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# DAM REGULATION EFFECTS ON SAND BAR MIGRATION ON THE MISSOURI RIVER: SOUTHEASTERN SOUTH DAKOTA

By

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Dam Regulation Effects on Sand Bar Migration on the Missouri River: Southeastern South Dakota

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The Missouri River is widely considered America's "most endangered river" (American Rivers Council, 2004), with only three "natural" stretches remaining. The first is a reach from Fort Benton, MT to Robinson Bridge, MT, the second reach runs from Pickstown, SD to Runningwater, SD; and a third reach extends from Yankton, SD to Ponca NE. This third 55-mile reach from Yankton to Ponca, NE contains the reach that is the focus of this study (Figure 1). Reservoirs dominate the flow regime upstream, and downstream the river is dredged for shipping purposes. Dams have changed the riparian habitat along the Missouri and these changes need to be evaluated to determine the effects of dams on this alluvial river.

This project compares natural flow regimes to dam regulated flow regimes to determine the effect dams are having on the Missouri River. Sand bars from 1940-1941 were compared to bars from 2004-2005. Three hypotheses were evaluated during the course of this research project. First, measurements of sand bar migration were taken using sand bar centroids to measure movement. Second, area and perimeter were measured under two flow regimes to determine changes in size of the sand bars between the historical to recent periods. Third, a quadrat analysis was applied to each set of sand bars to determine the amounts of clustering of bars during each time period.

It was concluded from this project that a much more dynamic environment existed under natural flow regimes. Sand bars were larger, migrated more, and were less clustered under a natural flow regime. A more static environment exists under dam regulated rates of flow.

# Acknowledgements

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## Chapter 1: Introduction

The Missouri River is widely considered America's "most endangered river" (American Rivers Council, 2004), with only three "natural" stretches remaining. The first is a reach from Fort Benton, MT to Robinson Bridge, MT; the second reach runs from Pickstown, SD to Runningwater, SD; and a third reach extends from Yankton, SD to Ponca NE. This third 55-mile reach from Yankton to Ponca, NE contains the study area that is the focus of this study (Figure 1). These reaches are not necessarily "natural" in a true sense. Here, the author defines a natural reach of river as one with a natural flow regime that is not dammed or altered structurally by man and is part of an entire watershed unaltered structurally by man. Irrigation may affect the discharge but it does not structurally alter the river, so it is allowed within the author's definition of a natural river.

Flow in the study reach is dominated by reservoirs upstream; and downstream the river is dredged for shipping purposes. Dams are changing the riparian habitat along the Missouri and these changes need to be evaluated to determine the effects of dams on this alluvial river. Before the construction of dams, natural hydrologic cycles created the riparian habitat on the Missouri River. Seasonal change drove rising and falling waters that defined ecological processes. Spring snowmelt would flood the river, rearranging the sand bars to create new islands and sand bars. Receding summer flows exposed sand bars that provided crucial nesting habitat for birds. These low summer flows also made it easier for fish to access shallow and low flow areas for feeding. Since the 1940's, dam-regulated flows have not allowed natural flow regimes to occur, thus limiting the amount of movement of the sand bars, shorelines, and channels, and limiting sand bar and channel migration (Nilsson and Berggren, 2000).

**Figure 1: Map of study area location.**

Migration of sand bars is directly related to sediment transport, sediment load, degradation, aggradation, channel migration, and bank erosion. Sand bars are composed of the very material that is being eroded and deposited during the annual cycles. The formation and movement of the sand bars governs the formation of and distribution of riparian environments. When studying the movement patterns of sand bars, the effects of all river processes can be related to the sand bar (Rahn, 1977).

By studying sand bars and their behaviors one is not only observing hydrologic processes, but also habitats that are relied upon by riparian species. Sand bars comprise a large portion of the habitat for many aquatic and terrestrial species. In the case of the Missouri River, some of these aquatic and terrestrial species are endangered. Least tern, piping plover, paddlefish, and pallid sturgeon are species that are threatened by the dam regulated flow regimes and the migration of sand bars.

Inadequate sediment loads may cause degradation, one symptom of which is the elevation of sand bars relative to the previous river bed. This, in turn, can cause reduced movement of sand bars and lead to the establishment of permanent islands. Establishment of permanent islands reduces sand bar migration, leading to a lack of habitat. Aggradation can cause the accretion of sand bars, the formation of new sand bars, and shallow water areas creating new habitat for aquatic species but also potentially hindering navigation. Channel migration and bank erosion causes movements in the sand bars while the lack of channel migration and a static environment can lead to lack of new habitat. Thus changes in sediment regimes in either direction can significantly affect available habitat.

Alluvial rivers such as the Missouri need an annual influx of sediment to remain in equilibrium. Equilibrium implies that the channel size, cross-sectional shape, and slope are adjusted to quantities of sediment and water transported so that the streambed neither aggrades nor degrades (Williams and Wolman, 1984). This equilibrium is disrupted by dams, which do not allow for the transport of sediment downriver to sediment-depleted areas. It is known that the combination of sediment depletion and regulated flows affects the amount of lateral channel migration (Shields, Simon, and Steffen, 2000) and the amount of suspended sediment being transported (Nilsson and Berggren, 2000). Thus two questions logically follow. Is the combination of sediment depletion and regulated flows affecting the natural migration of sand bars? What effects are dams having on the migration of sand bars which so strongly characterize the Missouri River?

There is a large gap in the knowledge of sand-bar behavior. During the research portion of this study, not one paper was found that dealt with the behavior of sand bars in the Missouri River. Papers on sand bars on the Grand Canyon of the Colorado River were located (e.g. Sondossi and Schmidt, 2001), but that is a very different environment. The Colorado is constricted and defined by a canyon environment creating a significantly different fluvial geometry than that which exists in the Missouri River floodplain. The purpose of this research is to uncover some of the behaviors of sand bars in an alluvial river floodplain.

## **Chapter 2: Background**

Many variables effect alluvial rivers and control how they are managed, but change is most dramatically as a result of change in discharge or sediment supply (Mitchell, 2000). The Missouri River is no exception. When studying rivers, one must examine the natural and regulated flow behaviors that shape today's rivers. How do altered flow regimes effect the distribution and movement of sediment? How do flow regimes and processes affect the formation and movement of islands and sand bars? How do these changes affect the Missouri?

### 2.1. Alluvial River Characteristics:

Alluvial rivers transport major amounts of sediment, creating riparian habitat for fish, birds, and larger species of animals. Alluvial rivers are characterized by the ability to mutually adjust morphology, sediment load, hydraulic characteristics, and particle size of the bed material in response to changes in independent variables such as discharge, sediment supply, and valley slope (Simon and Darby, 1997). Alluvial channels are considered to be systems of equilibrium. To be considered a state of equilibrium, channel shape, size, and slope depend on the amount of sediment and water transported and is adjusted so that the streambed neither aggrades nor degrades (Williams and Wolman, 1984). Alluvial river channels migrate laterally across a floodplain by eroding and depositing sediment along their banks. Alluvial rivers exhibit a balanced migration across the floodplain. This means a balance between high bank erosion and the building of new land through sediment deposition (Mellema and Wei, 1986). By reducing high flows and the amount of sediment that is transported, dams tend to reduce lateral channel migration.

Vegetation is also a factor that can determine amounts of channel migration, island formation, and erosive properties (Gurnell et al, 2001). Information on changes in vegetation between 1940 and 2005 was not available due to the difficulty of analyzing vintage black and white aerial photographs. It was decided to assume that vegetation did not affect the sand bars in this study. Casual observation indicated the vegetated bars in this reach behaved similarly to non-vegetated bars, in terms of migration.

## 2.2. Impacts of Human Alteration on Alluvial Rivers:

Dams alter the natural flow regime of rivers they impound by reducing or eliminating floods. Flow regimes under dam regulations tend toward medium levels of discharge in contrast to the seasonal cycle of high (peak) flow in spring and receding flows throughout the summer into fall and winter. Mid-level ranges flows are a result of hydrologic power generation (Choi, Yoon, and Woo, 2005). Their study of the Hwang River in southeastern Korea revealed that flow between the 40th and 60th flow-duration percentiles had increased by a factor of two since dam construction. Their post-dam channel surveys indicated minor bed elevation changes with a maximum of 3.5 m of incision with 2-3 m of degradation throughout the reach. Shields et al. (2000) found that channel migration was severely affected by regulated flows. In their study area along the Missouri from Fort Peck to approximately 100 km down river, channel migration rates decreased from an average of 6.6 m/yr between 1890 and 1910, to 1.8 m/yr in the period between 1971 and 1991.

Altered flow has been one of the primary consequences of human alterations. These human alterations include impoundments, channelization, water diversions, and landscape changes in the catchment area. Typically, changes in the flow regime will be complex and the nature of the disturbances may be difficult to predict, especially when many alterations occur on the same river (Pegg, Pierce, and Roy, 2003). Magnitude of discharge, frequency of extremes, timing of extremes, duration of given flow conditions, and rates of change of flows all regulate riparian processes. Channelization by the armoring of shorelines, water diversion through side channels, and straightening of the channel can influence flow by causing rapid transport of water downriver (Pegg et al., 2003).

Pegg et al. (2003) conducted a study of flow pattern differences resulting from human alteration using mean daily streamflow data from 10 Missouri River gauges. They found higher daily mean flows at all gauges, post-alteration, over the entire year with the exception of spring flood periods. At Bismarck N.D., post-alteration daily mean flows measured an average of 16% higher. Post-alteration daily mean flows average 10% higher at the gauge at Yankton S.D. Examination of pre and post-alteration of spring floods show dramatic differences in flows. Gauges located in the middle reaches of the Missouri in which the alterations are the most concentrated, showed the largest effects (Pegg et al., 2003). Typical spring daily flows at Bismarck N.D. were 32% lower during the post-alteration periods. Yankton S.D. averaged 28% lower spring flows during post-alteration periods.

The disruption of natural hydrologic cycles can cause aggradation or degradation and prevent balanced migration across the flood plain. The Missouri is a meandering river on a floodplain environment. Degradation and aggradation occur because the rate sediment entering the reach differs than the sediment that is transported out of the reach (Sayre and Kennedy, 1978). Floods naturally control the rebuilding of new lands by depositing large quantities of sediment. While dams reduce the floods, bank erosion still occurs. Land is converted into river channel and sand bars but is not deposited on the bank sides, leading to widening of the river channel.

Dams trap sediment, preventing downriver deposition in sediment-depleted areas. Zones of degradation usually start immediately after the dam and continue downstream to some length depending on a variety of factors (Williams and Wolman, 1984). Reaches of degradation are often followed by reaches of aggradation, which can last for miles before the river reverts to equilibrium. For example, following Missouri River dam construction the mean annual sediment load decreased from 320 million metric tons during 1949-1952 to 109 million metric tons during 1957-1980 at the Missouri-Mississippi confluence (Williams and Wolman, 1984).

Factors affecting sediment supply include: dams trapping sediment, land-use practices promoting erosion, tributaries that carry sediment to the main stem river, aeolian-transported deposits, bank erosion, solid waste input to the river system, floodplain accretion from overbank flows, and dredging. Of these factors, dams are considered to be the most dominant, with sediment yields of tributaries and bank erosion next in the order of importance, respectively (Sayre and Kennedy, 1978). Factors influencing sediment-carrying capacity include training structures (such as revetments or jetties) that increase flow velocities, flow regulation, runoff cycles such as floods carrying sediment loads through tributaries, change in slope affecting flow velocities, bed armoring that decreases bed erosion, change in bed particle size, artificial temperature changes, diversions reducing discharge amounts, boat traffic causing turbulence, and shorefast ice which may promote bank erosion. Training structures and flow regulations are judged to be the primary influences on sediment transport capacity (Sayre and Kennedy, 1978).

Dams change the riparian environment along the rivers that they regulate (Rahn, 1977). Surian (1999) suggests that the hydraulic geometry of stream channels adjusts to the discharge that transports the most sediment over a long period. Studies have shown that dam regulated flows tend to slow the natural geomorphologic processes, reducing the amount of annual change in riparian habitats. Dams increase erosion downstream, leading to reduced geomorphologic activity in the river-bed and channel simplification (Nilsson and Berggren, 2000).

The Mississippi River is one of the most regulated rivers in the world (Kesel, 2003). Human alterations to the Mississippi include dams and reservoirs, artificial levees, dikes, concrete revetments, and channel cutoffs that attempt to straighten the river. Prior to modification in the 1930's, the lower Mississippi River was mainly a classic meandering river with an aggrading channel. Aggradation was reflected in the growth of channel bars and a rise in thalweg elevation prior to 1935 (Kesel, 2003). Sediment reductions came from a decrease in sediment input from tributaries and channel and floodplain sources. Revetment construction resulted in a 90% reduction in bank caving (Kesel, 2003). These modifications changed many channel features, including channel bars. A large change in size of the channel bars due to revetments occurred between Cairo and Red River Landing, Illinois. Between 1880 and 1935, aggradation caused growth in the channel bars, but after human modification, (1935 to 1948), Kesel (2003) recorded an 80% reduction in sediment deposited on channel bars. The reach was meandering and exhibited great flexibility in channel-bar numbers and size. The reach of river below Red River Landing is confined and does not migrate, showing little variation in bar size.

Darby and Thorne (2000) examined the effects of dam regulation on incision and bank erosion on the Missouri between Fort Peck Dam and the confluence with the Yellowstone River (290 km). From channel centerline maps pre-dam bank erosion rates have been estimated to range from 2.5 to 27.7 m/yr between 1890 and 1916 (Darby and Thorne, 2000). Bank erosion rates declined from 8.8 m/yr between 1894 and 1949, to 1.3 m/yr between 1980 and 1991. The study also concluded that 1.6 m of overall bed degradation has occurred, with some localized degradation events of up to 3.3 m in the Fort Peck reach.

Before the dam system was built the Missouri was a natural meandering river. Erosion material from cut banks on the outside of a meander was subsequently deposited downriver on the inside of the meander. Erosion and deposition on alternate sides of the meander bend has been replaced by active erosion along both sides of the meander (Figure 2) and the meander crossing, creating a shallower, ever-widening, braided stream (Rahn, 1977).

The alluvium is typically the most easily eroded material and contributes most to the sediment load. Underwater erosion causes the formation of vertical cut banks. These cuts banks tend to fail and slump into the river and over time the pile is eroded away and debris is sorted and distributed (Rahn, 1977). A dammed river, now lacking in the range

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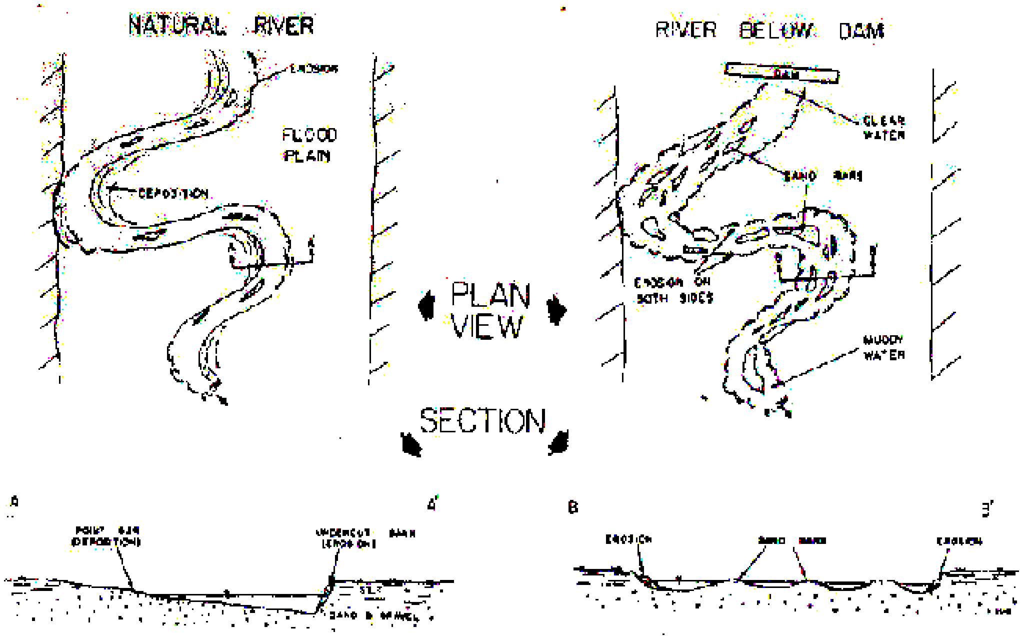

FIGURE 11. Idealized sketch map and cross-section showing changes in fluvial geometry caused by a dam.

**Figure 2: Drawing from Rahn (1977, page 172) depicting fluvial geometry changes caused by dam regulations.**

of natural flows, no longer has the ability to transport all sizes of debris. The silt and clay fraction is generally carried away in suspension out of the Missouri River study reach (Rahn, 1977).

The sand fraction leaves the bank as eroded debris and is re-deposited along the river bottom a short distance from the erosion point. Sand is deposited along the bottom of the river as bed load, ripples, and dunes of moving sand.

Changes in flow regimes may or may not affect vegetation (Gurnell et al. 2001) however, this topic was not researched in this study.

## Chapter 3: Study Area

### 3.1. The Missouri River:

Until the late 1930's, the Missouri River was an ever-changing, free-flowing river with a dynamic flow regime and channel boundaries. It is one of the largest rivers in North America, over 3,768 km in length, and drains nearly one sixth of the continent (Pegg, Pierce, and Roy, 2003). The completion of Fort Peck Dam in eastern Montana in 1940 brought about substantial hydrologic changes along the Missouri (U.S. Army Corps of Engineers, 2004).

Fort Peck was the first dam constructed on the Missouri River and remains the largest hydraulic fill embankment dam in the world (Darby and Thorne, 2000). Over the twenty years following Fort Peck's construction, the Missouri changed with six additional dams constructed by 1963 at strategic points to control floods and generate electricity. The Pick – Sloan Plan of 1944 allowed for the construction of these dams. This was a comprehensive plan by the federal government for the coordinated development of the Missouri River Basin. The plan allowed for the construction of 112 dams in the Missouri River drainage system. As of 2005, seven dams were constructed on the Missouri (Figure 3) and 80 dams on its tributaries (Columbia Electronic Encyclopedia, 2006). These seven in order from upriver to downriver are: Canyon Ferry Dam (Helena, Mt), Ft. Peck Dam (Ft. Peck, Mt), Garrison Dam (Bismarck, ND), Oahe Dam (Pierre, SD), Big Bend Dam (Ft. Thompson, SD), Ft. Randall Dam (Pickstown, SD), and Gavins Point Dam (Yankton, SD). These dams were constructed for primarily flood control so that each temporarily stores a portion of flood discharge for later release

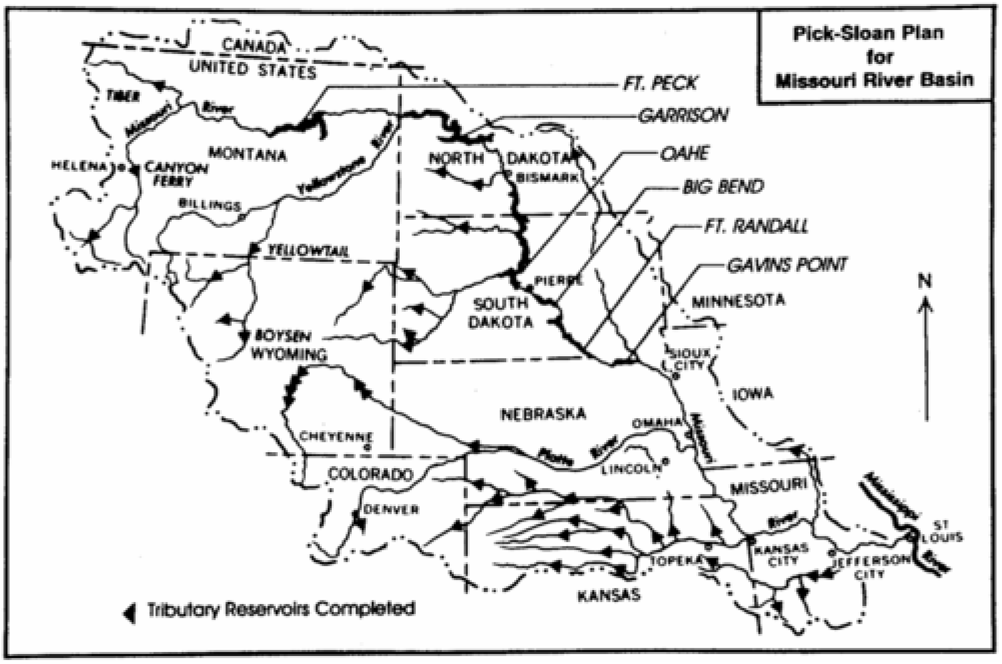

**Figure 3: Map of Missouri River Dams designed by the Pick-Sloan Plan. (Columbia Electronic Encyclopedia, 2006)**

to reduce flood peaks (Perry, 1993), this purpose also impacts downstream navigation, generation of hydroelectricity, irrigation, recreation, fish and wildlife, and municipal and industrial water supplies (Latka, Nessler, and Hesse, 1993). The dams also control and define the riparian environment, regulate flows, and act as filters trapping sediment, thus affecting the natural processes of the Missouri River.

