# AN INVESTIGATION OF GROWTH AND MOVEMENT PATTERNS OF MID-CHANNEL BARS IN THE MISSOURI RIVER

By

Noah James Underwood

Bachelor of Science, 2020
University of Tennessee, Knoxville
Knoxville, Tennessee

Submitted to the Graduate Faculty of the
College of Science and Engineering
Texas Christian University
in partial fulfillment of the requirements
for the degree of

Master of Science

August 2022

Acknowledgements

I would like to thank Dr. Holbrook, whose knowledge and support made this entire project possible. He provided me with guidance, wisdom, and advice far beyond what was expected of him. I also thank other committee members Dr. Maarten Kleinhans and Dr. Esayas Gebremichael for their help on various aspects of this project. I would also like to thank Jim Gribble for technical support related to GIS software. I also thank my parents Lori and Kyle Underwood for their ever-present support of my life inside and outside of academia. A final thank you to my colleagues and friends whose support in and out of the classroom allowed me to continue a successful pursuit of my academic goals.

**Table of Contents**

**List of Figures**

**List of Tables**

## 1. Introduction

Highly dynamic mid-channel bars are prominent in braided sand-bed rivers due to their relatively shallow channels and generally higher bedload proportion. Much is known about the formation factors of mid-channel bars including the accretion of unit bars, migration of bars within the channel, and docking mechanisms of these bars. However, little to no studies have been conducted which tracked comprehensive bar statistics over a significant period of time. Consequently, while much is known of the occurrence and geometry of various types of bars, little is known of their kinematics. Studies by Hooke, Holbrook & Allen, and Bartholdy & Billi have addressed life-cycles of individual bars or small datasets of bars, but all of the bars in a given river have not been published (Hooke 1986, Bartholdy & Billi 2002, Holbrook & Allen 2020). Other studies that track general statistics like average surface area and intrachannel migration patterns have been performed on individual/small sets of bars (Ashworth 1996, Rice et al., 2009, Mukherjee 2011, Kleinhans 2010, Ashmore 2013 among others). The Missouri River, and its size being well observable from space, offers an opportunity to perform a similar study to the previously mentioned studies on a larger and more comprehensive scale.

The advancement of remote sensing technologies and Geographic Information System (GIS) software presents a unique opportunity to track mid-channel bars en masse over long periods of time. Previous studies of mid-channel bars relied almost exclusively on models and field observations before advances in remote sensing collection and processing capabilities. Over the last 30-40 years, multiple satellite image collection missions have been run, including the Landsat Mission. Landsat is a joint USGS/NASA image collection mission which specializes in visible, near infrared, and thermal remote sensing which began in the late 1970s. In addition to these satellite image collection missions, many advances have been made in remote sensing processing software and its capabilities. State of the art GIS processing software plus Landsat images from the last 30 years present ample and previously unavailable opportunity to track a river’s changes over a long period of time in totality.

This study focuses on an 88 km uncanalized stretch of the Missouri River (**Figure 1**) between Gavin’s Point dam in Yankton, SD and Sioux City, IA (**Figure 2**). The Missouri River has been highly channelized by the US Army Corps of engineers for ease of access, flood control, and commerce purposes. However, the stretch of the river investigated in this study has remained largely unaltered and presents close to natural braided river conditions (US Army Corps of Engineers, Rahn 1977). This uncanalized and unaltered section of the river allows one to study the Missouri River approximately as it was before human intervention and presents unbiased data in a statistical study of the transformation of the braided river system. In this study, 29 years of Landsat images were acquired and processed in ArcMap, a key component of Environmental Systems Research Institute (ESRI)’s ArcGIS suite used for GIS data analysis, in order to track all of the compound mid-channel bars in this stretch of the Missouri River. All in all, 104 compound mid-channel bars were tracked between 1989 and 2018. Characteristics like life-cycle, surface area, docking patterns, and downstream migration were tracked and analyzed in order to create a comprehensive profile of the mid-channel bars in this stretch of the Missouri River. It is expected that a large amount of mid-channel bars will dock at meander bends, further increasing point assemblages and sinuosity in the channel. It is also expected that most of the bars in the river will be fixed or semi-fixed, with few fully free bars which leave their respective meander bend. Bars are also expected to be confined to wider stretches of the channel with few mid-channel bars to be found in narrow areas of the channel.

## 2. Background

### 2.1 The Meandering Braided Missouri River:

The Missouri River is a 2,639 mi (4,247 km) long river that runs through eight states before joining the Mississippi River in St. Louis, Missouri. The headwaters of the Missouri are formed by the confluence of the Gallatin, Madison, and Jefferson Rivers in western Montana. The Missouri River drains approximately 529,000 square miles or 1.3 million square kilometers and its basin drains most of the Eastern and Northern Rocky Mountains, or about 17% of the contiguous United States (Laustrup & LeValley 1998; Spooner 2001; Holbrook & Allen 2020). In the early 1900s, the US Army Corps of Engineers began channelizing and damming portions of the Missouri River in an effort to regulate water flow as well as make the river more navigable (Laustrup and LeValley 1998; U.S. Army Corps of Engineers, 2004). By the 1960's the river was completely channelized downstream of Ponca City, Nebraska, and fully submerged under dammed reservoirs upstream of Yankton, South Dakota, leaving only the 88 km stretch in between roughly unmodified (Sanford 2007, Jacobson et al. 2009, Holbrook & Allen 2020).

The dammed and regulated Missouri River is much less dynamic than it was before modification, when stream morphology was more dynamic and water and sediment discharge more commonly ranged higher. Prior to the damming and channelization, the Missouri River transported a sediment load of 135 million tons per year (Mellema & Wei, 1986). The Missouri River discharge post-regulation has decreased to approximately 22 million tons of sediment per year, a decrease of approximately 75% (Rus et al., 2013).

The Missouri River has been referred to as "the braided river that meanders" by Holbrook and Allen (2020) given the prevalence of both sinuosity and mid-channel bars in the uncanalized section of the river. The unmodified river was predominantly single thread meandering upstream of Great Falls, Montana and multi-thread braided downstream. Changes in various sections of the river over the last 3,000-4,000 years have caused shifts between single thread meandering and multi-thread braided (Kashouh et al., 2012, Holbrook & Allen 2020). The braided sections feature mid-channel bars that form via accretion of unit bars into larger compound bars. These compound bars migrate and accrete to the bank or to lateral bars that collectively form bar assemblages that resemble the typical point bars that are seen in meandering rivers (Holbrook & Allen 2020).


**Figure 1:** The entirety of the Missouri River Basin. Study area highlighted by red box (ESRI).

**Figure 2:** 88 Km study area between Yankton, SD (top left) and just upstream of Sioux City, SD. Source: Google Earth.

## 2.2 Fluvial Bar Types:

Point bars, lateral bars (also alternate or side bars), and mid-channel bars (multiple mid-channel and compound mid-channel bars) each form in the braided meandering Missouri River (**Figure 4**). Point bars are associated with meandering rivers but are present in the braided meandering Missouri due to inner bank sediment deposition and mid channel bar docking and give the Missouri River relatively high sinuosity for a braided river system (Holbrook & Allen 2020). Lateral and mid-channel bars are typical in braided river systems and are abundant in the Missouri River. Lateral and mid-channel bars are the focus of the tracking in this study while point bar formation via mid-channel bar docking is of interest as a primary termination point of mid-channel bars' life-cycles.

Continued building of point assemblages on inner bends helps the Missouri grow and maintain sinuous meanders. Point bars are also present locally in bends. Point bars differ from point assemblages in that they are a compound bar through the addition of unit bars to a bar accretion surface rather than by addition of compound bars to the bank. Bars can also attach to any part of the cutback to form large counterpoint assemblages. Point bars form as bank attached bars along the inner (convex) portion of a meander bend. Flow velocity and sediment transport capacity increase along the (outer) cutbank and decrease along the inner bank around the meander. Lower inner bank velocity results from the lower depth and lower momentum and thus reduces the river's sediment carrying capacity, which makes these areas of the channel more prone to deposition (Einstein 1926, Jackson, 1976, Andrews 1979, Langbein & Leopold 1966 Seminara 2006, Kleinhans 2010). Centrifugal forces running perpendicular to the bank also contribute a little to cutbank scour, especially in sharper bends, and support point bar growth. Transformation and migration result from lateral shifts in channel position due to deposition on the inner bank and erosion on the cutbank (Hayashi 1971, Jackson 1976, Fredsoe 1978). Accordingly, in addition to translation and expansion of meanders by generation of point assemblages, the Missouri River can contract or retreat meander bends though formation of counterpoint assemblages; thus, all four of the possible component vectors for meander migration generate in the Missouri River (Holbrook & Allen, 2020).

Braided rivers mostly differ from meandering rivers by the relative dominance of mid-channel bars. Mid-channel bars are typical of braided rivers, which tend to have large width to depth ratios, high sediment yield, and typically move more coarse bedload than a meandering rivers (Williams & Rust 1969, Rust 1972, Miall 1977, Ashworth et al., 1986) Compound mid-channel bars form when unit bars coalesce onto preferential accretion surfaces and form a larger compound bar (Ashworth 1996, Ashworth et al. 2000). Mid-channel bars originate in the center of a river channel and may continue to grow until they create semi-permanent mid-channel floodplains, thus separating an anabranch from the other channel (Ashworth 1996). More commonly, mid-channel bars will grow then shrink until they disappear or move laterally or downstream until they dock to a bank and join the floodplain laterally. Mid-channel bars generally have a larger average grain size than point bars due to higher flow velocities in braided rivers (Ashworth 1996, Best et al. 2003, Luchi et al. 2010).

The third most common bar type seen in the Missouri River is the lateral/side bar (which leads to side-attached bars). Side bars are types of elongated mid-channel bars (rather than a unique bar type) that have popped up near the side of the channel or laterally migrated there. Side bars share similar formation factors to mid channel bars but are mostly seen in straight, non-sinuous portions of the river. Many side bars will migrate downstream or wash away, but many of them will dock to the shore and become side-attached bars. Side-attached bars will often attach on alternate sides of the channel moving downstream and will give straight portions of the channel a sinuous path (Crosato & Mosselman 2020).

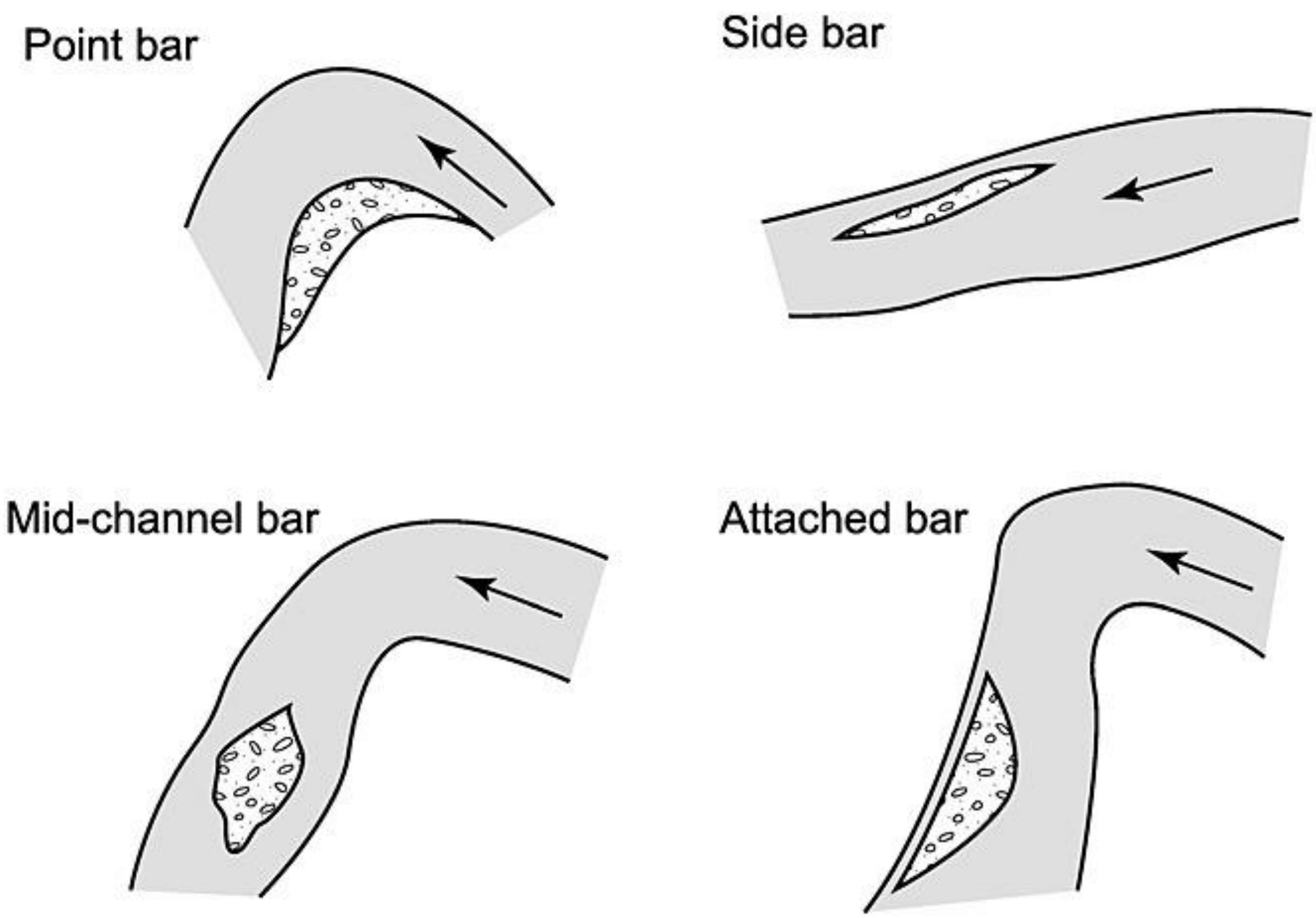



**Figure 3:** A figure of common fluvial bars seen in the Missouri River adapted from Hooke 2011. Point bars are seen in meander bends. Multiple bars and mid-channel bars are products of the Missouri's braided river characteristics. Side bars are mid-channel bars which can dock to the bank and create point bars.

