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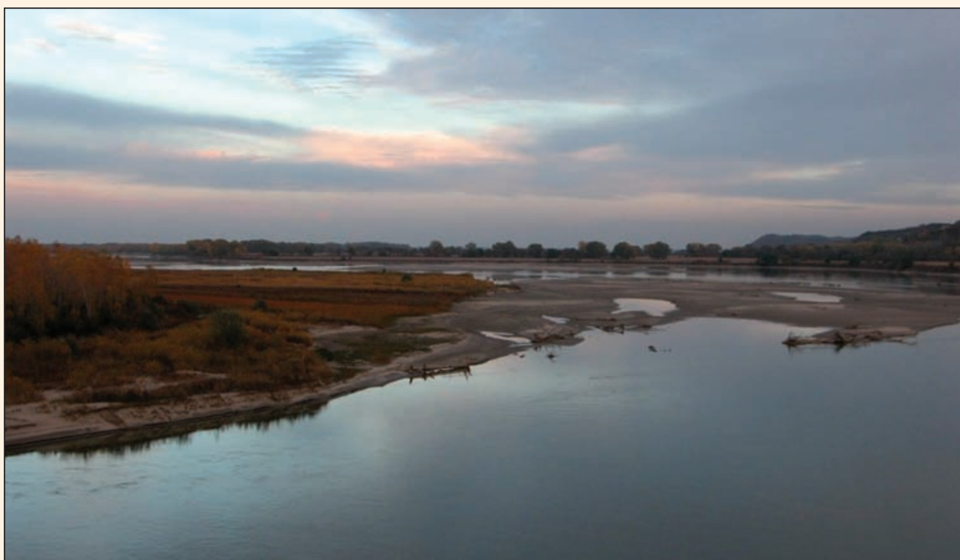
Geomorphic Classification and Assessment of Channel Dynamics in the Missouri National Recreational River, South Dakota and Nebraska



Scientific Investigations Report 2006–5313

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of the Missouri National Recreational River 59-mile segment, which extends from Gavins Point Dam, Nebraska and South Dakota, to Ponca State Park, Nebraska. Photograph taken by Caroline M. Elliott, U.S. Geological Survey, 2006.

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
metric ton per year	1.102	ton per year (ton/yr)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Geomorphic Classification and Assessment of Channel Dynamics in the Missouri National Recreational River, South Dakota and Nebraska

By Caroline M. Elliott and Robert B. Jacobson

Abstract

A multiscale geomorphic classification was established for three segments of the Missouri River on the border of South Dakota and Nebraska: the 39-mile and 59-mile segments of the Missouri National Recreational River administered by the National Park Service, and an adjacent segment, Kensler's Bend. The objective of the classification was to define naturally occurring clusters of geomorphic characteristics that would be indicative of discrete sets of geomorphic processes (process domains), with the intent that such a classification would be useful in river-management and rehabilitation decisions. The statistical classification was based on geomorphic characteristics of the river collected from 1999 digital aerial orthophotography. Persistence of classified units was evaluated by comparison with similar datasets for 2003 and 2004. Changes in channel location and form were also explored using imagery and maps from 1993 to 2004, 1941, and 1894. The multivariate classification identified a hierarchy of naturally occurring clusters of reach-scale geomorphic characteristics. The simplest level of the hierarchy divides the river from segments into discrete reaches characterized by single and multithread channels. Additional hierarchical levels established 4-part and 10-part classifications. The utility of the classifications was established by exploring persistence of classified units over time and by evaluating variation of bank erosion rates by geomorphic class. The classification system presents a physical framework that can be applied to prioritization and design of bank-stabilization projects, design of habitat-rehabilitation projects, and stratification of monitoring and assessment sampling programs.

Introduction

The 39-mile and 59-mile segments of the Missouri National Recreational River (MNRR) on the South Dakota and Nebraska state border retain much of the natural channel morphology that characterized the preengineered Missouri River (fig. 1). Whereas designation of these segments as a national recreational river in 1978 and 1991 charged the National Park Service (NPS) with preserving its free flowing condition, the river is also subject to management by other agencies and private landowners. Although flow regimes in these segments have been substantially altered, they are minimally affected by channelization and only the downstream-most part of the 39-mile segment is affected by reservoir inundation. As a result, the river in the MNRR has numerous sand bars, variably vegetated islands, and laterally eroding banks characteristic of the historical, braided-anastomosed river.

Land adjacent to the MNRR includes a patchwork of public and private land in Nebraska and South Dakota. Many entities are engaged in actions intended to stabilize banks, maintain habitats for threatened and endangered species, and improve recreational opportunities. In the past few decades, an estimated 12.5 percent of the banks along the 39-mile segment and 32 percent of the banks along the 59-mile segment have been stabilized by rock revetment, mostly to protect private land (Biedenharn and others, 2001; Wilson, 2005). During this same time, ecologists and engineers have developed an understanding that some channel migration (and related bank erosion) is a necessary process in river-corridor ecosystems because of its role in creating and rejuvenating aquatic and flood-plain habitats (Busch and Scott, 1995; Trush and others, 2000; Fischenich, 2003). Opposing views of the costs and benefits of channel migration present potential management conflicts in settings like the MNRR.

This report is based on the premise that improved understanding of spatial variability of river processes can contribute useful information to those who make decisions about the river and its resources (Kondolf and others, 2003). Specifically, a classification that delineates relatively discrete reaches with common suites of geomorphic processes and rates (process domains, in the sense of Montgomery, [1999]) should provide managers with information to vary management actions according to the inherent characteristics of river reaches. In the case of bank-stabilization decisions, a classification system may delineate reaches in which channel migration rates are inherently low or high. Such information can be used to determine where channel migration can be tolerated and where channel migration presents unacceptable conflicts with other uses of the river corridor.

In this report, sections of the river are described as either a “segment” or “reach.” Segment is used to describe lengths of river characterized by similar hydrology and valley-scale geology. Segments are delineated by significant tributary junctions, dams, or geologic contacts; the term is used specifically in this report to denote the broad classes of the MNRR. To the NPS, the concept of segment is also synonymous with “district,” a management construction-unit.

Segments contain multiple reaches, which are defined as lengths of river characterized by one or more repetitions of channel unit or channel-crossover sequences (after Frissell and others, 1986). The term reach is used less precisely than segment and denotes contiguous sections of channel with varying length, but encompassing at least one channel-crossover unit and occurring within a segment.

River miles are the universally used address system on the Missouri River, and are retained here as the basic descriptor of location. The river miles used are the U.S. Army Corps of Engineers 1960 river miles (U.S. Army Corps of Engineers, unpub. data, 2000).

Purpose and Scope

The objective of this project was to develop a reach-scale geomorphic classification of the MNRR that delineates process domains amenable to different management strategies. The main tool to accomplish this objective was a continuous, longitudinal classification using data collected from 1999 digital orthophotography for the Missouri River between river miles 880 and 729. The classification was validated by documenting temporal variations from aerial orthophotography taken between 1993 and 2004.

The analysis focuses on segments of the Missouri River that are included in the MNRR: the 39-mile (Fort Randall) segment and 59-mile (Gavins Point) segment. For comparison, we have also included some analysis of the extensively stabilized Kensler’s Bend segment (fig. 1).

Physical and Historical Setting of the Lower Missouri River

The Missouri River is the longest river in the United States and drains one sixth of the area of the continental United States from its headwaters in Montana and Wyoming to its confluence with the Mississippi River near St. Louis, Missouri (fig. 1*A*). Development of the Missouri River in the 19th and 20th century for socioeconomic benefits, including flood control, navigation, irrigation, hydropower, water supply, and recreation, has been associated with substantive changes in its hydrologic and sediment regimes, water quality, and channel morphology (Galat and others, 2005). The relative severity of these changes varies along the river. The segments of the Missouri River addressed in this report have been substantially affected by altered flow and sediment regimes, but minimally affected by channel engineering. This situation contrasts with the Missouri River downstream of Sioux City, Iowa. In the downstream 1,173 km of the river, natural variability of the flow and sediment regimes tends to recover as additional flow is added from tributaries (Galat and Lipkin, 2000). This part of the river, however, has also been extensively engineered for navigation and bank stability (Ferrell, 1996).

Alteration of Flow and Sediment Regimes

The Missouri River’s flow is controlled in large part by six mainstem reservoirs built from 1937 to 1963 by the U.S. Army Corps of Engineers (USACE) for flood control and navigation. The 39-mile segment of the MNRR is located downstream of Fort Randall Dam, which was completed in 1954. The river then flows into the headwaters of Lewis and Clark Lake, an impoundment created by Gavins Point Dam. The 59-mile segment is downstream of Gavins Point Dam, which was closed in 1957.

The Missouri River Reservoir System (MRRS) is managed as a unit by the USACE, and specific dams and reservoirs are managed differently to achieve system performance (U. S. Army Corps of Engineers, 2006a). Within this system, Fort Randall Dam is operated primarily to evacuate water from Lake Francis Case in the fall to provide volume for winter power-generation flows from upstream and to provide daily hydropeaking flows during the summer months. Gavins Point Dam is operated mainly as a reregulation facility to dampen fluctuations from upstream operations, to achieve downstream flow targets for authorized purposes, and to comply with provisions of the Endangered Species Act.

The result of flow regulation of the MRRS has been to eliminate peak spring–summer flows and increase late summer–fall flows (fig. 2; see also Galat and Lipkin, 2000; Jacobson and Heuser, 2001; Pegg and others, 2003). The decrease of annual peak flows has been attributed to the diminishing of frequency and magnitude of sediment transporting and geomorphically effective events in the MNRR (National Research Council, 2002). The increase in late summer flows has been implicated in loss of shallow, slow-velocity rearing habitat for native fishes (National Research Council, 2002; U.S. Fish and Wildlife Service, 2003).

Although peak flows have been substantially diminished downstream of MRRS dams, the nearly complete loss of sediment load in the reservoirs resulted in channel degradation (bed lowering). As much as 1.5 meters (m) of mean cross-sectional degradation occurred in the tailwater of Fort Randall Dam and as much as 3.4 m of degradation occurred in the tailwater downstream of Gavins Point Dam (U.S. Army Corps of Engineers, 2004b). Sediment load increases downstream as sediment is added from tributaries and bank erosion. From essentially zero annual sediment load at Gavins Point, the river increases to approximately 68 million metric tons per year sediment load at Hermann, Missouri (Horowitz, 2003).

Channel Engineering

Clearing, snagging (removal of large woody debris), and stabilizing the Missouri River channel began in the early 1800s to improve conditions for steamboat navigation (Chittenden, 1903). The pace of channel engineering increased with authorizations made by Congress in the late 1800s and early 1900s (Ferrell, 1996). Most of the rock dikes and revetments apparent in the modern channel, however, are the direct result of the 1945 Missouri River Bank Stabilization and Navigation Project (Ferrell, 1996). Wing dikes and revetments have stabilized the river banks, and they have narrowed and focused the thalweg to maintain a self-dredging navigation channel from Sioux City, Iowa to St. Louis, Missouri. The result has been the creation of a narrow, swift, and deep channel from what was historically a shallow, shifting, and braided river.