These dams intercept sediment from one of the greatest sediment sources in the United States. The sediment load passing through Gavins Point was once 135 millions tons per year, consisting of about 20% sand and about 80% silt and clay (Mellema and Wei, 1986). This has dropped to almost none. Virtually all of the Missouri's sediment is entrapped by reservoirs extending for 1055 miles along its length. Only 327 miles of river lay between these reservoirs with an additional 807 miles of river below (Mellema and Wei, 1986). Of the 807 miles of open river below the last main stem dam, only 55 miles has not had predominant bank stabilization to improve river navigation. Some bank stabilization has occurred in the study area reach, but on a much smaller scale. There is a quarter mile stretch of cabins on the river from Goat Island extending upward. Several parcels of land (including one owned by the author's family) lost approximately 100 feet of ground in a two year period. In the mid 1970's the U.S. Army Corps of Engineers installed wing dams as a demonstration project to prevent further loss of property (I. Perkins and R. Perkins, personal communication, 2006). This bank stabilization confines the channel in that area and prevents channel migration.

Gavins Point is the farthest dam downstream on the main stem, and below this the river begins to resume a closer to "natural" state. The most important exception to this "natural" state is the lack of sediment load. Other exceptions include lack of spring floods, mandatory flows for barge traffic, dredging, and bank stabilization. Prior to the construction of dams, the mean annual discharge at Sioux City was 32,000 cubic feet per second (cfs). Flood flows exceeded 100,000 cfs and summer to winter flows dwindled to 10,000 cfs or less (Figure 4); under regulated flow regimes (Figure 5), high discharges reach 35,000 cfs and winter flows range from 14,000 to 21,000 at Sioux City (Mellema and Wei, 1986). Figures 4 and 5 represent the availability of complete data sets; i.e. other years close to these time periods did not contain complete data sets.

Water released from Gavins Point comes from Lewis and Clark Reservoir, which has dropped the sediment out of suspension. Once released from the dam, the river immediately begins to erode and pick up a new sediment load by eroding the bed. According to Rahn (1977), this new load of sediment is derived primarily from lateral erosion of the river banks. Inspection of aerial photography from 1953, 1973, and 1976

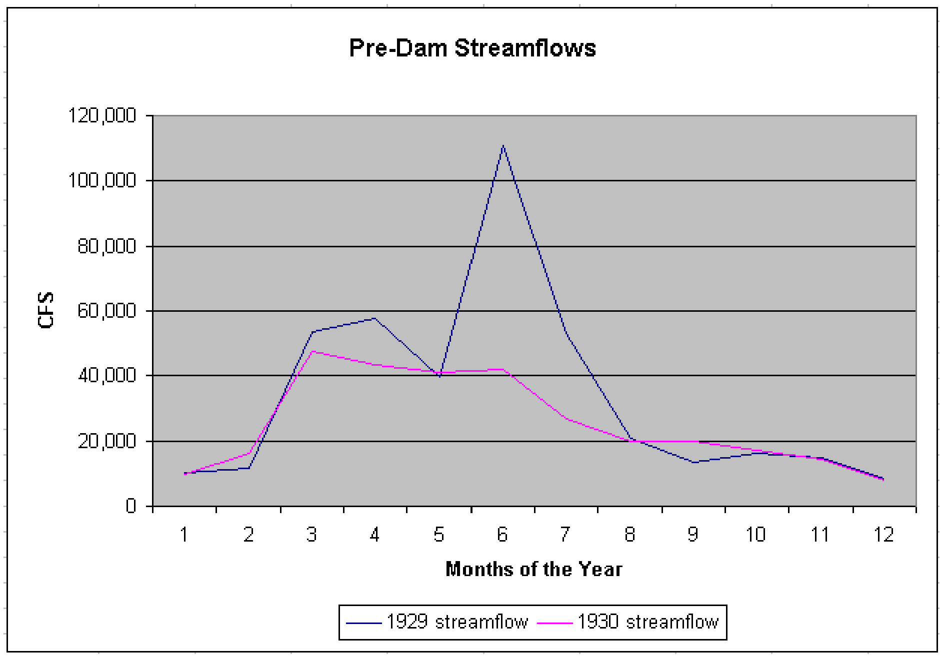

Figure 4: Historical Streamflow Data for the Missouri River at Sioux City, Iowa, pre-dam.

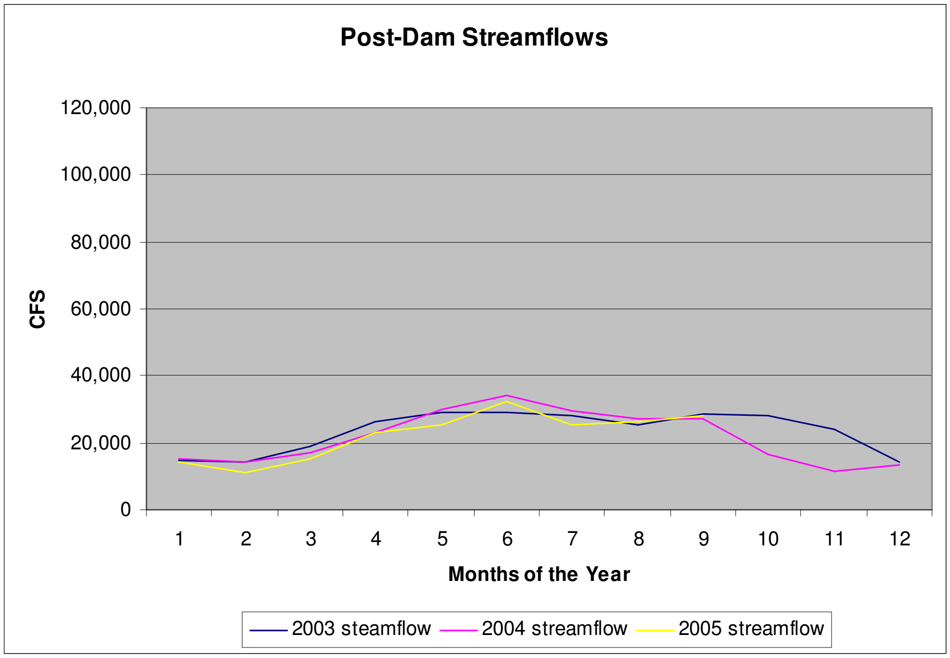

Figure 5: Streamflows for the Missouri River from Sioux City, Iowa, post-dam.

showed where active erosion had taken place (Rahn, 1977). The 55 mile reach from Gavins to Ponca has the greatest erosion problem on the Missouri. During low to medium flows (flows not exceeding 30,000 cfs), eroded sand is deposited as bars and islands (Rahn, 1977). Because of the growth of the islands and bars and the change in the geomorphology of the river bed, it is difficult to find a channel over 6 ft in depth as of 1977 and even today as experienced by the author.

The Missouri River has been experiencing bed degradation throughout the entire reach from Gavins Point Dam to the mouth of the Platte River 25 miles south of Omaha, NE. In the mid 1970's degradation was approximately 8 ft just south of Gavin Point Dam, about 6 ft in Sioux City, and 0 ft in Omaha, NE (Sayre and Kennedy, 1978). Degradation decreased downriver almost linearly. Degradation has led to concern over the stability of constructed works on the riverbed, difficulty in maintaining water-intake structures, deterioration of fish and wildlife habitats and recreational resources, changes in property boundaries, and headcutting of tributaries. All of these problems are related to the sediment supply and sediment carrying capacity.

Temperature can affect carrying capacity and relate directly to degradation of the river bed and movement of the sand bars. The fall velocity, a measure of the speed below which particles will settle to the bed, is a direct function of the size and shape of the particle and also of the temperature of the water (Straub, 1954). The Missouri River water temperatures range from approximately 32˚F to 78˚F (Straub, 1954; Shen, Wang, and Dorough, 1986). In a closed setting using a flume and sediment trap, it was determined that there is an inverse relationship between temperature and sediment-carrying capacity. This study found almost double the sediment carrying capacity at 40˚F than at 80˚F (Straub, 1954). This effect, coupled with increased winter-time discharge due to dam regulation, explains some of the degradation and establishment of permanent islands on the Missouri River that were found later in this study. Shen, Harrison, and Mellema (1978) found that between summer and winter flows the Missouri River bed forms changed from dunes to planar beds respectively. Decreasing flow temperature decreased roughness in the bed.

In the early days of mechanical navigation on the Missouri River, large paddle-driven steam ships used to pass this reach using channels deep enough to support this mode of transportation (Rahn, 1977). As observed by the author in approximately 1990, a modern paddle ship used for casino gambling had severe difficulty in navigating the modern channels. Today it must be carefully negotiated even with much smaller watercrafts through a shallow channel system.

### 3.2. Study Reach:

In the 55-mile reach from Yankton, SD to Ponca, NE the Missouri forms the Nebraska-South Dakota border. This reach of the Missouri does not fit into any of the standard morphological categories (Leopold, Wolman, and Miller, 1964), but instead demonstrates characteristics of both a braided river system and a meandering river system. Rivers transporting a mixed load (i.e. cobbles, gravel, sand, silt, clay, etc.) can exhibit straight, braided, or meandering channels (Huggett, 2003). Braided channels are controlled by deposition that occurs when the flow divides into a series of braids separated by bars (Huggett, 2003). A classic meandering river exhibits point bar deposition (Huggett, 2003) which is lacking on this reach of river even though the river as a whole is migrating. The study reach could be described as an island braided river system with laterally active channels (Huggett, 2003). Islands and bars create multiple deep-water channels similar to a braided system while the entire river migrates laterally across the floodplain with large meander bends similar to a meandering river system.

Sand bar deposition in this reach is controlled by suspended sediment load, bed load, and flow velocity. Higher water levels mean higher flow velocities, which will move larger amounts and sizes of sediment. Increased sediment causes more deposition to occur (Huggett, 2003). Natural flow regimes typically demonstrate higher flow velocities during peak runoff time compared to dam controlled regulated rates of flow. Dam regulated flows may not even experience simulated annual peak flows, which is the case of the study reach. Sediment free water, released from Gavins Point Dam, immediately begins to erode causing degradation and carries sediment from the study reach (Williams and Wolman, 1984). This should reduce the amount of deposition in this reach. One would expect to see larger and more numerous bars under natural flow regimes with sediment rich water. Pre-dam, annual peak flows would submerge sand bars and move sediment through a dynamic bar environment. Regulated rates of flow may impede sand bar deposition due to lack of sediment load and degradation in the river bed, resulting in fewer and smaller bars. Degradation of the bed and lack of peak flows may cause stabilization of sand bars to occur by raising the elevation of the bars relative to bed levels.

The landscape is usually flat with the exception of small loess bluffs that are approximately 200 feet. The floodplain in the area is about five miles wide, and the meander belt is approximately two miles wide (Rahn, 1977). The meanders rarely strike the valley side which is marked by the loess bluffs and is mainly contained within the flood plain. One notable exception to this is within the study reach where the river comes into contact with loess-capped bluffs of chalk and shale for a half mile section. The river in this region is a mid-latitude continental river eroding through rich agricultural soils and sedimentary bedrock occasionally. The bedrock of the loess-capped bluffs are the Cretaceous Niobrara Formation, a weakly consolidated chalk, overlying the Carlile Shale, a semi-consolidated black shale (Rahn, 1977).

Mid-latitude steppe climate dominates the region. The South Dakota State University Climate Center records a mean annual temperature of 47.6˚F and a mean annual precipitation of 23 to 25 inches. As the Missouri makes its way through the North Dakota and South Dakota prairies it migrates across a floodplain that consists of fine, thick, rich soils. Grasslands and agricultural fields dominate the landscape along most of the Missouri’s path through the Midwest. Locally, along the study reach, agricultural fields and deciduous forest dominate the landscape.

The study area for this project is located in southeastern SD, 10 miles east of the community of Vermillion. The representative reach is approximately 4 miles in length, determined by the availability of historical aerial photography from 1940 and 1941 and time constraints. The study reach is unique in the fact that it falls within the zone of river degradation. The zone of aggradation is well downriver of the study area near the mouth of the Missouri at St Louis, Mo.

## Chapter 4: Methodology:

### 4.1. Hypotheses:

Three hypotheses have been formulated to investigate the effects of dam regulation and regulated rates of flow on the Missouri River.

1) Migration rates of sand bars have been reduced due to regulated rates of flow and the lack of a natural flow regime.
2) Lack of a natural flow regime has decreased the size of sand bars and reduced the annual change in the areal extent and perimeter size of sand bars. In other words cyclical changes in area and perimeter measurements in sand bars are less today than they were during pre-dam conditions.
3) Sand bars, under controlled rates of flow, and due primarily to degradation of the river bed, are more clustered than they were under natural flow regimes.

To address these hypotheses, this study compared historical sand bar measurements from aerial photographs to recent sand bar field measurements collected with a differentially correctable global positioning system (DGPS). By comparing the movements of sand bars over a one year period prior to dam (1940 to 1941) closure and to those over a one year period after dam closure (2004 to 2005), it could be determined how regulated flow has effected the riparian environment.

### 4.2. Aerial Photography:

Historical aerial photography was obtained from the National Archives. Many researchers (e.g. Castiglioni and Pellegrini, 1981; Bravard and Bethemont, 1989; Hooke and Redmond, 1989; Castaldini and Piacente, 1995) have found aerial photography to be very useful for the analysis of channel changes and river regulation (Surian, 1999). The earliest available historical aerial photos of the study reach were taken 5 July 1940, 16 September 1941, and 7 October 1941. All sets of aerial photography were taken at a scale of 1:10,000. Ft. Peck Dam closed its gates in 1937 (Sigmundstad, 2006), and construction continued until completion in 1940. The location of the dam on the river, so far above the study reach, allowed a natural flow regime to resume before it passed through the 55 mile reach due to tributaries and runoff that contributed to the flow regime. Mean monthly streamflow at Yankton, South Dakota (USGS, 2006), was used to determine that the rates of flow mimicked a natural flow regime during 1940 and 1941 and Fort Peck dam was not affecting flow during this period. Further details on flow regimes are discussed in Section 4.4. Thus these photos are considered a representation of a natural hydrologic flow regime.

The historical photos were geometrically corrected using ERDAS Imagine 8.6 software. Photographic rectification corrects for distortions in an image caused by the earth's curvature, topography, lens irregularities, and variations in orthogonality (Merritt and Cooper, 2000). After multiple attempts to run a simple polynomial geometric correction technique, it was determined that an orthobase technique was required to correct and mosaic the photos from 1940 (ERDAS, 1999). The technique required a reference Digital Orthoquadrangle (DOQ) and a 30 m Digital Elevation Model (DEM), both from USGS (2005).

The 1941 set of historical photos were corrected using a simple polynomial geometric correction technique (ERDAS, 1999). The field study area has very little relief (tens of feet) and did not require orthorectification, because the correction for the 1941 photos was checked and determined to be accurate. These mosaic ked photos were also verified for accuracy.

Sand bars from each mosaic were then digitized using ESRI's ArcGIS© software. From these digital outlines the movements of individual bars could be seen from year to year. The 1940 and 1941 sand bars were overlaid to show the change in shape, size, and location of each bar (Figure 6). Xtools, an ArcGIS extension, was used to determine the area and perimeter of each bar. These measurements and the number of bars present were then used to determine the amount of change over one year under a "natural" flow regime.

These aerial photos were also used in a transect analysis. Using the aerial photographs transects were create and also used for a point pattern analysis to determine the amount of channel widening or narrowing throughout the study reach.

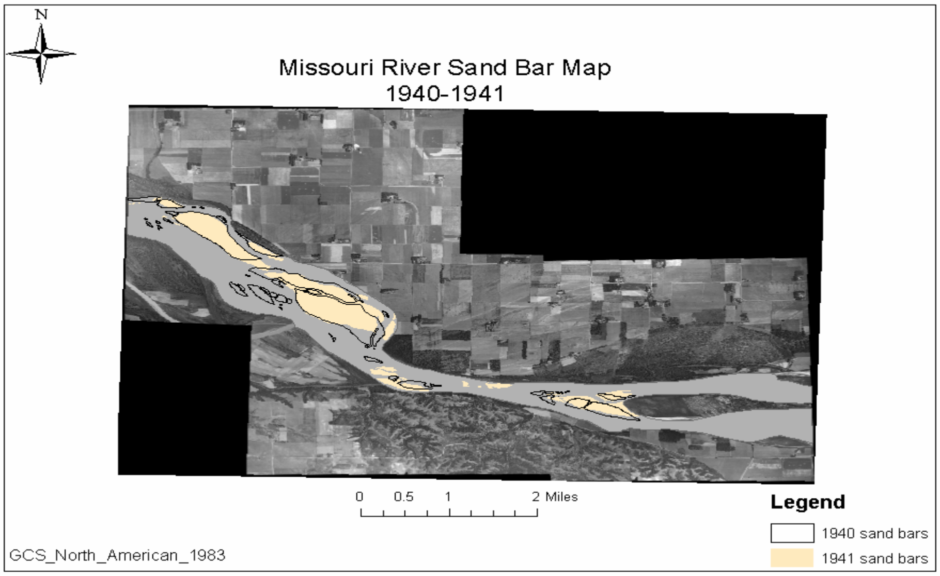

**Figure 6: Map of 1940-1941 Missouri River sand bars.**

## 4.3. Field Mapping:

Primary data for the modern comparison were collected through the use of field mapping using a Trimble GeoExplorer 3© in 2004 and a Trimble GeoXM© in 2005. Sand bar size, shape, and position were determined by walking the perimeters of each bar taking a point every second for smaller bars or every five seconds for larger bars (to limit the size of the files created). Sizes were determined by the author on a case by case basis. A slower pace was used at intricate points in the bar traverse to preserve the shape of the outline. Once again, Xtools was used to determine the area, perimeter, and number of bars each year.

Primary data collection took place in midsummer each year (19-28 July 2004 and 20-26 July 2005) each year. This data underwent a differential correction process to reduce any error or distortion in the data collection process due to the GPS instrument. Pathfinder Office version 3.0 (2003) was used in the differential correction process. Shapefiles were then used in ESRI's ArcGIS Arcmap to assess how the size, shape, and position of each bar had changed (Figure 7).