## 2.3 Mid-channel Bars in Braided Rivers:

Mid-channel bar (or "braid bar") formation is a result of instabilities in bedload and turbulent flow along the channel bottom. This turbulent flow results in very uneven sediment transport along a slightly uneven bed, which causes sedimentation-erosion patterns and eventually causes the river to bifurcate around growing mounds (bars) of deposited sediment. Coarser grain sediment will remain at the head of the bar while grain size trends finer toward the tail due to selective sorting (Leopold & Wolman 1957, Ashmore 1991). Lateral accretion of other smaller dunes/bars will occur simultaneously, which further enhances the bar growth process (Ashworth et al. 2000, Lunt & Bridge 2004). In this stage the major drivers of bar growth are lateral accretion, deposition downstream of bank erosion, and deposition after high flow events (Ashworth et al. 2000, Lunt & Bridge 2004). Once a mid-channel bar reaches a certain size, it can split river flow significantly enough to cause an anabranch with increased flow velocity on one or both sides of the bar (Ashworth et al. 2000). The presence of these anabranches with increased flow velocity means higher erosion rates on the bar itself and the banks adjacent to the anabranch. This increased erosion leads to immediate deposition on the furthest downstream portion of mid-channel bars which elongates the tails of bars (Ashworth et al. 2000). Once compound bars are formed, they sometimes migrate laterally towards either bank via flow discrepancies between the bifurcations which surround the bar (Ashworth 1996, Shields et al. 2000). Compound bars can also migrate downstream via headward erosion and subsequent downstream deposition of sediment on the bar's tail (Bristow 1987, Ferguson & Ashworth 1992, Ashworth 1996, Ashworth et al. 2000, Schuurman & Kleinhans 2015). Mid-channel bars can also not migrate at all then completely erode away and disappear. The large compound bars can also continue to grow and sometimes become permanent floodplain fixtures in the channel.

Once a compound bar forms, the time it takes for it dissolve or dock would be referred to as its "life cycle". Few studies (with widely varying results) have been published on the life cycle of mid channel bars. One of the first studies (Hooke 1986) suggests a life cycle of 5-15 years for gravelly mid channel bars in the River Dane. Bartholdy and Billi (2002) suggested that bars in the Cecina River (Italy) form as a result of moderate level flood events and recycle in major flood events of 10-20 year recurrence intervals. A more recent study conducted in the Fraser River (Canada) finds some bars in "protected" portions of the river can survive some 30-100 years – albeit in low flow/sediment flux conditions (Rice et al., 2009). In a study on the Missouri River, Holbrook & Allen (2020) performed a lifespan analysis on multiple bars in the same bend of the river. Holbrook & Allen (2020) addressed the time from bar initiation, growth, and floodplain accretion to be ~15 years. This study will use currently available imagery and GIS software, to generate a more comprehensive estimate of bar life cycle on the Missouri River. Braid bar migration and docking (or "welding") are supported as the primary processes of floodplain development in braided rivers (Hooke 1986, Ashworth et al. 2000, Bridge 2003, Parker et al. 2013; Holbrook & Allen 2020), and the Missouri River in particular (Holbrook & Allen, 2020). Unit bars can coalesce into the banks and directly form lateral bars or accrete in the middle of the channel into compound mid-channel bars which may remain in the middle of the channel or migrate towards a bank and form lateral bars (Holbrook & Allen 2020). Ashworth et al. (2000) were one of the first to track the ontogeny of mid-channel bar. A mid-channel bar emerged in the middle of the Jamuna River, Bangladesh and docked to the bank in a 3-year period. It was seen over these three years that bar migration was driven by unit bar accretion on the bankside of the braid bar. Once the anabranch was filled with smaller, sandy unit bars, finer material filled in the space until the bar was integrated into the floodplain (Ashworth et al, 2000).

A possible driver of lateral (bankward) bar migration is asymmetrical flow between channel branches on either side of a mid-channel bar. The asymmetry between the two branches can lead to one side of the bar having a branch with much less sediment carrying capacity, which leads to mass sediment deposition in that section of the channel. This sediment deposition leads to channel fill and eventual welding of the bar to a bank once the channel fills all the way, thus leaving the bar migrated and docked (Ashworth et al. 2000, Hood 2010, Gorrick & Rodriguez 2014, Holbrook & Allen 2020). Bathymetry measurements in Holbrook & Allen show that preferential flow and deposition at bifurcations is a process that is native to the Missouri River (Holbrook & Allen 2020). Bar docking in rivers is an important concept because lateral accretion bars can drive a river to become more or less sinuous based off of where the bars dock. If bars migrate and dock on inner bends, the forced cutbank erosion will cause the channel to have higher amplitude sinuosity. Opposite, if a bar docks on the outer bend of a river, then the channel is straightened by subsequent point erosion (Bridge 2003). Since meanders in a braided river can be heavily influenced by bar docking, this can cause the meander bends to transform in contradiction to their previous expansional and translational patterns which were largely governed by slope and sediment erosional resistance (Lunt & Bridge 2004, Holbrook & Allen 2020). What is not known on a large scale is what proportion of mid-channel bars in a given stretch of a river system dock to the banks and integrate into the floodplain versus simply dissolve or erode away in place with no preservation record.

Mid-channel bars are rarely stable in terms of area, length, shape, and position in the river. In this study, fixed bars -also referred to as forced or non-migrating bars in literature- are bars which have little to no downstream movement and either stay stationary or migrate laterally towards the bank. In addition to lateral migration, mid-channel bars can move downstream in some instances (Ashmore 1991, Ashworth 1996, Kleinhans 2010, Mukherjee 2011, Ashmore 2013). Such bars in this study that move significantly downstream are considered semi-fixed or free bars depending on their degree of movement. Changes in channel morphology, discharge, and sediment load cause mid-channel bars to change quickly and often (Callander 1968, Hooke & Yorke 2011, Wang 2017). Riverbeds generally lack cohesion and will lose stability in a perturbed, random pattern due to turbulent flow. Instability in turbulent flow and the resultant erosion of a riverbed is the main driver in bar migration (semi-fixed and free bars) (Callander 1968, Parker 1976, Seminara & Tubino 1989, Kleinhans 2010, Wintenberger et al., 2015). Migrating/free bars are mostly formed and influenced in flood years due to higher discharge and thus larger turbulent flow effects while they remain less changed and perhaps move less in lower stage years for the opposite reasons (Seminara & Tubino 1989). Conversely, non-migrating (fixed) bars are theorized to be the result of the forcing effects of channel curvature, which generally relegate fixed bars to the immediate area in which they formed (Seminara & Tubino 1989, Repetto et al., 2002, Wu & Yeh 2005). It is important to note that in the case of fixed (forced) bars, the general discussion is relegated to point bars in a meandering river. However, braid bars can also remain in place with little to no downstream migration. In this study, mid-channel bars that fit this description are also considered “fixed” bars as there is no downstream movement. The mechanisms that drive bars to be forced or free is well understood through models, but comprehensive real-world studies are lacking. Especially true is the fact that no known studies have been published on the proportion of braid bars in a braided river system that remain fixed vs. bars that migrate downstream (semi-fixed or free). The abundance of mid-channel bars in the Missouri River provides an excellent opportunity to study the migration patterns of an entire stretch of a river system.

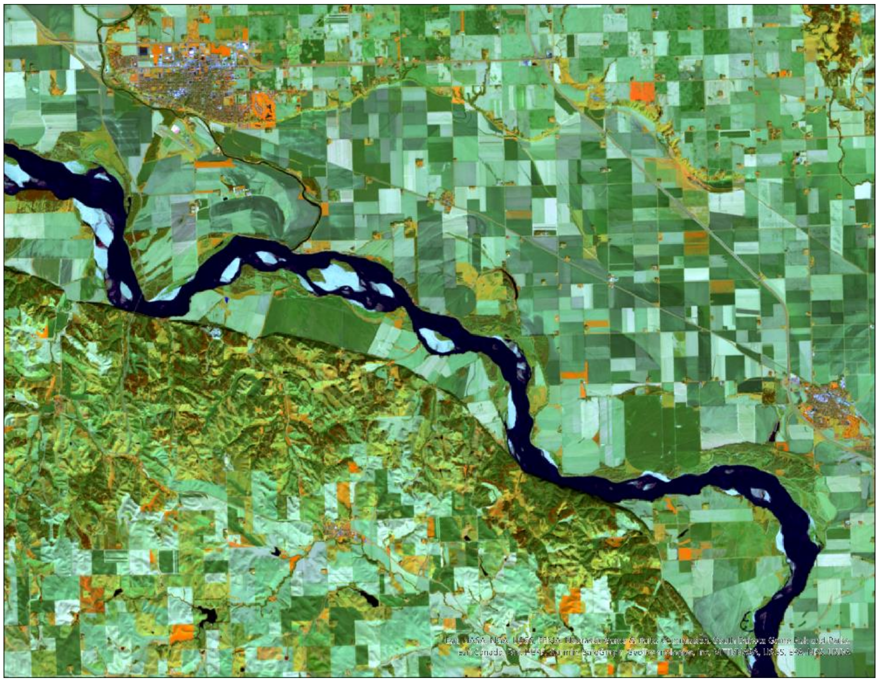
## 3. Methods:

Landsat imagery from Landsat 4, 5, and 8 with multiband visible and infrared light were used for mapping bars over yearly time steps to track bar evolution. The USGS Earth Explorer page (https://earthexplorer.usgs.gov/) was used to access Landsat collection 1 images from 1986 to 2021. Image quality before 1986 was poor and was not suitable for proper data analysis, while stream data was inconsistent or poor past 2018. Worldwide Reference System (WRS) path 29 row 30 was selected for the image footprint area, which contained the entirety of the study area in one image . Cloud and snow cover filters were set at 10% or less in order to produce clear images. Images were selected between the months of March and October to limit snow and ice cover.

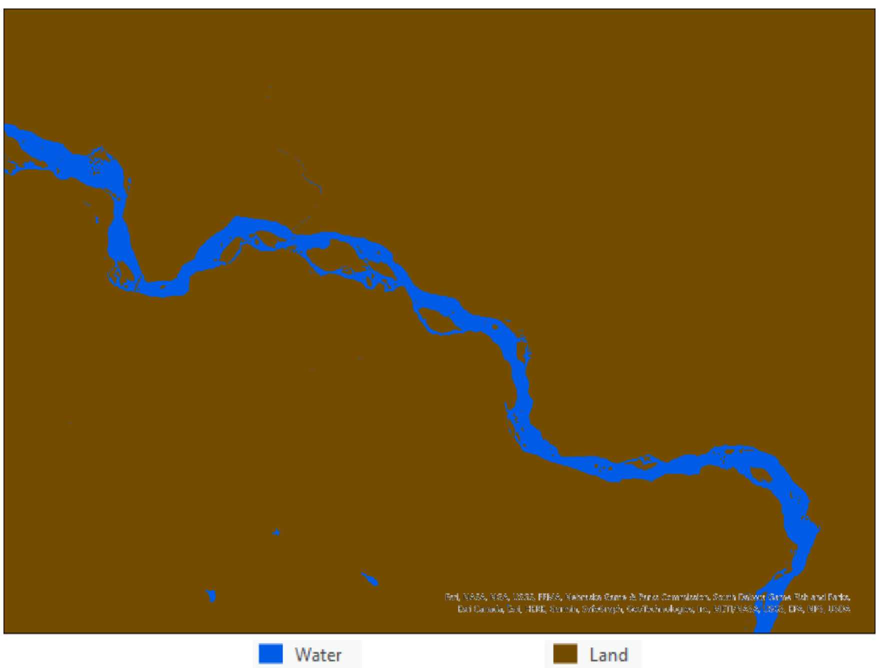
Landsat images from 1986 through 2018 were selected based off those images which met the streamflow, cloud cover, and land cover criteria which provided a consistent comparison between imagery and stream conditions across the 32-year window. Images were selected where the a common low river stage range so bars could be compared year to year at a similar water levels. Streamflow data from the USGS (waterdata.usgs.gov) at the Yankton (USGS 06467500) and Gayville (06478526) gages in the Missouri River were compiled from the years 1986 through 2021. Average gage height in feet was calculated at both locations, with the average gage heights at Yankton being 13.4 ft (4.1 m) and Gayville at 47.3 ft (14.4 m). Images selected based on when gages read a water level of 1.5 ft (0.45 m) on either side of the average (4.1 m at Yankton and 14.4 m at Gayville). The range of 0.45 m from the average water level was selected due to the total range (0.9 m) being approximately 10% of bankfull river stage (Anderson et al. 2021). The restricted river stage range used equated to a window from 40-50% of bankfull flow, which reflects a compromise between maximum constancy for image comparison  without compromising the available selection of images. It was also found that approximately 50% of bankfull river stage was where changes in water level least affected bar surface area. Near infrared (NIR) and shortwave (SWIR) infrared light were used where available because they are absorbed by water and reflected by land at a high contrast. Infrared light is absorbed by water near three wavelengths: 1,100 nm, 1,300 nm, and 3,000 nm (https://earthobservatory.nasa.gov/). All three of these wavelengths fall within near infrared and/or shortwave infrared spectrum (NIR/SWIR). The Landsat Multi-spectral scanner (MSS) carried 4 bands: Red, Green, and two Near Infrared wavelengths. The investigated times/years in this study using the images taken by the MSS instrument were years 1986-1990 and 2012. Images acquired by the MSS sensor have poor quality in terms of spatial resolution (60 m) and available wavelengths (4 bands). As a result, the best band combination for land water delineation was 321 (NIR, Red, Green). Landsat images taken by the Thematic Mapper (TM) instrument were used from 1991-2011, taking up the largest portion of the dataset. TM images provide clearer false color images due to the addition of the SWIR band which is the closest wavelength to the 1,300 nm absorption wavelength of water. A band combination of 4, 5, 3 (NIR, SWIR, Red) was used in the Thematic Mapper composite band images. Landsat 8's Operational Land Imager (OLI) instrument uses 11 bands: coastal aerosol, blue, green, red, NIR, SWIR 1/2, panchromatic, cirrus, and thermal infrared (TIR) 1/2. Landsat images acquired by the OLI instrument were used for the interval 2013-2018 and provided the greatest flexibility in composite band synthesis. Landsat OLI images (5, 6, 4) used a band combination similar to Landsat TM images (4, 5, 3) and contained NIR, SWIR 1, and red bands (**Figure 6a**).

