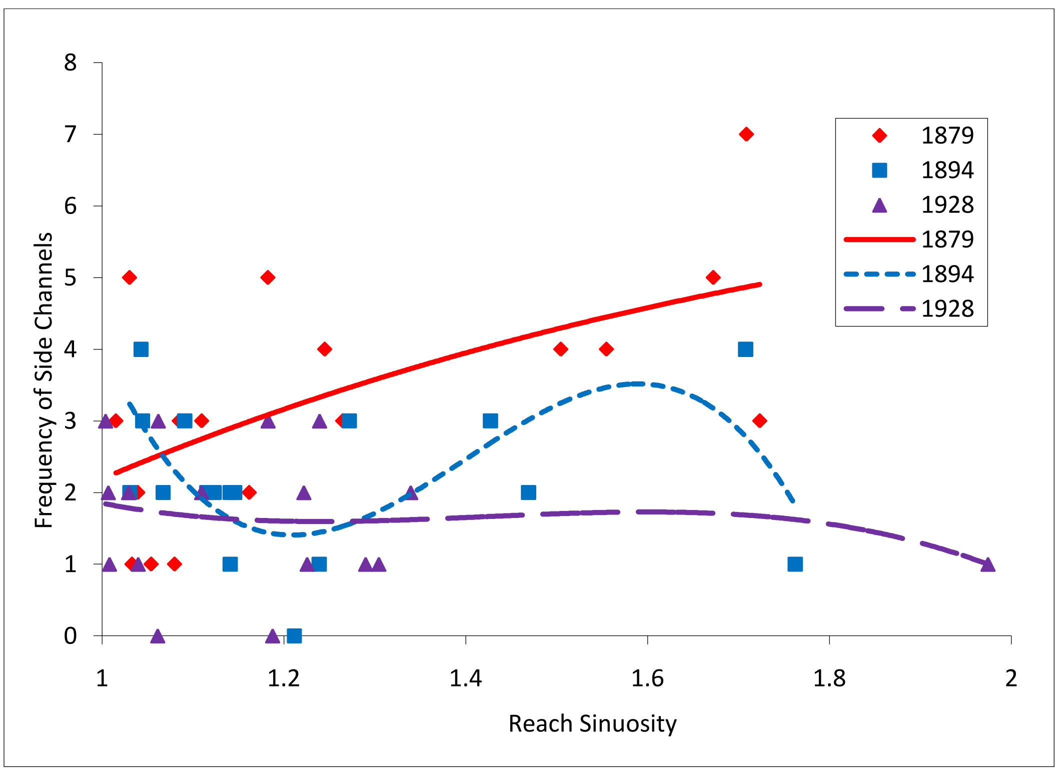


Figure 4.22 Relationship between Side Channel Frequency and Reach Sinuosity



When plotting average side channel density against average reach sinuosity, only a very weak linear relationship was observed (Figure 4.23). However, better third-order polynomial relationships are observed when plotting year-specific side channel density with year-specific sinuosity (Figure 4.24). Side channel density and sinuosity had the same pattern for each year. There does appear to be a good relationship between reach sinuosity and another non-side channel variable evaluated – valley width (Figure 4.25).

Figure 4.23 Relationship between Average Side Channel Density and Average Reach Sinuosity