Riverine habitat loss on the lower Missouri River has been estimated to be as much as 400 square kilometers (km^2) (Funk and Robinson, 1974), and substantial declines in ecosystem integrity have been associated with this habitat loss (Hesse and Sheets, 1993; Galat and others, 2005). Recognition of the scope of habitat loss has increased interest in rehabilitating parts of the Missouri River (Latka and others, 1993).

Physical and Historical Setting of the Missouri National Recreational River

The MNRR is administered by the NPS and consists of two segments of the Missouri River, a segment of the Niobrara River, and a segment of Vertigre Creek. This report addresses the two Missouri River segments of the MNRR. Both MNRR segments were established as a national recreational river under the authorities of the Wild and Scenic Rivers Act (Wild and Scenic Rivers Act, 1968). The 59-mile (Gavins Point) segment was designated in 1978 and the 39-mile (Fort Randall) segment in 1991 by amendments to the Wild and Scenic Rivers Act. Both segments were assigned to the NPS for

A

B

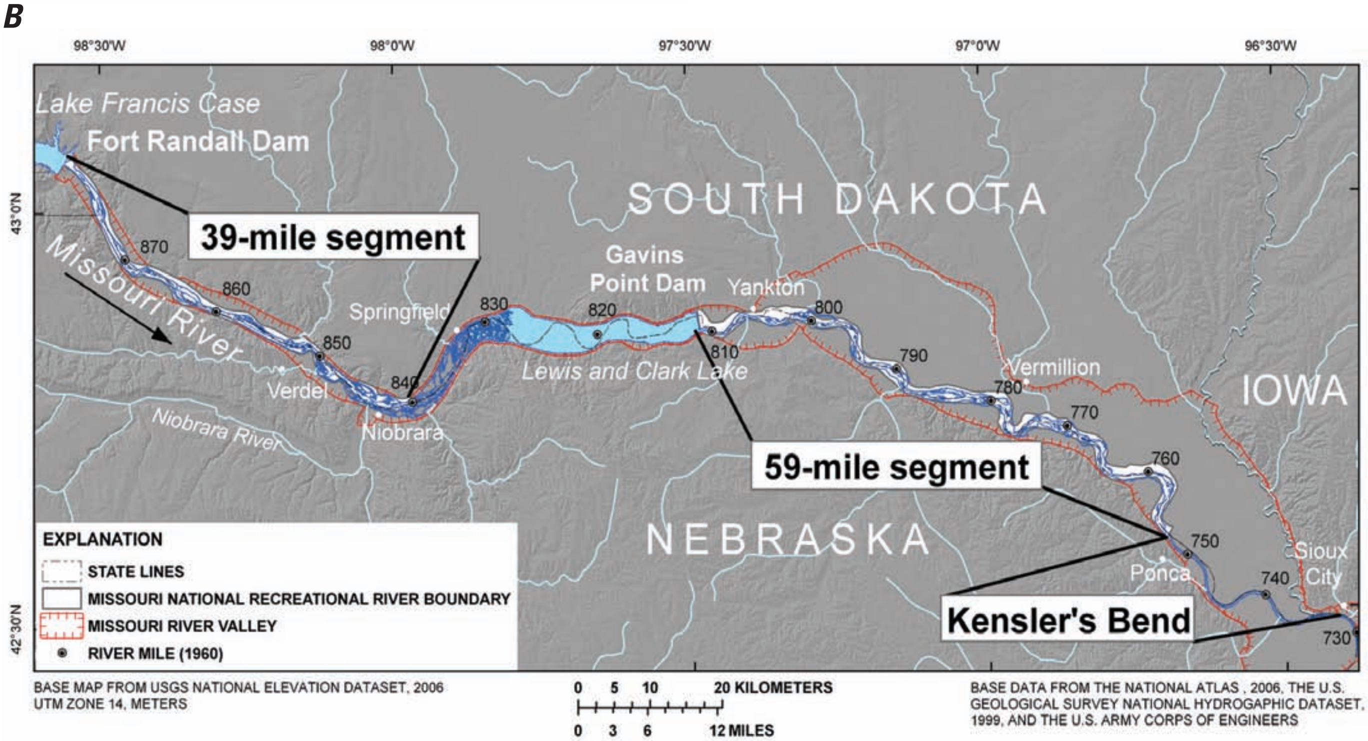


Figure 1. Location of the Missouri River segments analyzed for the geomorphic classification. *A,* The project area is located within the Missouri River Basin on the border of South Dakota and Nebraska. *B,* The three Missouri River segments studied in the project are the 39-mile and 59-mile of the Missouri National Recreational River and Kensler's Bend.

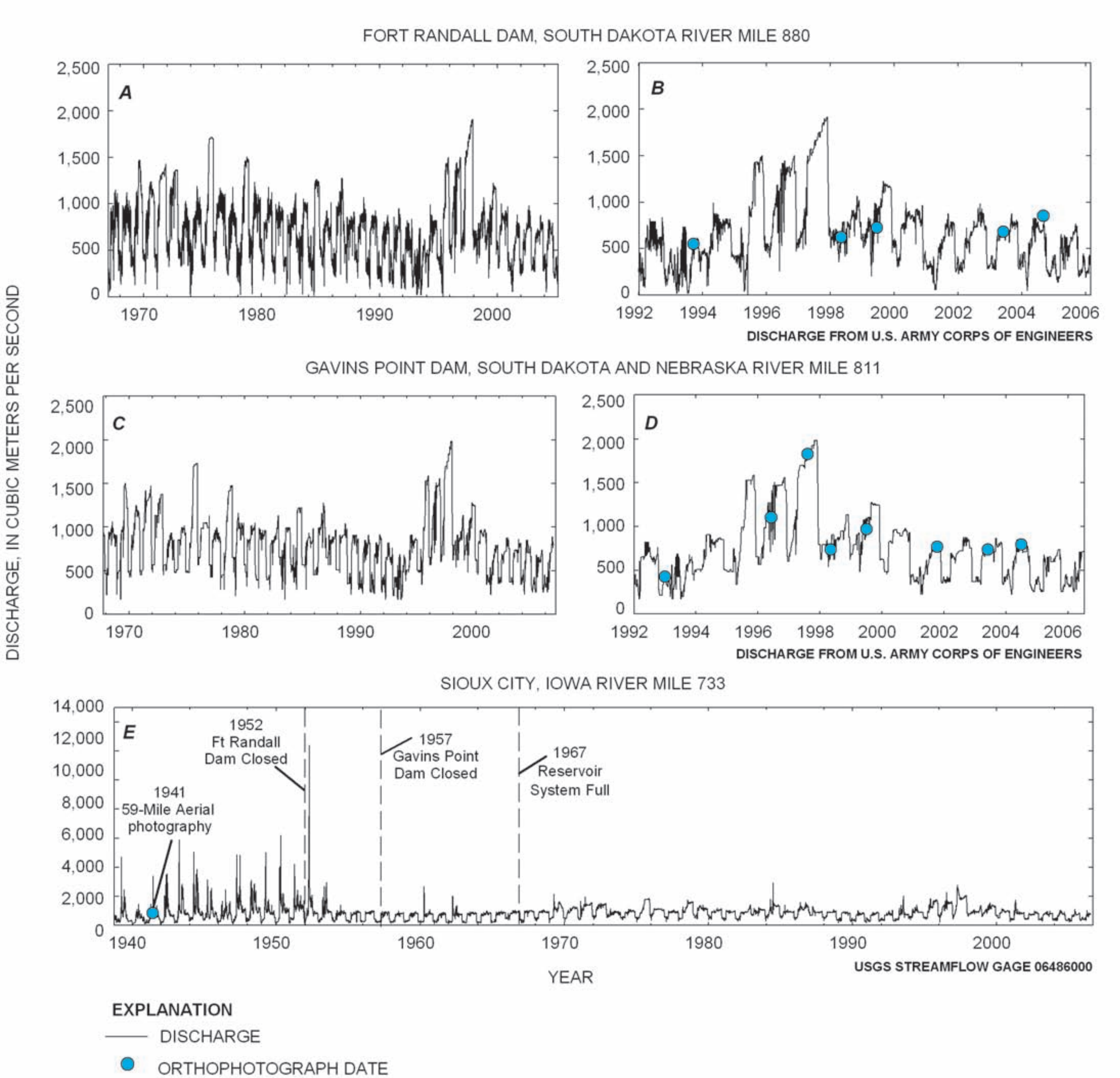


Figure 2. Missouri River discharge records for the three segments with orthophotography dates indicated. *A–B,* Fort Randall Dam, South Dakota. *C–D,* Gavins Point Dam, South Dakota and Nebraska. *E,* USGS gage at Sioux City, Iowa.

management, and are also managed under the authorities of the NPS's Organic Act (The National Park Service Organic Act, 1916). The two segments have highly altered hydrology but relatively natural channel morphology. They are subject to a wide range of potentially competing management objectives, including power generation, flood control, bank stabilization, endangered species management, and recreation. Understanding the distribution of geomorphic processes within the MNRR may provide a basis for reconciling some of the competing objectives.

Geologic and Hydrologic Setting

On the South Dakota and Nebraska border, the river flows through a valley cut in Cretaceous rocks consisting of interbedded shale, sandstone, and limestone (Nebraska Conservation and Survey Division, 1996; Martin and others, 2004; Johnson and McCormick, 2005). The valley is relatively narrow until near river mile 800, just 11 kilometers (km) downstream of Gavins Point Dam where the valley widens considerably (fig. 1*B*, 3). Pleistocene glacial deposits occur on the northern boundary of the Missouri River Valley in this area. The valley morphology indicates that the Missouri River channel has migrated extensively across the valley, as have channels of the James and Vermillion Rivers, and other tributaries that join the Missouri River from the north (Cowman, 2005; Lundstrom and others, 2006).

In summer months, Fort Randall Dam is managed by semipeaking, or releasing extra water at times of the day when electrical demand is high. It is therefore not unusual for large variations in discharge to occur daily (U.S. Army Corps of Engineers, 2006a). Lake Francis Case is generally evacuated in the fall to provide storage for water used for winter power generation upstream. The mean daily flow for the period of record available for Fort Randall Dam (1967–2005) is 762 cubic meters per second (m^3/s; fig. 2*A*). The high flows of record relevant to the time frame of this study occurred in 1997, with a maximum flow of 1,911 m^3/s. During that year, flows were sustained above 1,700 m^3/s for 115 days (fig. 2*B*).

Gavins Point Dam was closed in 1957 and is regulated to dampen upstream peaking flows, provide flood control, and provide downstream navigation flows (U.S. Army Corps of Engineers, 2006a). Regulation therefore diminishes spring peaks, provides for relatively high and constant flows during navigation season, and, in wetter years, includes high flows in the fall to evacuate Lewis and Clark Lake (U.S. Army Corps of Engineers, 2006a). The mean daily flow for 1967–2005 was 791 m^3/s. The 1997 high-flow event from Gavins Point Dam peaked at 1,985 m^3/s (fig. 2*C,D*). Flows in 1997 exceeded 1,700 m^3/s for 206 days.