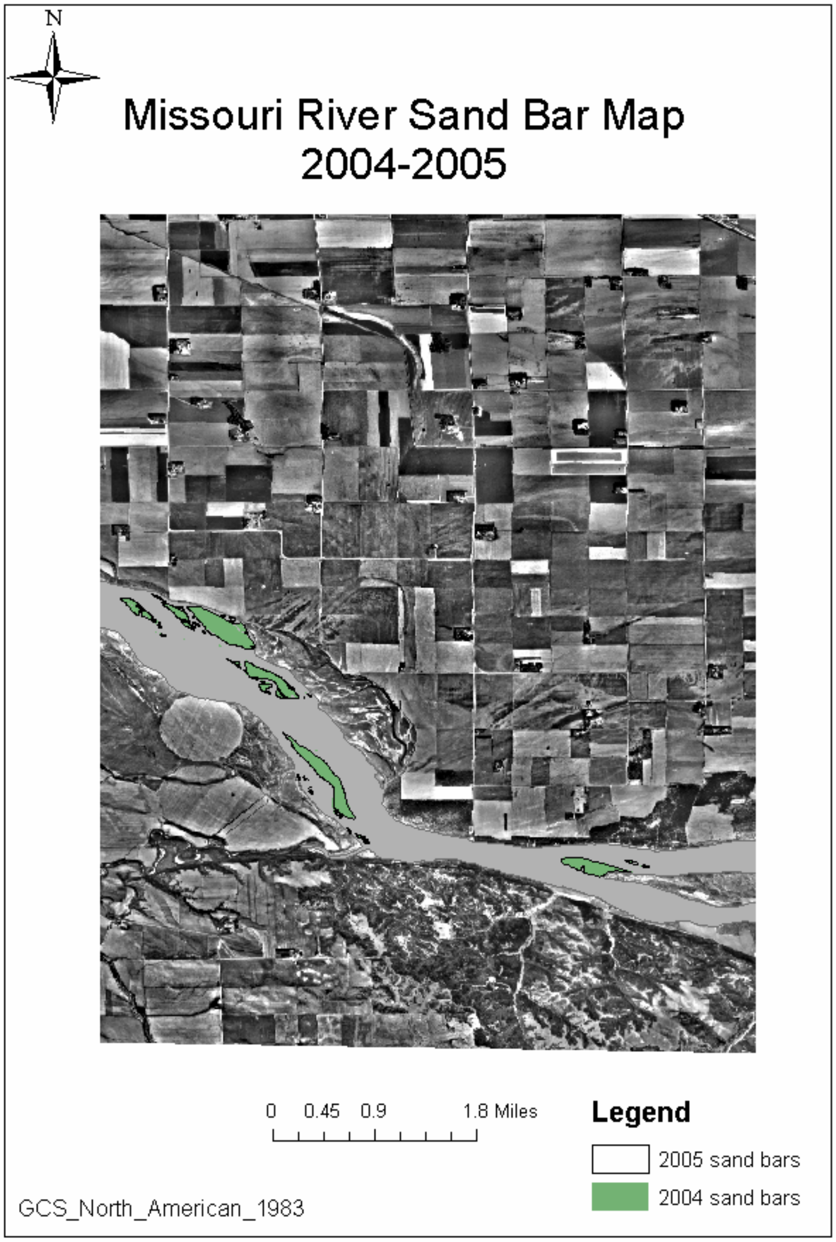

**Figure 7: Map of Missouri River sand bars from 2004-2005.**

## 4.4. Analysis:

Under absolutely ideal conditions, aerial photography and primary data would be available from the exact same water level (25,000 cfs) during the month of July to correspond with the field data. Aerial photography from pre-dam time periods proved to be difficult to obtain, especially for successive years. Multiple challenges arose when preparing this study. The differences in the dates of the historical aerial photos, the difference in the discharge and how that relates to gauge height, and potential degradation of the river bed were evaluated. The only available aerial photography was from 5 July 1940 with a water level of 29,000 cfs and 7 October 1941 with a flow of 20,300 cfs. This constitutes a difference of 8,700 cfs. Upon examination of the data available, it was determined that due to degradation in the river bed and change in channel morphology an exact number correlation between gauge height in feet and cfs could not be accurately determined (Figures 8). Figure 9 shows the degradation of the river bed over time (comparing cfs and gauge heights from specific years) that contributes to the inability to correlate cfs and gauge height. Therefore a direct correlation between the two cannot be made. While a direct correlation cannot be made, it is assumed for the purpose of this project that the difference in gauge height is minimal and will not have a large effect on sand bar size and shape.

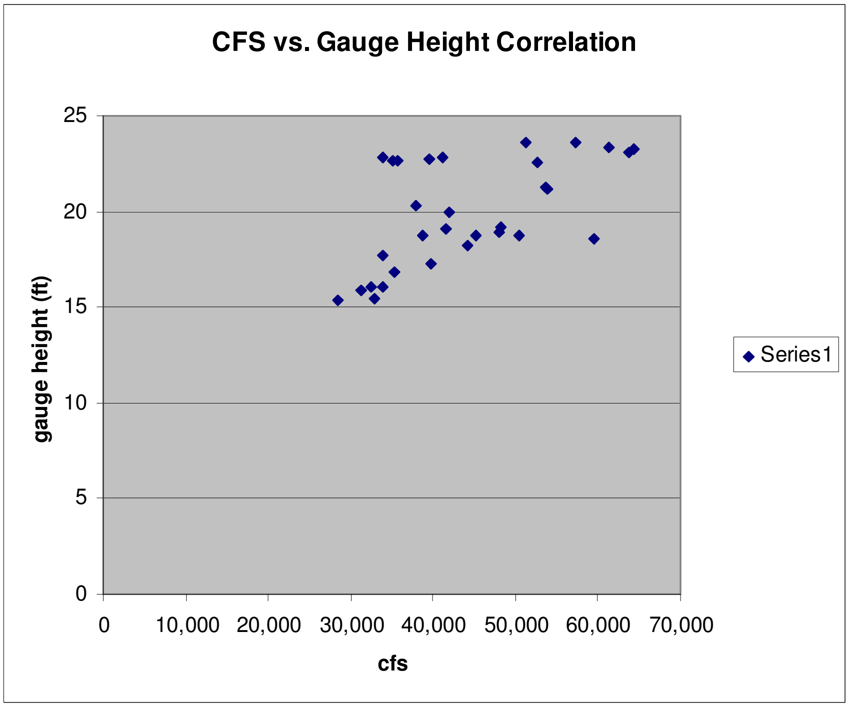

Figure 8. Graph displaying gauge height to cfs correlations.

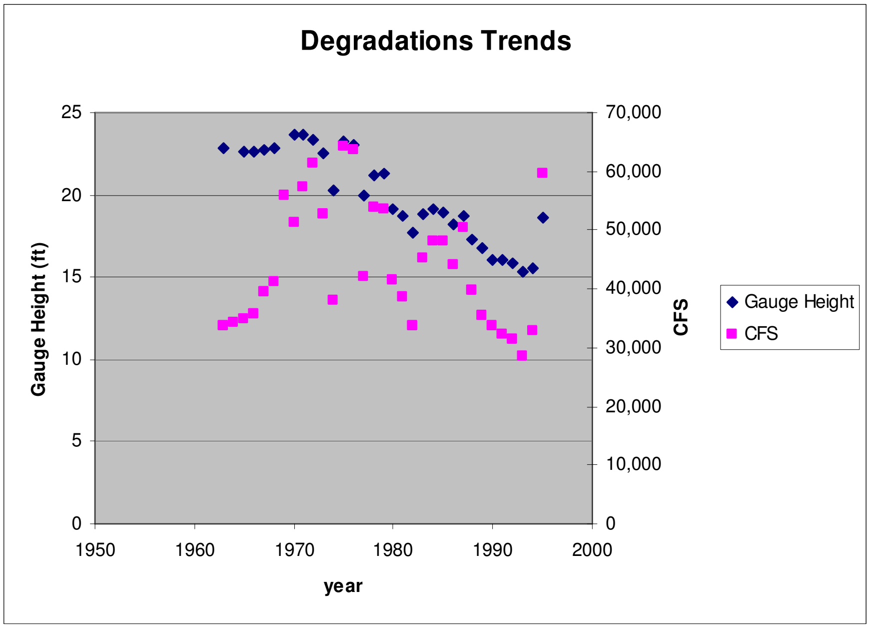

Figure 9. Graph showing bed degradation trends in the Missouri River.

The aerial photography from 7 October1941 covered approximately 75% of the study area after the completion of the mosaic. In order to provide complete coverage of the study area, aerial photography from 16 September1941 with a water level of 44,000 cfs was used. As stated earlier, Fort Peck Dam closed its flood gates in 1937. Upon analysis of the mean monthly streamflow (Figure 4) and mean annual peak flow discharges (Figure 10), it was determined that a simulated natural flow regime was occurring for the periods of available aerial photography and that Fort Peck Dam did not have a strongly regulated flow in 1940 and 1941. The 44,000 cfs flow on the aerial photography from 16 September 1941 is an anomaly that introduces some inaccuracies to the study in the northwestern 25% of the study area. This water level reduces the resulting effects found by this study of regulated rates of flow on sand bar migration by underestimating the areal extent of the bars. If the coverage of the entire study area for the historical analysis were available with more similar flows, it could be predicted that it would increase the amounts of change in the 1940-1941 time period, thus strengthening the conclusion of this study even more.

The flow regimes in the study area have changed greatly since the closure of the main stem dams. Mean annual peak flows have changed drastically since dam regulated flows have been installed (Figure 10). Mean annual peak flows ranged from 46,500 cfs to 480,000 cfs until the year 1953. After 1953, under regulated rates of flow, mean annual peak discharges range from 30,000 to 50,000 cfs. Frequency of high, medium, and low water years varied depending on snow pack and precipitation amounts before 1953. From 1954 to the present a much more stable annual peak flow regime has been maintained by dam regulation. High medium and low peak flows are still dependent on the amount of snow pack and precipitation, but also depend on reservoir levels and the water needed downriver for barge traffic. According to Figure 10, the times slices used in this project are from 1940-1941 and 2004-2005. These are representatives of both pre- and post-dam conditions respectively.

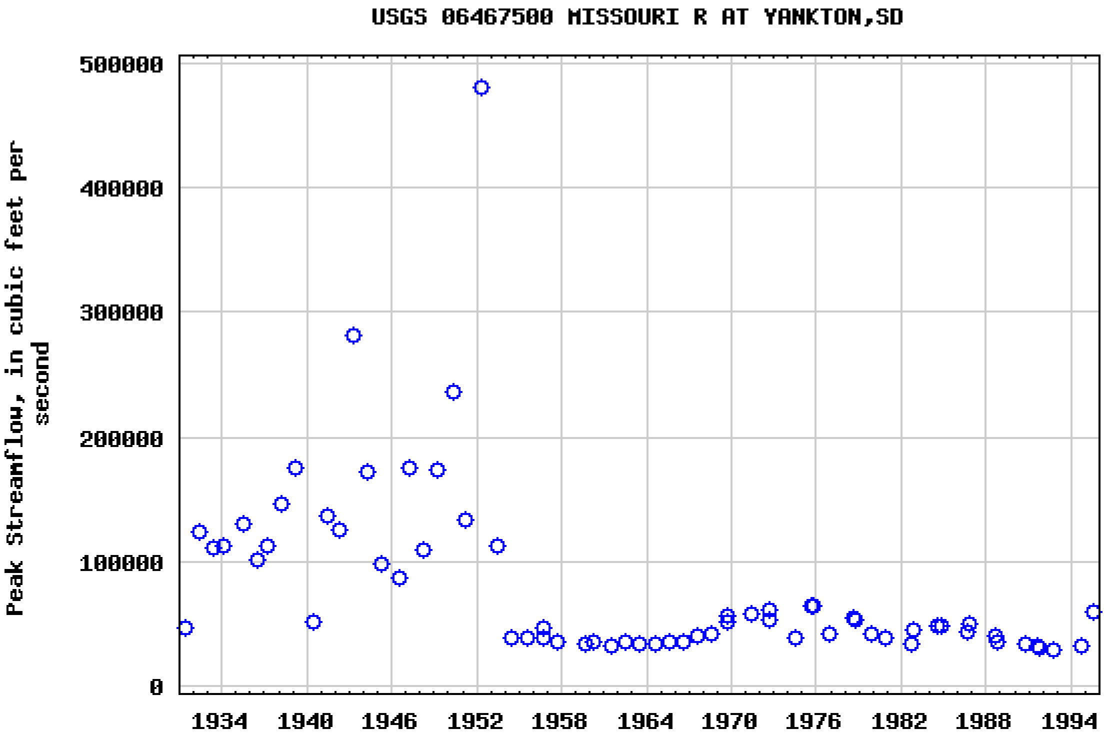

**Figure 10. Graph showing mean annual peak flow discharges for the Missouri River at Yankton S.D. (USGS, 2006).**

Recent dam management releases from Gavins Point Dam are regulated in such a manner that the water levels at any given time during a given year will be very similar to the previous year (Figures 4, 5, and 10). Following the initial survey in 2004, the second year of data collection was planned with a one year lag to have very similar water levels. The flow in 2004 and 2005 measured 25,000 cfs and 22,500 cfs, respectively (USACE, 2004; 2005).

### 4.4.1 Migration Rates

Analysis of the hypothesis on migration rates involved both quantitative and qualitative techniques. Six cases were found in which it was determined that the bar in 1940 and 1941 was the same bar with a different size, shape and position. The same procedure was used in the 2004 and 2005 data to identify six bar pairings. The 1940 and 1941 data only presented six identifiable cases. In 2004 and 2005 many cases were identified but only six were analyzed for control. From the change in centroid position, obtained from the digital outlines, the movement of the sand bar was quantified in each of the six cases for each time period. The movement of sand bars was also explained qualitatively by examining the aerial photography and digital outlines.

### 4.4.2 Size and Shape

The second hypothesis compares the size of bars and amount of change that occurred under a natural flow regime (1940-1941) to the amount of change over time under regulated rates of flow (2004-2005). It was addressed by comparing the total area and perimeter of sand bars for the time periods, percentage of change in total bar size from year to year between the two time periods, average bar size and their percentage of change, and the percentage of change on a bar by bar basis.

### 4.4.3 Point-Pattern Analysis

Statistical analysis quantifying the amount of clustering of the sand bars from 1940-1941 and 2004-2005 was used to answer the third hypothesis. A quadrat analysis was applied to the maps from each time slice. The study area was divided into nine quadrats each 0.5 miles apart in an east-west direction. The binding margin at the top and bottom of each quadrat was the shoreline of the river. Ideally, each quadrat would be a square of equal size, but given the shape and size of the study area this was not feasible. Statistical values of $\chi^2$ (McGrew and Monroe, 2000) were calculated from the data for 1940-1941 and 2004-2005 to determine the amount of clustering during each time period and then were compared to one another to determine the change in clustering of the sand bars under different flow regimes. P-values were used to compare the probability of the clustering in each case.

## **Chapter 5: Results and Discussion**

The overall conclusion of this study is that there are measurable differences in the movement patterns of sand bars under the two flow regimes. The pre-dam time period, under a natural flow regime, shows more dynamic sand bar movements. This includes drastic changes in shape, area, and perimeter of the sand bars. The contemporary data, under a regulated flow regime, shows bars which have minimal change annually. The sum totals reveal that distance moved by all the bars in 2004-2005 (Figure 7) is overall smaller than distance traveled by some single sand bars in 1940-1941 (Tables 1 and 2). The recent data also show little change in area and perimeter. Figures 6 and 7 illustrate how much more the sand bars changed shape between 1940 and 1941 than the sand bars between 2004 and 2005. The differences in shapes of sand bars from year to year are easily distinguishable in 1940-1941, but they are not in 2004-2005.

### 5.1. Migration of Centroids:

To measure the movement of a sand bar, one sand bar must be identified at the beginning and end of the time period on a pair of aerial photos and then centroids can be calculated for each. One must be able to say without a doubt that the sand bar is the same in both years. This was difficult for the years of 1940 and 1941. Only six sand bars were definitively identified (Figure 11). Seven cases were evaluated but Case 7 involves the coalescing of bars, not the movement of one bar. Case 7 was not used in any of the calculations of bar movements. The bars were analyzed on a case by case basis. To compare bar movement under differing flow regimes, six bars were chosen from the recent data as well (Figure 12).

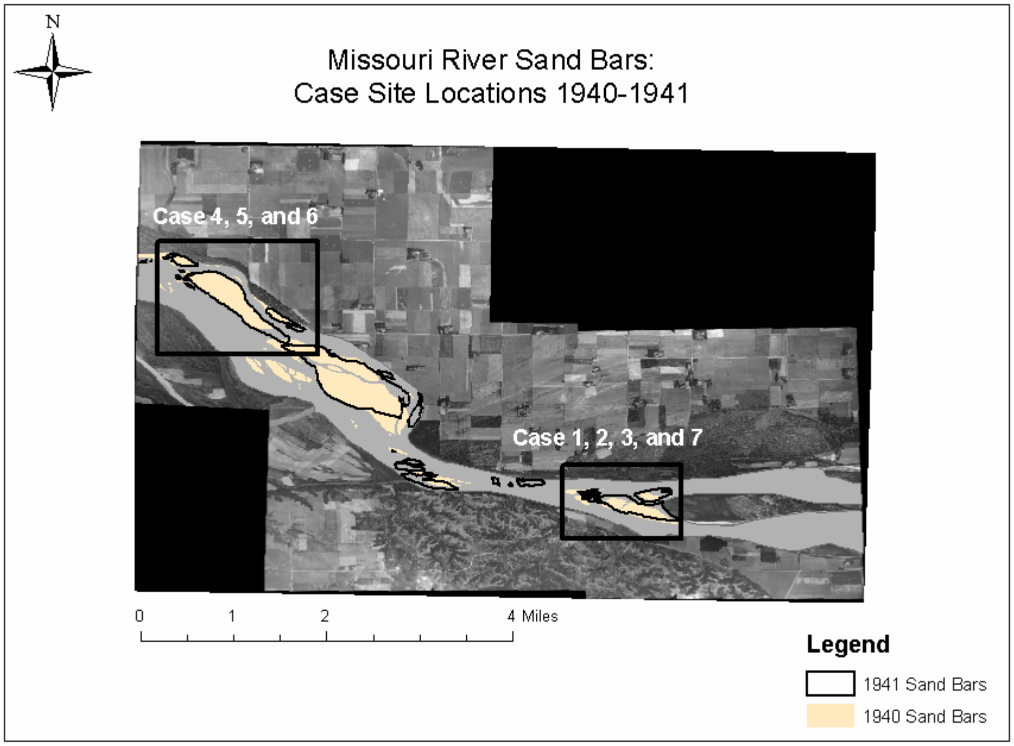

**Figure 11: Map of Case Site locations for 1940-1941.**

These bars were selected based on two criteria: a) bars were to be in similar areas of geomorphic settings, i.e. straight channel or meander bend; and b) bars were to represent a broad range of sizes. The bars from the historical data were spaced across the study area with four downriver in a narrower straight section in the middle of the channel and the others upriver in a wider section of channel near the shoreline (Figure 11). The bars from the recent data were chosen in similar locations to try to control for geomorphic setting (Figure 12). Bars were categorized into small, medium, and large bars using three class sizes: 1) small bars range in size up to ten acres, 2) medium bars range from 10

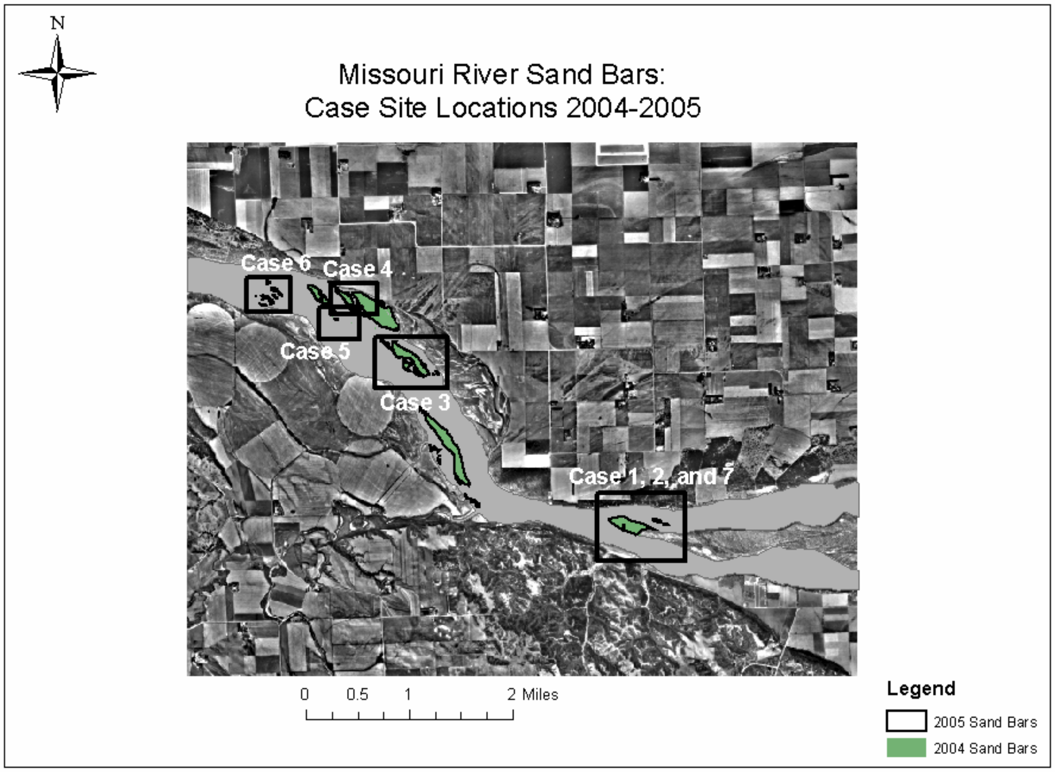

**Figure 12: Map of Case Site locations for 2004-2005.**

acres to 30 acres, and 3) large bars measure a size greater than 30 acres. However, for the pre-dam period it was difficult simply to locate the same bar and no small bars were present on the photographs. Between 2004 and 2005 three small-bar pairings were found (Figure 12, Cases 1, 2, and 5).