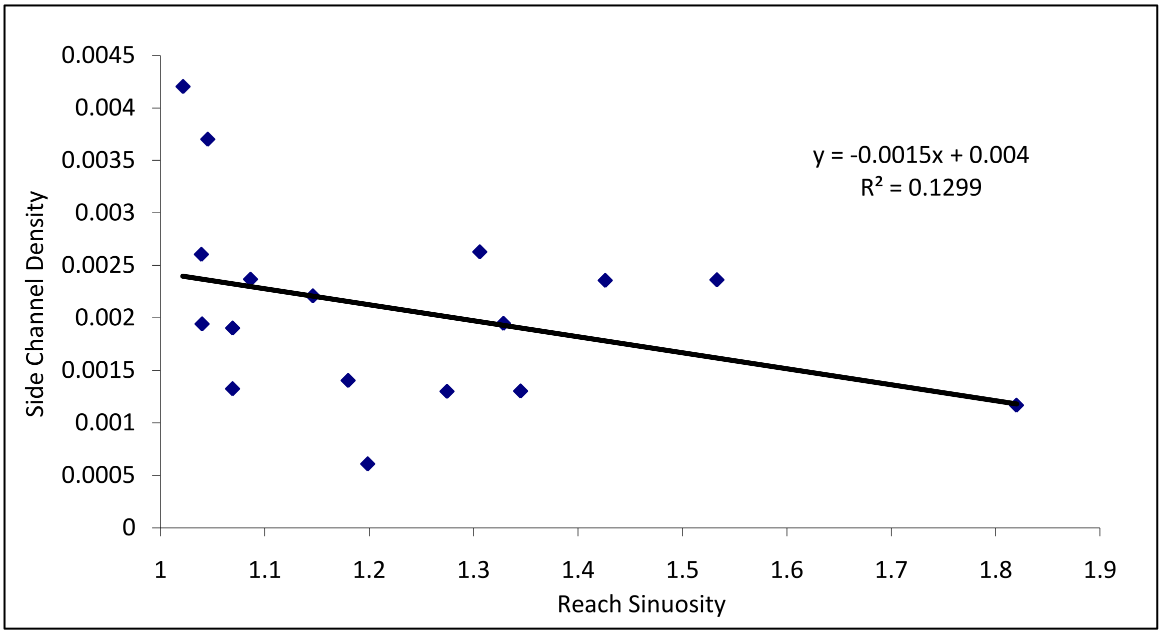


Figure 4.24 Relationship between Side Channel Density and Reach Sinuosity

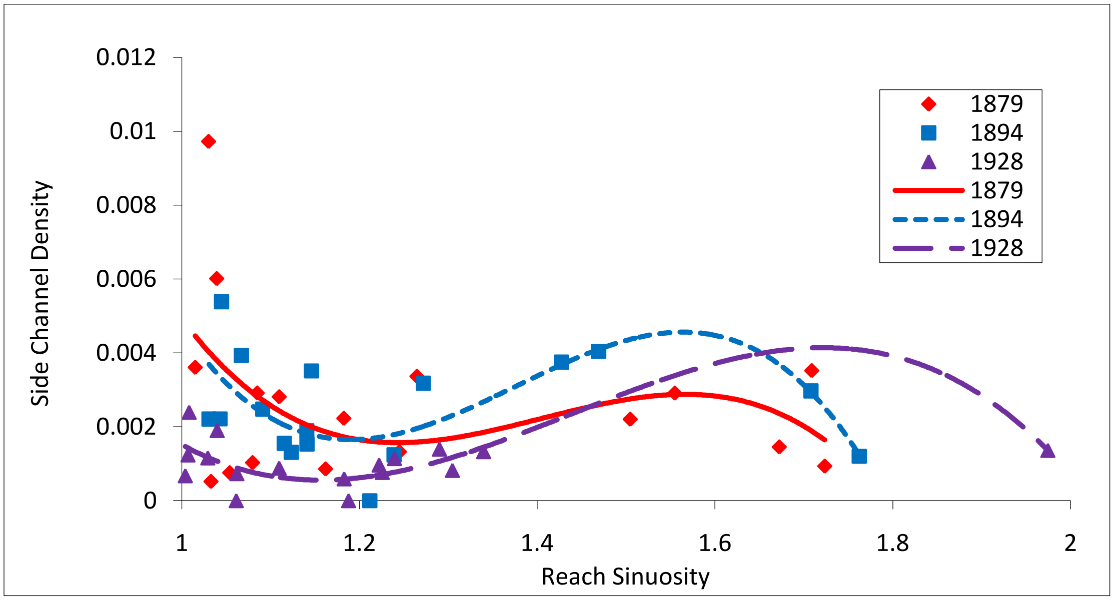
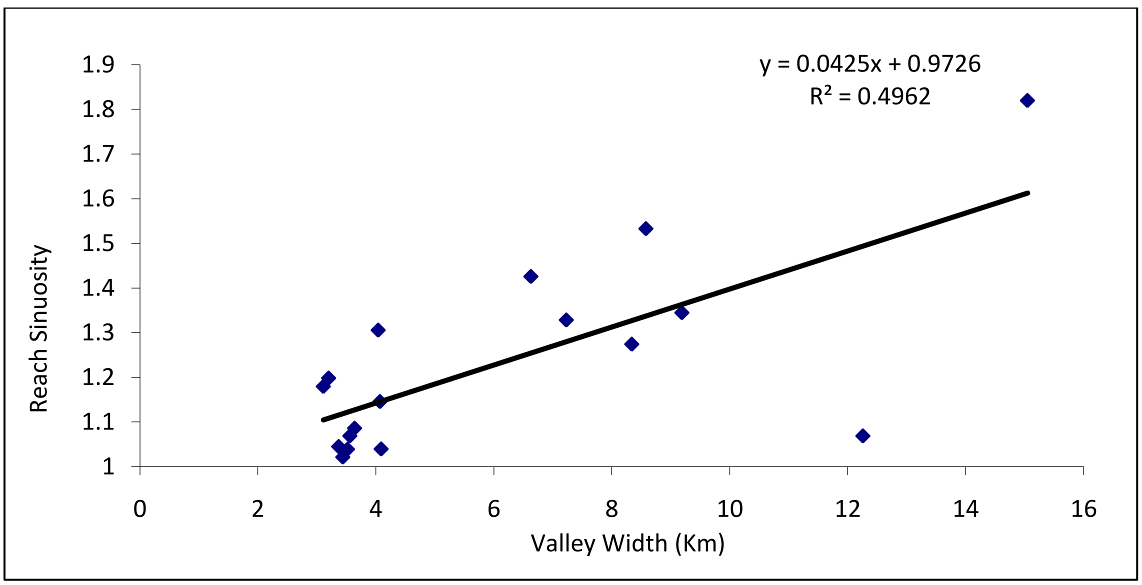


Figure 4.25 Relationship between Average Reach Sinuosity and Average Valley Width



Relating the reach valley width values to side channel frequency showed a r^2 value of .30 (Figure 4.26 and Figure 4.27). Valley width could potentially explain 30% of why side channels occurred in the locations. The graphs show the highest number of side channel frequency was when valley width was between 6-10 kilometers wide. Side channel frequency and valley slope showed more correlation with valley slope on the south side of the Missouri River (Figures 4.28 and 4.29). Valley slope on the north side of the river and side channel frequency had a very weak correlation. Highest R squared values are when looking at side channel frequency. Side channel frequency correlated more with the river variables then side channel density.