Discharge records for the Sioux City, Iowa, stream gage (USGS streamflow gage 06486000; river mile 732, 125.5 km downstream from Gavins Point Dam) began in 1929 and provide a long-term view of hydrologic variation (fig. 2*E*). Mean annual flow at the Sioux City gage is 833 m^3/s for 1967–2006 (fig. 2*E*). By comparison, the preregulation mean annual flow was 846 m^3/s, and peaks greater than 2,800 m^3/s occurred in 15 years between 1929 and 1955. The peak of record was 12,488 m^3/s in 1952. The 1997 high-flow event peaked at 2,758 m^3/s at Sioux City (fig. 2*E*).

In recent years the USACE has additionally managed Gavins Point Dam for the benefit of two endangered and one threatened species: the pallid sturgeon (*Scaphirhynchus albus*), interior least tern (*Sternula antillarum*), and piping plover (*Charadrius melodus*). Flow releases from April to June follow patterns intended to maximize emergent sand-bar habitat available to the bird species while minimizing flooding of nests on emergent sand bars. These strategies include steady flows at stages that are high enough to maintain midsummer navigation and/or cycling flows that serve to push bird nests to higher elevations on sand bars.

The USACE does not rely on managed flows to create sand-bar habitat in the MNRR, arguing that discharges needed to transport sand and to scour encroaching vegetation are at odds with other project purposes and outside limits of authorizations (U.S. Army Corps of Engineers, 2003). Flows in 1997 were an example of geomorphically effective discharge that created abundant emergent sand-bar habitat (Vander Lee, 2004); however, these flows were in excess of power plant

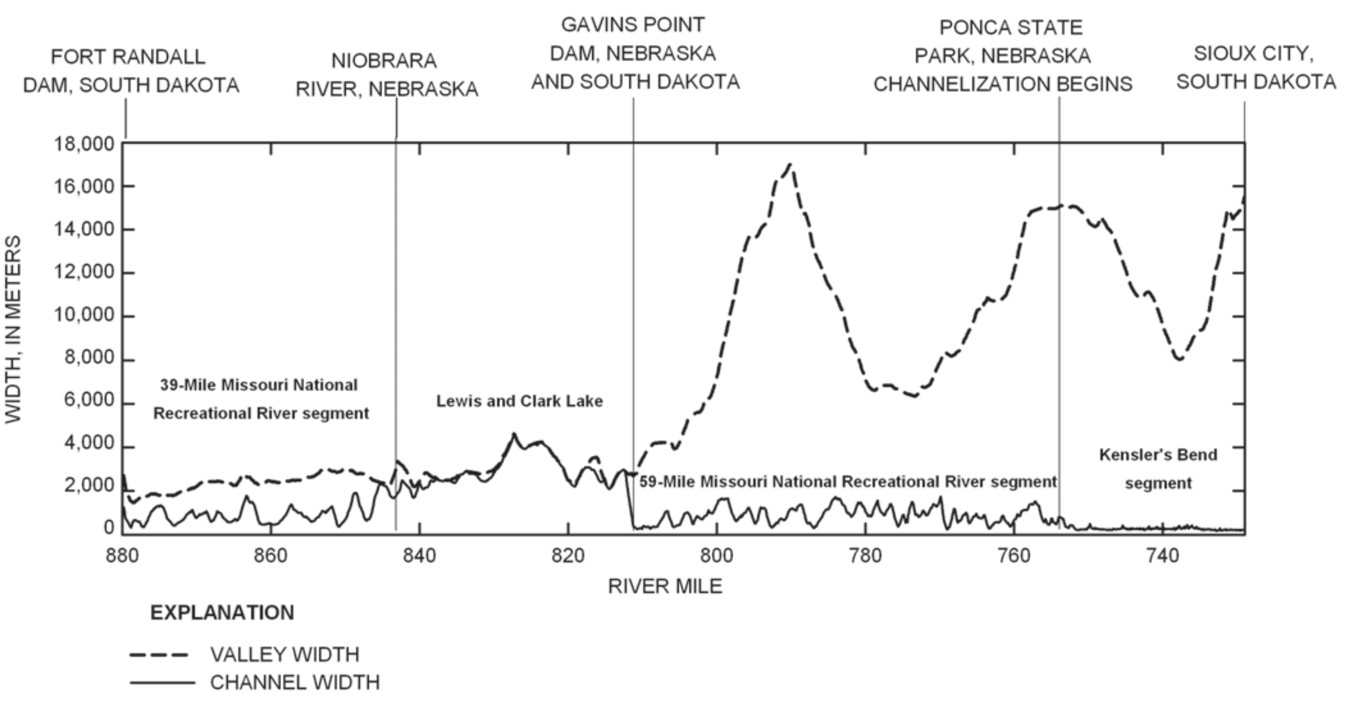


Figure 3. Missouri River regional longitudinal river characteristics from Fort Randall Dam, South Dakota to Sioux City, Iowa, river miles 879.8–728.3.

capacity (about 990 m^3/s) for more than 250 days, and the runoff challenged the flood-control capacity of the system (U.S. Army Corps of Engineers, 2006a).

In spring 2006, a "spring pulse" was implemented from Gavins Point Dam. The spring pulse was designed to mimic the natural, double-peaked spring hydrograph but with somewhat different timing of peaks and substantially smaller magnitude compared to the natural hydrograph (U.S. Army Corps of Engineers, 2006b; fig. 4). The dominant design objective for the spring rise was to provide an environmental spawning cue for the pallid sturgeon (U.S. Fish and Wildlife Service, 2003). The design flow pulses were substantially smaller than those known to be geomorphically effective (fig. 4).

Channel Engineering and Conditions in the Missouri National Recreational River

The USACE has monitored channel changes in the 39-mile and 59-mile Missouri River segments since the dams were closed, including cross-section monitoring, referred to as "sedimentation" and "degradation" ranges, as well as sediment sampling and aerial photography analysis to assess bank erosion. Bed degradation has been well documented in the Missouri River downstream of both Fort Randall and Gavins Point Dams (U.S. Army Corps of Engineers, 2004b).

39-mile Segment

The 39-mile segment of the MNRR (fig. 5) extends from Fort Randall Dam (river mile 880) to Lewis and Clark Lake (river mile 840) and comprises degrading, transitional, and aggrading reaches (Dangberg and others, 1988). Directly downstream of the dam, the tailwater region has experienced 1.8 m of bed degradation since 1953, and bed material has coarsened in the first 16 km below the dam (U.S. Army Corps of Engineers, 2004b). Bed aggradation has occurred in the reach beginning near river mile 849, 48.6 km downstream from Fort Randall Dam. This reach is affected by backwater from Lewis and Clark Lake as well as hydrologic and sedimentation effects of the Niobrara River. The Niobrara River is a sand-bedded tributary with a large sediment load that enters the Missouri River 58 km downstream of Fort Randall Dam and just upstream from the headwaters of Lewis and Clark Lake. The USACE estimates that the Niobrara River contributes 60 percent of the sediment inflow into Lewis and Clark Lake (U.S. Army Corps of Engineers, 1994). A delta has developed in the upstream third of the lake as a result of the river's reduced capacity to carry sediment. Stages in tributaries and the ground-water table have also risen as a result of aggradation (U.S. Army Corps of Engineers, 1994). The annual estimated transport of sediment to the lake is 2.5 million cubic meters, which would result in complete filling of the lake by

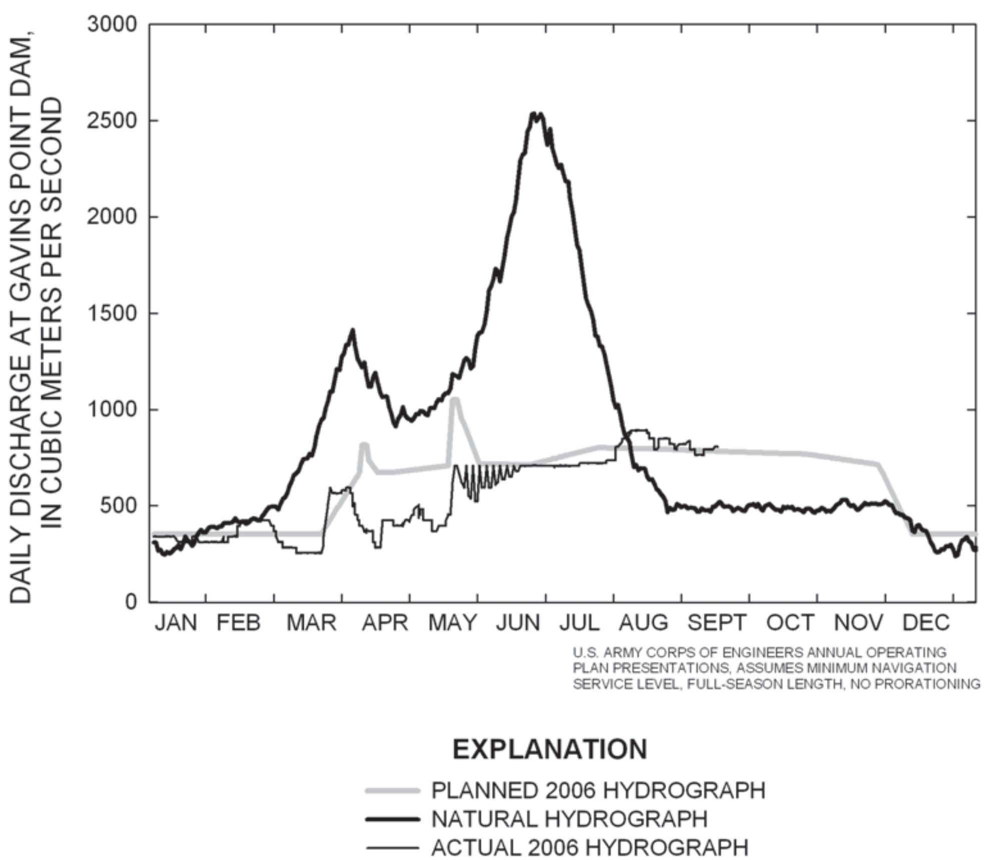


Figure 4. The preimpoundment average annual discharge of the Missouri River at Gavins Point Dam, South Dakota and Nebraska, compared to the 2006 actual discharge and planned flow modification.