Evaluation of each sandbar pair showed that the pre-dam period experienced more dynamic movements than the post-dam period (Figures 13-18). Only one bar pair moved less than 100 ft during 1940-1941 (Table 1). Three of the six bars moved over 350 ft with a maximum movement of 475 ft. All of the bars from 1940-1941 moved parallel to flow in a downriver direction.

The bars from 2004-2005 demonstrate a much more static environment (Figures 19-24). None of the six cases show movements of 100 ft, with a maximum of just 96 ft (Table 2). Two of the six bars moved less than 10 ft. Not all of the bars from 2004-2005 displayed movement patterns consistent with flow direction. In Cases 4 and 5 (Figures 22 and 23), a lateral shift is shown. Case 6 (Figure 24) displays movement upriver.

Sand bar behavior from 2004-2005 is inconsistent with 1940-1941 behavior. These movement inconsistencies are believed to be due to the regulated rates of flow and lack of a suspended sediment load post-dam, based on this study.

Based on the centroid migration it appears that the bars under a natural flow regime from 1940-1941 are considerably more dynamic than the bars from 2004-2005. Bars from 1940-1941 migrated considerably larger distances.

| **Case Number** | **1940** | **1941** | **Distance Moved** | **Direction of Movement** |
|---|---|---|---|---|
| Case 1 | Bar 1 | Bar 0 | 140 ft. | Parallel to flow, downriver |
| Case 2 | Bar 5 | Bar 6 | 377 ft. | Parallel to flow, downriver |
| Case 3 | Bar 7 | Bar 2 | 475 ft. | Parallel to flow, downriver |
| Case 4 | Bar 62 | Bar 28 | 132 ft. | Parallel to flow, downriver |
| Case 5 | Bar 45 | Bar 30 | 365 ft. | Parallel to flow, downriver |
| Case 6 | Bar 59 | Bar 31 | 86 ft. | Parallel to flow, downriver |

**Table 1. Sand bar centroid measurements from hypothesis 1 for 1940-1941.**

| **Case Number** | **2004** | **2005** | **Distance Moved** | **Direction of Movement** |
|---|---|---|---|---|
| Case 1 | Bar 4 | Bar 58 | 58 ft. | Parallel to flow, downriver |
| Case 2 | Bar 3 | Bar 57 | 96 ft. | Parallel to flow, downriver |
| Case 3 | Bar 63 | Bar 38 | 39 ft. | Parallel to flow, downriver |
| Case 4 | Bar 25 | Bar 21 | 7 ft. | Perpendicular to flow, lateral shift |
| Case 5 | Bar 47 | Bar 17 | 4 ft. | Perpendicular to flow, lateral shift |
| Case 6 | Bar 38 | Bar 59 | 38 ft. | Parallel to flow, upriver |

**Table 2. Sand bar centroid measurements from Hypothesis 1 for 2004-2005.**

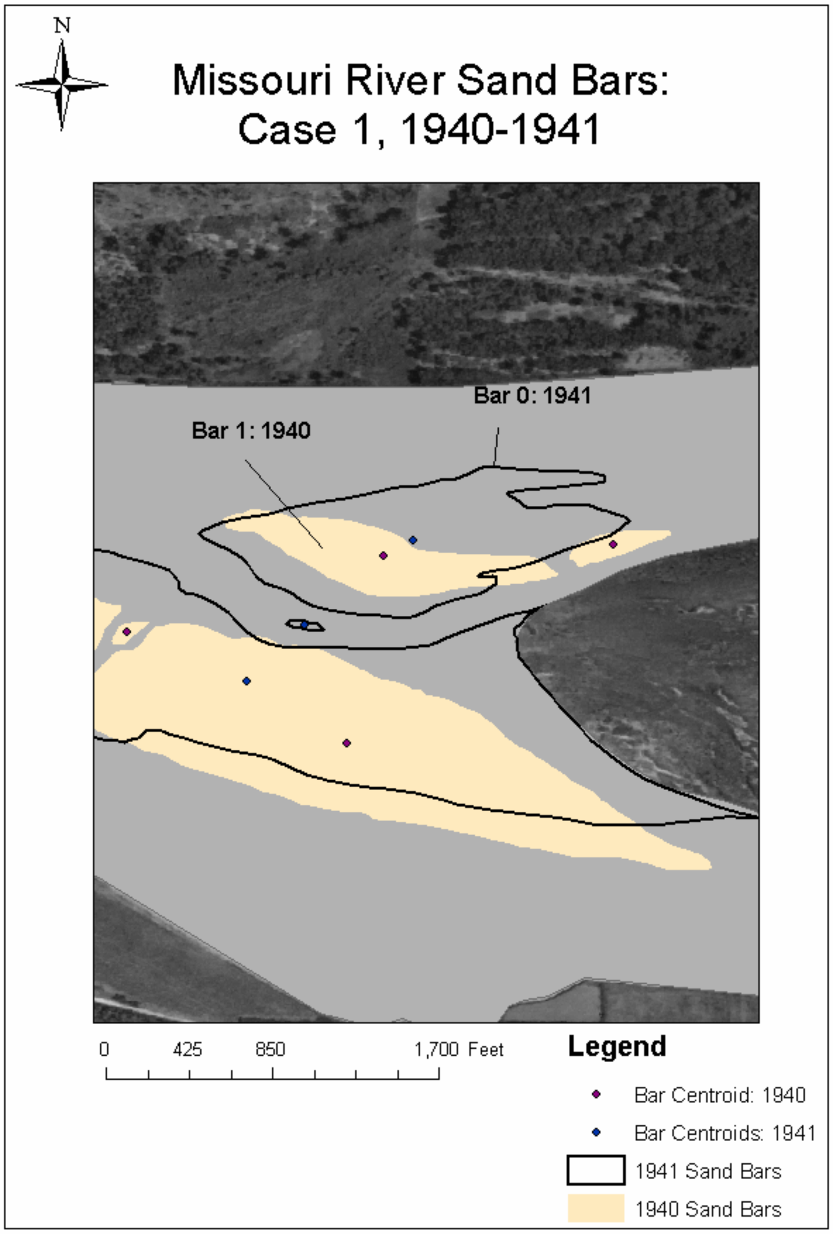

Figure 13: Map of Case 1 sand bars from 1940-1941.

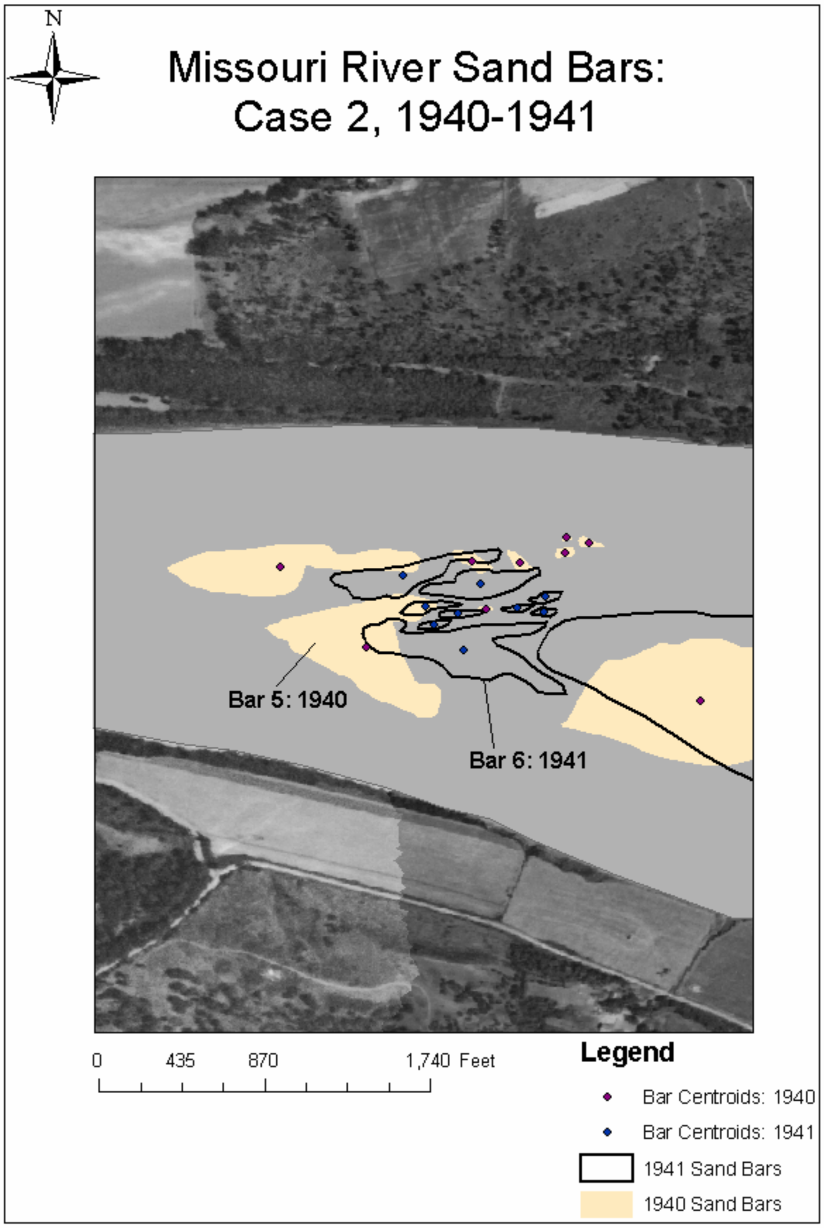

**Figure 14: Map of Case 2 sand bars from 1940-1941.**

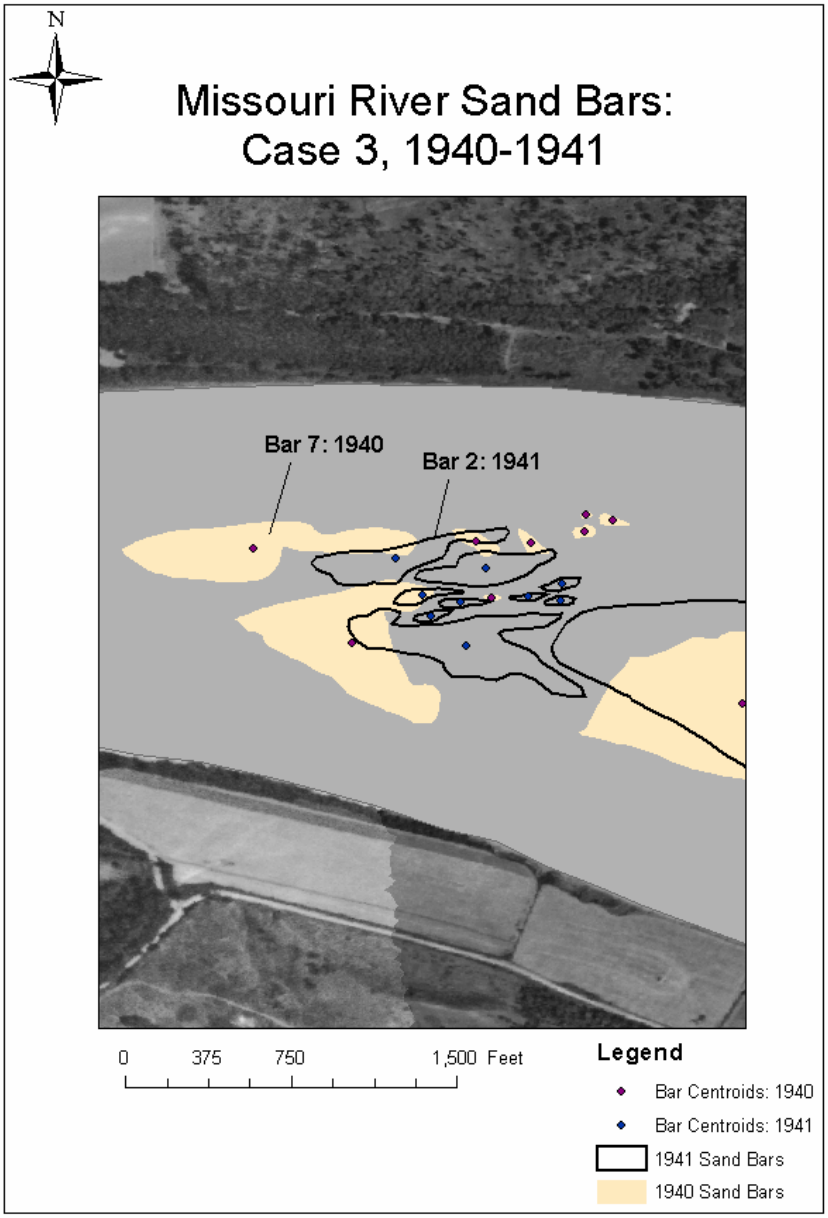

Figure 15: Map of Case 3 sand bars from 1940-1941.