Figure 4.26 Relationship between Average Side Channel Frequency and Valley Width

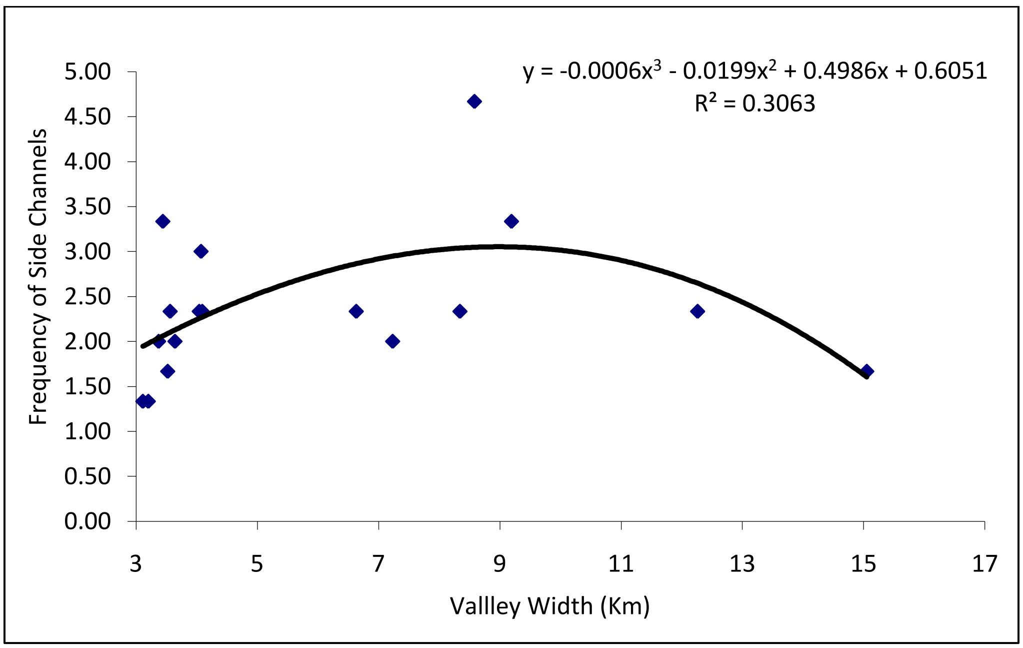


Figure 4.27 Relationship between Side Channel Frequency and Valley Width

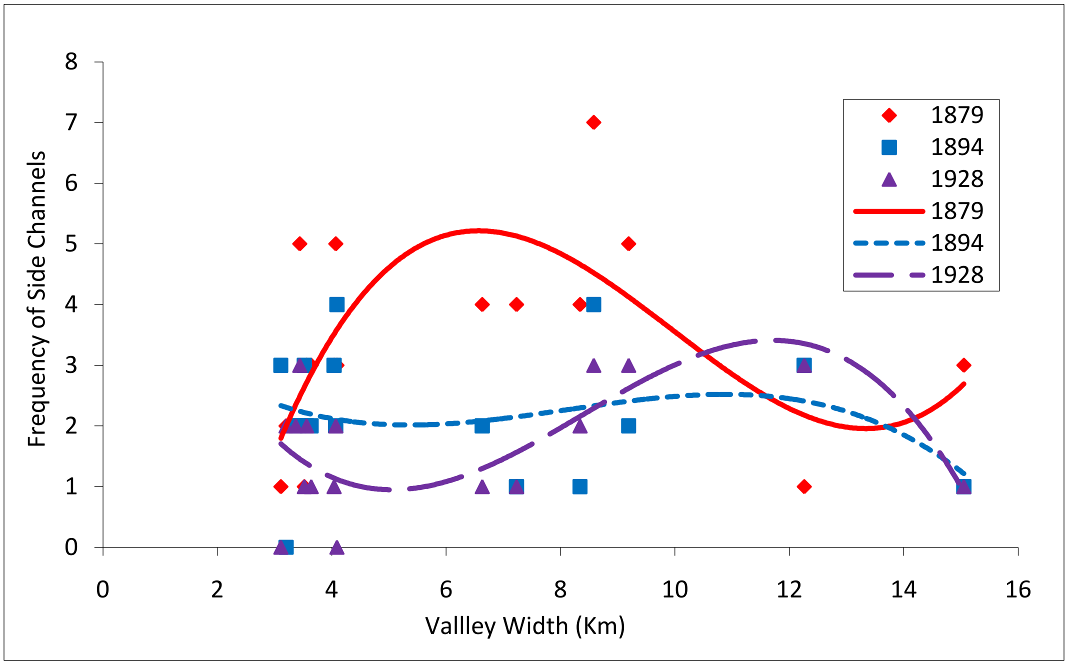


Figure 4.28 Relationship between Average Side Channel Frequency and Valley Slope North of the River

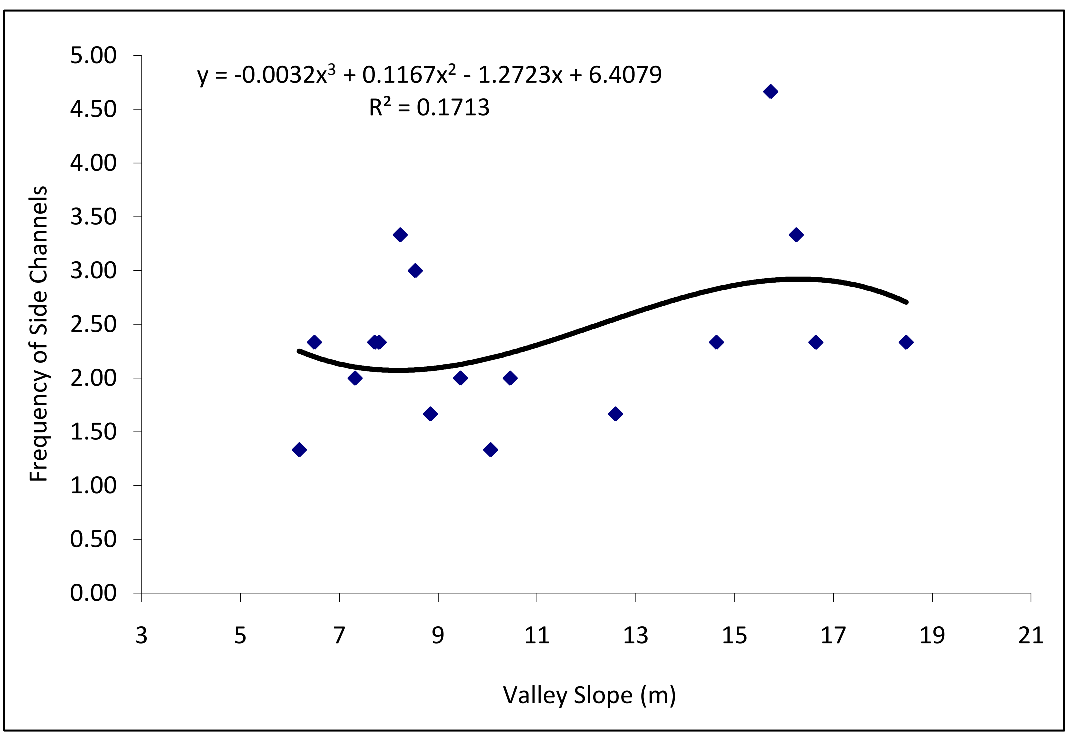


Figure 4.29 Relationship between Side Channel Frequency and Valley Slope North of the River