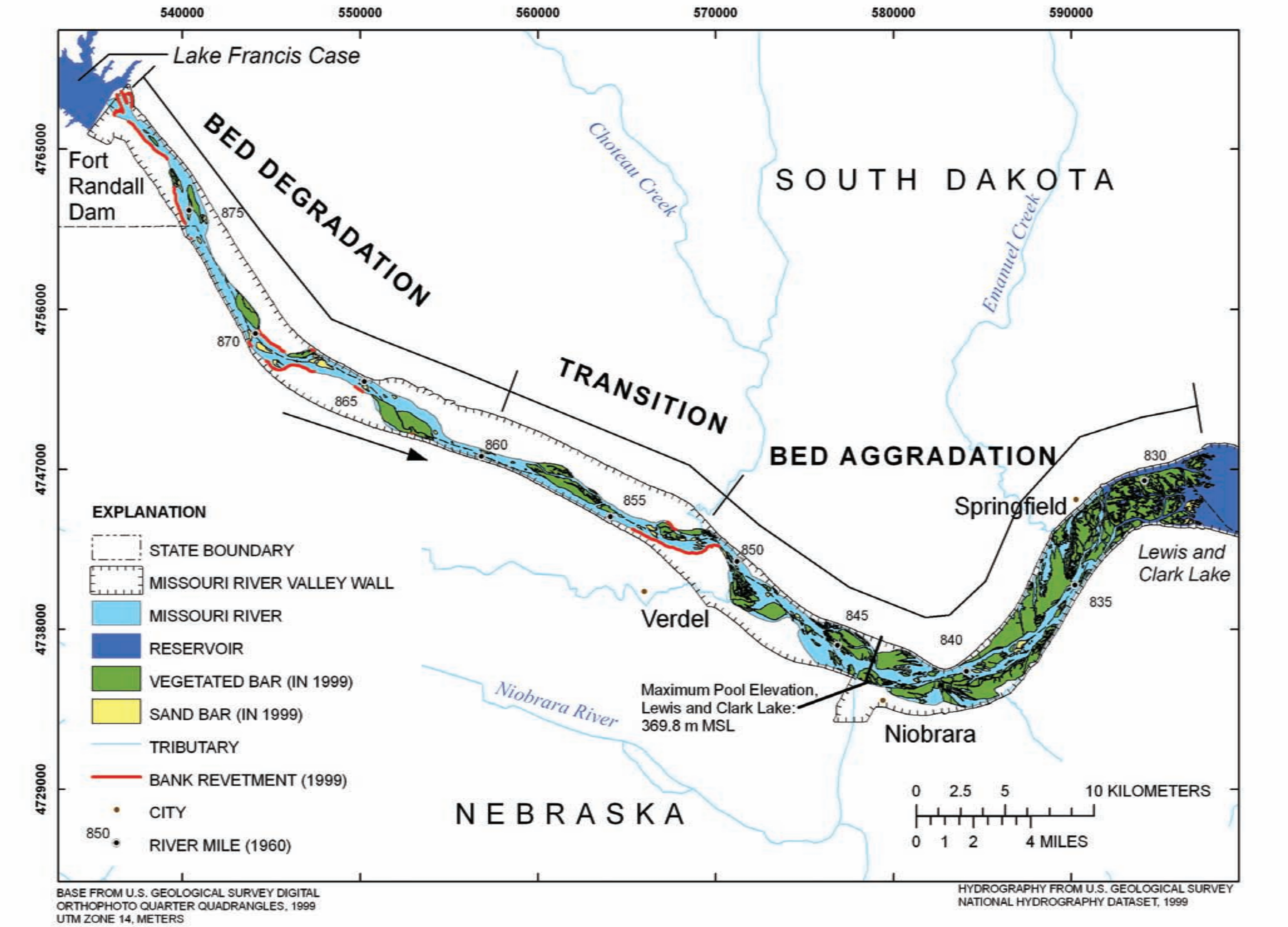


Figure 5. The 39-mile segment from Fort Randall Dam, South Dakota to the headwaters of Lewis and Clark Lake, South Dakota and Nebraska. Degradation, transition, and aggradation reaches follow Dangberg and others (1988). The free-flowing reach is above the Niobrara confluence and maximum pool elevation for Lewis and Clark Lake. The delta reach is downstream of the Niobrara River confluence.

the year 2175 (U.S. Army Corps of Engineers, 2001). For the purposes of this project the 39-mile segment was divided into a free-flowing reach and a delta reach, with the division occurring at the Niobrara River confluence. The Niobrara confluence is also the location of the 369.8 m elevation contour, the maximum lake elevation for Lewis and Clark Lake.

59-mile Segment

The 59-mile segment of the MNRR (fig. 6) extends from Gavins Point Dam (river mile 811) to Ponca State Park, Nebraska (river mile 753; fig. 6) and has experienced considerable bed degradation since dam closure along its entire length. The cross-sectional-average bed elevation has decreased 3.5 m in the first 17.7 km downstream of the dam and an average of 1.8 m in the rest of the reach (West Consultants, 2002). The amount of bed degradation is approximately twice the amount of the 39-mile segment (West Consultants, 2002). Bed sediment size has also changed from medium sand to fine and medium gravel in the first 4.8 km downstream of the dam (West Consultants, 2002). Bed material changes are not evident at river mile 795, 25.7 km downstream of the dam (West Consultants, 2002).

Kensler's Bend Segment

The segment between Ponca State Park, Nebraska (river mile 753) and the Big Sioux River (river mile 734) has been stabilized with dikes and revetment under the Kensler's Bend Project (U.S. Army Corps of Engineers, 2006a). Known as Kensler's Bend (fig. 7), this segment is intermediate in engineering design between the noncommercially navigated segment upstream of Ponca State Park, Nebraska and the navigated segments downstream of Sioux City. In general, constriction of flow between wing dikes and the opposite bank is not sufficient to maintain a consistent, deep thalweg through crossovers. Few published bed-monitoring data are available for the Kensler's Bend segment. In this report, data analysis for the Kensler's Bend segment extends from Ponca State Park to South Sioux City, Nebraska (river mile 727.8).

The Sioux City gage is located at the downstream end of the Kensler's Bend segment (fig. 7). Gage records at Sioux City indicate a decreasing trend in Missouri River stage with a total of 2–3 m degradation since 1955 (U.S. Army Corps of Engineers, 2004b).

Bank Erosion in the Missouri National Recreational River

Bank erosion in the MNRR has been measured by the USACE with various methods. The USACE defines bank erosion as "aerial surface loss in acres of usable or productive land along the river's banks," including "potentially productive land" (River PROs, 1986; HDR, 1999). This broad definition limits what is measured as eroded lands from georeferenced imagery because only loss of flood-plain or alluvial terraces would be included as "usable or productive land." Fluxes of sediment to and from bars and islands may be ignored under this definition.

The USACE also has commissioned several analyses of bank erosion that are based on cross-sectional analysis, using historical sedimentation/degradation range data, and extrapolating these rates for the entire segment as a volume (Pokrefke and others, 1998). These studies assess net sediment fluxes from the entire cross section, including bars, banks, and terraces, and explicitly measure changes in the vertical dimension.

Most of the previous studies addressing bank erosion in the MNRR have used georeferenced aerial photography. Methods for measuring bank erosion from aerial photography have been inconsistent among studies and incompletely documented. None of the studies explicitly address uncertainties in erosion calculations (Rahn, 1979; River PROs, 1986; Pacific GeoScience, 1998; Pokrefke and others, 1998; HDR, 1999; Resource Consultants and Engineers, Inc, 1992; U.S. Army Corps of Engineers, 1980, 2006a; Biedenharn and others, 2001; West Consultants, 2002).

In the 39-mile segment, previous estimates of postdam bank erosion rate averaged 10 hectares per year (ha/yr), compared to predam bank erosion rates that were estimated at 60 ha/yr (U.S. Army Corps of Engineers, 2004a; table 1). Cross-sectional data suggest there has been considerably more bed erosion than bank erosion in this river segment (Pokrefke and others, 1998). Cross-sectional analysis also indicated that bank erosion rates have decreased since dam closure; bank erosion rates were twice as high from 1954 to 1975 compared to 1975–85 (Pokrefke and others, 1998). Decreasing bank erosion rates are consistent with generally decreasing trends in bed degradation (U.S. Army Corps of Engineers, 2004b).

The 59-mile segment has had historically higher bank erosion rates, both before and after dam closure, compared to the 39-mile segment based on cross-sectional data. Average bank erosion rates were more than six times higher in the 59-mile segment for the 1974–97 period (West Consultants, 2002; table 1). The USACE (2004b) estimated an average of 50 ha/yr erosion since 1956, and 80 ha/yr in the predam era in the 59-mile reach of the MNRR. USACE postdam annual estimates ranged from 20 to 110 ha/yr (West Consultants, 2002). Estimates of bank erosion indicated that bank erosion has decreased since 1975 and then significantly increased during the time period that encompassed 1995–97 high flows (West Consultants, 2002). Decreasing bank erosion rates are consistent with generally decreasing degradation trends, with the exception of the period of higher degradation and bank erosion associated with 1997 flows (U.S. Army Corps of Engineers, 2004b).

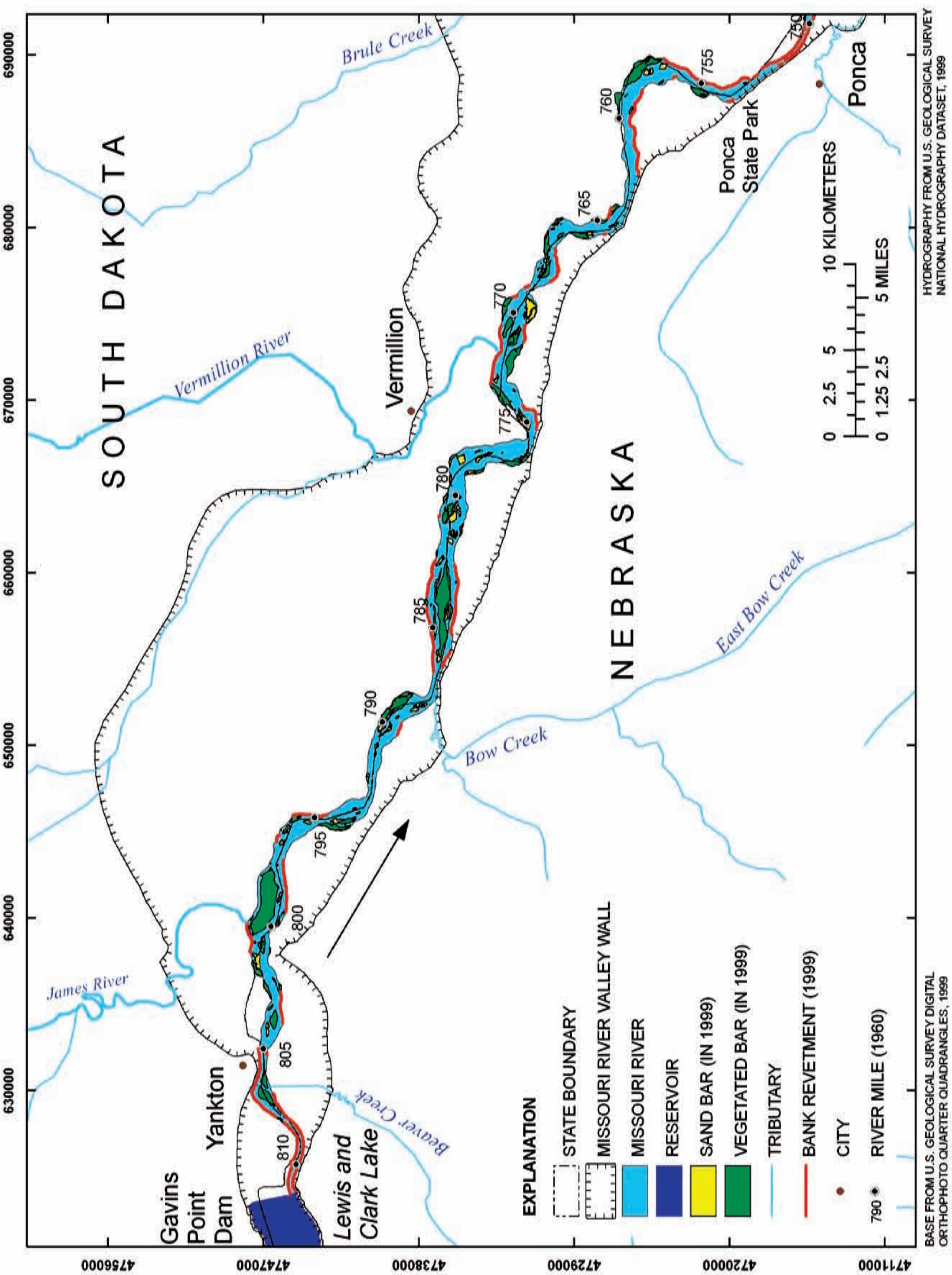


Figure 6. The 59-mile segment from Gavins Point Dam, Nebraska and South Dakota, to Ponca State Park, Nebraska.