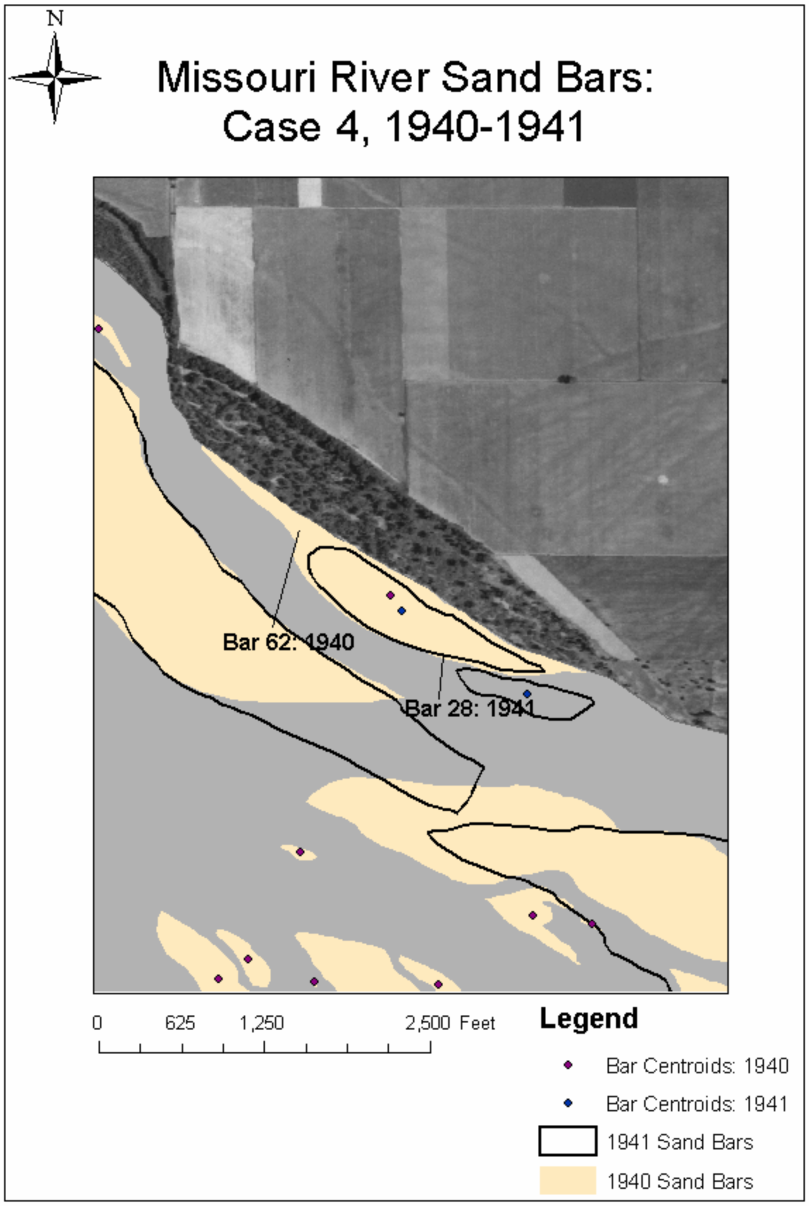

**Figure 16: Map of Case 4 sand bars from 1940-1941.**

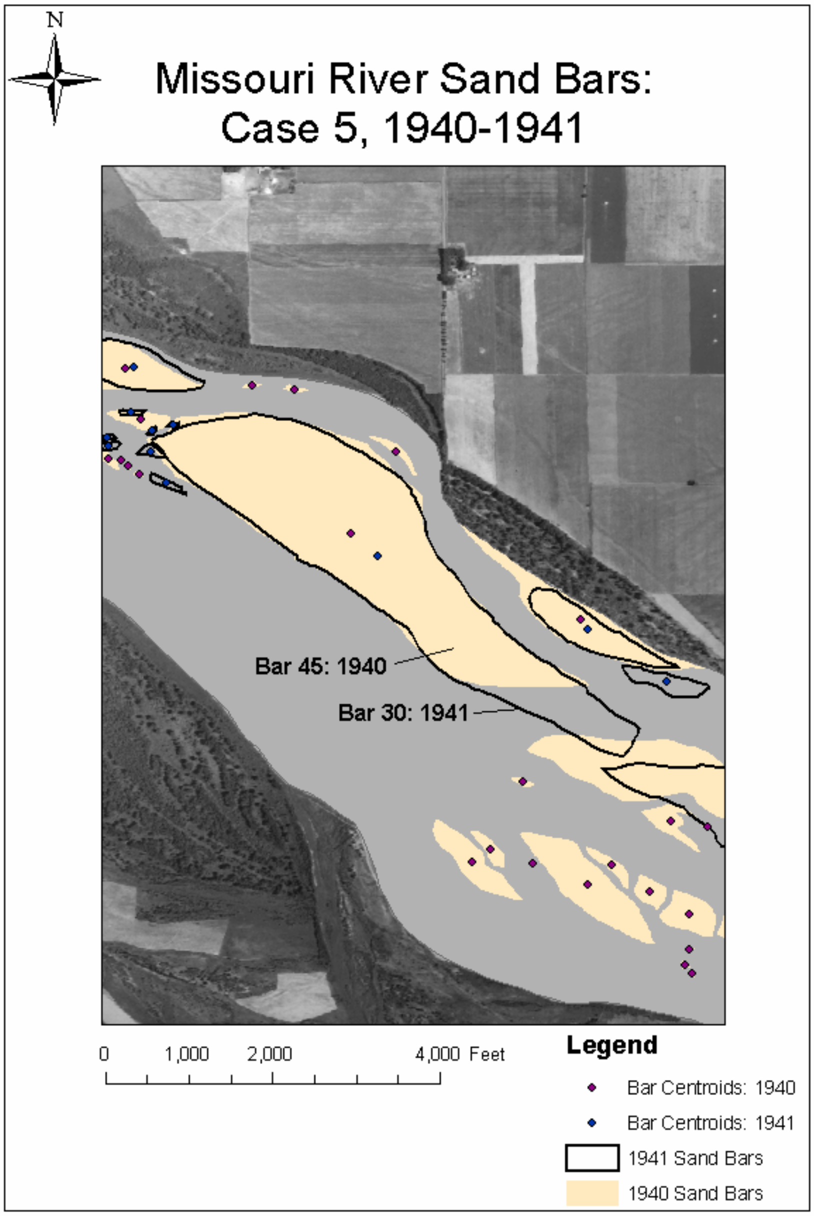

**Figure 17: Map of Case 5 sand bars from 1940-1941.**

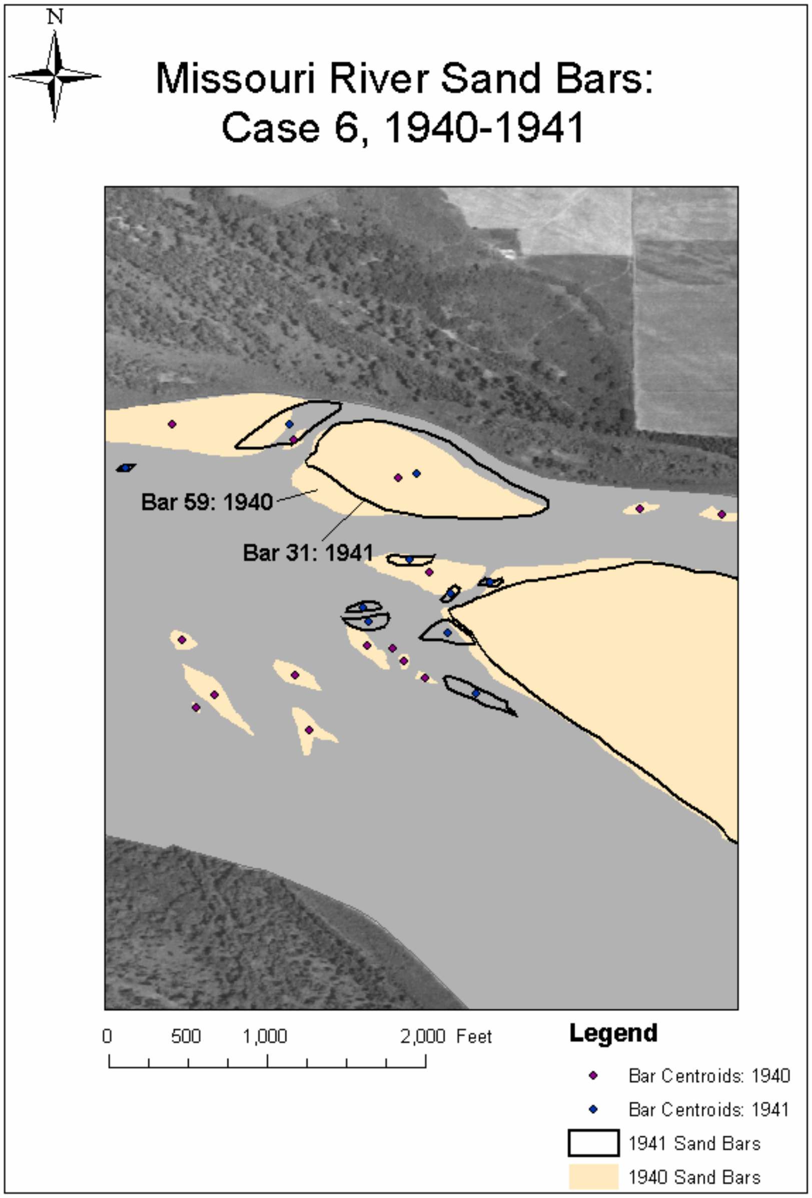

**Figure 18: Map of Case 6 sand bars from 1940-1941.**

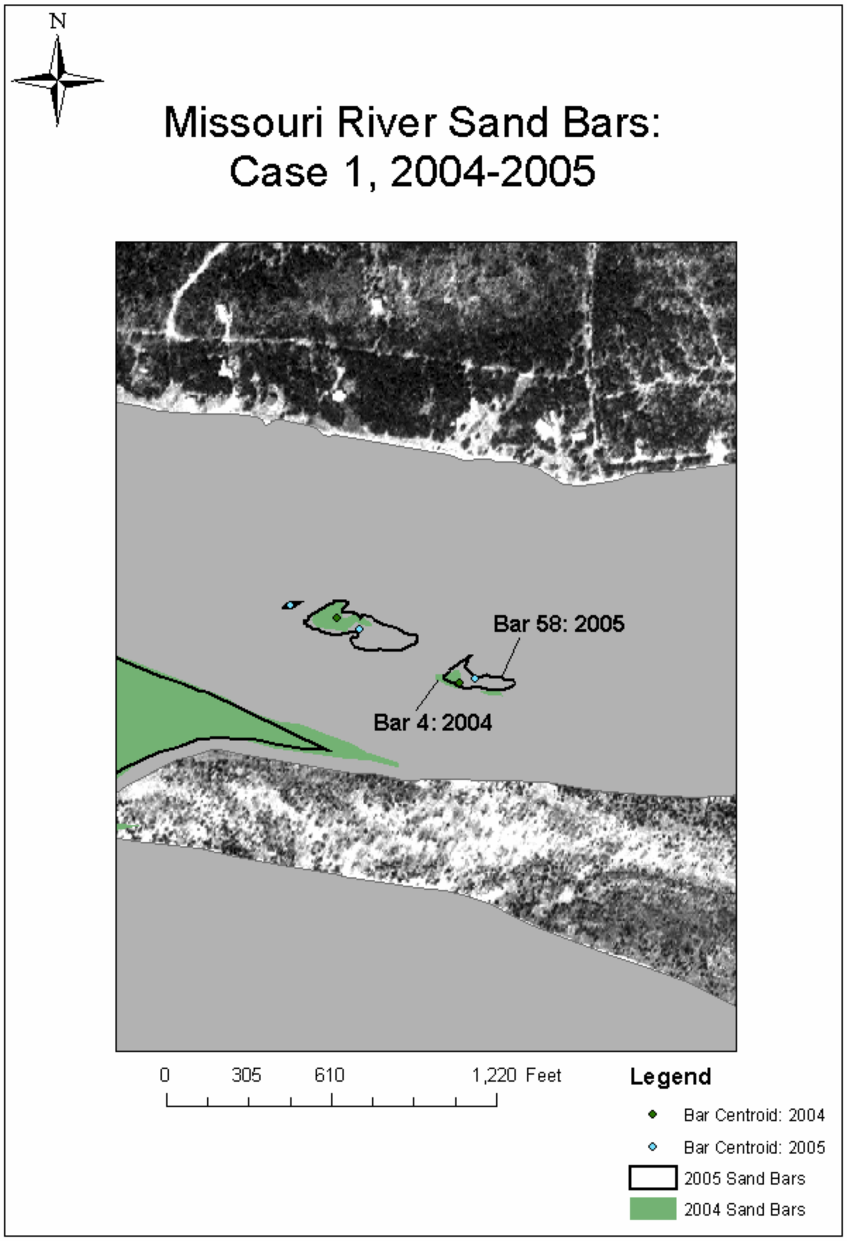

**Figure 19: Map of Case 1 sand bars from 2004-2005.**

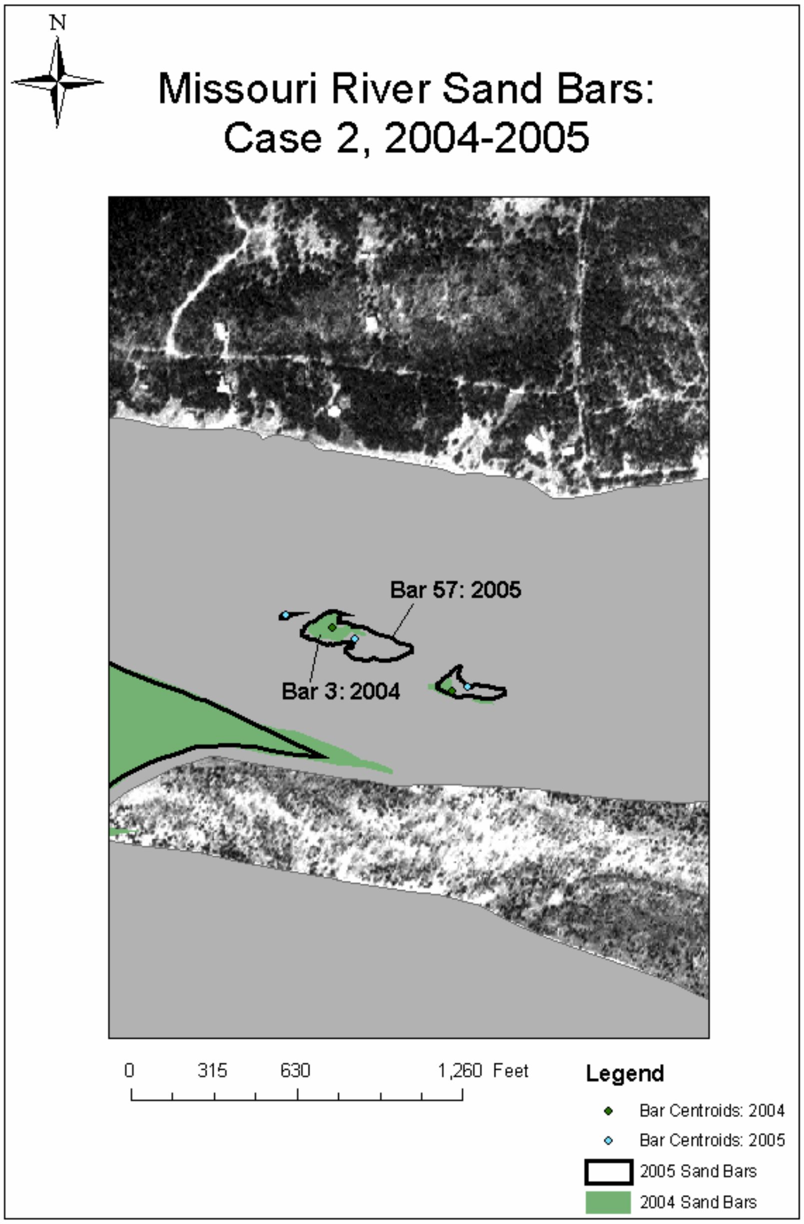

**Figure 20: Map of Case 2 sand bars from 2004-2005.**

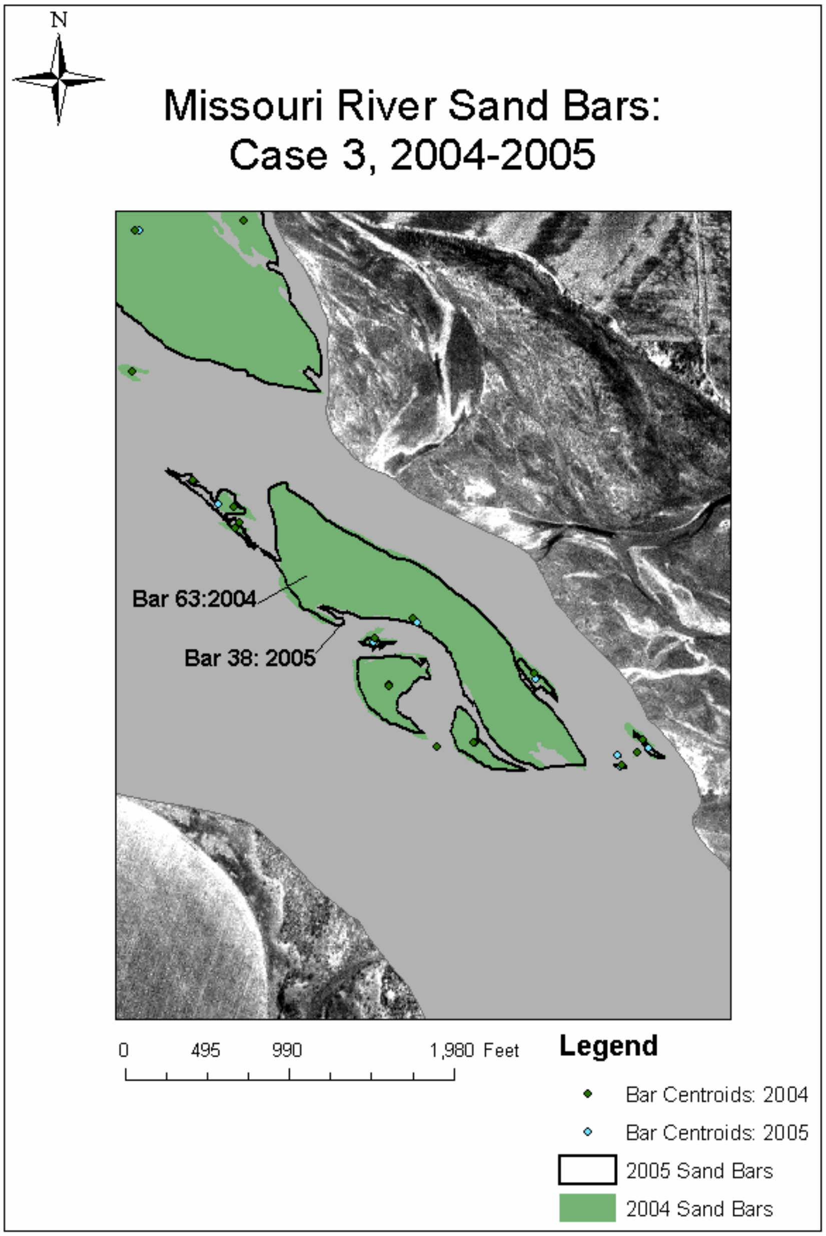

Figure 21: Map of Case 3 sand bars from 2004-2005.