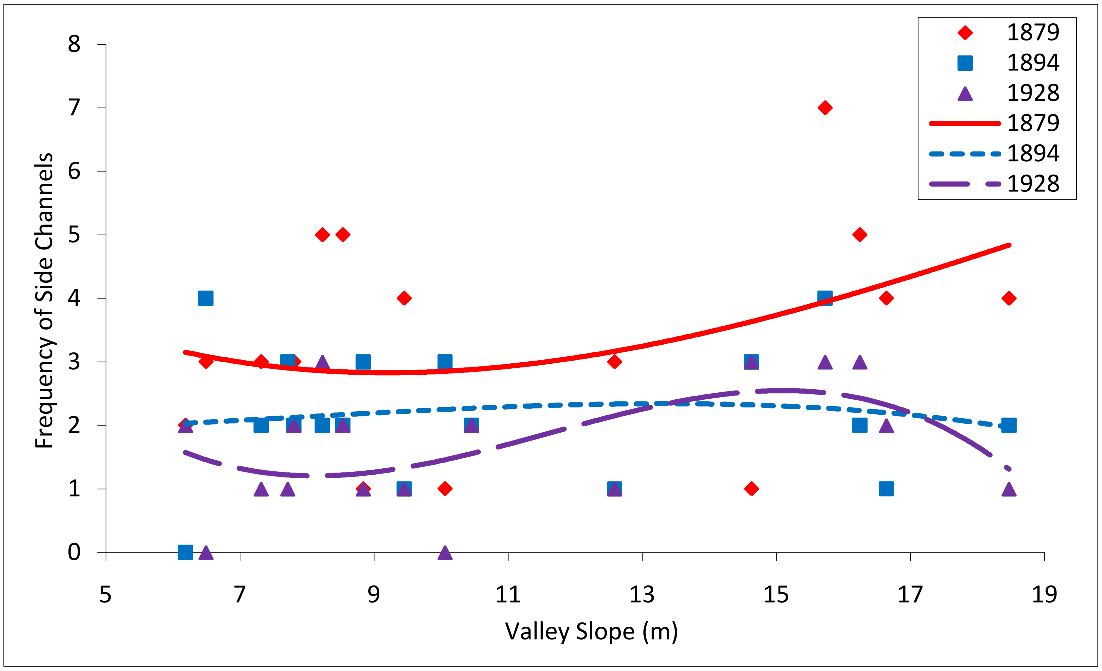


Figure 4.30 Relationship between Average Side Channel Frequency and Valley Slope South of the River

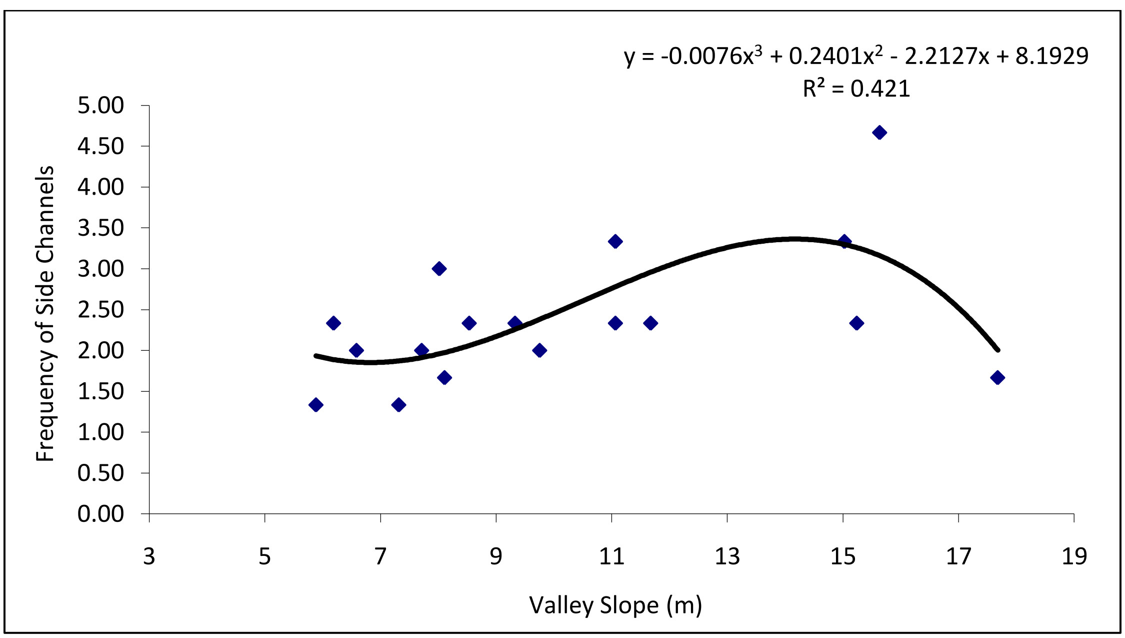
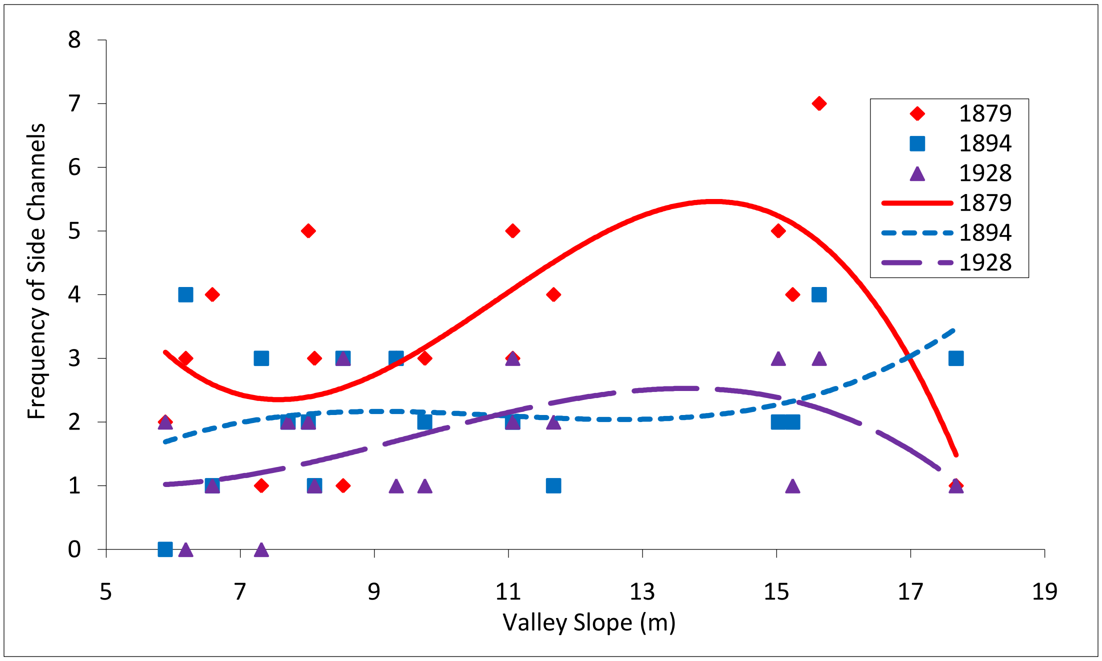


Figure 4.31 Relationship between Side Channel Frequency and Valley Slope South of the River



Side channel density and valley width had no correlation or trend (Figure 4.32 and 4.33). Valley width and side channel density has an R squared value of .19. Side channel density cannot be predicted by reach sinuosity values (Figure 4.23 and Figure 4.24). Side channel density showed a higher correlation with valley slope on the north side of the river (Figure 4.34 and Figure 4.35). The data shows valley slope south of the river and average side channel density with a slight positive correlation (Figure 3.36). 1894 side channel density increases the most with valley slope south of the river (Figure 3.37). This study also looked at the relationship between the river variables.