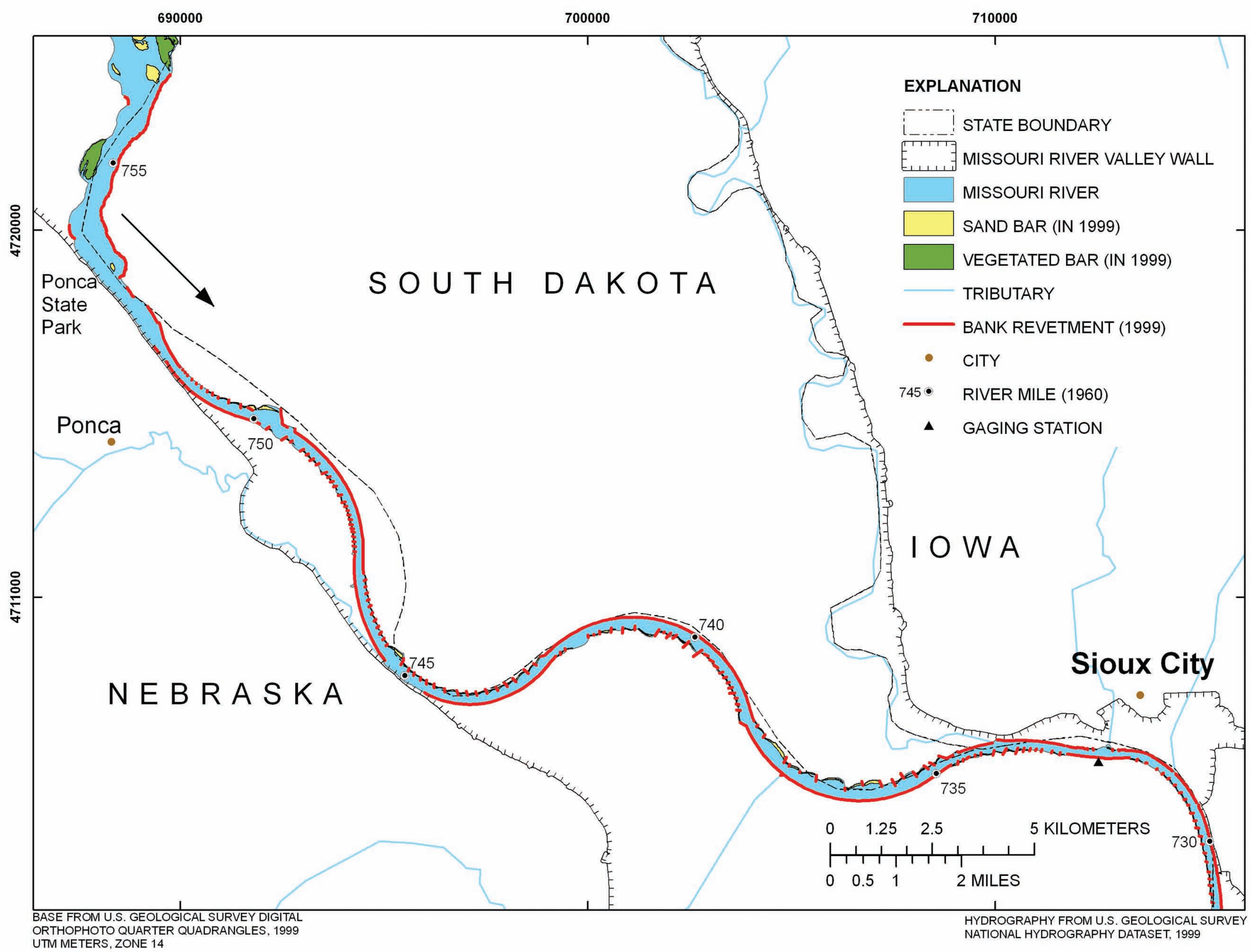


Figure 7. The Kensler's Bend segment from Ponca State Park, Nebraska to Sioux City, Iowa.

Approach and Methods

A fundamental premise of this project was that an objective geomorphic classification of the MNRR can provide useful information, and perhaps predictive understanding, about geomorphic processes present in the river corridor. Many approaches exist for river classification, and application of any particular system should be based on specific objectives (Kondolf and others, 2003). In this project, our objective was to provide a classification system that would resolve spatial and temporal variation in geomorphic processes along the river to inform management decisions at the reach scale.

Reach-scale river classification has been typically addressed through one of two broad approaches. In the first, predetermined classification systems are applied to assign portions of a river to physically meaningful classification units. The most frequently cited system is the geomorphic classification proposed by Rosgen (1996); this deductive classification system is based on assumptions that well-understood processes determine channel form and that the channel form is indicative of geomorphic processes. A contrasting approach is based on inductive reasoning and involves measuring a broad suite of channel-geomorphology characteristics, followed by application of multivariate statistical techniques to extract naturally occurring clusters of characteristics. Statistical classification systems have advantages in minimizing dependence on prior, potentially untested, assumptions; however, even in these statistical approaches, some basic assumptions about geomorphic form and process are necessary to determine variables and statistical procedures. Because of the potentially unique character of the Missouri River within the MNRR, we chose to pursue classification through an inductive statistical approach.

Our general strategy for geomorphic classification was to use readily available digital, geospatial datasets to characterize the river. We mapped channel characteristics from multiple years in order to assess both spatial and temporal geomorphic variability. The datasets were then subjected to multivariate statistical classification. The purpose of statistical classification of the MNRR was two-fold: (1) to determine whether geomorphically-defined clusters would prove to be indicative of fundamental variation of geomorphic processes and thereby define reaches that would be amenable to different river-management strategies; and (2) to explore whether or not such naturally occurring groups persisted over time and could be associated with variation in bank erosion rates. The first objective was approached by using a multivariate statistical analysis of channel-geomorphology characteristics based on imagery from 1999. Clustering and discriminant analysis of the 1999 dataset provided an objective, natural classification of channel morphology along the river. Persistence of classified units was evaluated by using the discriminant functions from 1999 to classify river reaches mapped in 2003 and 2004. Linkage of classes to erosion rates was assessed by analyzing erosion rates by classified unit.

Data Resources

All available digital data were evaluated for inclusion in the classification (table 2). We relied primarily on interpretations from aerial orthophotography available for various years from 1993 to 2004. Orthophotography was supplemented with various other data to put mapped channel characteristics in context. We included the moderately engineered Kensler's Bend segment with the 39-mile and 59-mile segments, to increase the range of channel characteristics. We included the Lewis and Clark Lake delta, but did not include measurements in the lake downstream of the delta front. Because of the wide geographic scope that includes the border between two states, considerable data were available, but it was not always possible to obtain data throughout the study area on identical dates or under comparable climatic or hydrologic conditions.

Table 1. Bank erosion estimates for the 39-mile and 59-mile segments of the Missouri National Recreational River.

[--, no data; totals are indicated in **bold**]

Period	Number of years	Total hectares lost	Hectares lost (per year)	Hectares lost (per year per kilometer)
Predam, 39-mile[1]				
--	--	--	60	0.1
Predam, 59-mile[2]				
1930-1946	16	1,240	80	1.3
1946-1956	10	900	90	1.5
Totals	**26**	**2,140**	**80**	**1.4**
Postdam, 39-mile[1]				
--	--	--	10	0.4
Postdam, 59-mile[2]				
1956–1959	3	100	30	0.5
1959–1969	10	670	70	1.1
1969–1972	3	320	100	1.8
1972–1974	2	180	90	1.6
1974–1975	1	110	110	1.9
1975–1979	4	160	40	0.7
1979–1985	6	190	30	0.5
1985–1995	10	230	20	0.4
1995–1997[3]	2	220	110	1.9
Totals[3]	**41**	**2,180**	**50**	**1.2**

[1]U.S. Army Corps of Engineers, 2004a.

[2]U.S. Army Corps of Engineers, 1996.

[3]West Consultants, 2002.

Aerial Orthophotography

We used high-spatial-resolution aerial orthophotography of the 39-mile, 59-mile, and Kensler's Bend segments taken in 1996, 1997, 1998, 1999, and 2001 provided by the USACE (fig. 2; table 2). These orthophotograph sets were supplemented with available digital orthophoto quarter-quadrangles (DOQQ) from 1993, 2003, and 2004 taken by the U.S. Geological Survey (USGS) and the Farm Service Agency's National Agricultural Imagery Program (FSA/NAIP). Rectified aerial photography from 1941 was provided by the South Dakota Geological Survey (table 2). The 1941 predam imagery was only available for the 59-mile segment of the MNRR. The photos were compressed when possible, mosaicked, and compiled in a geographic information system (GIS) by using the ArcGIS software package (ESRI, Redlands, Calif). All data derived from orthophotography have the horizontal datum North American Datum, 1983 (NAD83). The projection used for all data associated with this report is Universal Transverse Mercator Zone 14, Meters (UTM 14).

Elevation Information

Elevation information was acquired from the USGS National Elevation Dataset for the entire study area (U.S. Geological Survey, 2006). These data have a spatial resolution of 1 arc-second, or 30 m. An additional high-resolution elevation dataset of points and breaklines for the entire Missouri River Valley between river miles 811 and 729 was provided by the USACE (U.S. Army Corps of Engineers, unpub. data, 1999). In this dataset, points and breaklines in the flood plain were acquired by photogrammetry and merged with transect-based bathymetry in the Missouri River; however, the channel bathymetry was surveyed in 1996 before the 1997 sustained high-flow event and should be considered specific to that date. The points and breaklines were converted into a digital elevation model by using the kriging method of point interpolation in Surfer 8 (Golden Software, Golden, Colo.) and producing a grid with a 10-m point spacing.