| Landsat Mission | Sensor | Years Used |
| --- | --- | --- |
| **Landsat 4-5** | Multi-Spectral Scanner | 1986-1990, 2012 |
| **Landsat 6** | Thematic Mapper | 1991-2011 |
| **Landsat 8** | Operational Land Imager | 2013-2018 |

**Table 1:** Table of Landsat missions and years used.



**4a**




**4b**

**Figure 5a:** Composite image of a portion of the river channel from 2016 (OLI). Bands combined were red, NIR, and SWIR1

**Figure 5b:** A photo of the same stretch of river post-classification. Coffee colored pixels are land while Blue pixels are water.

ArcMap GIS software was used for image analysis and visualization. False color composite images were generated and stitched together, showing electromagnetic radiation wavelengths both inside and outside the visible electromagnetic spectrum. The supervised learning image classification tool in ArcMap was used to classify the Landsat images into a set number of feature classes. In this procedure, training samples representing the investigated feature types were created and a pixel-based supervised classification algorithm detects and maps the features throughout image based on the spectral properties of the individual pixels. Only two classes were used in this study: land (coffee color) and water (blue)(**Figure 6**). After images were classified, ArcMap's raster to polygon tool was used to create simplified polygons of water and land, defining the channel banks and emergent parts of bars.

Polygon rasters of mid-channel bars were defined from Landsat images for each year, and measured area, XY centroid coordinates, and length. A threshold of 36,000 square meters was established to differentiate unit bars and compound bars. Unit bar sizes were estimated based on Alexander (2013) and Holbrook & Allen (2020) The largest unit bar (based on visual estimation) was approximately 12,000 square meters. This value was then tripled (36,000 sq. meters, shown in **figure 7**) in order to effectively reduce the dataset to only include bars that were sufficiently large to assure they were indeed compound bars (as opposed to unit bars), and to reduce the sample to a manageable size for year-to-year tracking. The sample of tracked bars was further limited to those lasting at least 2 years within the data's timeframe. Each bar meeting these thresholds of size and duration was manually tracked over the 28 years of data for migration direction and changes in size. Fixed bars were defined as bars whose centroid did not move more than a bar length downstream during the bar's lifespan. Semi-fixed bars were described as bars whose centroid moved more than a bar length downstream but remained within the same meander-bend reach. Free bars were described as bars that migrated outside of their meander bend during their life cycle.

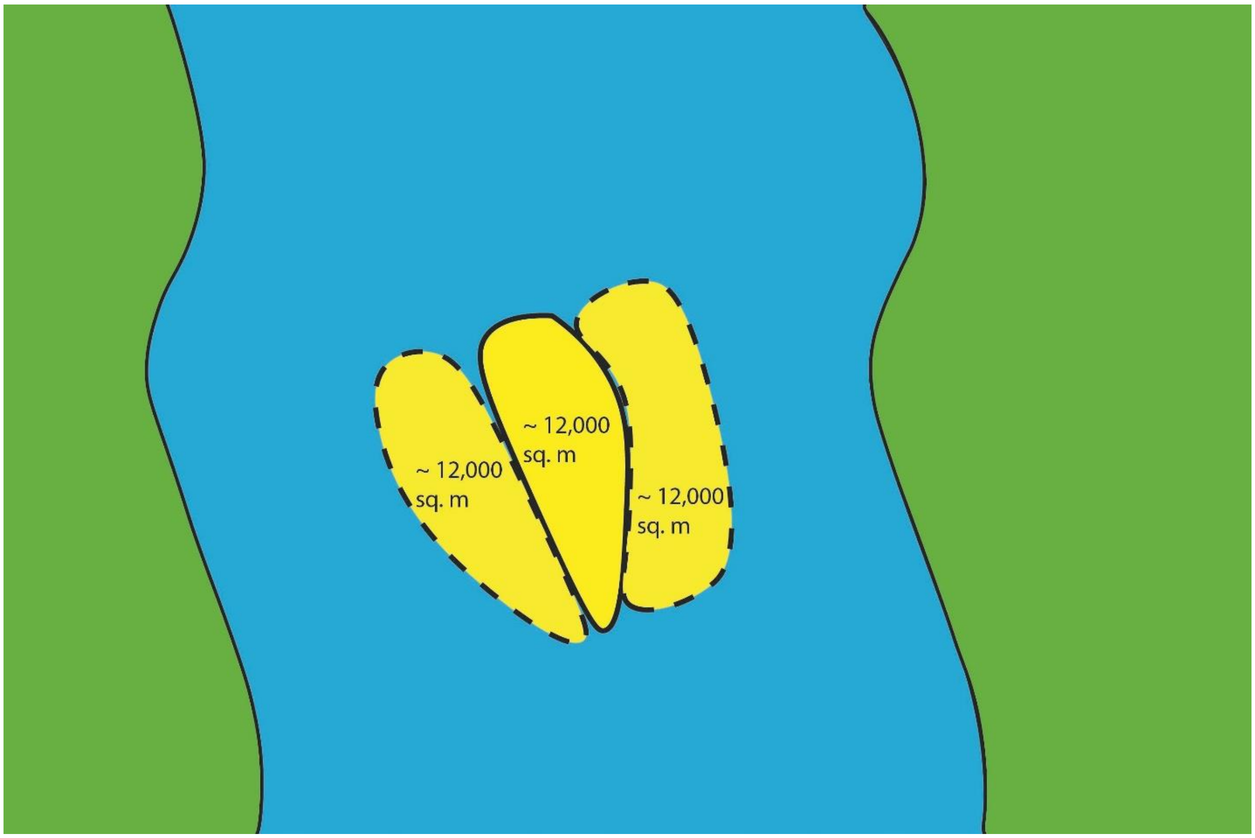



**Figure 5:** A rough diagram of the unit/compound bar threshold established in this study. The middle bar (outlined in solid) was considered the upper limit of the size of a unit bar. The two equally sized unit bars (dashed outlines) illustrate the other unit bars or sediment deposition necessary to transform the unit bar into a compound bar for the purposes of this study.

Bars exceeding the 36,000 square meter and two-year thresholds, were binned according to area, total bar movement, fixed vs. semi-fixed, and docking or non-docking. Average area and duration of each bar was calculated. Nominal age categories based on life cycle were created for the bars as follows: short lived (2-5 years), medium lived (6-10 years), long lived (11-20 years), or islands (20+ years). For bars that ended by docking instead of reworking, the location that docking bars welded to the floodplain was recorded in the following categories: inner bank of meander bend, outer bank of meander bend), straightaway/crossover, and mid-channel floodplain between anabranches. Additionally maps of the modern river channel and the channel survey from the 1860’s (USGS) was compared to estimate the minimum rate at which the floodplain was reworked by channel migration from bar processes, and the degree of floodplain reworking over century scales

## 4. Results:

The main variables tracked in this study for bars that met the size and longevity criteria were bar life-cycle length, average area, fixed vs. semi-fixed, and docking vs. non-docking. A total of 104 bars met the 36,000 square meter exclusion criteria as well as existing for at least two consecutive years in the dataset. Having met these two criteria, these 104 bars were tracked in depth over the 28-year time period of this study (**Table 2**).

| MR | Age | Dock? (Dock Bank) | Fixed or Semi-fixed | Nominal Age | Avg. Area |
|---|---|---|---|---|---|
| 1 | 29+ | no | fixed | long | 736947 |
| 2 | 29+ | no | fixed | island | 698914 |
| 3 | 10+ | no | fixed | medium | 338458 |
| 4 | 3 | no | fixed | short | 128931 |
| 5 | 12 | no | fixed | long | 36434 |
| 6 | 3 | no | fixed | short | 124520 |
| 7 | 29+ | no | fixed | island | 750962 |
| 8 | 3 | no | fixed | short | 190149 |
| 9 | 29+ | no | fixed | island | 707176 |
| 10 | 29+ | no | fixed | island | 480020 |
| 11 | 2 | no | fixed | short | 148677 |
| 12 | 29+ | no | semi-fixed | island | 110664 |
| 13 | 9 | no | fixed | medium | 96810 |
| 14 | 3 | no | fixed | short | 129026 |
| 15 | 9 | no | semi-fixed | medium | 203057 |
| 16 | 12 | no | fixed | long | 251733 |
| 17 | 18 | no | semi-fixed | long | 91189 |
| 18 | 20 | no | fixed | long | 77926 |
| 19 | 3 | no | semi-fixed | short | 103088 |
| 20 | 8+ | no | fixed | medium | 187127 |
| 21 | 3 | no | semi-fixed | short | 99351 |
| 22 | 2 | yes (fp) | fixed | short | 51689 |
| 23 | 2 | no | fixed | short | 77365 |
| 24 | 29+ | no | fixed | long | 661456 |
| 25 | 4 | no | fixed | short | 210546 |
| 26 | 8 | no | fixed | medium | 702979 |
| 27 | 2 | no | fixed | short | 36979 |
| 28 | 3 | yes (fp) | fixed | short | 105505 |
| 29 | 6 | yes (fp) | semi-fixed | medium | 28785 |
| 30 | 2 | no | fixed | short | 61970 |
| 31 | 2 | no | fixed | short | 83070 |
| 32 | 3 | no | fixed | short | 86499 |
| 33 | 8 | yes (o) | semi-fixed | medium | 70740 |
| 34 | 2 | no | fixed | short | 87490 |
| 35 | 9 | yes (o) | semi-fixed | medium | 181988 |
| 36 | 23 | no | semi-fixed | island | 102322 |
| 37 | 9 | no | fixed | medium | 71325 |
| 38 | 6 | yes (fp) | fixed | medium | 88220 |

| MR | Age | Dock? (Dock Bank) | Fixed or Free | Nominal Age | Avg. Area |
|---|---|---|---|---|---|
| 39 | 8 | yes (fp) | fixed | medium | 178151 |
| 40 | 17 | yes (o) | fixed | long | 92720 |
| 41 | 19 | yes (o) | semi-fixed | long | 207640 |
| 42 | 8 | yes (fp) | fixed | medium | 102000 |
| 43 | 2 | yes (i) | fixed | short | 113042 |
| 44 | 3 | no | semi-fixed | short | 48603 |
| 45 | 3 | yes (i) | fixed | short | 200126 |
| 46 | 3 | no | fixed | short | 52562 |
| 47 | 7 | no | semi-fixed | medium | 190586 |
| 48 | 20 | yes (o) | semi-fixed | long | 284001 |
| 49 | 20 | yes (o) | semi-fixed | long | 266114 |
| 50 | 21 | yes (o) | fixed | island | 215989 |
| 51 | 7 | no | semi-fixed | medium | 299570 |
| 52 | 2 | no | fixed | short | 92245 |
| 53 | 6 | yes (i) | fixed | medium | 94196 |
| 54 | 21+ | yes (o) | fixed | island | 203874 |
| 55 | 25+ | yes (o) | fixed | long | 472020 |
| 56 | 22+ | no | semi-fixed | island | 518538 |
| 57 | 5 | yes (s) | fixed | short | 220103 |
| 58 | 22 | no | fixed | island | 302717 |
| 59 | 9 | yes (i) | fixed | medium | 132583 |
| 60 | 10 | yes (i) | fixed | medium | 149769 |
| 61 | 20 | yes (i) | fixed | long | 57214 |
| 62 | 8 | yes (s) | fixed | medium | 182876 |
| 63 | 4 | no | fixed | short | 70768 |
| 64 | 6 | no | semi-fixed | medium | 101677 |
| 65 | 21+ | no | semi-fixed | island | 164049 |
| 66 | 21+ | no | fixed | island | 162139 |
| 67 | 21+ | no | fixed | island | 125408 |
| 68 | 5 | no | fixed | short | 97817 |
| 69 | 6 | no | fixed | medium | 104139 |
| 70 | 28+ | no | fixed | island | 120285 |
| 71 | 6 | no | fixed | medium | 48815 |
| 72 | 6 | no | fixed | medium | 99019 |
| 73 | 2 | no | semi-fixed | short | 34321 |
| 74 | 8 | yes (s) | semi-fixed | medium | 74216 |
| 75 | 6 | no | fixed | medium | 117572 |
| 76 | 2 | yes (o) | fixed | short | 71575 |
| 77 | 3 | no | semi-fixed | short | 116746 |
| 78 | 21+ | no | fixed | island | 96979 |
| 79 | 2 | no | fixed | short | 67048 |
| 80 | 2 | no | fixed | short | 94601 |

| MR | Age | Dock? (Dock Bank) | Fixed or Free | Nominal Age | Avg. Area |
|---|---|---|---|---|---|
| 81 | 2 | no | fixed | short | 56534 |
| 82 | 15+ | no | fixed | long | 217429 |
| 83 | 2 | no | fixed | short | 60324 |
| 84 | 2 | yes (o) | fixed | short | 91120 |
| 85 | 19+ | no | semi-fixed | long | 157181 |
| 86 | 2 | no | fixed | short | 200162 |
| 87 | 5 | yes (o) | fixed | medium | 36837 |
| 88 | 14+ | no | fixed | long | 117086 |
| 89 | 8+ | no | fixed | medium | 91304 |
| 90 | 18 | yes (s) | semi-fixed | long | 87939 |
| 91 | 6 | yes (o) | fixed | medium | 199028 |
| 92 | 8+ | no | fixed | medium | 124755 |
| 93 | 8+ | no | fixed | medium | 252788 |
| 94 | 8+ | no | fixed | medium | 208277 |
| 95 | 2 | no | fixed | short | 50017 |
| 96 | 3 | no | fixed | short | 172502 |
| 97 | 19 | yes (s) | fixed | long | 120527 |
| 98 | 3 | no | fixed | short | 75428 |
| 99 | 3 | no | fixed | short | 76860 |
| 100 | 5 | yes | fixed | short | 95775 |
| 101 | 21 | yes (s) | fixed | island | 268182 |
| 102 | 7 | yes (o) | fixed | medium | 65002 |
| 103 | 8 | yes (o) | fixed | medium | 443300 |
| 106 | 12 | no | fixed | long | 69208 |