Figure 4.32 Relationship between Average Side Channel Density and Valley Width

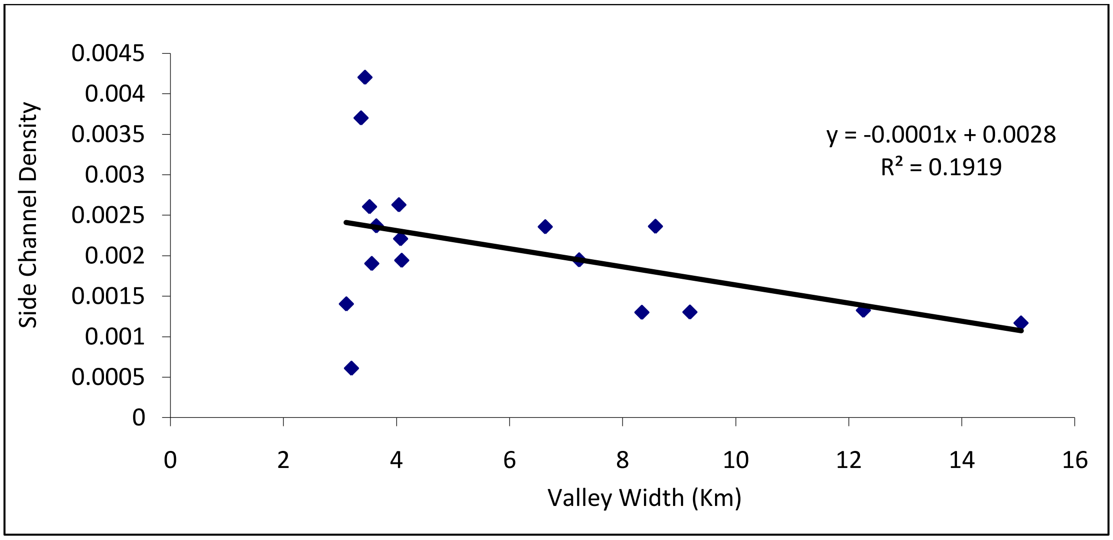


Figure 4.33 Relationship between Side Channel Density and Valley Width

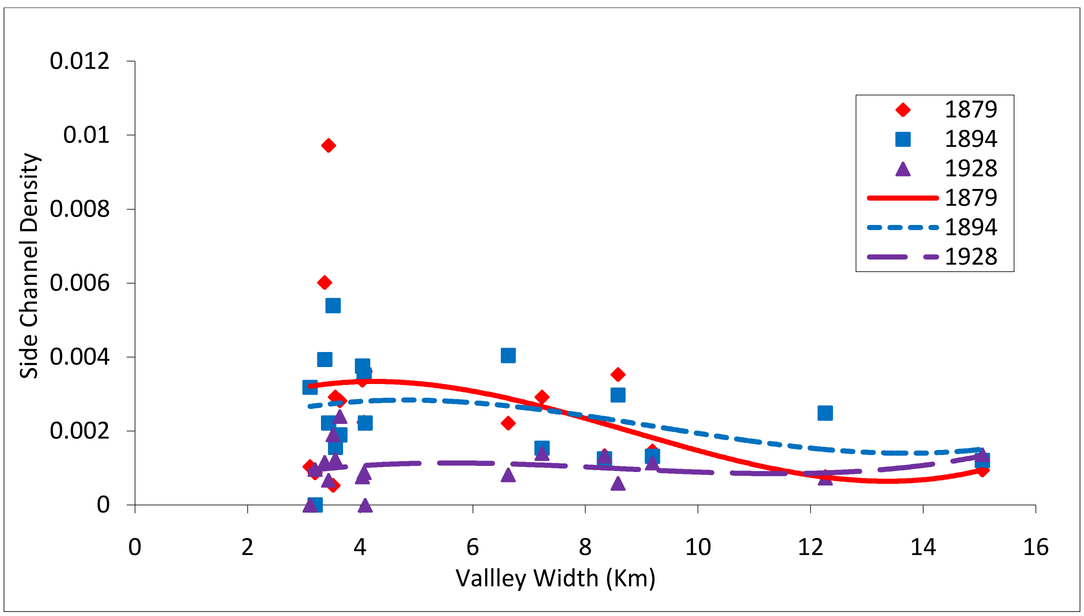


Figure 4.34 Relationship between Average Side Channel Density and Valley Slope North of the River

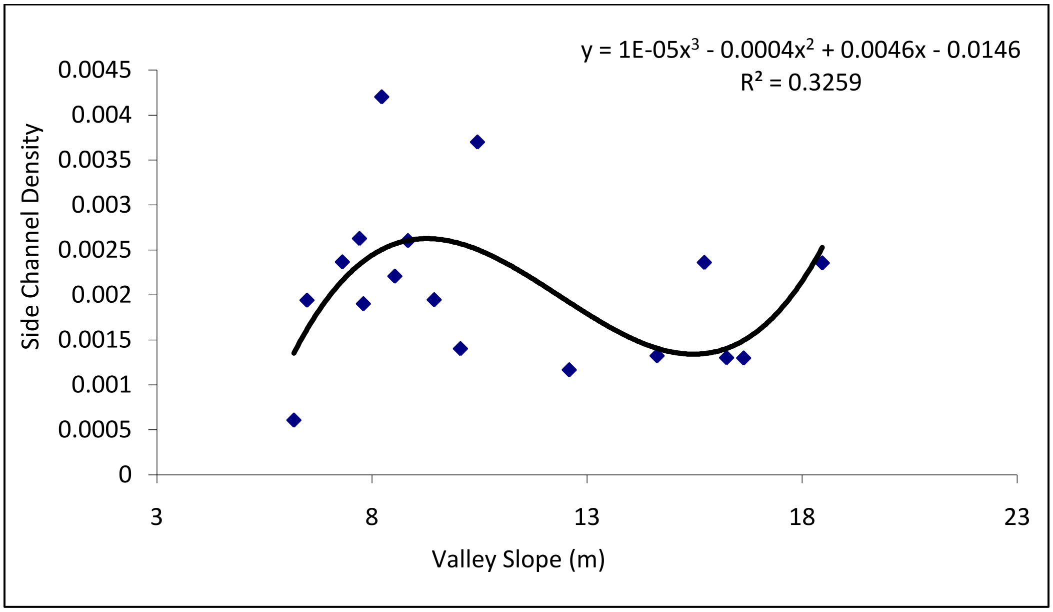


Figure 4.35 Relationship between Side Channel Density and Valley Slope North of the River