Supplemental Data

Supplemental data were acquired and used where applicable. Shapefiles created from 1894 Missouri River Commission Map plates were utilized to measure the pre-dam conditions of the Missouri River (Missouri River Commission, 1894; Miller, 2002). The USACE provided degradation and sedimentation range cross-sectional data for the 39-mile and 59-mile segments (Resource Consultants and Engineers, 1992; West Consultants, 2002; U.S. Army Corps of Engineers, unpub. data, 2004). Regional geologic and soils maps were assembled and acquired from various state and national on-line sources (Nebraska Conservation and Survey Division, 1996; Martin and others, 2004; Soil Survey Staff, 2004a, 2004b; U.S. Department of Agriculture, 2004a, 2004b; Johnson and McCormick, 2005). Results from ongoing surficial geologic investigations and mapping were useful in understanding the Missouri River's history in the MNRR (Cowman, 2005; Lundstrom and others, 2006).

Bankline Determination

The tops of the river banks were digitized on a computer screen at a 1:1000 scale on the USACE orthophotographs and at the highest possible resolution on additional orthophotographs. Placing the bankline at the top of the bank, rather than the water's edge, allowed for comparison of channel width and bank location between multiple years independent of river discharge (fig. 8). The bank-to-bank method also estimated bankfull dimensions to allow comparisons of channel widths among orthophotographs with highly variable discharges. Bankline locations were verified on field visits and by comparison with the degree of inundation during the 1997 high-flow event although the discharge at the time of the 1997 photography was not at peak discharge. The resulting banklines were error checked and compiled.

Banklines provide a robust and systematically identifiable geomorphic datum for comparing change. Use of banklines identified at the earliest date (primary bankline) can be problematic in incising river systems where new flood plain is being formed at lower elevations. Typically, channel adjustment downstream of dams results in simpler, smaller cross sectional areas and top widths as new flood plain is formed (Williams and Wolman, 1984; Ligon and others, 1995; Grant and others, 2003). In such systems, the channel eventually starts eroding newly deposited flood-plain sediments and abandons erosion of the previous bankline. Use of the primary (first-identified) bankline as a datum will underestimate fluxes of sediment from young flood-plain deposits, but avoids ambiguities of identifying new banklines. Use of the primary bankline also focuses understanding on adjustments of the channel relative to the date of the primary bankline.

The primary bankline identified in the 1993 orthophotography was, in some cases, the predam bank. Where the river had migrated or narrowed since dam closure, however, the primary bank could have been eroding into the postclosure flood plain. In all cases, the 1993 bankline was used as the primary datum for the study.

Because of a lack of detectable bank erosion over most of the 39-mile segment, banklines in 1993, 1998, 2003, and 2004 were only digitized where detectable erosion had occurred. In the 39-mile segment complete banklines were digitized for 1999. In the 59-mile segment complete banklines were digitized for all available photo years (1941, 1993, 1996, 1997, 1998, 1999, 2001, 2003, and 2004).

Table 2. Digital orthophotography used for the Missouri National Recreational River and adjacent Missouri River segments.

[m^3/s, cubic meters per second; BW, black and white; CIR, color-infrared; CO, color; DOQQ, Digital Orthophoto Quarter Quadrangle; FSA/NAIP, Farm Service Agency, National Agricultural Imagery Program; SDGS, South Dakota Geological Survey; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey]

Photo Series	Type	Scale	Resolution (meters)	Year	Dates	Source	Discharge range (m^3/s)[1]
39-mile segment orthophotograph series							
DOQQ	BW	1:12,000	1	1993	vary	USGS	91–490
Fort Randall Dam, South Dakota to Springfield, South Dakota	CIR	1:12,000	0.30	1998	5/3, 5/4	USACE	521–524
DOQQ	BW	1:12,000	1	1999	vary	USGS	439–759
Fort Randall Dam, South Dakota to Springfield, South Dakota	CIR	1:12,000	0.3	1999	6/17	USACE	680
Fort Randall Dam, South Dakota to Gavins Point Dam	CO	1:40,000	2	2003	6/03, 9/03	FSA/NAIP	606–881
Fort Randall Dam, South Dakota to Gavins Point Dam	CO	1:40,000	2	2004	Vary	FSA/NAIP	677–796
59-mile segment orthophotograph series							
Gavins Point Dam to Ponca State Park, Nebraska[2]	BW	1:12,000	2.5	1941	8/10, 6/1, 9/16, 10/7	SDGS USACE	549–1,039[3]
DOQQ	BW	1:12,000	1	1993	vary	USGS	198–656[4]
Gavins Point Dam to Ponca State Park, Nebraska[2]	CIR	1:12,000	0.3	1996	6/4	USACE	1,104[4]
Gavins Point Dam to Sioux City, Nebraska	CO	1:12,000	0.3	1997	8/5, 8/8	USACE	1,758–1,826[4]
Gavins Point Dam to Ponca State Park, Nebraska	CIR	1:12,000	0.3	1998	5/4	USACE	736[4]
DOQQ	BW	1:12,000	1	1999	vary	USGS	401–906[4]
Gavins Point Dam to Sioux City, Nebraska	CIR	1:12,000	0.3	1999	6/16, 7/7	USACE	963–1,087[4]
Gavins Point Dam to Ponca State Park, Nebraska	CO	1:20,000	0.3	2001	10/11	USACE	764[4]
Gavins Point Dam to Sioux City, Nebraska	CO	1:40,000	2	2003	6/03, 9/03	FSA/NAIP	733–864[4]
Gavins Point Dam to Sioux City, Nebraska	CO	1:40,000	2	2004	vary	FSA/NAIP	702–792[4]

[1] Discharge at Fort Randall Dam, U.S. Army Corps of Engineers data.

[2] Missing photos; not complete.

[3] Discharge at Sioux City, U.S. Geological Survey streamflow gage 06486000.

[4] Discharge at Gavins Point Dam, U.S. Army Corps of Engineers data.

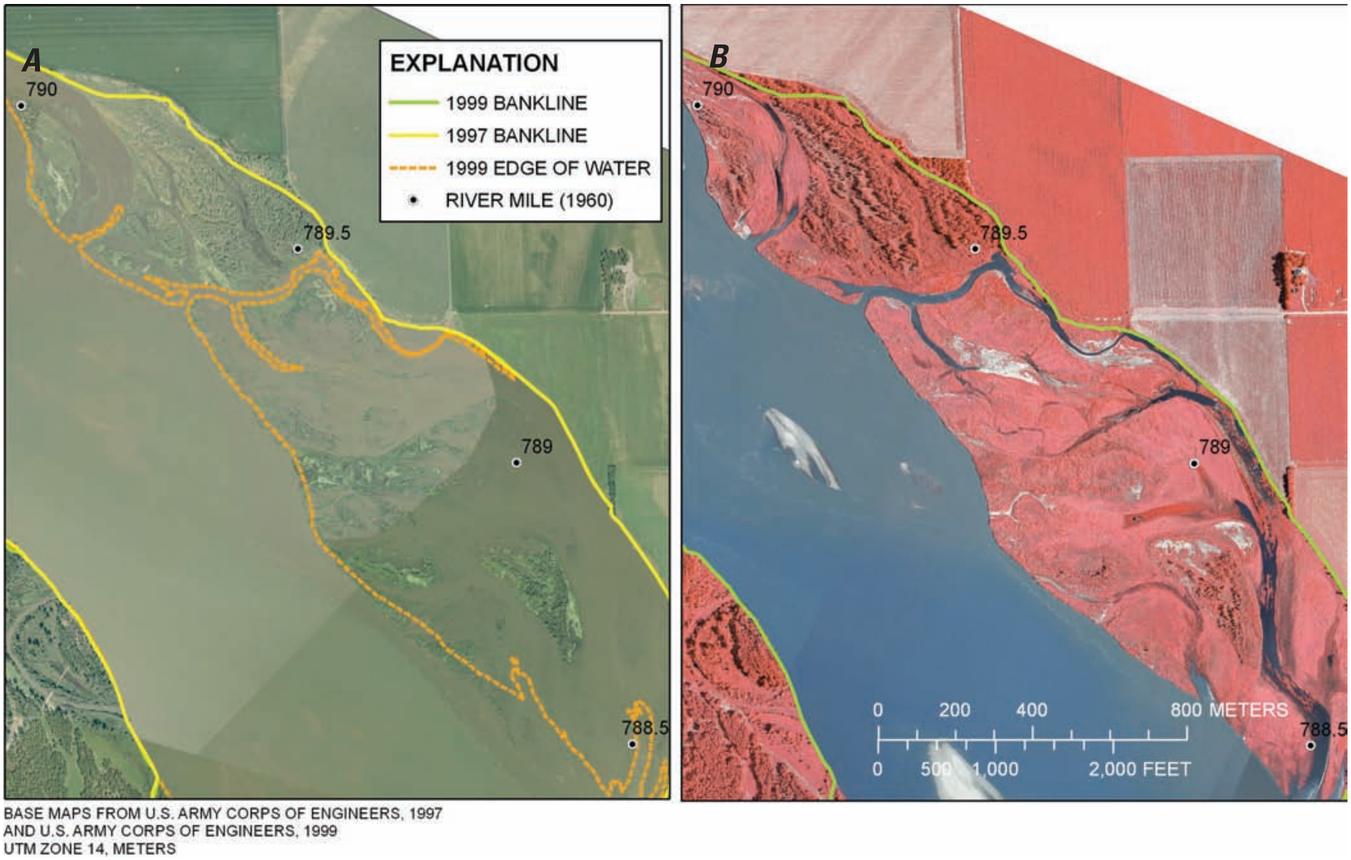


Figure 8. Comparison of channel width and bank location depending on discharge at river miles 790.0–788.5. *A,* In 1997 at 1,825 cubic meters per second. *B,* In 1999 at 1,025 cubic meters per second.

Assessment of Georectification Error in Aerial Orthophotographs

A fundamental requirement for the analysis of a multi-temporal collection of aerial orthophotography is that the data sets are spatially coregistered and that positional accuracy can be quantified. To estimate the spatial position error among the various dates of aerial orthophotography and the implications of this error for mapping channel characteristics, we chose stable test points at intervals of approximately every river mile and identified these points on as many orthophotography sets (dates) as possible. These test points were selected based on the recommendations of Hughes and others (2006): points chosen were close to the river, located within the valley walls, and consisted of "hard" points such as the corners of building roofs, if possible. In total, 489 test points were identified at 71 locations for the 59-mile and Kensler's Bend segments. We then compared the test points from all other photography years to the 1999 orthophotography, which was selected because of its high resolution coverage of nearly all the study area, and because it falls in the middle of the study period. The results of the analysis indicated that the mean distance between the points from all the photography years was 2.9 m (standard deviation 0.98 m). A cumulative frequency function of the differences in distance among the photographs (fig. 9) showed that the high resolution USACE datasets (1996, 1997, 1998 and 2001) had less error than the DOQQ's and FSA/NAIP photograph sets (1993, 2003, and 2004); therefore, error buffers of ± 2 m (the 90th percentile value for the USACE orthophotography), and ± 3 m (the 90th percentile for the additional orthophotography) were chosen for the digitized banklines. Because the orthophotography sets for the 39-mile segment correspond to equivalent data sets for the 59-mile segment, the same error values were assumed. The 1941 aerial orthophotography predates many of the structures used to check georeferencing. It is evident that the 1941 orthophotography was not georeferenced as well as the recent aerial orthophotography. Locations from banklines and bars digitized from the 1941 data set should not be considered as accurate as data derived from the 1993 to 2004 orthophotography.