**Table 2:** A table displaying the basic information for each bar. **MR** # was the naming convention for this study. The MR column points to the sample number. Age column displays the bar age, a "+" next to the age demarks a bar which already existed in the beginning of the study interval or did not disappear before the study interval ended; thus, its age is longer that determined from this study. **Dock?** demarks bars which did or did not dock eventually dock as the completion of the life cycle (yes), vs. reincorporated into the bedload (no). **Dock Bank** indicates which bank a bar docked to if it docked ("yes" in column "Dock?"). **O:** Outer Bank, **I:** Inner Bank, **S:** Straightaway, **FP:** Bar docked to mid channel floodplain. **Avg. Area** provides the bar's average surface area during its lifespan above 36,000 $km^2$. **Fixed or Semi-fixed** tells whether the sample was fixed or semi-fixed. **Nominal Age** provides the age range of a bar. Short= 2-5 years, medium= 6-10 years, long= 11-20 years, island= 21+ years.

One of the main purposes of this study was to determine the average life-cycle length for the mid-channel bars in the Missouri River. Thirty-five of the 104 bars were either already present in 198 or did not complete their life cycle (dock or reincorporate) by 2018, so their life-cycle was incomplete and underminable within the timeline of this study. Of the 69 bars whose life cycle begins and ends within the study time period; the average age was 7.9 years. While 7.9 years was the overall average age, the average age of each bar type (docking/non-docking, fixed/semi-fixed, etc) varied between 4.5 years and 11.3 years.

Another way to consider bar life cycle is grouping the bar ages into nominal categories. The nominal age category lengths were determined by examining the data clustering and trying to create intervals at natural breaks (natural breaks method) in the data while keeping interval length mostly consistent (manual classification). Bars which completed their life cycle in 2-5 years were considered “short-lived”. Bars which survived 6-10 years were considered “medium-lived”. Bars which existed for 10-20 years were considered “long-lived”. Finally, bars which survived 21-30 years OR did not originate and dissipate within the bounds of the study interval were considered “islands”. The distribution of bars by nominal age category is as follows: 38 short-lived bars, 32-medium lived bars, 18 long-lived bars, 16 island bars (**Figure 9**). The average age of all bars (7.9 years) in the tracked dataset falls into the “medium-lived” category. Note a generally linear downward progression of the distribution of the bar types by nominal age. When this is included with the smaller (<36,000 sq. m) bar average life cycle of <2 years, the distribution shows a clear downward trend in numbers as age increases.

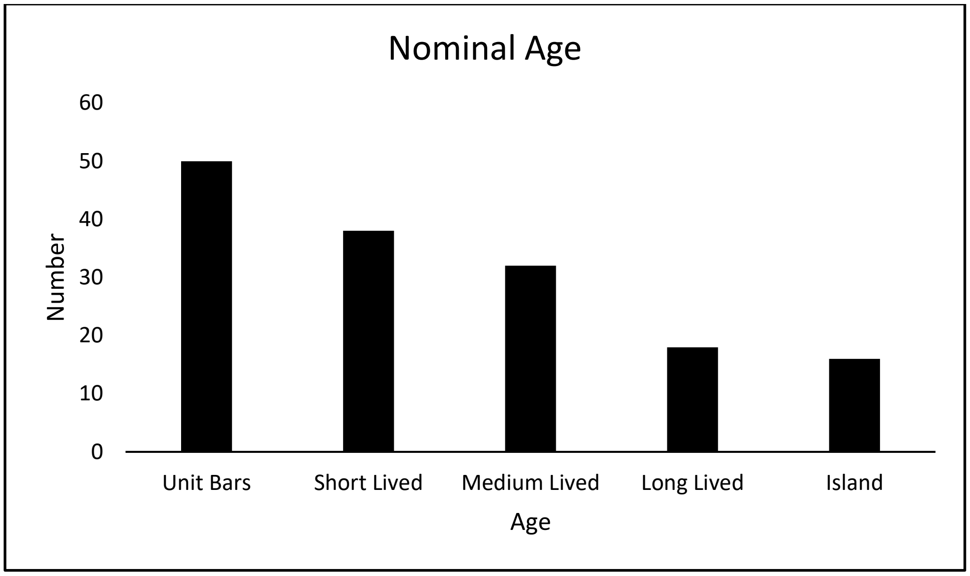



**Figure 6:** Nominal age of 50 sampled unit bars and the 104 tracked compound bars

Docking vs non-docking differentiates the bars that eventually become part of the floodplain (docking) from those that are not preserved as floodplain (non-docked) even temporarily. Of the 104 bars, 34 (32.7%) of the bars ended their life cycle by docking to the floodplain. Conversely, 70 (67.3%) of the bars did not dock to floodplain and ended their life cycle by eroding and reincorporating back into the bedload in mid-channel (**Figure 10**). Cross-referenced by duration, docking bar life cycles lasted 8.2 years on average while non-docking bar life cycles lasted 5.7 years on average. In addition to age, average area was also compared for docking and non-docking bars in the Missouri River. Average area for a docking bar was approximately 154,495 square meters while the average area for a non-docking bar was 184,703 square meters. A box and whisker plot was made, and similar to the fixed/free bars, it was seen that the non-docking dataset had multiple high outliers. The discrepancy in area is likely due to the presence of large outliers in the non-docking dataset, perhaps the same bars seen as outliers in the fixed bar dataset. Bars that eventually docked to become part of the floodplain on average were longer lasting and slightly smaller. Bars that docked, docked in one of four general docking locations: inner bank (inner bank of a meander bend), outer bank (outer bank of a meander bend), straightaway/crossover (no discernable meander bends/ between meander bends), or mid-channel floodplain islands. Of the 34 docking bars, 6 bars docked to the inner bank, 6 bars docked to the straightaways, 6 bars docked to mid-channel floodplains, and 16 bars docked to an outer bank, showing a preference to the outer-bank docking, but no preferences otherwise.

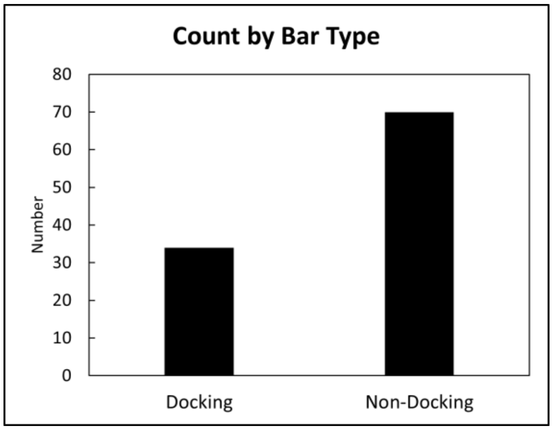



**Figure 7a**: Count of docking vs. non-docking bars

| Samples | Count | Percent (%) |
|---|---|---|
| Docking | 34 | 32.7 |
| Non-Docking | 70 | 67.3 |
| **Total** | **104** | **100** |

**Figure 7b:** Table of docking vs. non-docking count.

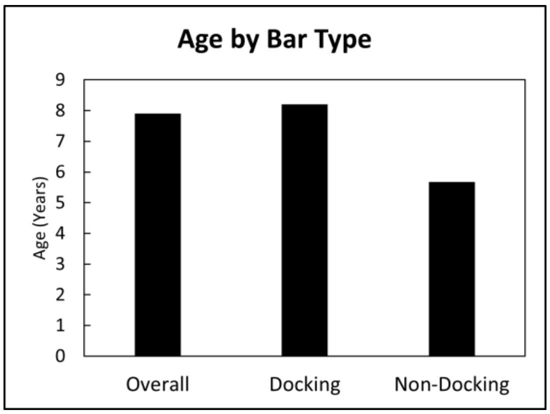



**Figure 7c:** Count of average age of docking vs. non-docking bars.

| Samples | # of Samples | Avg. Age |
|---|---|---|
| Docking | 25 | 8.2 |
| Non-Docking | 44 | 5.7 |
| **Total** | 69 | |

**Figure 7d:** Table of docking vs. non-docking age.

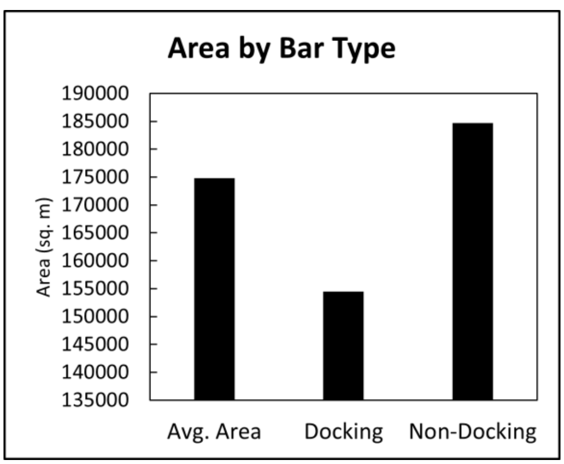



**Figure 7e:** Count of area od docking vs. non-docking bars.

| Samples | Average Area (sq. m) |
|---|---|
| Docking | 154495 |
| Non-Docking | 184703 |

**Figure 7f:** Table of docking vs. non-docking area.

Bars were also binned as fixed vs semi-fixed. A fixed bar was defined as a bar which did not migrate downstream more than one bar length over its life cycle. A semi-fixed bar migrated at least one bar length downstream over its life cycle. This analysis was performed by using the coordinates of the centroid from the start and the end years of the bar combined with the initial bar length to determine distance migrated for a given bar. Of the 104 tracked bars, 81 (77.8%) of the samples were classified as fixed bars (**Figure 11**). Conversely, 23 (22.2%) of the samples were classified as semi-fixed bars. There were no bars in this stretch of the Missouri River which migrated outside of their meander bend, or for that matter out of their half of their meander bend; thus, there were no fully free bars. Fixed bars had a life cycle length of 5.5 years on average while semi-fixed bars had a life-cycle length of 9.7 years on average. Fixed bars also had an average area of 180,737 square meters while semi-fixed bars had an average area of 154,015 square meters.  Fixed bars had a much shorter duration and were slightly smaller than semi-fixed bars. However, upon further investigation via a box and whisker diagram, it was seen that the difference in average area between fixed and semi-fixed bars was due to a few outliers in the fixed bar dataset. The overall boxes of both bar types closely resemble each other and thus it can be assumed that this difference is simply the result of outliers in the datasets.