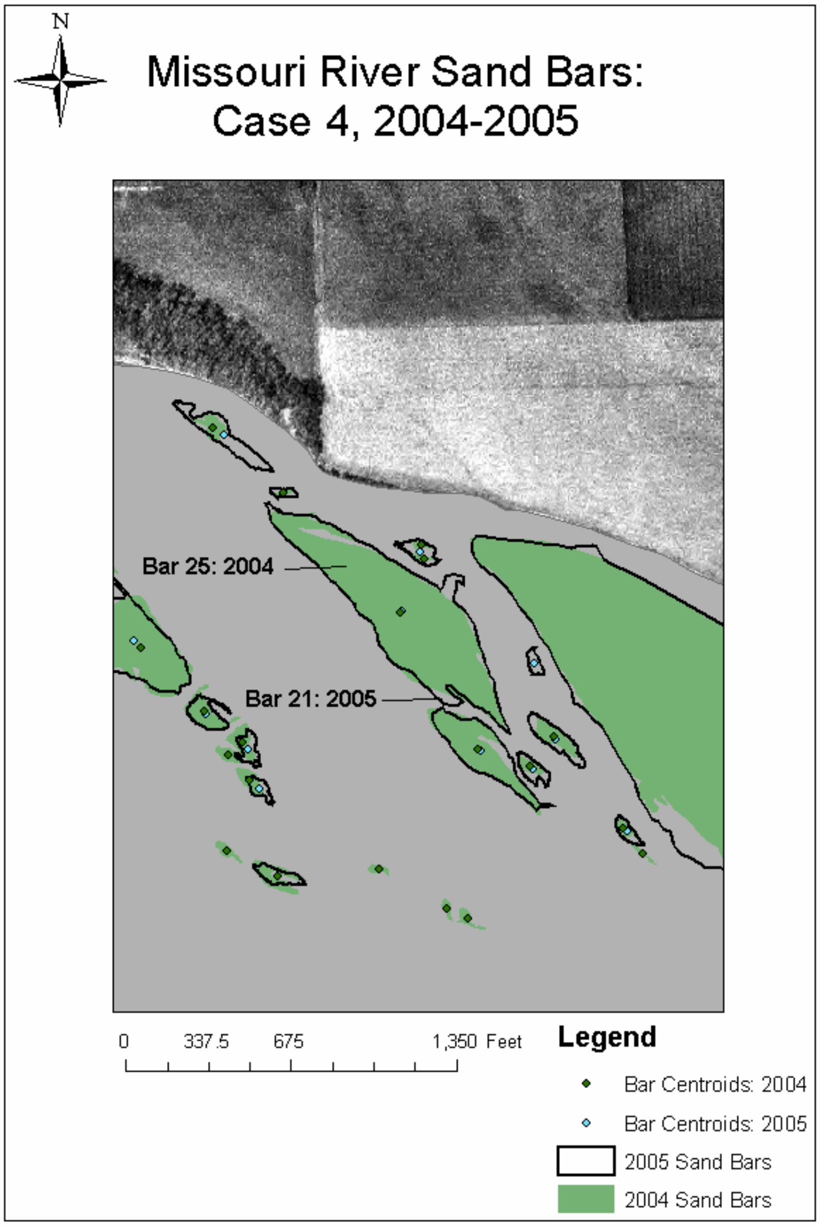

**Figure 22: Map of Case 4 sand bars from 2004-2005.**

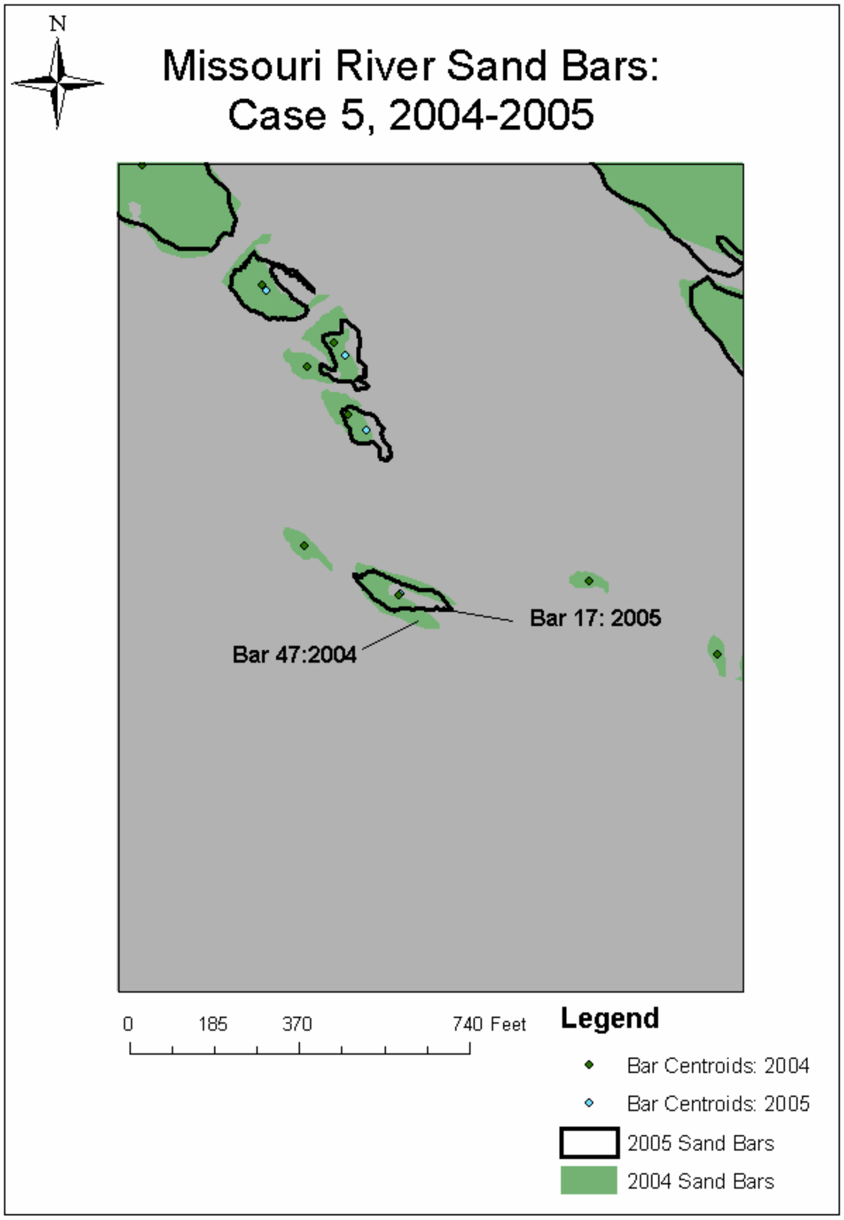

**Figure 23: Map of Case 5 sand bars from 2004-2005.**

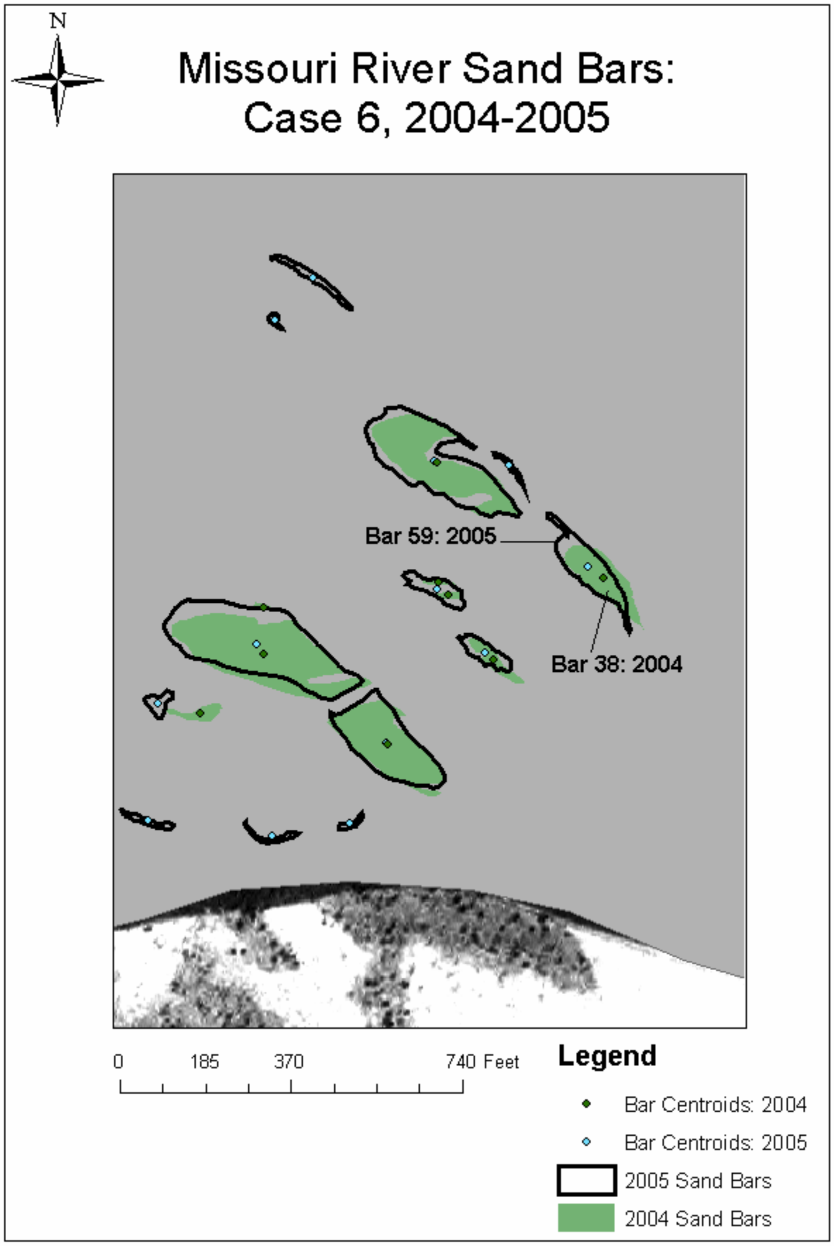

**Figure 24: Map of Case 6 sand bars from 2004-2005.**

### 5.2. Qualitative Assessment of Movement:

Qualitatively, the movements of the bars can be explained using maps (Figures 25-31). Some of the most surprising differences in bar migrations came from the larger, vegetated bars. Vegetation causes stabilization and promotes island formation, thus slowing bar migration by creating more permanent vegetated islands. Remotely sensed data used in this study proved too inconclusive to accurately map vegetation on historical islands. Attempts to map vegetation on the bars were unsuccessful from the aerial photography. Visual examination indicates little tonal differences between the pre and post-dam images. However, this was not the focus of this study and was assumed constant over the time period. Large bars (islands) from 1940-1941 demonstrate considerable amounts of movement in comparison to the bars from 2004-2005. Multiple large bars were seen merging into a single bar with a different size and shape between 1940 and 1941 (Figure 25). Figure 26 shows the little change and no coalescing in large bars from 2004 to 2005. Small and medium bars were seen coalescing and breaking up between years as well in the pre-dam period (Figures 25, 27-29). This is a phenomenon that was not seen in any bars from 2004-2005. In fact no bar from 2004-2005 showed substantial change from one year to the next (Figures 30 and 31).

All of the bars showed considerably more change between 1940 and 1941 than did the bars between 2004 and 2005. In many cases bars that were present in 1940 were not present in 1941 (Figure 27). The opposite was also found, areas that contained no bars in 1940 had bars present in 1941 (Figure 28). Many similar cases could have been selected like those in Figures 27 and 28. Some of the bars fragmented such that one could not definitively determine between one bar and another (Figure 29). Almost every bar in 2004 had a match to it in 2005 (Figures 30 and 31).

Clearly, recent bar movements do not show the same characteristics as earlier periods. Bars of all sizes in 2004-2005 show very minor amounts of change in comparison to the 1940-1941 bars (Tables 1 and 2 and Figures 30 and 31). Measurements of centroids show conflicting migration behaviors between the time periods. Case-study maps (Figures 13-18) show bars shifting in downriver directions under natural flow regimes. Lateral, upriver, and downriver shift directions occurred under regulated flow regimes (Figures 19-24). Comparison of 1940 to 1941 (Figures 25, 27-29) revealed the appearance and disappearance of bars, suggesting major amounts of sediment being reworked. No bars from the post-dam period displayed this behavior.

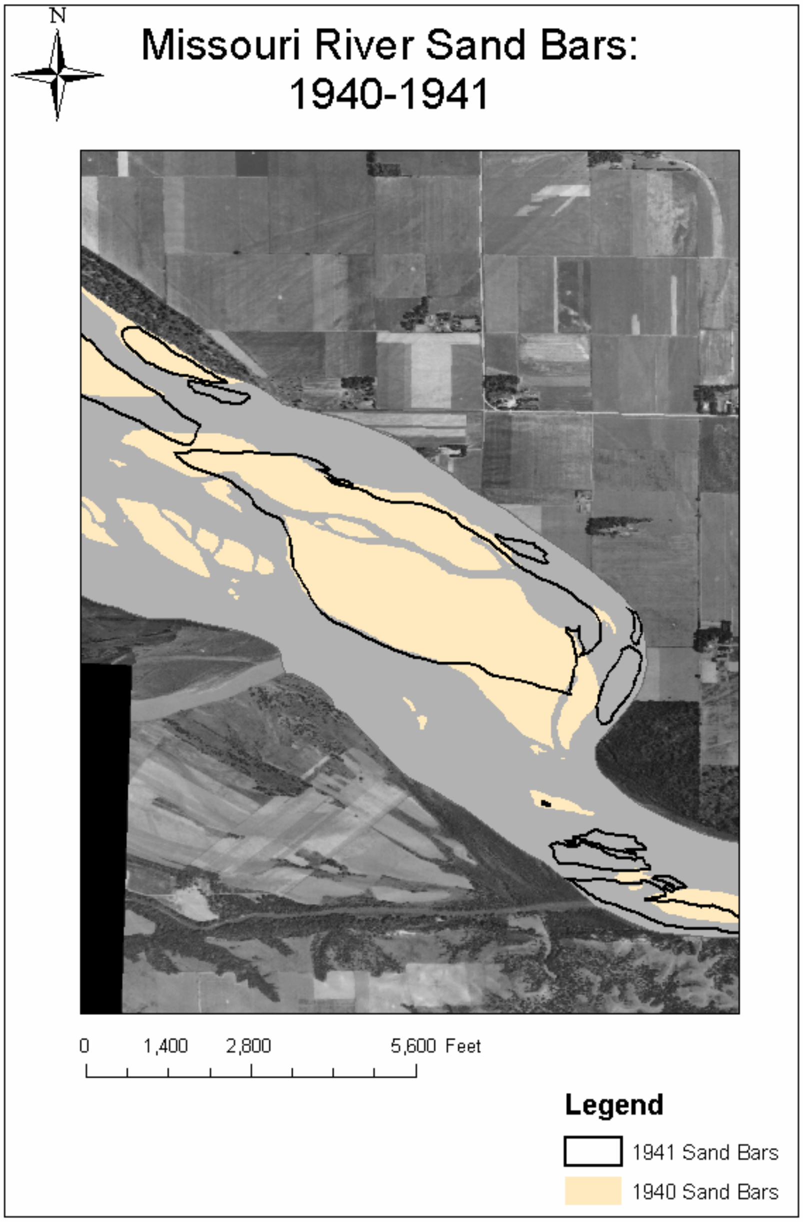

**Figure 25: Map of large bars from 1940-1941 showing accretion of multiple bars into one larger bar.**

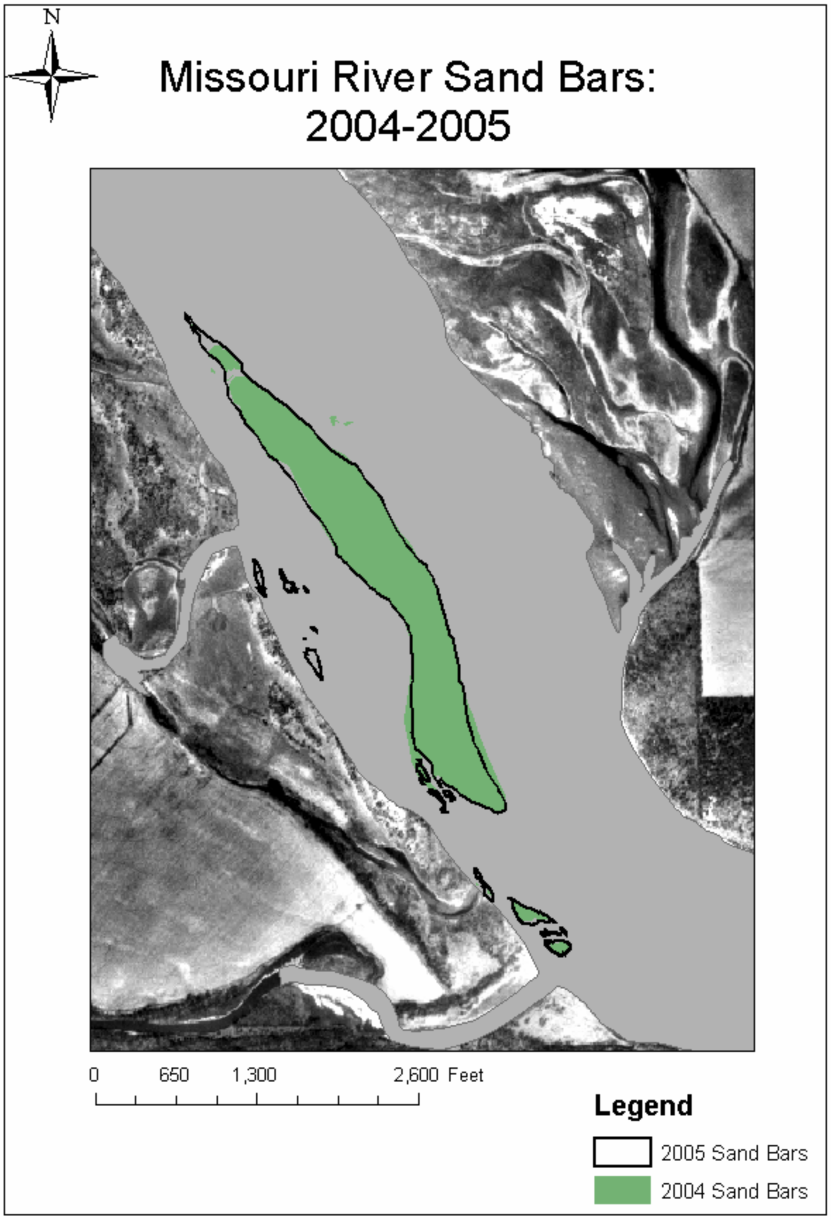

Figure 26: Map showing a typical movement of a large bar from 2004-2005.

Figure 27: Map showing dynamic movement common in sand bars between 1940 and 1941.

**Figure 28: Map showing open water in 1940, sand bars in 1941.**

Figure 29: Map depicting difficulty in finding bar pairs in 1940-1941.

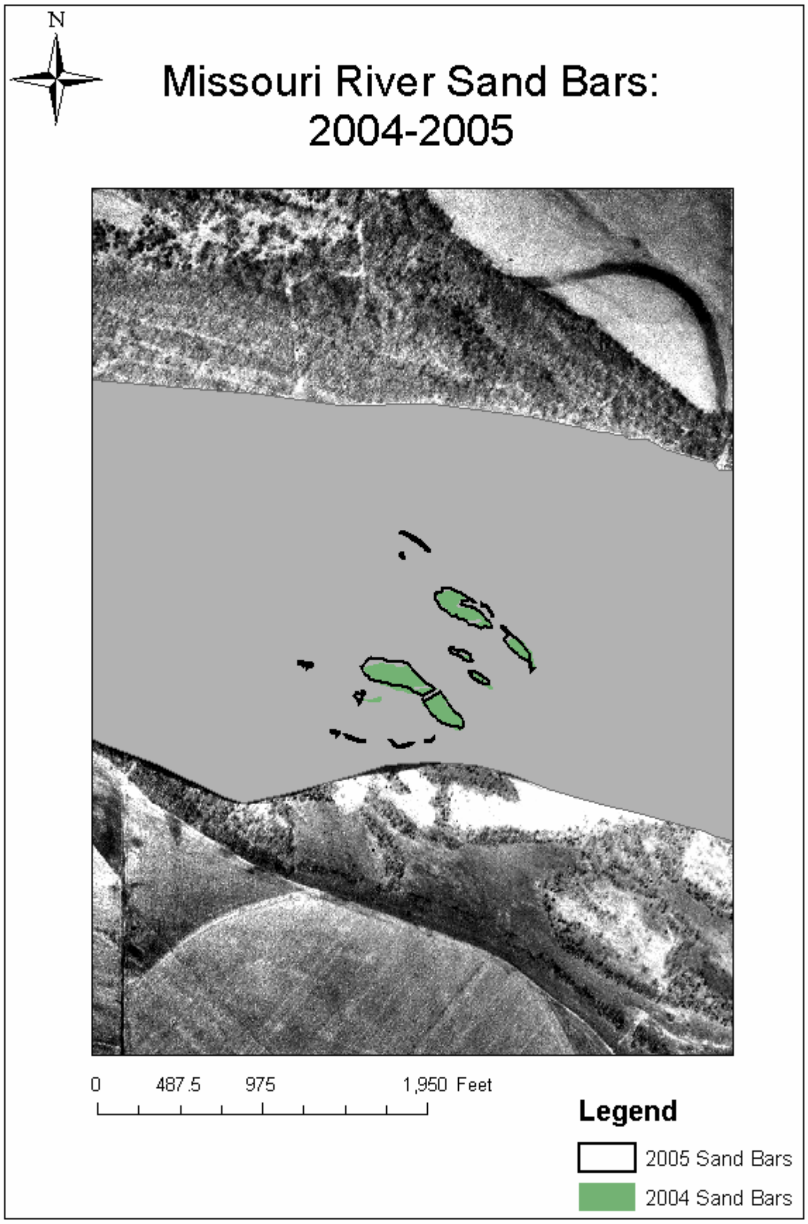

Figure 30: Map showing minor changes in bars between 2004 and 2005.

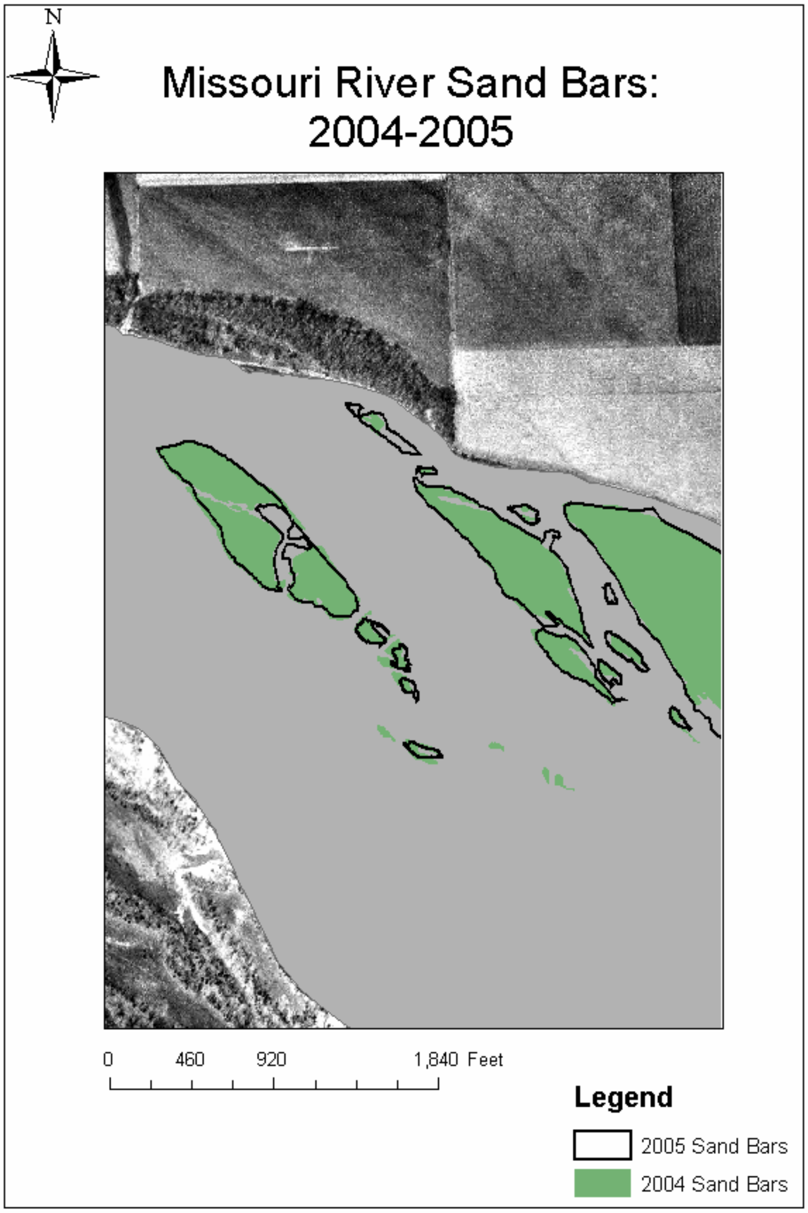

Figure 31: Map showing minor changes in bars between 2004 and 2005.