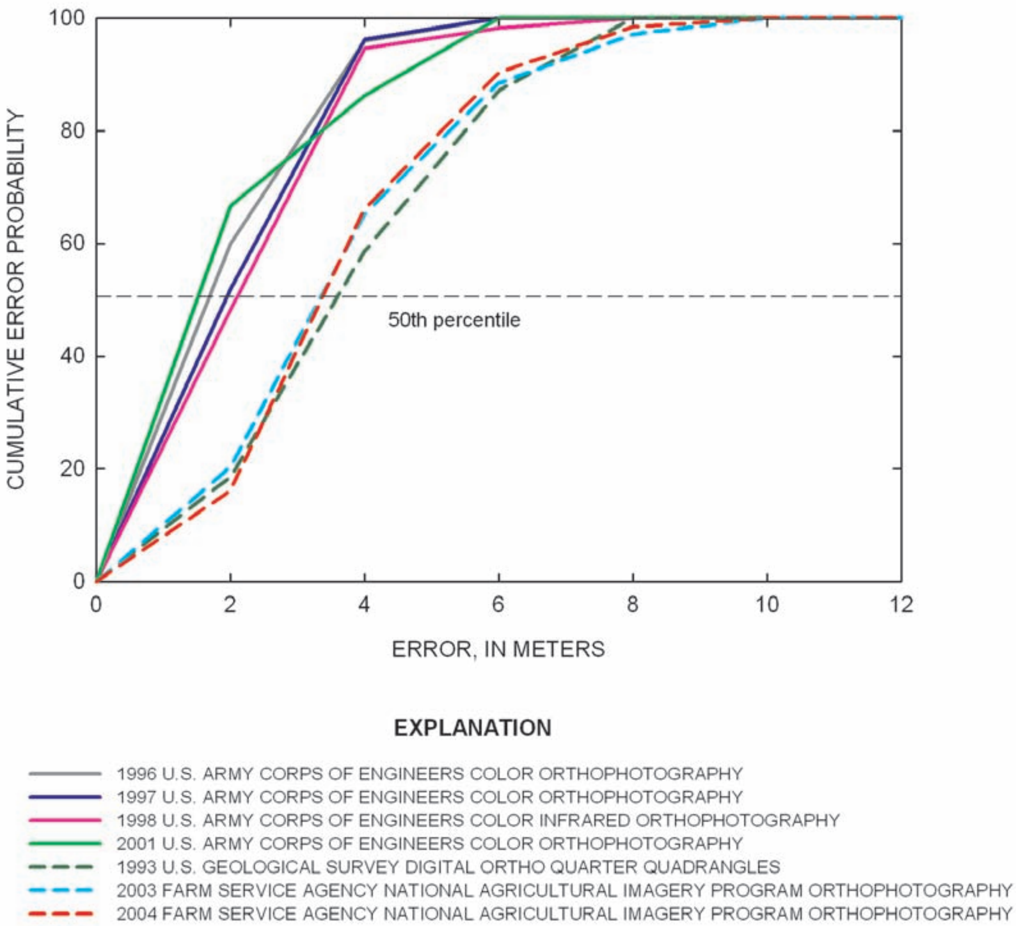


Figure 9. Cumulative error probability curve for orthophotograph error as compared to the 1999 U.S. Army Corps of Engineers' high-resolution orthophotography.

Bank Erosion and Error Calculations

Bank erosion areas were calculated by intersecting banklines from different years and creating erosion polygons. Erosion buffers were placed on the banklines, with values of ±2 or ±3 m depending on the resolution of the orthophotography (fig. 9). Erosion regions were intersected to create maps delineating where bankline erosion has occurred. The bankline buffer polygons were subtracted from the erosion polygons to calculate actual erosion (fig. 10). Buffer areas were tabulated to quantify uncertainties.

Address System

The 1999 USACE orthophotography set was used to establish a longitudinal address system for the collection and display of spatial patterns in bank erosion and channel form following methodology outlined in Panfil and Jacobson (2001). The address system provides for easy visualization of how river characteristics vary along the river and provides a dataset useful for statistical analysis (fig. 11).

To establish the address system, the channel centerline was digitized between the 1999 banklines. This line was used as an approximation of the thalweg of the river. The centerline address points were used instead of the existing USACE 0.1 mile river points because 1960 USACE river miles do not always follow the current position of the Missouri River in the MNRR. In several reaches the river has migrated substantially away from the 1960 USACE river mile locations. A 200-m spacing was chosen for address points. This spacing is approximately equivalent to the minimum channel width in the MNRR and Kensler's Bend segments of the Missouri River.

Geomorphic channel attributes were spatially joined in a GIS to the address points, thereby assigning longitudinal locations to the channel attributes. To collect attributes from polygons such as sand bars, a polygon address system was established by using generally perpendicular transects that sliced the channel into quadrilateral polygons that partition space equally along the address-point system. Attributes of polygon features were assigned to address points by intersecting the address polygons with the relevant feature polygons. Features which occurred in multiple address polygons were dissected in the analysis, and parts of polygons were assigned to the immediately downstream address point.

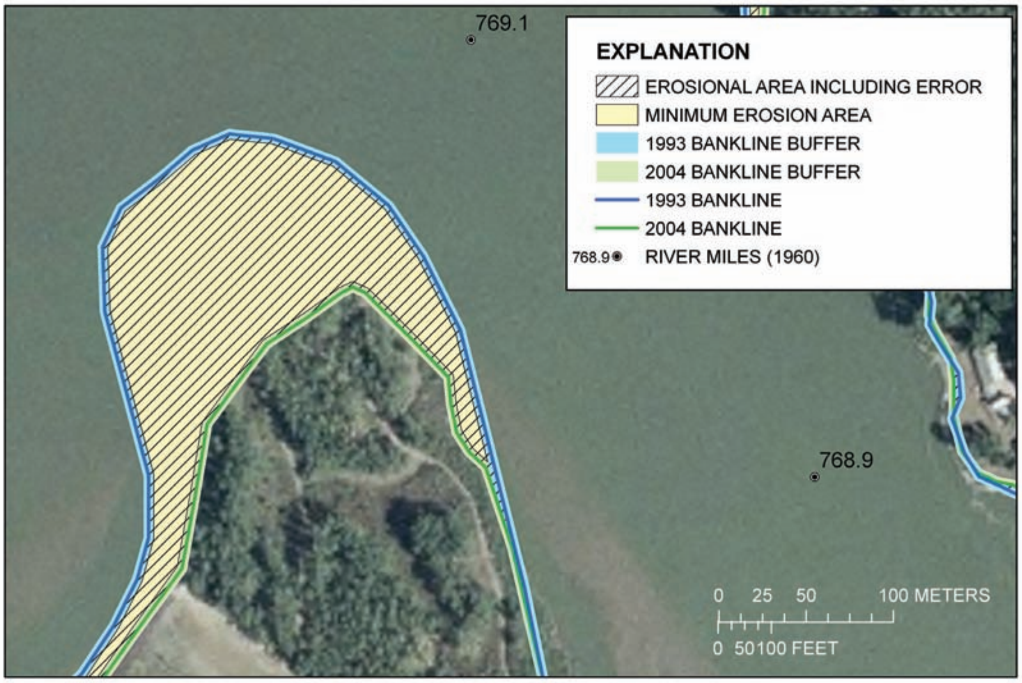


Figure 10. Application of bankline buffers to determine erosion area error. A 3-meter buffer was placed on both sides of the 1993 and 2004 banklines. The minimum erosion area was determined by subtracting this buffer from the area between the 1993 and 2004 buffer lines.

Geomorphic Measurements

Geomorphic measurements were made of channel attributes which were then applied to the address points. Geomorphic channel attributes were extracted from the maps using automated procedures and scripts within ArcMap (ESRI Inc., Redlands, Calif). In the following sections, the geomorphic channel attributes are described.

Channel and Valley Width

The digitized banklines were converted to closely-spaced points (2 m apart) to calculate river width. A distance function was then used to measure the distance from an address point to the closest bankline point on the right and left banks (right and left bank, by convention refer to the right and left descending banks of the river when looking downstream). These values were added together and used to calculate the width between the banks. Channel width was calculated for every year the banks were digitized. For the predam (1894 and 1941 datasets) new centerlines were digitized for width measurements. Channel-width measurements go from primary bank to primary bank and include midchannel bars and islands.

The valley wall was digitized for river miles 880–729 by using the 1999 USGS DOQQ, regional geologic maps, digital elevation models, and 1:24,000 USGS topographic maps to identify the consistent slope break at the base of the bluffs. The process used to calculate channel width was also used to calculate valley width and the distance between the banks and the bluffs. A buffer of 50 m was placed on the valley walls to develop a data layer indicating where the river channel was within 50 m of the valley wall.

Revetment and Other Channel Structures

Bank revetments consist of rock, wood, concrete, or other hard materials placed on river banks to prevent or slow bank erosion. Revetment was mapped based on where it occurred on the banks in the 1999 orthophotography. No effort was made to differentiate between public or private revetment, or to determine the date of placement. Where bank stabilization projects consisted of groupings of hard points, or small protected areas separated by longer reaches of unprotected bank, the entire length of bank was mapped as undifferentiated protected bank. Our 1999 revetment totals are consistent with results from ongoing high-resolution bank-revetment mapping efforts by the NPS (Wilson, 2005). In the Kensler's Bend segment, dikes and other channel structures were mapped based on their position and condition in the 1999 orthophotography. We did not attempt to map revetment and stabilization projects over other dates of orthophotography.

Sinuosity

Channel sinuosity (the ratio of distance along the thalweg to the straight line distance between points) can be an informative variable as it relates to channel curvature, flow separation, and hydraulic diversity (Barbour and others, 1999). We could not map the complex thalweg of the MNRR with confidence using remotely-sensed imagery; therefore, sinuosity values were based on channel length defined along the centerline between the 1999 high banks. These sinuosity values did not accurately reflect true channel curvature at the channel-unit scale; hence, sinuosity was used in exploratory analysis but was not used in subsequent classification.

Sinuosity was calculated at every address point for 400-m, 800-m, 1.6-km, 2.4-km, 4.8-km, and 9.6-km long reaches along the channel. Sinuosity also was calculated over the entire length of the three river segments for 1894 and 1999, as well as for 1941 in the 59-mile segment by using centerlines digitized for those dates.

Bare Sand Bars and Vegetated Bars

Bare sand bars and vegetated bars were digitized to characterize bar locations in 1999 and to calculate braiding index and sand-bar persistence over time. The focus was on bar abundance, location, and relative size. We did not emphasize areal changes over time as bar area changes substantially with discharge, and prevailing discharge at the time the imagery was collected could not be controlled (table 2). Bars were digitized for 1999 and 2004 in the 39-mile segment, and 1941, 1996, 1997, 1998, 1999, 2003, and 2004 in the 59-mile segment. The bars in the Lewis and Clark Lake delta were digitized from the 1993, 1999, 2003, and 2004 digital orthophotography. Bars were classified as bare or vegetated, and areas of each were tabulated. For bars with bare sand and vegetation, the dominant surface material was used for classification (a vegetated bar has approximately 50 percent or greater vegetation coverage). Vegetated bars that had mature woody vegetation, and were clearly higher in elevation, were identified as islands.