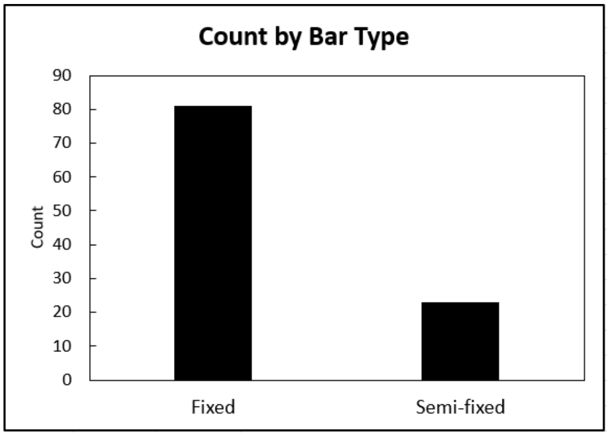



**Figure 8a:** Count of fixed vs. semi-fixed bars.

| Samples | Count | Percent |
|---|---|---|
| Fixed | 81 | 77.8 |
| Semi-Fixed | 23 | 22.2 |
| **Total** | **104** | **100** |

**Figure 8b:** Table of fixed vs. semi-fixed count.

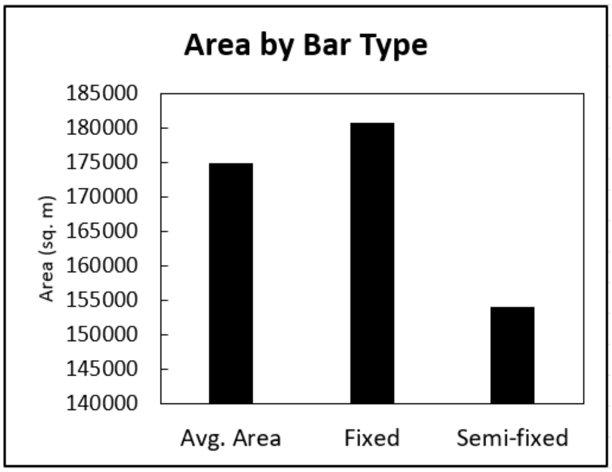



**Figure 8c:** Area of fixed vs. semi-fixed bars.

| Samples | Average Area (sq. m) |
|---|---|
| Fixed | 180737 |
| Free | 154015 |

**Figure 8d:** Table of fixed vs. semi-fixed bar areas.

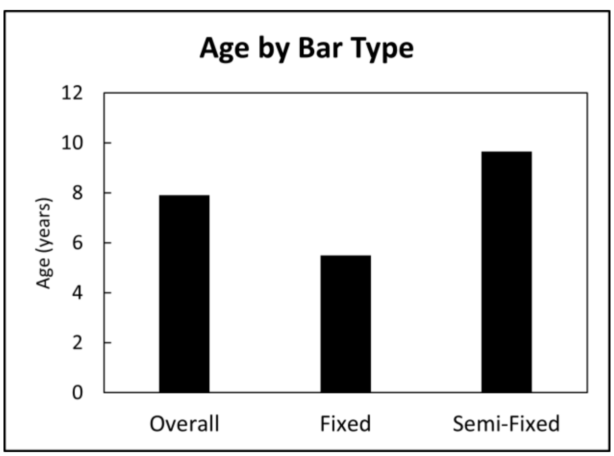



**Figure 8e:** Average age of fixed vs. semi-fixed bars.

| Samples | # of Samples | Avg. Age |
|---|---|---|
| Fixed | 51 | 5.5 |
| Semi-Fixed | 18 | 9.7 |
| **Total** | **69** | |

**Figure 8f:** Table of average area of fixed vs. semi-fixed bars.

All 104 bars were assigned one of four specific categories: docking fixed, non-docking fixed, docking semi-fixed, or non-docking semi-fixed. There were 26 (25%) bars that were docked and were fixed, 55 bars (52.9%) were non-docking and fixed, 8 (7.7%) bars were docking and semi-fixed, and 15 (14.4%) bars were non-docking and semi-fixed (**Figure 12**). The average ages for the four bar categories are: 7.2 years for docking fixed bars, 11.3 years for docking semi-fixed bars, 4.5 years for non-docking fixed bars, and 8.8 years for non-docking semi-fixed bars. The average area for the four bar categories is: 155,823 square meters for docking fixed bars, 150,177 square meters for docking semi-fixed bars, 192,514 square meters for non-docking fixed bars, and 156,062 square meters for non-docking semi-fixed bars. As was the case before, docking bars are generally longer cycled than non-docking bars in both fixed and semi-fixed form with negligible area difference, but in this case the semi-fixed bars lasted longer than the fixed bars in both docking and non-docking bins.

| Samples | Count | Percent (%) |
|---|---|---|
| Docking Fixed | 26 | 25 |
| Docking Semi-fixed | 8 | 7.7 |
| Non-Docking Fixed | 55 | 52.9 |
| Non-Docking Semi-fixed | 15 | 14.4 |
| **Overall** | **104** | **100** |

**Figure 9a:** Table of bar category counts.

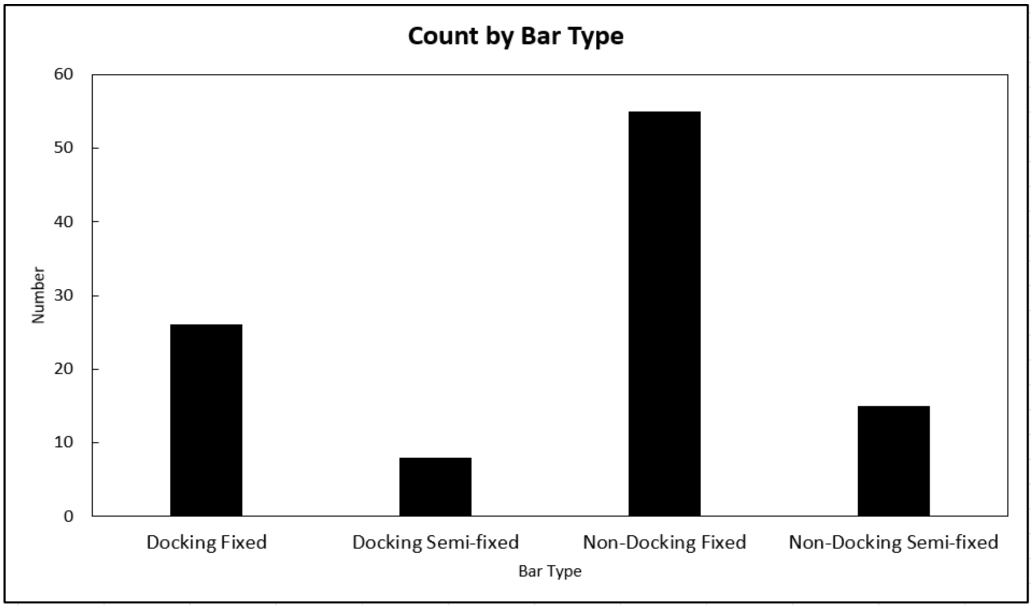



**Figure 9b:** Counts of bar categories.

| **Samples** | **# of Samples** | **Avg. Age** |
|---|---|---|
| Docking Fixed | 19 | 7.2 |
| Docking Semi-fixed | 6 | 11.3 |
| Non-Docking Fixed | 32 | 4.5 |
| Non-Docking Semi-fixed | 12 | 8.8 |
| **Overall** | **69** | 7.9 |

**Figure 9c:** Table of the average age of bar categories.

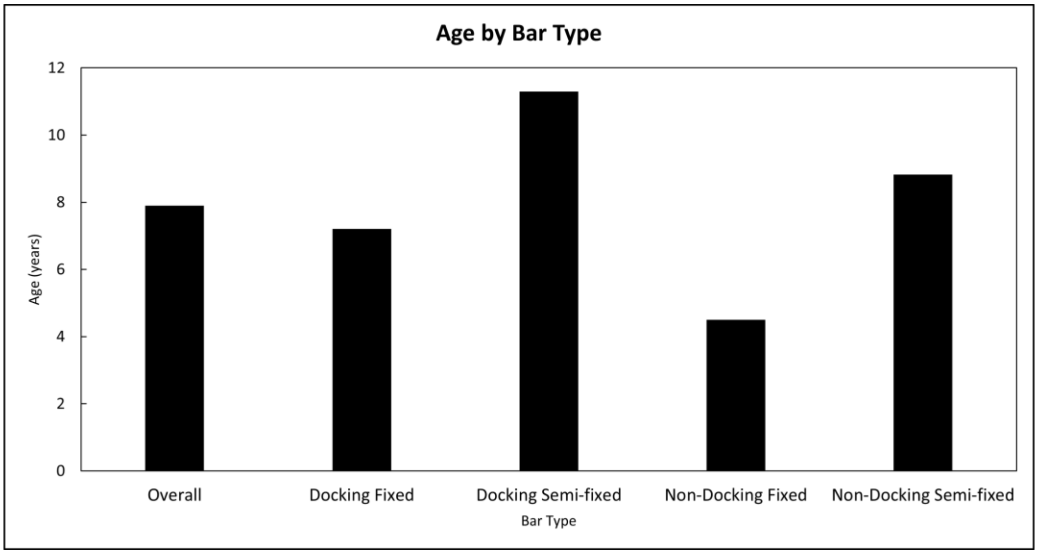



**Figure 9d:** Average age of each bar category.

| Samples | Average Area (sq. m) |
|---|---|
| Docking Fixed | 155823 |
| Docking Semi-fixed | 150177 |
| Non-Docking Fixed | 192514 |
| Non-Docking Semi-fixed | 156062 |
| **Average** | **174827** |

**Figure 9e:** Table of the average area of each br category.

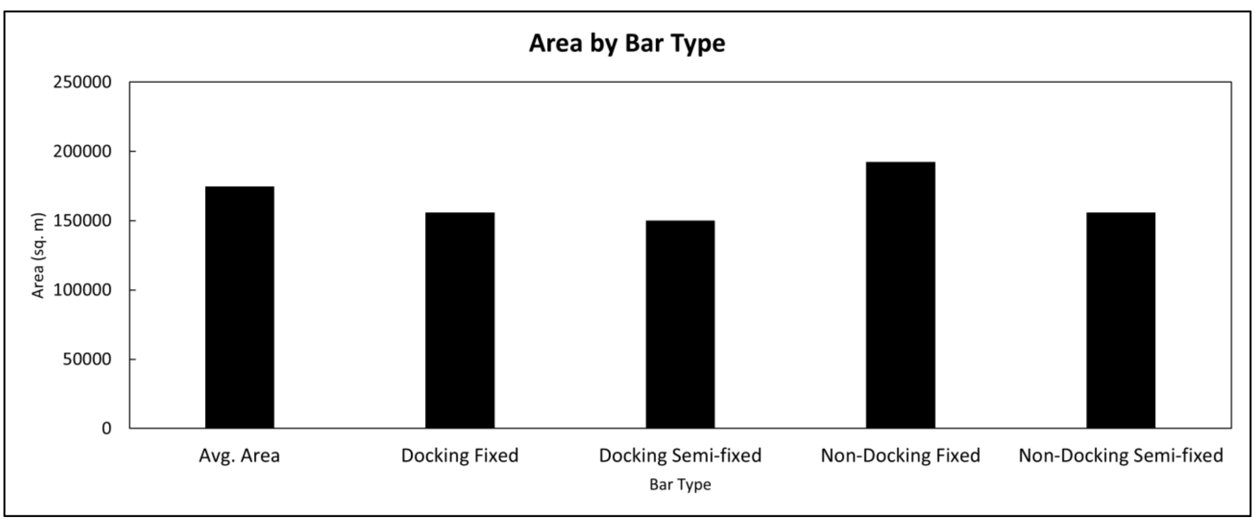
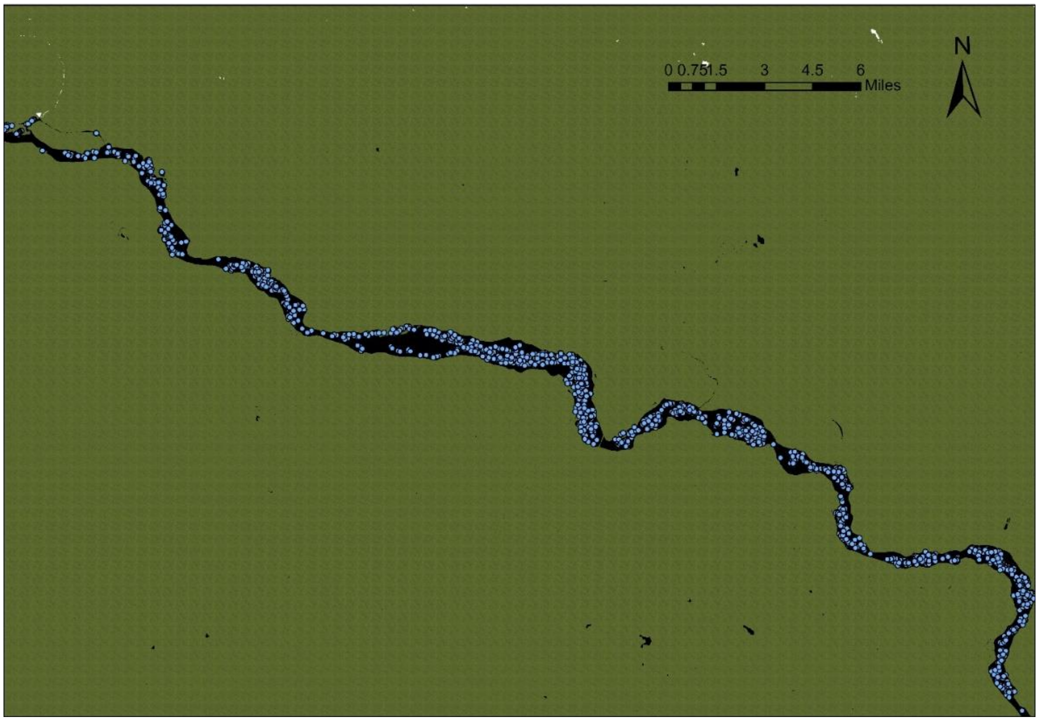