## 5.3. Area and Perimeter:

The second hypothesis predicted that regulated flow has reduced the annual change in the aerial extent and perimeter of sand bars. In other words, quantitative changes in sand bar area and perimeter over a one year time frame are less today than during pre-dam conditions. Amounts of change are reported here in percentage of the number of bars lost or gained, perimeter lost or gained, and area lost or gained. Amounts of change are examined on a case by case basis using the same bars introduced earlier, with the addition of one more case that appears to be the same bar group in both the pre- and post-dam aerial photographs (Figures 11 and 12). It was not included in the centroid analysis because three bars had merged to form one bar between 1940 and 1941, complicating analysis. The evaluation of hypothesis 2 is not concerned with simply whether the bars grew larger or smaller, but with the amounts of change occurring in a typical year pre- and post-dam.

Statistics were calculated for all of the bars digitized using the method described in sections 4.2 and 4.3. Results are shown in Table 3. The total sand bar acreage changed from 472 in 1940 to 153 in 2004. These two years were the only two years used in this portion of the analysis because of the similar number of sand bars, 63 and 65 in 1940 and 2004, respectively. This similarity in the total number of bars from the two years indicates that bar size pre dam was much larger than bars post dam. The perimeter measurements correspond accordingly, with the total perimeter of 110,129 ft for all 63 bars in 1940 and the total perimeter of 70,444 for 65 bars in 2004 (Table 3). Examination of the aerial photographs (Figures 11 and 12) will support the conclusion that bars were larger pre-dam than the bars from the post-dam period.

| Year | # of Bars | Total Area (acres) | Total Perimeter (ft) | Mean Area (acres) | Mean Perimeter (ft) | Water Levels (cfs) |
|---|---|---|---|---|---|---|
| 1940 | 63 | 472.1 | 110,129 | 7.5 | 1748 | 29,000<br>5-7-1940 |
| 1941 | 44 | 468.5 | 88,387 | 10.6 | 2009 | 20,300<br>7-10-1941[1] |
| % change | | 0.8% | 20.0% | 42.0% | 15.0% | |
| 2004 | 65 | 152.6 | 70,444 | 2.3 | 1084 | 25,000 |
| 2005 | 63 | 154.9 | 67,637 | 2.5 | 1074 | 22,500 |
| % change | | 1.5% | 4.0% | 4.7% | 0.9% | |

**Table 3: Shows the perimeter and area measurements and percentages involved in the analysis of Hypothesis 2 for sand bars from 1940-1941.**

The difference in total acreage for sand bars under a natural and a regulated flow regime is substantial. Water level affected acreage very little. This is illustrated by comparing the flows in 1940 and 2004 (29,000 cfs and 25,000 cfs). With 4000 cfs less flow one would expect there to be more exposed sand in 2004. There were 319 less acres of bar in 2004. The difference is due to the changes in sediment availability between the two periods. In 1940 the river was managed under a natural flow regime with only one dam, far upstream, to stop the sediment transport. Sediment-rich waters were able to deposit sand, silt, and clay in larger amounts after the receding of spring floods. In 2004, after 48 years of dam control, the amount of sediment in the water below the dam was significantly reduced. Dams can be considered analogous to large corks in the river that prevent the movement of sediment; therefore the water released into the river below the dam is low in sediment. This causes intensive degradation to occur for significant

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[1] A small portion of the study area was covered by aerial photography from later date and higher water level.

distances below the dam. According to Williams and Wolman (1986), the study area for this project is in the reach of degradation that has developed below Gavins Point Dam. The low sediment water and resulting degradation has caused a reduction in the acreage and distribution of the sand bars currently present in this reach of the Missouri River (Figure 32).

Percent change of the bar totals for area and perimeter were also calculated. The acreage of bar changed by 3.6 acres (0.08%) from 1940 to 1941. Bar area changed by

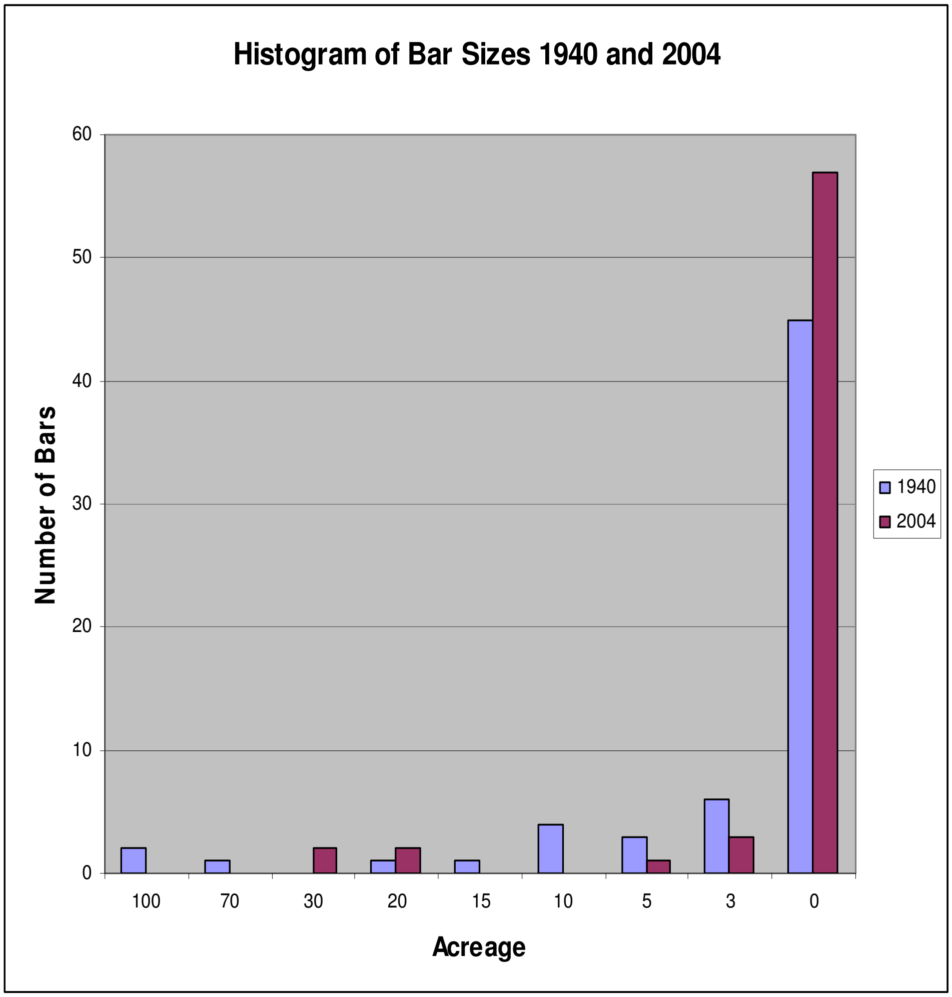

**Figure 32. Histogram showing ranges in sand bar sizes comparing the years 1940 and 2004. Acreage indicates the minimum size of the bar in that category.**

2.3 acres (1.5%) from 2004 to 2005. Bar perimeter shows a greater difference. A 20% change in bar perimeter was shown between 1940 and 1941, while only a 4% change was demonstrated between 2004 and 2005. This indicates that under natural flow regimes bars change shape considerably more than bars post-dam. The dramatic changes in shape observed during the pre-dam period demonstrates a more dynamic geomorphologic situation.

The average amounts of change are quite different between the two time periods. The annual change in bar area pre-dam was 42% and post-dam was 4.7%. The change in bar perimeter was 15%, and 0.9% respectively. These are substantial differences, especially given the possibility that there might have been considerably more than 44 bars in 1941 if images were available for consistent water level. The difference in water levels for the aerial photos used in the 1941 mosaic differs from 20,300 cfs to 44,000 cfs for the extreme northwest end of the study area. If aerial photography of the northwest quarter of the study area were available with similar water levels, the pre-dam period might display even more change, making the difference in changes between the two time periods more drastic.

Individual bar measurements for area and perimeter were evaluated qualitatively on a case by case basis using the previous six cases with the addition of a seventh (Figures 33 and 34). However, these cases were not picked at random, instead selected if a bar pair could be identified and the location of the bar fit the earlier mentioned criteria. Thus, these bar pairings can not be considered representative of the entire bar population, statistically. However, examination of the cases reveals that these bars (Figures 6 and 7) behave much as predicted statistically in Table 3. Given the number of sand bars and the rarity of bar pairs, it would be difficult to randomly pick bars that have a match from the following year.

Sand bar area and perimeter changes were more dynamic under a natural flow regime. Pre-dam sand bars showed area changes ranging from 6 to 170% (Table 3). Cases 5 and 6 (Figures 17 and 18) show minimal changes in area, while the remaining five bar pairings show changes ranging from 20 to 170%, with four of the five pairings showing change above 35% (Table 4; Figures 17 and 18). Sand bars from 2004-2005 show much less change overall than do the bars from 1940-1941. Change in area ranges from 0.018 to 131% from 2004-2005. Four of the seven cases measured show a change of less than 10%. The remaining three cases show changes of 30%, 65%, and 131% (Table 5).

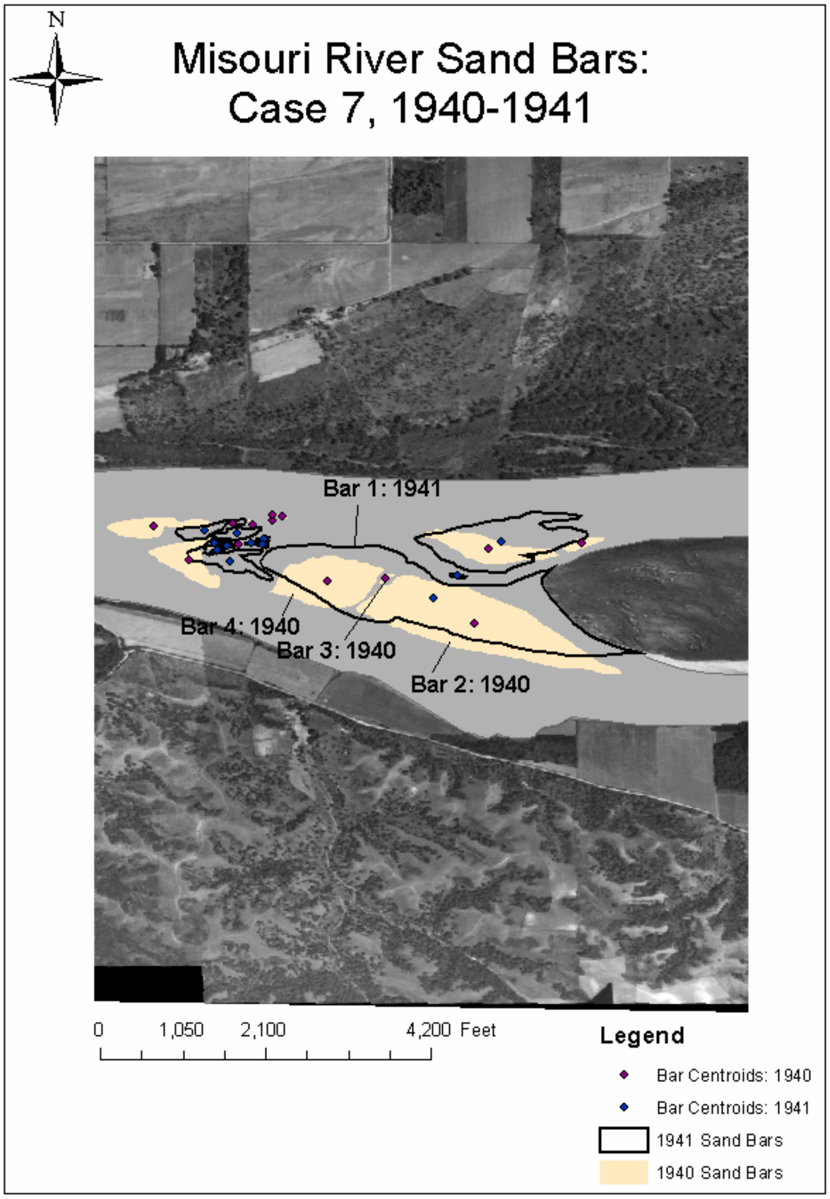

Figure 33: Map of Case 7 showing coalescence of bars from 1940-1941.

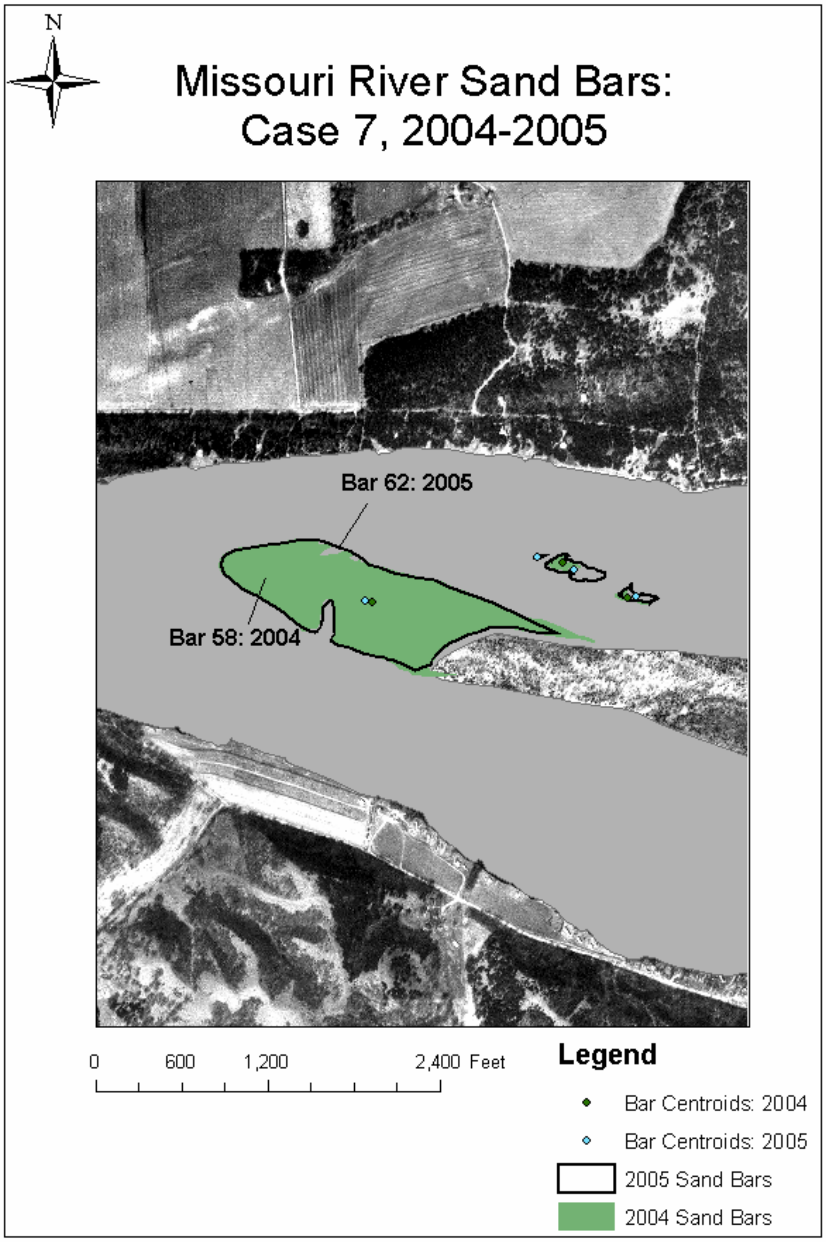

Figure 34: Map of Case 7 from 2004-2005.

| | 1940 | | 1941 | | Change | |
|---|---|---|---|---|---|---|
| | Area (acres) | Perimeter (ft) | Area (acres) | Perimeter (ft) | Area (%) | Perimeter (%) |
| Case 1 | 6.0 | 2860.7 | 16.0 | 4687.3 | 171 | 64 |
| Case 2 | 4.9 | 2375.5 | 3.1 | 2481.0 | 37 | 4.4 |
| Case 3 | 3.6 | 2281.2 | 1.5 | 1563.1 | 58 | 31 |
| Case 4 | 15.1 | 5875.6 | 9.3 | 3440.1 | 39 | 41 |
| Case 5 | 100.2 | 11019.6 | 106.9 | 12391.3 | 7 | 12 |
| Case 6 | 10.2 | 2937.4 | 9.5 | 2777.4 | 7 | 5 |
| Case 7 | 41.2 | 9098.8 | 49.7 | 8727.1 | 20 | 4 |

**Table 4: Case by case analysis for 1940-1941.**

| | 2004 | | 2005 | | Change | |
|---|---|---|---|---|---|---|
| | Area (acres) | Perimeter (ft) | Area (acres) | Perimeter (ft) | Area (%) | Perimeter (%) |
| Case 1 | 0.1 | 623.0 | 0.3 | 679.6 | 131 | 9 |
| Case 2 | 0.8 | 1136.9 | 0.3 | 609.9 | 65 | 46 |
| Case 3 | 20.4 | 6824.0 | 20.4 | 6310.8 | 0 | 8 |
| Case 4 | 6.0 | 3663.4 | 6.4 | 3337.4 | 6 | 9 |
| Case 5 | 0.3 | 832.9 | 0.2 | 509.0 | 30 | 39 |
| Case 6 | 0.3 | 548.7 | 0.3 | 689.5 | 3 | 26 |
| Case 7 | 22.9 | 7209.7 | 21.7 | 5739.8 | 5 | 20 |

**Table 5: Case by case analysis for 2004-2005.**

## 5.4. Point-Pattern Analysis:

The third hypothesis states that sand bars today are more clustered under controlled rates of flow than they were under a natural flow regime. A quadrat analysis was applied to the sand bar centroid data in order to assess the clustering of the sand bars under a natural flow regime compared to a regulated flow regime. The analysis uses only two years, one from the pre-dam (1940) and one from post-dam (2004) time periods. These years were analyzed because of the similar number in bars. The difference between the number of bars is too great for the year 1941 and would skew the results. This comparison focuses on how clustered the sand bars were under a natural flow regime vs. regulated rates of flow (i.e. not a comparison of annual changes in bar clustering).

Of the array of point-pattern analyses commonly used, the technique of quadrat analysis was the most applicable to the study area in this project (Figures 35 and 36). Nearest neighbor analysis was considered, but the results could be skewed because a nearest neighbor point-pattern analysis assumes a square study area and the centroid point data for this project is not even within a rectangular area, but instead of an elongated, irregularly shaped polygon (i.e. the shape of the river area throughout the study area). The calculations of a quadrat analysis (Table 6) were based upon McGrew and Monroe (2000, pg. 180). The results from the quadrat analysis are used to calculate a $\chi^2$ test statistic to determine the amount of clustering based on the size of the $\chi^2$ value and the associated p-value (Table 7). The results were calculated by hand.