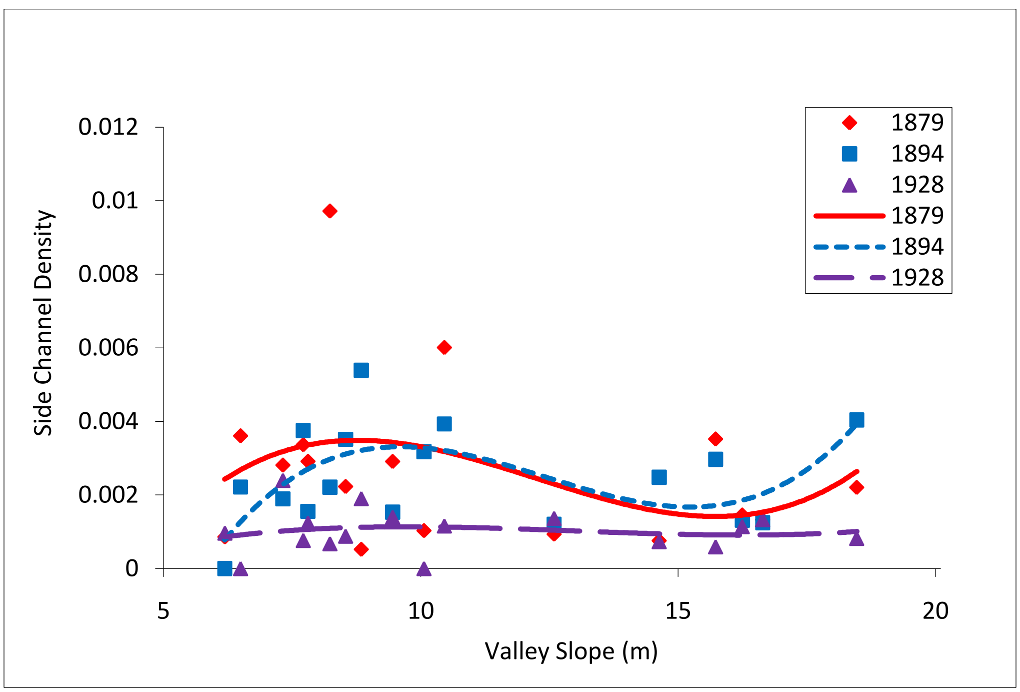


Figure 4.36 Relationship between Average Side Channel Density and Valley Slope South of the River

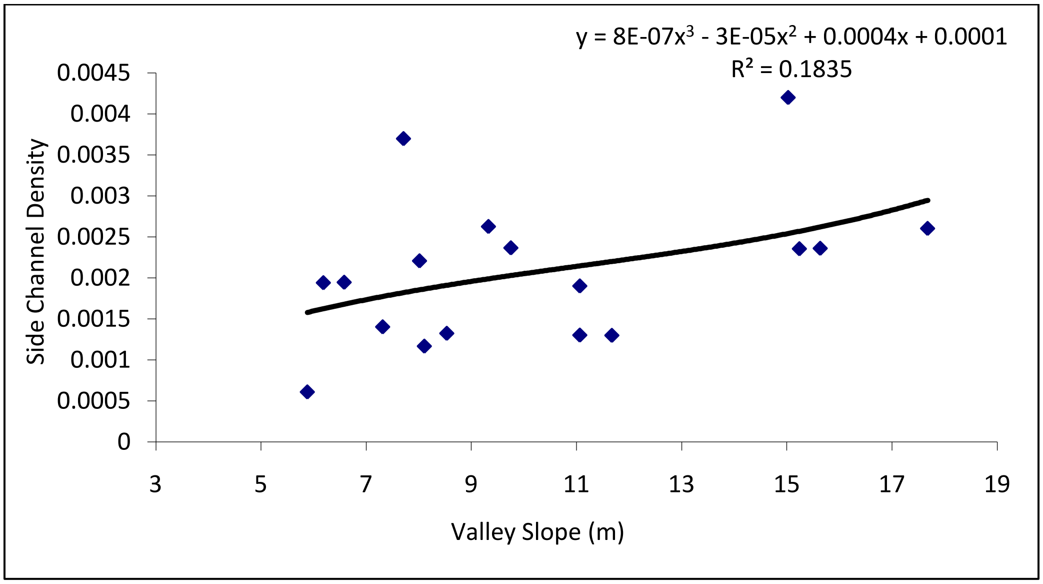
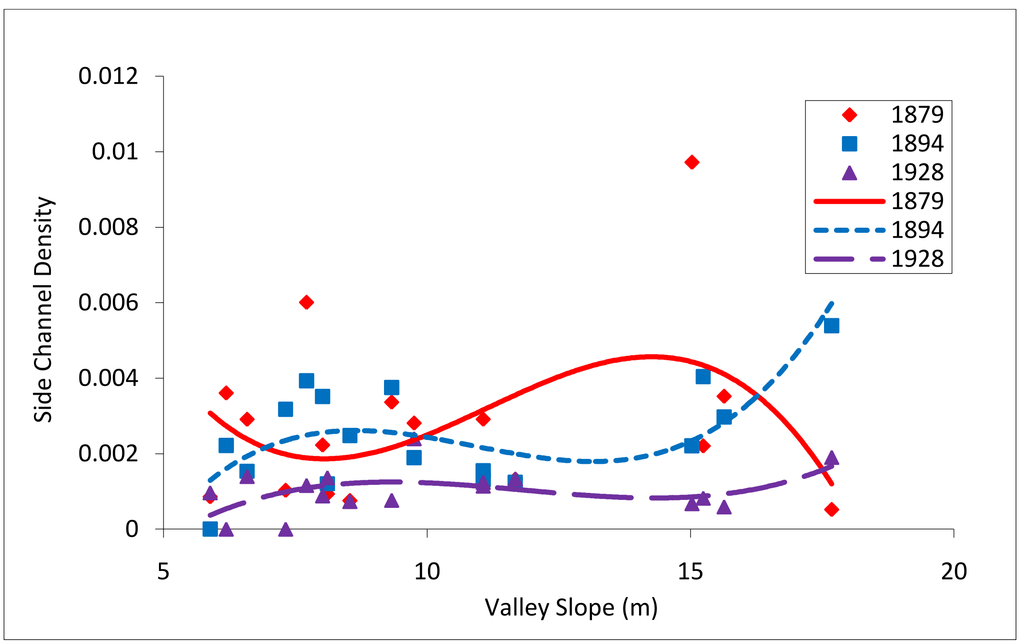


Figure 4.37 Relationship between Side Channel Density and Valley Slope South of the River



Sinuosity and valley slope values did not have a strong correlation (Figure 4.38 and Figure 4.39). Valley slope south of the river and reach sinuosity had the lowest R squared value, .0022.