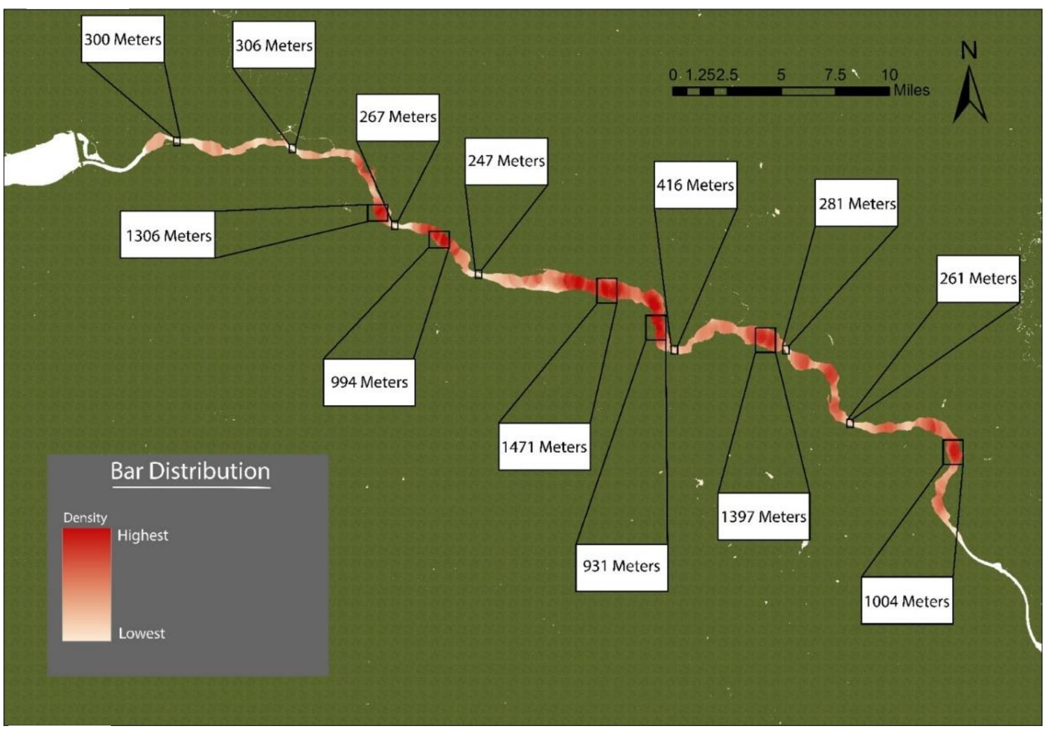

**Figure 9f:** Average area of each bar category.

Smaller (<36,000 sq. m) bars that did not meet criteria for tracking were sampled (50 bars, 1992-1994) to make note of bar behavior before they potentially coalesced into the larger compound bars. 76% of the small bars did not last for more than one year. Only the bars with a surface area closer to the 36,000 square meters (24%) threshold lasted for two years or more. The smaller unit bars almost never docked (4% or two samples docked) and tended to still be mostly fixed, but with a higher proportion of the bars being semi-fixed than the larger (>36,000 sq. m) unit bars. Of the of small bars that lasted more than a year, 7 of 12 or 58% were semi-fixed bars while 5 of 12 (42%) were fixed.

Bars tend to form in wider parts of the channel. Previous authors propose that mid-channel bars tend to form in wider channel reaches (Rahn 1977, Lewin 1981, Bertoldi & Tubino 2005, Hooke & Yorke 2011, Pierik et al. 2022). Visual inspection supports this assertion (**Figure 13)** after a correlation between channel width and bar centroid position shows that a higher density of the bars' centroids lie in wider areas of the channel (Hooke 1986, Kleinhans et al. 2013, Holbrook & Allen 2020, Pierik et al. 2022)




**10a**




**10b**

**Figure 10a:** A dot distribution of the 104 compound bars that were tracked in this study. More than 104 dots are present because the centroid from each individual year of the bar's existence was plotted. This presents a 1,100-point

**Figure 10b:** A distribution density map of the bars in the Missouri River. More bars form in areas where the channel is wider (~1,000 meters and up) while less bars form in narrower areas of the channel (~ 400 meters or less).

Bars centroids are generally denser in wider reaches. A digital heat map of centroids reveals that bar centroids over time concentrate at wider reaches and are less common at narrow reaches (**Figure 13**). The highest and lowest density areas of the river were measured for numerical comparison. The channel widths in the lower density areas were as follows (meters): 300, 306, 267, 247, 416, 281, and 261. These measurements produce an average channel width of 296 meters in the lowest density areas. The channel widths in the higher density stretches of the channel are as follows (meters): 1306, 994, 1471, 931, 1397, 1004. These measurements produce an average channel width of 1,184 meters in the higher density areas. In a similar fashion, it was found that these wider reaches averaged 32 bars per km while the narrower stretches averaged 7 bars per km.

A comparison of channel areas between the modern day Missouri River channel and the pre-industrial river channel provides useful insight into changes in the river over the past 150 years (Table 1). A stitched map profile of the 1894 Missouri River channel (**figure 14**) was sourced from Holbrook & Allen 2020 (map plates sourced by USGS), digitized, and field geometries were calculated. The 1894 channel areas over the 88km study reach were: channel and bars -- **59.8 sq. km**, channel only -- **48.9 sq km**, and bars only -- **10.8 sq km**. In the 2018 channel areas were: channel and bars -- **56.2 sq. km**, channel only -- **46.9 sq. km**, and bars only -- **9.2 sq. km**. Overall, the 1894 Missouri River had about 6% more area in combined channel and bar area, 15% more area in terms of bars alone, and about 4% more area in terms of the channel only. One should keep in mind that the maps from 1894 lack the detail that current maps possess. This could be a factor in the differences in area, especially differences in bar area.

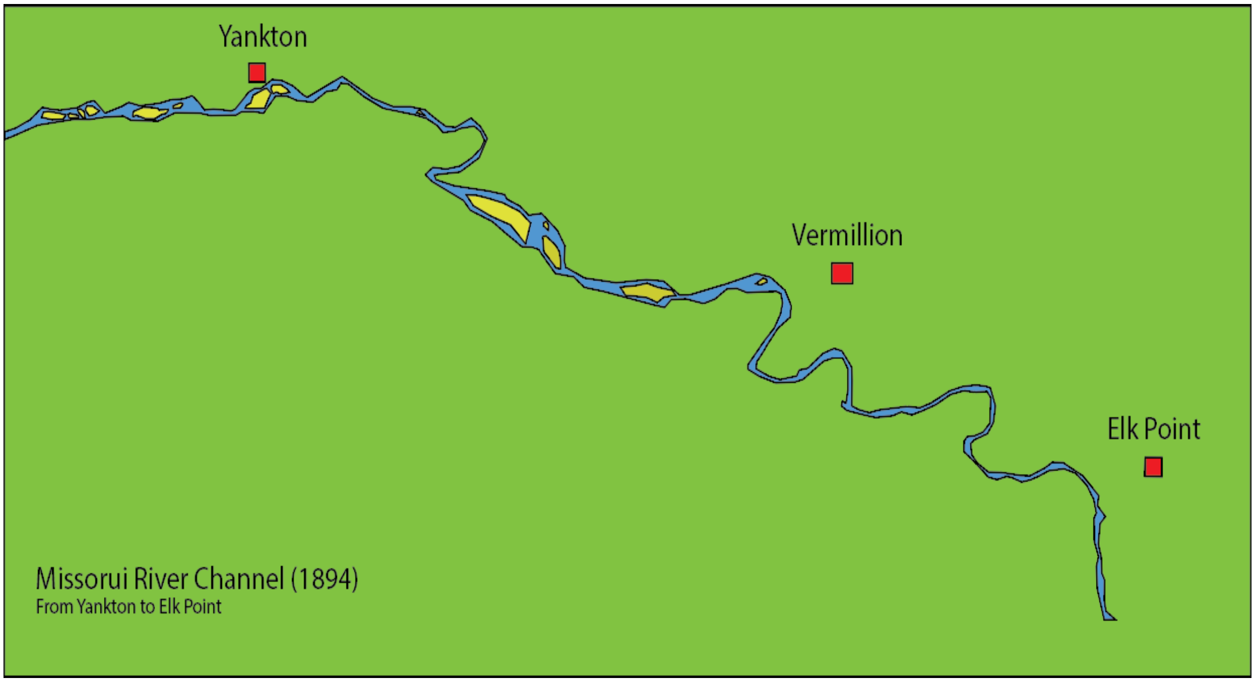



**Figure 11a:** A digitized map of the Missouri River between Yankton and Elk Point (1894). Note there are generally less bars, but the bars seem to be bigger. Source: USGS.

| Year | Channel + Bars | Channel Only | Bars Only |
|---|---|---|---|
| 1894 | 59.8 sq. km | 48.9 sq. km | 10.8 sq. km |
| 2018 | 56.2 sq. km | 46.9 sq. km | 9.2 sq. km |

**Figure 11b:** Comparison of the areas in the channel between 1894 and 2018

**5. Discussion:**

Mid-channel bars appear confined to wider river reaches and rarely appear in narrow reaches. The fact that there are zero free bars suggests that the river may constrict at meander bends in a way that discourages bar migration past them and instead forces bars to dock or dissolve with no way through the bottlenecks. These bottlenecks are also not conducive to bar generation, which leaves distinct interbend areas the most populated with bars and the only place that bars can migrate within. Many studies have arrived at the conclusion that mid-channel bars are most often found in wider areas of meander bends (Rahn 1977, Lewin 1981, Bertoldi & Tubino 2005, Luchi et al. 2011, Hooke & Yorke 2011, Zolezzi et al. 2012, Holbrook & Allen 2020, Pierik et al. 2022). These studies suggest the width accommodations support sediment deposition and leave ample room for channel bifurcation around mid-channel bars. The braided meandering nature of the Missouri river leads to high variance in channel width as one moves along the channel. Width ranges along bends by a factor of three according and allows ample space for the introduction of mid-channel bars (Holbrook & Allen 2020). The large variance in bar density - 7 bars/km in narrow stretches opposed to 32 bars/km in wider areas - supports prior literature that mid-channel bars tend to form in wider areas of the channel and that the Missouri River has high variance in width along meander bends.

Mid-channel bars in the Missouri River are fixed to semi-fixed, and do not move freely down the channel. The Missouri River has no truly free bars that left their original segment of the meander bend over there duration, and 78% did not even migrate a full bar length downstream.   None of the bars migrated out of the outer or inner part of the meander bend in which they originate. Previous studies suggest that fixed ("non-migrating" in some literature) are the result of local constraints like channel narrowing in meander bends and sometimes vegetative cover on the bars. ( Luchi et al. 2011, Zolezzi et al. 2012, Kleinhans & van den Berg 2011, Hooke & Yorke 2011, Wintenberger et al. 2019, Holbrook & Allen 2020). Tubino & Seminara (1990) use bend theory to detail increased channel curvature as a constraint in bar migration. Hooke & Yorke further confirms that fixed, immobile bars are much more common in high sinuosity sections of a river due to the downstream bottlenecking that forces decreased migration and may increase floodplain assimilation (Hooke & Yorke 2011). The data from this study supports these assumptions from previous works that fixed/forced bars are products of variation in channel planform. As previously mentioned, there is a large variation in channel width oscillations in the Missouri River. This causes sections of large width bookended by more narrow areas, which constrains the mid-channel bars to short reaches of the river and does not allow for the bars to leave their meander bends and truly be free/migratory bars.

A few interesting differences in fixed vs. semi-fixed bar life cycle and area were seen and warrant discussion. Semi-fixed bars outlived fixed bars by 4.2 years on average (9.7 to 5.5 years). One assumption for the discrepancy in average age could be semi-fixed bars' ability to adapt to changes in channel morphology like channel widening or constriction. This means semi-fixed bars can survive slightly longer than fixed bars, which have lower mobility and are more susceptible to dissolving or docking when channel morphology changes. It was observed that fixed bars' area was 26,722 square meters greater than semi-fixed bars on average. It is noteworthy that one bar type would be dramatically larger (17%) than the other. This difference in size could further explain the discrepancy in age between fixed and semi-fixed bars. This suggests that larger bars are harder to move and would lead to less adaptability and quicker termination.

Most of the mid-channel bars in the Missouri River do not preserve in the floodplain. Two-thirds of the bars in this stretch of the Missouri River do not dock and instead end their life-cycle by dissolving and reentering the sediment load of the river. This suggests that only one-third of the mid-channel bars eventually become integrated with the floodplain. The process of mid-channel bars docking (or "integrating) to either the cutbank or point bank of a meander bend is well documented (Ashworth et al. 2000, Bridge 2003, Hooke & Yorke 2011, Parker et al. 2013, Schuurman & Kleinhans 2015, Holbrook & Allen 2020). Bend theory suggests meander bends will translate, expand, or contract based on where bar assemblages integrate with floodplain. Occasionally bars form in the middle of the channel instead (mid-channel bars), and then migrate to dock on the inner bend of a meander to grow bends more abruptly through accretion of larger sediment volumes (Hooke 1986, Ashworth 1996, Luchi et al 2010). If bar assemblages dock to the inner (point) bank of a meander bend, expansion and higher sinuosity results (Ikeda et al. 1981, Blondeaux et al. 1985, Smith 1987, Bridge 2003, Luchi et al. 2011, Fustic et al 2012, Ghinassi et al. 2016). When new floodplain is suddenly added to the outside of a meander bend, the channel narrows due to this. In response, the channel will generally widen **via point bank erosion** and straighten the channel (Bridge 2003, Holbrook & Allen 2020)**.** Of the 34 bars that docked, 16 of them docked to the outer bank of a meander bend while only 6 docked to the inner bend (6 on straightaways and 6 on mid channel floodplain). With most bars within meander bends docking to the outer bank, this suggests that the current meander bends may be straightening, causing lower sinuosity in these areas. It is also noted that 6 bars docked to straightaway stretches in the river. These bars docked as side bars or alternate bars. Opposite of the previously explained process, alternate bars tend to increase the sinuosity of a river.