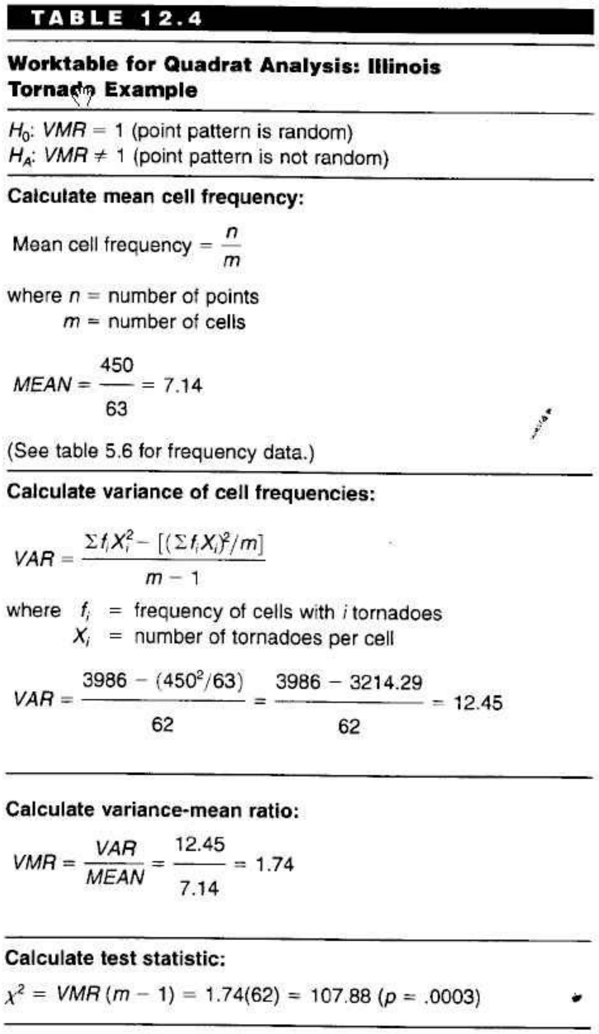

**TABLE 12.4**

**Worktable for Quadrat Analysis: Illinois Tornado Example**

$H_0$: $VMR = 1$ (point pattern is random)
$H_A$: $VMR \neq 1$ (point pattern is not random)

**Calculate mean cell frequency:**

$$\text{Mean cell frequency} = \frac{n}{m}$$

where $n$ = number of points
$m$ = number of cells

$$MEAN = \frac{450}{63} = 7.14$$

(See table 5.6 for frequency data.)

**Calculate variance of cell frequencies:**

$$VAR = \frac{\Sigma f_i X_i^2 - [(\Sigma f_i X_i)^2/m]}{m - 1}$$

where $f_i$ = frequency of cells with $i$ tornadoes
$X_i$ = number of tornadoes per cell

$$VAR = \frac{3986 - (450^2/63)}{62} = \frac{3986 - 3214.29}{62} = 12.45$$

**Calculate variance-mean ratio:**

$$VMR = \frac{VAR}{MEAN} = \frac{12.45}{7.14} = 1.74$$

**Calculate test statistic:**

$\chi^2 = VMR\,(m - 1) = 1.74(62) = 107.88$ ($p = .0003$)

**Table 6: Formulas for calculating the $\chi^2$ test statistic from McGrew and Monroe (2000, pg. 180).**

McGrew and Monroe (2000) state that the closer the p-value is to 0 the more clustered the point pattern, and the higher the chi-squared ($\chi^2$) value the more clustered the point pattern is. The results show that while the p-value for both the analyses is 0, the 2004 data displayed a higher $\chi^2$ value than the 1940 data (Table 8). Based on these numbers, one can conclude that the 2004 sand bars are more clustered than the 1940 sand bars. The mean cell frequency is simply the average number of points per cell. The variance is the unobservable variance of a whole finite population. The VMR (variance to mean ratio) is a measure of the dispersion of a probability distribution. It is a good measure of the degree of randomness. The sand bars under a regulated flow regime are slightly more clustered than the sand bars are under a natural flow regime.

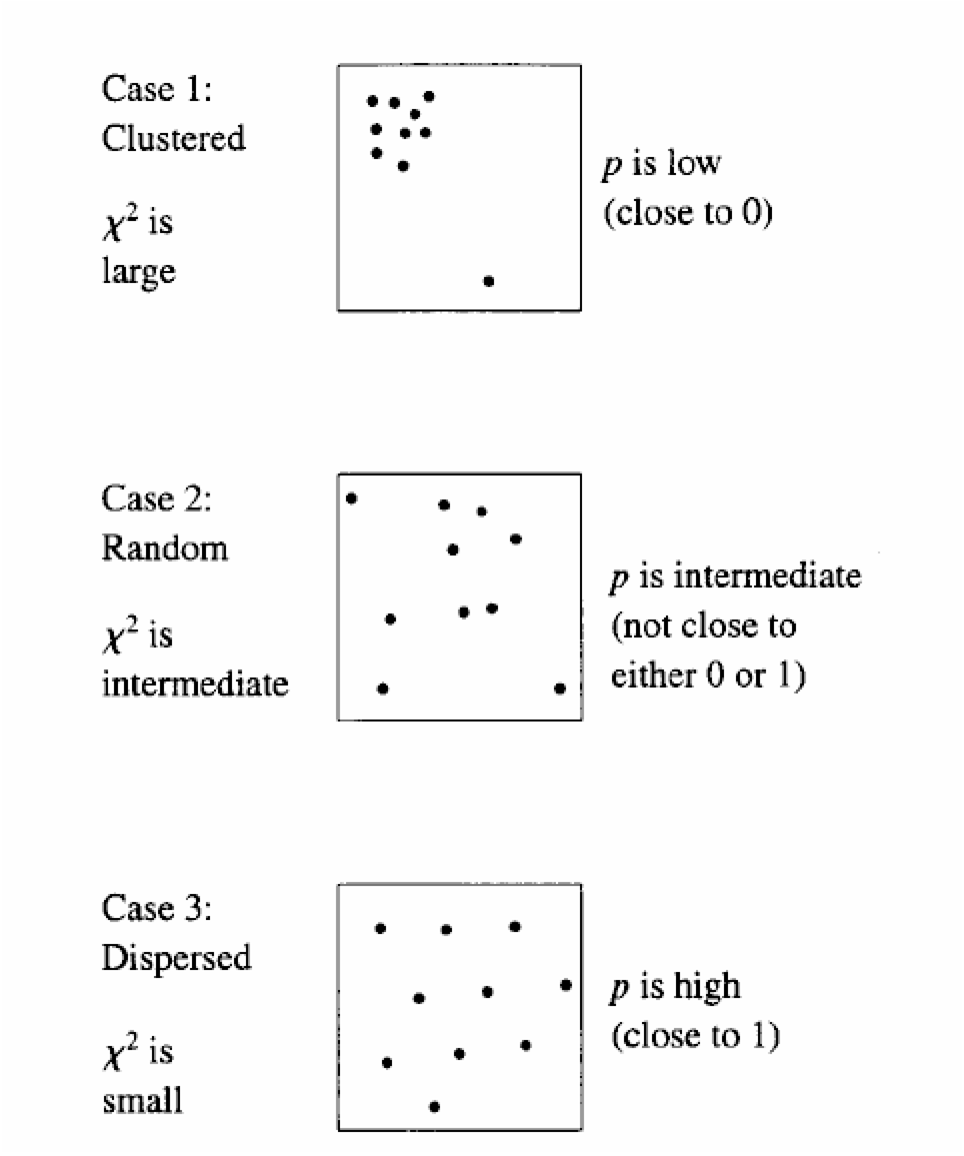

**Table 7: Examples the relationship of the $\chi^2$ value and the P-value (McGrew and Monroe, 2000, page 179).**

| Year | Bars/Quadrat | Variance | VMR | $\chi^2$ | P-value |
|---|---|---|---|---|---|
| 1940 | 7.00 | 27.25 | 3.89 | 31.12 | 0.00 |
| 2004 | 7.22 | 51.45 | 7.13 | 57.04 | 0.00 |

**Table 8: Calculations for Quadrat Analysis**

Clustering of sand bars and how it relates to sediment load and flow regulations was not found to have been reviewed by any other authors during this research. It can be hypothesized that the clustering of sand bars can be related to sediment load and flow regimes. Lack of spring floods and reduced sediment have been shown to affect sand bar migration by slowing it down and creating a more static environment, according to this study. Lack of movement in the sand bars could cause clustering by reducing natural migration under natural flow regimes. Accretion could also increase clustering by allowing new bars to form in shallow areas around previously stationary bars and islands.

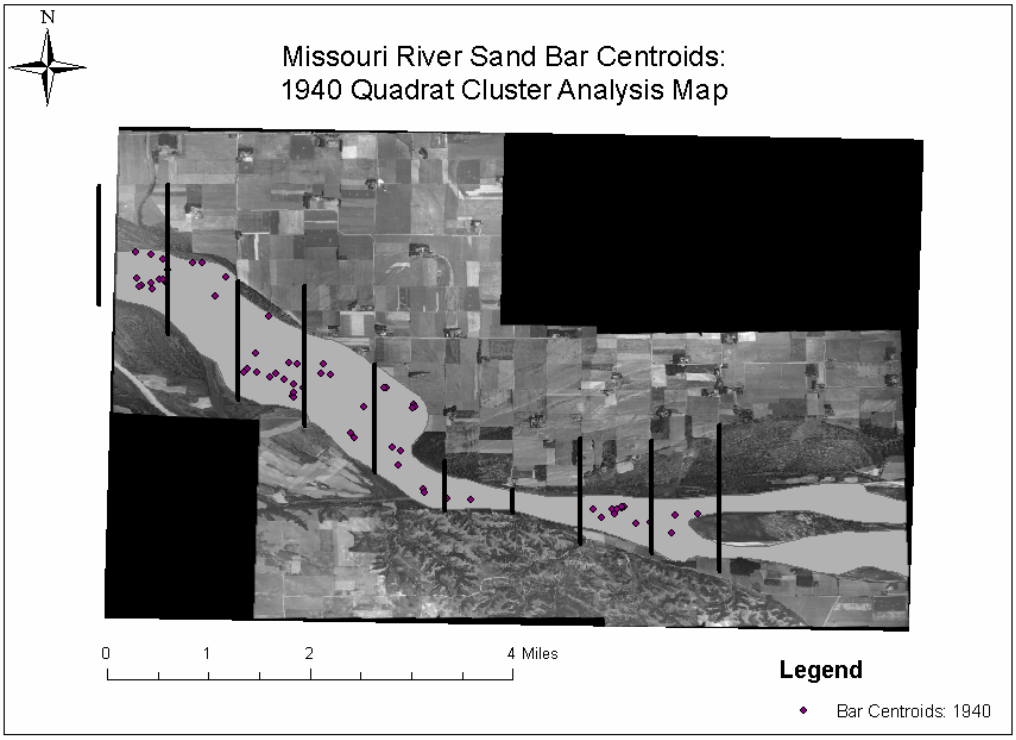

**Figure 35: Map of the Quadrats used for the Cluster Analysis 1940.**

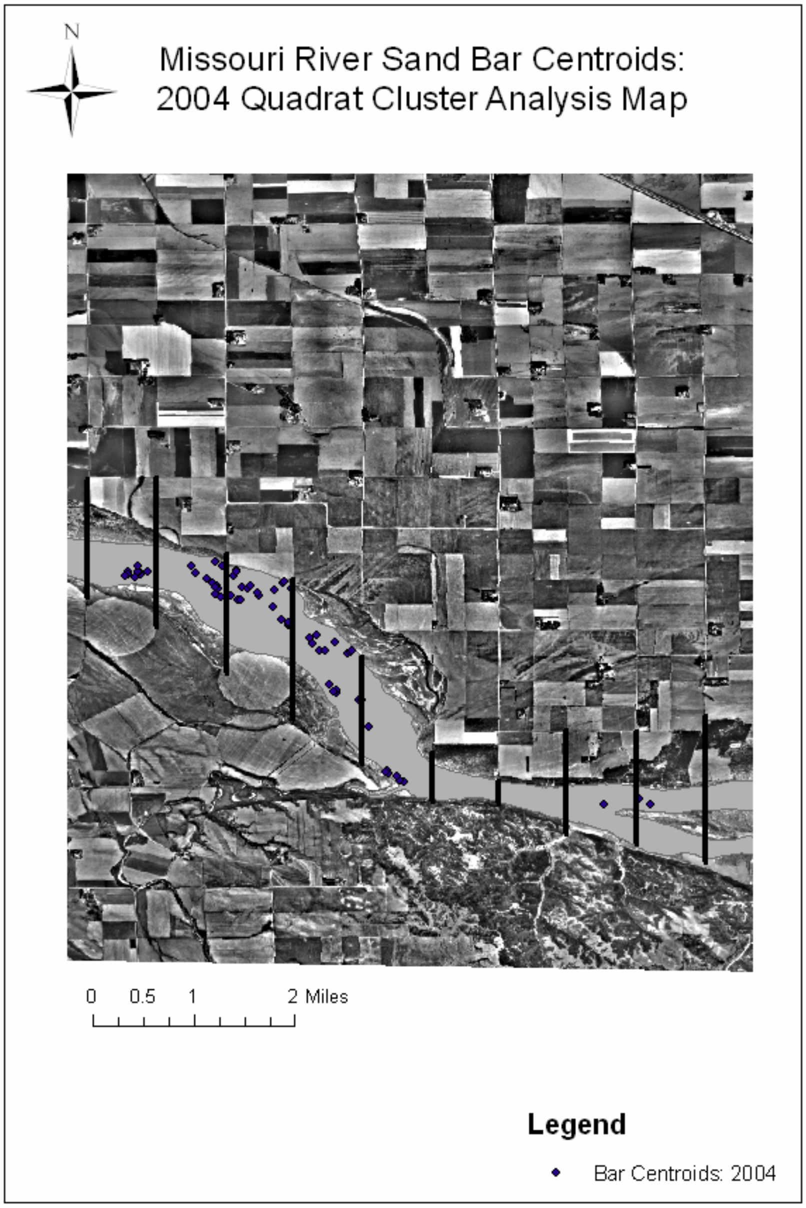

**Figure 36: Map of the Quadrats used for the Cluster Analysis 2004.**

### 5.5 Transect Analysis

Nine transects were measured using the quadrat boundaries in Figures 35 and 36 to determine the validity of Rahn’s theory of channel widening due to dam regulation. Four of the nine transects show a widening of the river bed. Five of the nine transects show a narrowing of the river bed. The transects are numbered one through nine starting downstream moving right to left (Table 9). Moving right to left in an upstream direction, the first three transects showed channel widening. Five of the next six showed channel narrowing. The three transects that show channel widening occur in a constriction in the river bed in which the water was then diverted around the large island, Goat Island. This constriction in the river was likely the cause of bank erosion and channel widening. A constriction in the river will cause excess pressure on the high banks and cause more erosion within and downstream of the constriction than in the environment associated with the other six transects. Transects 2 and 3 are in a small zone of bank stabilization conducted by the Army Corps of Engineers. As alluded to earlier, the landowners were losing ground each year and the Corps installed shoreline rock as an experiment to prevent erosion. This may have reduced the amount of channel widening. The other six transects lay in a broader and shallower section of the river. The narrowing of the river bed in this broader shallower area is due to sediment accretion on the northern bank of the river and is apparent when comparing Figures 35 and 36. Rahn’s theory (1977) is not wrong, but it may not apply to every situation encountered on this river.

| Transect | Width 1940 (ft) | Width 2004 (ft) | Difference 2004-1940 (ft) |
|---|---|---|---|
| 1 | 3245.6 | 3738.6 | 493.0 |
| 2 | 2621.4 | 3153.8 | 532.4 |
| 3 | 1591.7 | 1817.1 | 225.4 |
| 4 | 1045.5 | 1002.5 | -43.0 |
| 5 | 1716.4 | 1848.4 | 132.0 |
| 6 | 5539.4 | 4772.4 | -767.0 |
| 7 | 4181.8 | 3947.4 | -234.4 |
| 8 | 5398.9 | 3968.3 | -1430.6 |
| 9 | 3448.4 | 2203.4 | -1245.0 |

**Table 9: Transect measurements from 1940 and 2004.**

## Chapter 6: Conclusions

Dam regulation on alluvial rivers is creating new geomorphologic situations and is directly affecting the riparian environments. The difference between regulated rates of flow and natural flow regimes can be quite large, especially during periods of peak runoff. The addition of reservoirs to the system is creating additional problems such as water with low sediment loads, which has more powerful erosive properties than sediment-rich water. This study has evaluated regulated and natural flow regimes to determine how these affect sand bar migration. Movement, size, and clustering were examined.

The centroid movement of the sand bars evaluated between 1940-1941 and 2004-2005 showed considerable differences (Figures 11-24). Sand bars under natural flow regimes (1940-1941) demonstrated a more dynamic environment than bars from a regulated flow regime (2004-2005). Only one bar from 1940-1941 demonstrated a centroidal movement of less than 100 ft (Case 6). The largest amounts, Cases 2, 3, and 5 moved 377, 475, and 365 feet respectively. No cases of bar pairings from 2004-2005 moved over 100 ft. The maximum movement was Case 2 with 96 feet. Two of the six bars from the contemporary data moved less than 10 feet.

The pre-dam sand bars (1940-1941) displayed movements parallel with the downstream current (Table 2). Bars from the recent time period were not as consistent. Cases 4 and 5 (2004-2005) demonstrated a lateral shift in migration perpendicular to flow direction. Case 6 (2004-2005) shows movement parallel to current, but upriver presumably due to accretion of sediment.

Qualitative analysis of bar movements was assessed through the use of maps (Figures 25-31). Bars of all sizes displayed significantly more movement in 1940-1941 than in 2004-2005. Large bars in 2004-2005 showed very little movement, while even the largest of bars in 1940-1941 showed significant movements. Movements in these bars were dramatic, breaking up and coalescing to such an extent that it was rare to be able to identify a mate in the following year. There were several instances where bars in some locations in 1940 were completely gone in 1941 (Figure 27). The opposite of this was also true, where open water in 1940 held a group of bars in 1941. This was not as prevalent in 2004-2005. Virtually every major bar from the recent time period had a mate the following year. The exceptions to this rule were very small bars in shallow areas (Figure 26).

Comparison of the average bar area and perimeter showed striking differences between natural and regulated flow regimes (Tables 4 and 5). Perimeter increased by 15% and area increased by 42% between 1940 and 1941, while between 2004-2005 perimeter decreased by 1% and area increased by 5%. Thus more change occurred under a natural flow regime than under regulated rates of flow. This demonstrates a more dynamic situation in the historical time period than in the recent time period, indicating more change under a natural flow regime than under regulated rates of flow.

One would predict that with the damming of the Missouri and the entrapment of the sediment in the reservoirs, smaller bars would be present today than in the past due to erosion, lack of sediment, and lack of deposition. When comparing pre- and post-dam periods, the area and perimeter decreased (Tables 4 and 5). In 1940 bar acreage was 472 while in 2004 it was 153. Perimeter totals decreased from 110,129 to 70,444 respectively.  Bars sizes have changed dramatically between the two time periods and the two types of flow regimes.  Larger size bars were present under a natural flow regime than under a regulated flow regime.  This is presumably due to a lack of sediment in the water released from Gavins Point Dam.

A quadrat analysis was applied to show how regulated rates of flow are affecting the clustering of sand bars (Table 8).  The $\chi^2$ values were 31 and 51 for 1940 and 2004 respectively, demonstrating that the sand bars in 2004 under regulated rates of flow are slightly more clustered than the bars from 1940 under a natural flow regime.

River regulation today is affecting the riparian habitats of this alluvial river.  New habitat is not being formed due to regulated rates of flow and the now static situation concerning sand bars in the Missouri.  In the case of the Least Tern and Piping Plover, two endangered species that thrive here and use these sand bars for their nesting ground, this study may provide some crucial insight as to how the water levels should be managed in order to maintain the amount of bars and islands necessary to ensure these populations survive.

While cutting down on erosion and loses of valuable farm land, these regulated rates of flow are cutting down on the diversity of the riparian environment by halting the formation of new islands and sand bars.  The controlled rates of flow in 2004 as compared to natural flows in 1940 have not changed the type of river system.  It remains a combination of a braided and meandering system.  The new flow regimes have only affected the amount of sediment and the rate at which it is transported.  Recreation on the Missouri, however, has been greatly increased by the addition of reservoirs to provide more boating opportunities and a stabilized channel system that allows for easier navigation on actual river reaches such as this study area.

The 55-mile reach from Gavins Point Dam in Yankton, S.D. to Ponca, NE is one of three remaining stretches of Missouri River left in a condition close to “natural”. The remainder of the river is either drowned as reservoirs or is dredged and channelized for shipping purposes. The regulation of this river and these few “natural” stretches is critical for many communities. The downstream effect of regulation on this river is displayed throughout this project. Stagnation of sand bars, reduced area and perimeter, and a slight increase in the clustering of bars was found. These are believed to be a direct result of regulated flows maintained on the Missouri River since the 1940’s.

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