Figure 4.38 Relationship between Average Reach Sinuosity and Valley Slope on the North Side of the River

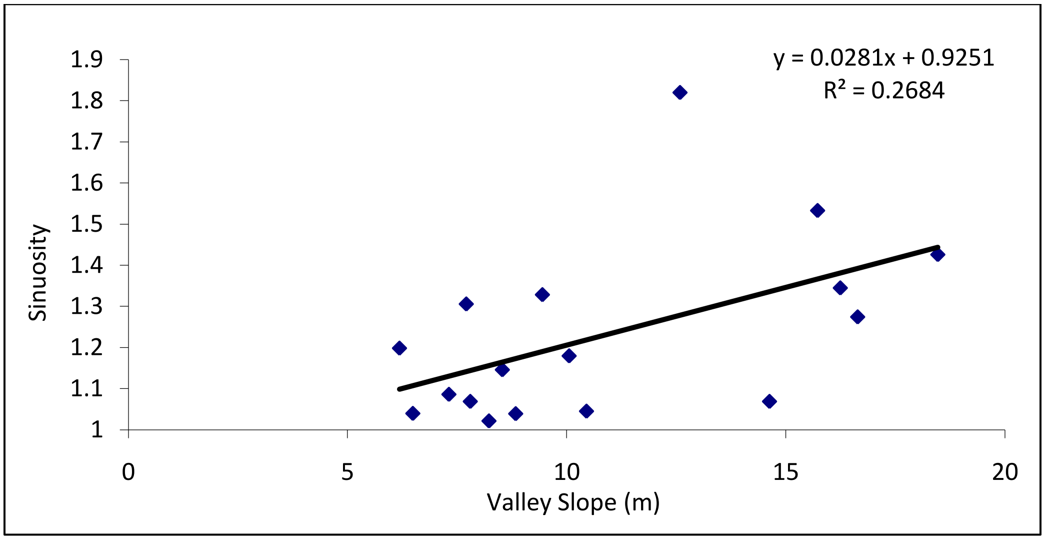
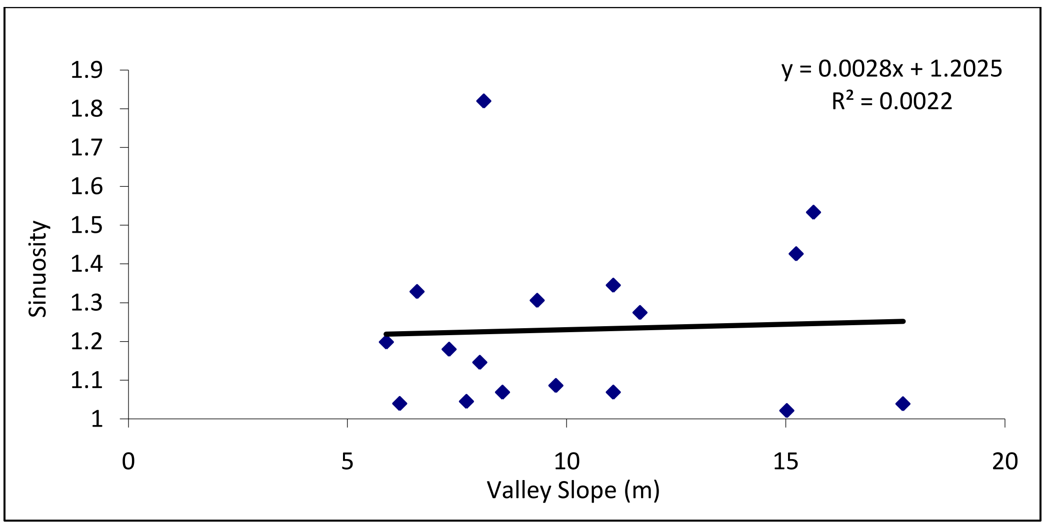
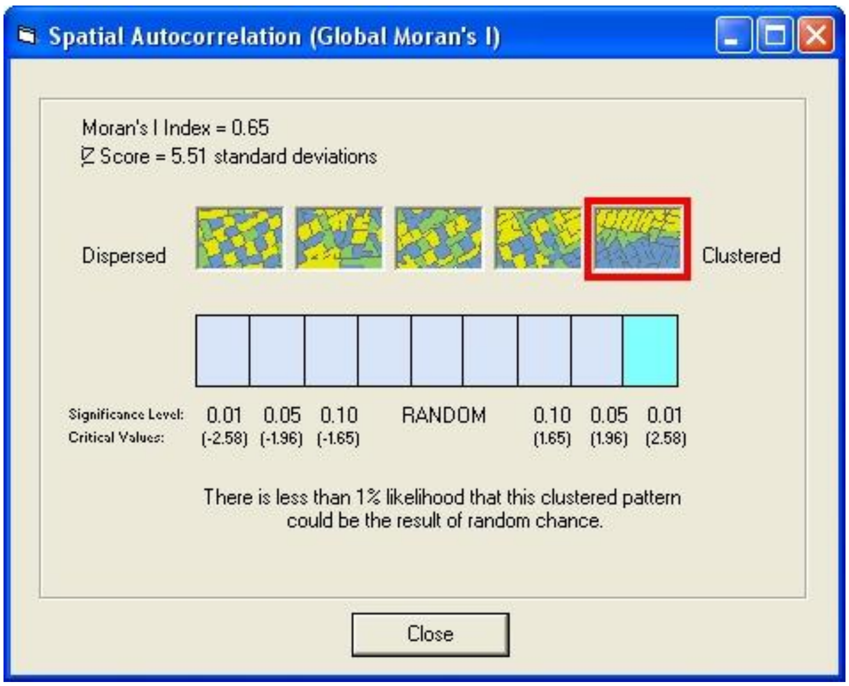


Figure 4.39 Relationship between Average Reach Sinuosity and Valley Slope on the South Side of the River



Arc GIS Moran's I tool results are displayed with a range of values to explain the spatial autocorrelation based on feature locations and attribute values (Figure 4.40). The Moran's I index for side channel locations and distance to the nearest confluence is 0.65. The variance is .014 and the z score is 5.51. Since the z score was higher than 2.58 the data shows a clustered spatial autocorrelation that is significant at a >1% level.