Age and area comparisons were also made between docking and non-docking bars to try to interpret any patterns in this dataset. In terms of life-cycle length, docking bars (25 samples) had an average age of 8.2 years while non-docking bars (44 samples) had an average age of 5.7 years. This leads to the conclusion that the longer a bar can survive in the channel, the more likely it is to dock into the floodplain. In terms of area, non-docking bars were significantly (20%) larger than docking bars with an average area 30,000 square meters larger. The assumption can be made that since docking bars are smaller, they can move towards the bank more readily. Their ability to move may pull them out of areas of maximum discharge and leave them less susceptible to erosion and dissolving. Conversely, the larger and less mobile non-docking bars stay further within the channel and dissolve away more quickly.

As with the fixed/semi-fixed and docking/non-docking data, age and area comparisons were performed upon the four specific categories of bars in the Missouri: docking fixed, docking semi-fixed, non-docking fixed, and non-docking semi-fixed (**Figure 15**). The average age was highest in docking semi-fixed bars (11.3 years) and lowest in non-docking fixed bars (4.5 years) with non-docking semi-fixed (8.8 years) and docking fixed (7.2) hovering close to the average of the dataset (7.9 years). Docking semi-fixed bars may have the highest average lifecycle due to their ability to adapt to the changes in channel morphology by moving laterally and downstream more freely. Conversely, non-docking fixed bars may have the shortest life-cycle due to their lack of mobility and higher probability of being influenced by changes in channel morphology. In terms of average area, non-docking semi-fixed had the largest average area at 192,514 square meters while docking fixed, non-docking semi-fixed, and non-docking fixed bars had areas of 155,823, 150,177, and 156,062 square meters respectively. Note that in previous sections, both non-docking bars and fixed bars contained the large areas with significant outliers. This would be a reasonable explanation for the non-docking fixed category having a significantly larger average area than the other categories. An alternative hypothesis could be that non-docking fixed bars are exposed to more sediment being stationarily situated in the middle areas of the channel. This could lead to more deposition and larger bar building events. However, non-docking fixed bars have the lowest average age at 4.5 years, so this amount of deposition and bar building seems unreasonable over that comparatively short period of time. When the top three outliers from the non-docking fixed area group were removed, it made a new average area of 158,879 square meters, which means that all 4 categories fall within 10,000 square meters of each other in average area. This pattern shows that there is likely a small general range of bar sizes in the Missouri River with a general cap around 160,000 square meters. This suggests that bar behavior is likely not related to size as much as position within the channel and channel morphology.

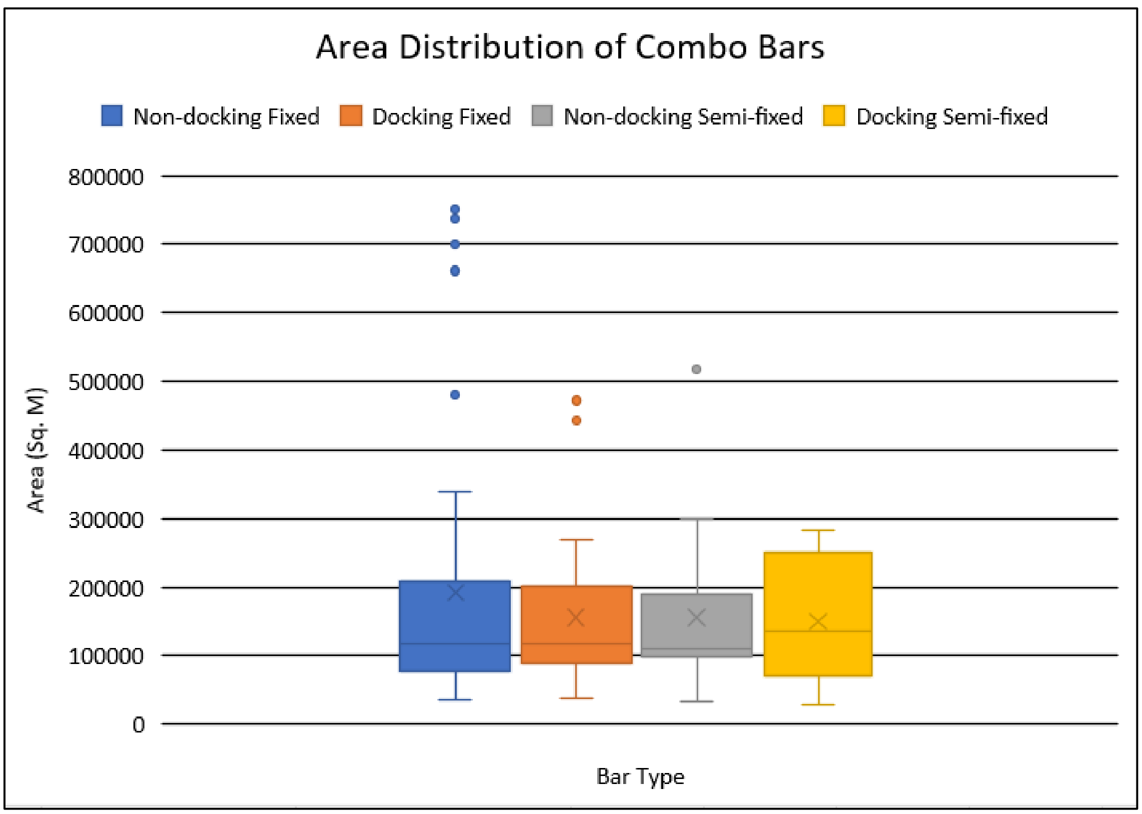



**Figure 12:** A box and whisker chart depicting the distribution in area of the four combo bar types

Also worth noting is the small sampling of unit bars which did not reach the 36,000 sq. m threshold of a compound bar. Of the of small bars that lasted more than a year, 7 of 12 or 58% were semi-fixed bars. This proportion is much higher than the 22% of compound bars which were fixed. This suggests that the smaller bars are more easily moved by turbulent flow in the channel. Studies on unit bars suggest that turbulent or high flow make unit bars easily movable within the channel (Tubino & Seminara 1990, Tubino et al. 1999, Reesnik & Bridge 2007, Schuurman & Kleinhans 2015, Holbrook & Allen 2020). Holbrook and Allen suggests that the smaller unit bars in this stretch of the Missouri River are readily movable, an assertion which is supported by the evidence put forth in this study. Only 2% of the sampled unit bars docked, likely due to their short lifespan. Unit bars have been found to be easily dissolvable and thus unlikely to dock to the bank and much more likely to coalesce to other unit bars (Miall 1977, Germanoski & Schumm 1993, Bridge & Lunt 2006). This data suggests that there is a large probability that a single unit bar will not grow or coalesce into a compound bar, as only 12 of 50 bars made it past a year in age and none of the observed bars coalesced into a unit bar. This could be because of their small size and high probability of being eroded back into the sediment supply before they can survive long enough to turn into a compound mid-channel bar.

Lastly, an area analysis of channels from 2018 and 1894 was performed in order to see how the channel may or may not have changed in the last ~150 years. The findings of this analysis clearly show that the modern, dammed channel is still very similar to the pre-dammed channel in 1894. These results indicate that this uncanalized stretch of the Missouri River has not changed all that much even with anthropogenic modifications to the river system. The largest difference between the channels is the 15% reduction in bar size from the 1894 channel to the modern channel. This slight reduction in in mid-channel bar size is likely due to upstream channelization and damming. The effects of the Gavins Point dam (and regulation in general) on flow and sediment load are present in multiple studies (Rahn 1977, Mellema & Wei 1986, Laustrup & LeValley 1998, Moody et al. 2003, Sanford 2007, Jacobson et al. 2009, Rus et al. 2015, Holbrook & Allen 2020, US Army Corps of Engineers). The pre-dam sediment load at Gavins Point has decreased by almost 135 million tons/yr and the resultant incision from sediment starvation has been ~ 2 meters near Yankton, SD (Mellema & Wei 1986, Sayre & Kennedy 1978, Sanford 2007). It has been suggested that Gavins Point dam creates a larger width to depth ratio below the dam and thus increases opportunity for mid-channel bar formation (Rahn 1977). Additionally, the loss of suspended load due to the dam is partially replaced (.2% of its original load at Yankton, with about 18.6 million tons/yr at the end of the study area) by bank and bar erosion of existing downstream sediment (Sanford 2007, Jacobson et al. 2009, Rus et al. 2015). Even with more room for bar formation and partial sediment replacement via channel incision and erosion, the channel still runs at a sediment deficit compared to its pre-damming years and thus the reduction in the size of mid-channel bars makes sense below the Gavins Point Dam. However, given the large loss of sediment due to damming, the overall reduction in bar surface area (15%) is rather small.

**6. Conclusion:**

The Missouri River, dubbed "the braided river that meanders" by Holbrook and Allen (2020), exhibits features of both meandering rivers (high sinuosity meander bends) and braided rivers (high width to depth ratio, plentiful mid-channel bars). Studies on the life cycle, growth patterns, and movement of mid-channel bars are certainly lacking, and Landsat data and GIS software present a unique opportunity to conduct such a study on the compound mid-channel bars in the Missouri River. Measurements of life-cycle length (age), bar area, fixed vs. semi-fixed, and bar distribution were all made for fixed/semi-fixed, docking/non-docking, and four more further specific bar types:

- 81 (78%) bars were fixed while 23 (22%) were semi-fixed, with no free bars. Fixed bars lifecycle was 4.2 years shorter than semi-fixed bars, suggesting a bar's ability to move may cause it to last longer.
- Only one third of bars dock to the banks of the Missouri. Docking Bars outlived non-docking bars by 2.5 years, suggesting that a bar's ability to move and dock can increase lifespan.
- Most bars dock on outer banks of meander bends, suggesting the Missouri River is straightening (lower sinuosity)
- The bars followed a trend of appearing the most (having the highest density) in wider areas of the channel as opposed to narrower areas.
- The Missouri has similar total channel area, but had larger bars than ~150 years ago which suggests that effects of anthropogenic modifications of the river are more minimal than expected.

References

Anderson, J. (2015). History of the Missouri River Valley from the Late Pleistocene to Present: Climatic vs. Tectonic Forcing on Valley Architecture (Doctoral dissertation, Texas Christian University).

Andrews, E. D. (1979). Scour and fill in a stream channel, East Fork River, western Wyoming (Vol. 1117). Department of the Interior, Geological Survey.

Ashmore, P. E. (1991). How do gravel-bed rivers braid?. Canadian journal of earth sciences, 28(3), 326-341.

Ashmore, P. (2013). Morphology and dynamics of braided rivers.

Ashworth, P. J. (1996). Mid-channel bar growth and its relationship to local flow strength and direction. Earth surface processes and landforms, 21(2), 103-123.

Ashworth, P. J., & Ferguson, R. I. (1986). Interrelationships of channel processes, changes and sediments in a proglacial braided river. Geografiska Annaler: Series A, Physical Geography, 68(4), 361-371.

Ashworth, P. J., Best, J. L., Roden, J. E., Bristow, C. S., & Klaassen, G. J. (2000). Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. Sedimentology, 47(3), 533-555.

Bartholdy, J., & Billi, P. (2002). Morphodynamics of a pseudomeandering gravel bar reach. *Geomorphology*, *42*(3-4), 293-310.

Bertoldi, W., and Tubino, M., 2005, Bed and bank evolution of bifurcating channels: Water Resources Research, v. 41, W07001

Best, J. L., Ashworth, P. J., Bristow, C. S., & Roden, J. (2003). Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar, Jamuna River, Bangladesh. Journal of Sedimentary Research, 73(4), 516-530.

Blondeaux, Paolo, and Giovanni Seminara. "A unified bar–bend theory of river meanders." Journal of Fluid Mechanics 157 (1985): 449-470.

Bridge, J.S., 2003, Rivers and Floodplains: Forms, Processes, and Sedimentary Record: Oxford, UK, Blackwell Science Ltd., 489 p.

Bridge, J. Alexander, R.E.L. Collier, R.L. Gawthorpe, J. Jarvis Ground-penetrating radar and coring used to study the large-scale structure of point-bar Deposits in three dimensions Sedimentology, 42 (1995), pp. 839-852

Bridge, J. S., & Lunt, I. A. (2006). Depositional models of braided rivers. In Braided rivers: Process, deposits, ecology and management (Vol. 36, pp. 11-50). Special Publication 36: International Association of Sedimentologists.

Bristow, C. S. (1987). Brahmaputra River: channel migration and deposition.

Bristow, C. S., & Best, J. L. (1993). Braided rivers: perspectives and problems. *Geological society, London, special publications*, *75*(1), 1-11.

Bluck, B. J. (1971). Sedimentation in the meandering River Endrick. *Scottish Journal of Geology*, *7*(2), 93-138.

Callander, R. A. (1968). Instability and river meanders (Doctoral dissertation, University of Auckland).

Callander, R. A. (1978). River meandering. Annual Review of Fluid Mechanics, 10(1), 129-158.

Cox, J. R., Leuven, J. R. F. W., Pierik, H. J., van Egmond, M., & Kleinhans, M. G. (2022). Sediment deficit and morphological change of the Rhine-Meuse river mouth attributed to multi-millennial anthropogenic impacts. Continental Shelf Research, 104766.

Crosato, A., & Mosselman, E. (2020). An integrated review of river bars for engineering, management and transdisciplinary research. Water, 12(2), 596.

Einstein, A. (1926). The cause of the formation of meanders in the courses of rivers and of the so-called Baer's law. Die Naturwissenschaften, 14(11), 223-224.

Eke, E., Parker, G., & Shimizu, Y. (2014). Numerical modeling of erosional and depositional bank processes in migrating river bends with self-formed width: Morphodynamics of bar push and bank pull. Journal of Geophysical Research: Earth Surface, 119(7), 1455-1483.