Figure 4.40 Spatial Autocorrelation Moran's I Results



Chapter 5 - Discussion

The results show that, prior to extensive engineering of the Missouri River, there were abundant side channels and that the river was very dynamic, with a variety of main and side channel configurations. The two sample years (1879 and 1894) derived from land survey data contained a greater occurrence of side channels, with 56 in 1879 and 37 in 1894. This is a dramatic change is side channel frequency in a short amount time that correlated with the beginning of channel stabilization and other engineering works to create a stable navigable river. The aerial photograph derived sample year, 1928, contained only 28. The overall declining frequency of side channels was likely the result of preliminary engineering works to control the Missouri River as demonstrated by Pinter and Heine (2005).

Results from my reach-scale analysis demonstrated that certain river sections did have a historically higher side channel presence than others. Reaches 6, 12, and 16 had the highest number of side channels in their 15 mile area (Table 4.1). Reaches 7 and 8 had the lowest number of side channels each with four (Table 4.1). Efforts to explore explanatory driving variables for side channel location met with mixed results. Valley slope and valley width were both weakly correlated with side channel frequency. However, channel sinuosity was moderately correlated with side channel frequency with an R squared value of 0.51(Figure 4.21) indicating that sinuosity alone could predict 51% of reach-scale side channel frequency. Areas with higher sinuosity values should then contain more side channels than less sinuous reaches. Plots of sinuosity values per year shows a decline in frequency of side channels due to the decrease of the sinuosity (Figure 4.22). These findings, particularly the moderately significant polynomial relationship between sinuosity and side channel frequency, support those of Hooke (2004) that greater sinuosity produces increased side channel formation. In particular, our findings suggest that certain sinuosity threshold relationships exist that may in large part control side channel formation. Side channel frequency was higher in very low sinuosity reaches (1.0-1.1), decreased to a minimum near 1.2, and then increased again between 1.3 and 1.5. Despite the absence of data points between 1.5 and 1.8, the relationship fits well to the outlier reach with sinuosity of 1.8. This type of relationship indicates that side channel formation may be driven by very low sinuosity or moderate sinuosity (1.3-1.5) but decline in more sinuous reaches. Such threshold behavior has also been observed in studies of river meandering, for example with the relationship between radius of curvature and meander migration (Schumm, 2005). While the chute-cutoff formation mechanism explored by Hooke (2004) follows the link to sinuosity, other many side channel measured in this study are not in a chute configuration. This may explain why there is only a moderate significance value to this relationship.

Finally, results of correlation analysis between major confluence locations and side channel locations showed that the side channel locations were significantly clustered around confluences (Figure 4.40). This finding suggests that confluence dynamics exert an influence on river planform dynamics beyond the confluence zone itself, something that has not previously been explored in the literature. It may be possible that large confluences introduce a planform instability that results in side channel formation via lateral forcing of flood flows during overbank discharges that could produce scour in the floodplain and side channel formation.

After analyzing the data and the historical distribution of side channels the working hypothesis of the distribution of side channels on the Missouri River was concentrated in reaches that were highly sinuous was supported, as was the expectation that major confluences were related to side channel locations. However, the results do not support the hypotheses that valley slopes or widths influence side channel locations.

Chapter 6 - Conclusions and Recommendations

Historical accounts have described the pre-engineered Missouri River as a dynamically meandering river with complex and numerous side channels. The results of this study confirm this widely held notion and provide quantitative analysis of that notion. The abundant side channels documented in this study likely provided critical diverse aquatic habitats and dramatically increased hydrologic connectivity of valley bottom to main channel (Jacobson, 2004). This study shows the decline in side channel frequency due to the construction on the Missouri River. The Missouri River before channelization benefitted most native plant and animal life as it was unconfined and unrestricted. The modern Missouri River being heavily engineered to support navigation, flood control and economics has had damaging effects to the natural plant and animal life along the river. Side channel chutes provide increased areas of sandbars and shallow, slow water habitats that enrich natural plant and animal life.

This study has demonstrated relationships between reach-scale sinuosity and confluence presence to the formation of large river side channels, adding to a very small literature on side channels. The implications of this study are limited by the dependence on three snap-shot data layers that were not entirely isolated from other human impacts in the Missouri River watershed. This study did base its implications on engineering being the reason behind the decline is side channel occurrence due to a study by Pinter and Heine (2005). However, it is the most extensive study of its kind, both in terms of temporal and spatial resolution.

The increased understanding of historical side channel location and dynamics produced by this study will assist the USACE in its efforts to restore side channels on the Missouri River. For example, the USACE can now prioritize for purchase lands that are located near large confluences and/or in the most sinuous reaches of the main channel as the most optimal areas for side channel restoration. Based on the results, the reach that has the best conditions for constructing a side channel chute is reach 17. The Little Blue River meets the Missouri River in reach 17, and this reach historically had higher than average presence of side channels and a high average sinuosity. Given this data reach 17 is the best reach for side channel construction. The location of large confluence points has not changed over time.

In addition to Reach 17, reaches 5, 6, 11, 12 all contain major confluences and are favorable locations for side channel restoration. Reaches 6, 12, and 16 also had large numbers of side channels (Figure 4.6, Figure 4.12, and Figure 4.16). Reach 4 has a favorable location for a side channel chute that could be constructed solely using the past planform measurements. In the westernmost area of Reach 4 is historical side channel that persisted from 1879 to 1894 with few planform adjustments. This is a beneficial chute to reconstruct because this side channel occurred naturally in this area. The USACE will have to use fewer resources to up keep this channel due to it having thrived in the past. Reach 16 has a similar example of a side channel that persisted in 1879 to 1894 and connects to the modern river channel. This side channel is located near river mile 320. This specific area is a significant location to construct a chute due to past side channels success.

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