Eke, E. (2014). Numerical modeling of river migration incorporating erosional and depositional bank processes (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Ferguson, R. I., & Ashworth, P. J. (1992). Spatial patterns of bedload transport and channel change in braided and near-braided rivers. Dynamics of Gravel-Bed Rivers; Billi, P., Hey, RD, Thorne, CR, Tacconi, P., Eds.

Fredsøe, J. (1978). Meandering and braiding of rivers. *Journal of Fluid Mechanics*, *84*(4), 609 -624.

Friend, P. F., & Sinha, R. (1993). Braiding and meandering parameters. Geological Society, London, Special Publications, 75(1), 105-111.

Fustic, M., Hubbard, S.M., Spencer, R., Smith, D.G., Leckie, D.A., Bennett, B., and Larter, S., 2012, Recognition of down-valley translation in tidally influenced meandering fluvial deposits, Athabasca Oil Sands (Cretaceous), Alberta, Canada: Marine and Petroleum Geology , v. 29, p. 219–232,

Galloway, J. M., Rus, D. L., & Alexander, J. S. (2013). Characteristics of sediment transport at selected sites along the missouri river during the highflow conditions of 2011. US Geological Survey Scientific Investigations Report, 5006, 31.

Germanoski, D., & Schumm, S. A. (1993). Changes in braided river morphology resulting from aggradation and degradation. The Journal of Geology, 101(4), 451-466.

Ghinassi, M., Ielpi, A., Aldinucci, M., and Fustic, M., 2016, Downstream-migrating fluvial point bars in the rock record: Sedimentary Geology , v. 334, p. 66–96,

Gorrick, S., and Rodriguez, J.F., 2014, Flow and force-balance relations in a natural channel with bank vegetation: Journal of Hydraulic Research , v. 52, no. 6, p. 794–810,

Hayashi, T. (1971). Theory of meandering of rivers. 中央大学理工学部紀要, (14), 9-18.

Holbrook, J. M., & Allen, S. D. (2020). The case of the braided river that meandered: Bar assemblages as a mechanism for meandering along the pervasively braided Missouri River, USA. GSA Bulletin.

Hood, W.G., 2010, Tidal channel meander formation by depositional rather than erosional processes: Examples from the prograding Skagit River Delta (Washington, USA): Earth Surface Processes and Landforms , v. 35, p. 319–330,

Hooke, J. M., & Yorke, L. (2011). Channel bar dynamics on multi-decadal timescales in an active meandering river. Earth Surface Processes and Landforms, 36(14), 1910-1928.

Hooke, J. M. (2007). Complexity, self-organisation and variation in behaviour in meandering rivers. Geomorphology, 91(3-4), 236-258.

Hooke, J. M. (1986). The significance of mid-channel bars in an active meandering river. Sedimentology, 33(6), 839-850.

Ikeda, S., Parker, G., & Sawai, K. (1981). Bend theory of river meanders. Part 1. Linear development. Journal of Fluid Mechanics, 112, 363-377.

Jackson, R. G. (1976). Depositional model of point bars in the lower Wabash River. Journal of Sedimentary Research, 46(3), 579-594.

Jacobson, R. B., Blevins, D. W., & Bitner, C. J. (2009). Sediment regime constraints on river restoration—An example from the Lower Missouri River. Geological Society of America Special Paper, 451, 1-22.

Kashouh, M.V., 2012, A Late Holocene Meander-Braid Transition of the Lower Missouri River Valley [Master's thesis]: Arlington, Texas, University of Texas at Arlington, 88 p.

Kleinhans, M. G. (2010). Sorting out river channel patterns. Progress in physical geography, 34(3), 287-326.

Kleinhans, Maarten G., and Jan H. van den Berg. "River channel and bar patterns explained and predicted by an empirical and a physics-based method." Earth Surface Processes and Landforms 36.6 (2011): 721-738.

Kleinhans, M.G., Ferguson, R.I., Lane, S.N., and Hardy, R.J., 2013, Splitting rivers at their seams: Bifurcation and avulsion: Earth Surface Processes and Landforms , v. 38, p. 47 61

Kleinhans, M. G., & van den Berg, J. H. (2011). River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surface Processes and Landforms, 36(6), 721-738.

Laustrup, M., & LeValley, M. (1998). Missouri River Environmental Assessment Program: Columbia. Mo., Missouri River Natural Resources Committee, USGS BRD Columbia Environmental Research Center.

Leopold, L. B., & Langbein, W. B. (1966). River meanders. Scientific American, 214(6), 60-73.

Leopold, L. B., & Wolman, M. G. (1957). *River channel patterns: braided, meandering, and straight*. US Government Printing Office.

Lewin, J., 1981, Contemporary erosion and sedimentation, in Lewin, J., ed., British Rivers: London, George Allen and Unwin, p. 34–58.

Li, J., Vandenberghe, J., Mountney, N. P., & Luthi, S. M. (2020). Grain-size variability of point bar deposits from a fine-grained dryland river terminus, Southern Altiplano, Bolivia. Sedimentary Geology, 403, 105663

Luchi, R., Hooke, J. M., Zolezzi, G., & Bertoldi, W. (2010). Width variations and mid-channel bar inception in meanders: River Bollin (UK). Geomorphology, 119(1-2), 1-8.

Luchi, R., Zolezzi, G., and Tubino, M., 2011, Bend theory of river meanders with spatial width variations: Journal of Fluid Mechanics , v. 681, p. 311–339,

Lunt, I.A., Bridge, J.S., and Tye, R.S., 2004, A quantitative, three-dimensional depositional model of gravelly braided rivers: Sedimentology, v. 51, p. 377 414, https://doi.org/10.1111/j.1365-3091.2004.00627.x.

Mat Salleh, M., & Ariffin, J. (2013). Flow and sediment matrix in mid-channel bar formation. *Int. J. Sci. Eng. Res*, *4*, 1757-1764.

Moody, John A. (John Alexander), et al. Lewis and Clark's Observations and Measurements of Geomorphology and Hydrology, and Changes with Time.,2003

Mellema, W. J., & Wei, T. C. (1986). Missouri River aggradation and degradation trends. In Proceedings of the Fourth Federal Interagency Sedimentation Conference March 24-27, 1986, Las Vegas, Nevada. (Vol. 1).

Miall, A. D. (1977). A review of the braided-river depositional environment. *Earth-Science Reviews*, *13*(1), 1-62.

Moody, J.A., Meade, R.H., and Jones, D.R., 2003, Lewis and Clark's Observations and Measurements of Geomorphology and Hydrology, and Changes with Time: U.S. Geological Survey Circular 1246, 110 p.

Mukherjee, J. (2011). No Voice, No Choice: Riverine Changes and Human Vulnerability in the ‘Chars’ Of Malda and Murshidabad. Occasional Paper 28, IDSK.

National Research Council. (2005). Review of the US Army Corps of Engineers Restructured Upper Mississippi River-Illinois Waterway Feasibility Study: Second Report. National Academies Press.

Parker, G., Shimizu, Y., Wilkerson, G. V., Eke, E. C., Abad, J. D., Lauer, J. W., ... & Voller, V. R. (2011). A new framework for modeling the migration of meandering rivers. Earth Surface Processes and Landforms, 36(1), 70-86.

Parker, N. O., Sambrook Smith, G. H., Ashworth, P. J., Best, J. L., Lane, S. N., Lunt, I. A., ... &Thomas, R. (2013). Quantification of the relation between surface morphodynamics and subsurface sedimentological product in sandy braided rivers. Sedimentology, 60(3), 820-839.

Parker, G., & Andres, D. (1976). Detrimental effects of river channelization. In *IN: RIVERS'76, PROC. SYMP. ON INLAND WATERWAYS FOR NAVIGATION, FLOOD CONTROL AND WATER DIVERSIONS; 3RD ANNUAL SYMP. OF THE WA* (Vol. 2, pp. 1248-1266).

RAHN, P. H. (1977). Erosion below main stem dams on the Missouri River. Bulletin of the Association of Engineering Geologists, 14(3), 157-181.

Reesink, A. J. H., & Bridge, J. S. (2007). Influence of superimposed bedforms and flow unsteadiness on formation of cross strata in dunes and unit bars. Sedimentary Geology, 202(1-2), 281-296.

Repetto, R., Tubino, M., & Paola, C. (2002). Planimetric instability of channels with variable width. Journal of Fluid Mechanics, 457, 79-109.

Rice, S. P., Church, M., Wooldridge, C. L., & Hickin, E. J. (2009). Morphology and evolution of bars in a wandering gravel-bed river; lower Fraser river, British Columbia, Canada. Sedimentology, 56(3), 709-736.

Rust, B. R. (1972). Structure and process in a braided river. Sedimentology, 18(3-4), 221-245.

Rus, D.L., Galloway, J.M., and Alexander, J.S., 2015, Characteristics of Sediment Transport at Selected Sites Along the Missouri River, 2011–12: U.S. Geological Survey Scientific Investigations Report 2015–5127, 34 p.

Sanford, J. P. (2007). Dam regulations effects on sand bar migration on the Missouri River: southeastern south Dakota.

Sayre, W.W., and Kennedy, J.F., 1978, Degradation and Aggradation of the Missouri River: Iowa Institute of Hydraulic Research (IIHR) Report 215, 67 p.

Schumm, S. A. (1963). Sinuosity of alluvial rivers on the Great Plains. Geologica Society of America Bulletin, 74(9), 1089-1100.

Schuurman, F., & Kleinhans, M. G. (2015). Bar dynamics and bifurcation evolution in a modelled braided sand-bed river. Earth surface processes and landforms, 40(10), 1318 1333.

Seminara, G., & Tubino, M. (1989). Alternate bars and meandering: free, forced and mixed interactions. River meandering, 12, 267-320.

Shields Jr, F. D., Knight, S. S., & Cooper, C. M. (2000). Cyclic perturbation of lowland river channels and ecological response. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management, 16(4), 307-325.

Smith, D. G. (1987). Meandering river point bar lithofacies models: modern and ancient examples compared.

Spooner, J. (2001). The Evolution of the Lower Missouri River: Preliminary Results of NMD Research at Lisbon Bottom (No. 2001-368). US Geological Survey.

Tubino, M., & Seminara, G.(1990). Free–forced interactions in developing meanders and suppression of free bars. Journal of Fluid Mechanics, 214, 131159.

Tubino, M., Repetto, R., & Zolezzi, G. (1999). Free bars in rivers. Journal of Hydraulic Research, 37(6), 759-775.

US Army Corps of Engineers 2004

van de Lageweg, W. I., van Dijk, W. M., Baar, A. W., Rutten, J., & Kleinhans, M. G. (2014). Bank pull or bar push: What drives scroll-bar formation in meandering rivers?. Geology, 42(4), 319-322.

Wang, B. (2017). Assessing morphodynamics of the lower Mississippi River from 1985 to 2015 with remote sensing and GIS techniques.

waterdata.usgs.gov

Williams, P. F., & Rust, B. R. (1969). The sedimentology of a braided river. Journal of Sedimentary Research, 39(2).

Wintenberger, C. L., Rodrigues, S., Bréhéret, J. G., & Villar, M. (2015). Fluvial islands: First stage of development from nonmigrating (forced) bars and woody-vegetation interactions. Geomorphology, 246, 305-320.

Wu, F. C., & Yeh, T. H. (2005). Forced bars induced by variations of channel width: Implications for incipient bifurcation. Journal of Geophysical Research: Earth Surface, 110(F2).

Zolezzi, G., Luchi, R., and Tubino, M., 2012, Modeling morphodynamic processes in meandering rivers with spatial width variations: Reviews of G

## VITA

Noah Underwood was born on December 23, 1997 in Sarasota, Florida. He is the son of Lori and Kyle Underwood. A 2016 graduate of Beech Senior High School in Hendersonville, TN, he received his Bachelor of Science degree with a major in Geology from the University of Tennessee, Knoxville in 2020.

Noah is currently employed as a Staff Geologist at Lord and Winter LLC in Nashville, TN. He is an active member of the American Association of Petroleum Geologists and the Geological society of America

# ABSTRACT

AN INVESTIGATION OF GROWTH AND

MOVEMENT PATTERNS OF MID-CHANNEL

BARS IN THE MISSOURI RIVER

By Noah James Underwood
Department of Geological Sciences
Texas Christian University

Thesis Advisor: Dr. John Holbrook, Professor of Geology

Much is known about the formation factors of mid-channel bars, which involves accretion of unit bars, migration of bars within the channel, and docking mechanisms of these bars. However, little to no studies have been conducted which tracked comprehensive bar statistics over a significant period of time. Consequently, while much is known of the occurrence and geometry of various types of bars, little is known of their kinematics. Studies of the life-cycles of individual bars or small datasets of bars have been performed, but all of the bars in a given river have not been published. The Missouri River offers an opportunity to perform a similar study to the previously mentioned studies on a larger and more comprehensive scale. 104 compound mid-channel bars were tracked between 1989 and 2018. Characteristics including life-cycle, surface area, docking patterns, and downstream migration were tracked and analyzed in order to create a comprehensive profile of the mid-channel bars in this stretch of the Missouri River. It was found that the average life-cycle of a compound mid-channel bar in this stretch of the Missouri River is 7.9 years. Additionally, bars tended to mostly form in wider areas of the channel and the post regulation Missouri has seen approximately 15% lower surface area on its mid-channel bars.

AN INVESTIGATION OF GROWTH AND

MOVEMENT PATTERNS OF MID-CHANNEL BARS

IN THE MISSOURI RIVER

By

Noah Underwood

Thesis Approved:

John Holbrook

Major Professor

M. Kleinhans

Esayas Gebremichael

For the College of Science and Engineering