Bar persistence over time was calculated for both bare sand bars and vegetated bars by converting bar polygons for each year to raster grids with a value of 1 for each 10-m cell that fell within a bare sand bar or vegetated bar. Grids from all years were then added together producing a grid with values indicating the number of years bars were present at each location (fig. 12). The bar-persistence analysis was performed separately for bare sand bars and vegetated bars in both segments. The analysis was generally indicative only of spatial persistence because of discharge variation among dates.

Braiding

A braiding index representing the total number of channels was calculated at each address-point location. This index was calculated by intersecting the perpendicular address transects with digitized bars. The number of channels was calculated by adding the total number of bars encountered by a transect and adding one. These values were corrected for bars that were attached to the banks and therefore lacked corresponding channels.

Large Woody Debris

Large woody debris locations were mapped where they were visible within the channel (between the high banks) and on bare sandbars on the 1999 orthophotographs for all segments. Large woody debris was mapped where it could be detected on the margins of vegetated bars, but not mapped on vegetated bar interiors. No attempt was made to calculate size or orientation of large woody debris. The 1999 orthophotographs were generally of sufficient resolution to map individual trunks greater than 1-m diameter (fig. 13). In multipiece large woody debris accumulations, large woody debris density was estimated by the number of recognizable tree boles.

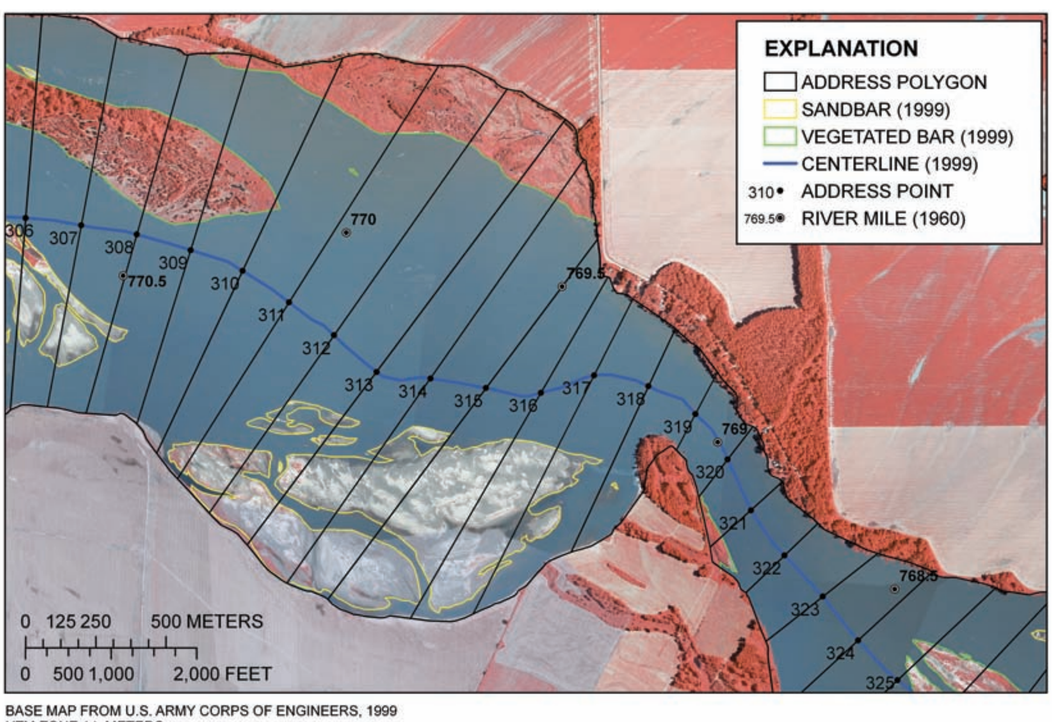
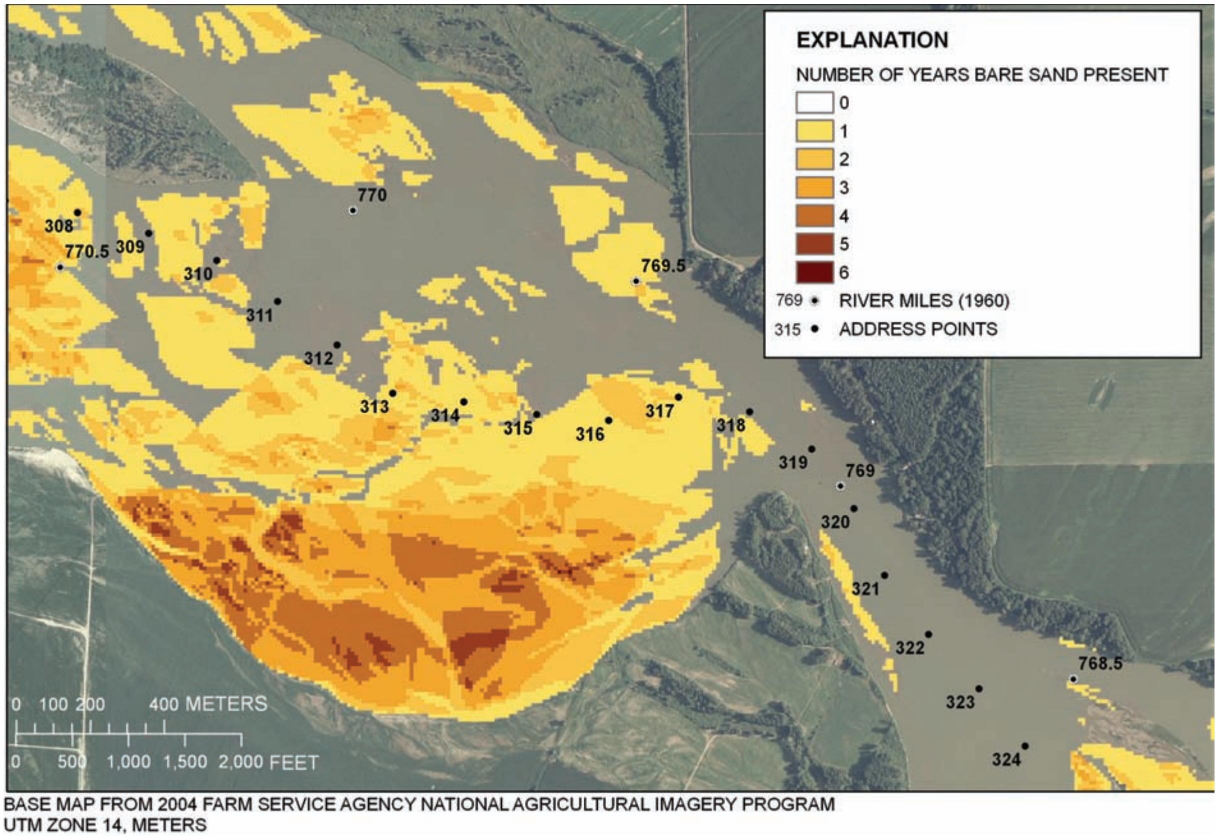


Figure 11. Address system created for data collection based on the channel centerline in 1999. Address points were created at intervals, such as 200 m (0.2 km) in the example, and referenced to kilometers downstream from Fort Randall or Gavins Point Dams. Address system includes polygons that can be intersected with data for linear-, point-, or polygon-based area data collection.



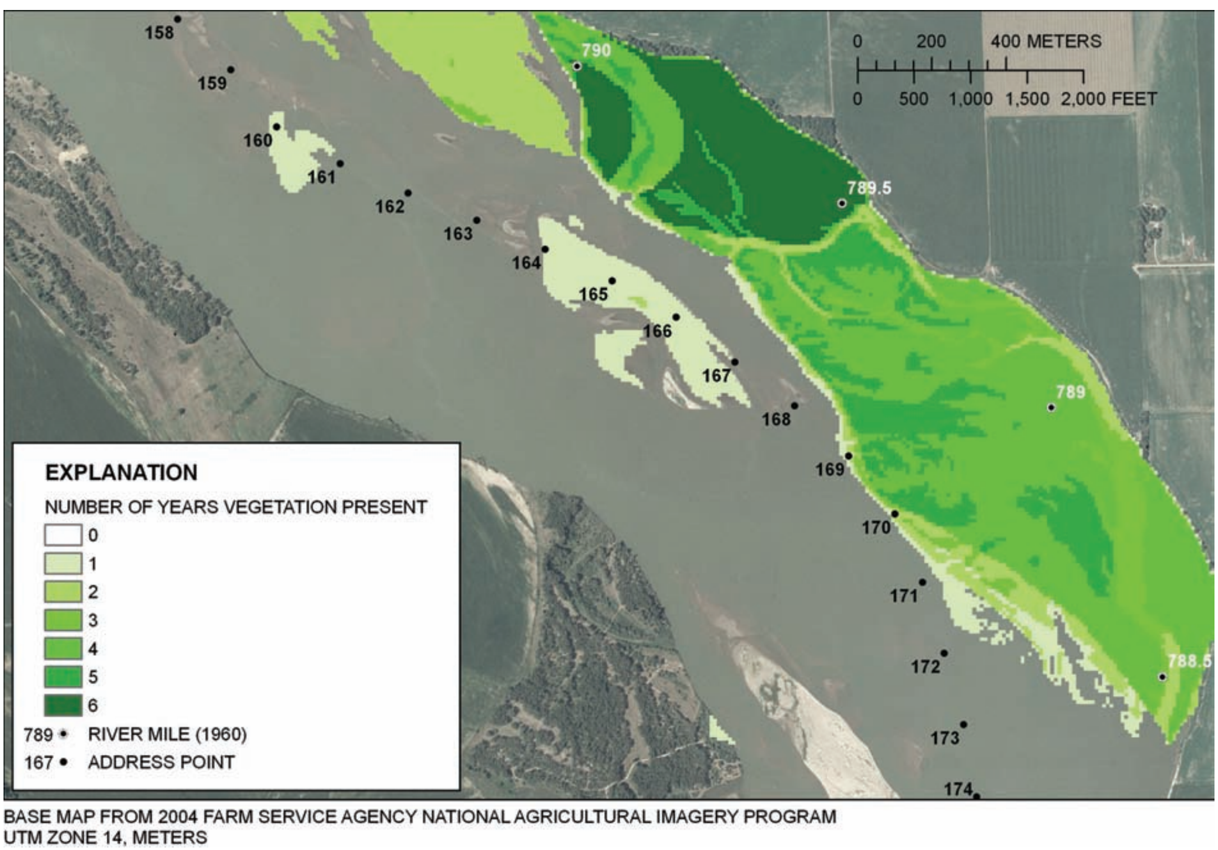


Figure 12. Persistance calculation example in the 59-mile segment of the Missouri National Recreational River for bare sand bars and vegetated bars.

Historical Channel Positions

For historical reference, we digitized the channel, chutes, and established islands from georeferenced 1894 Missouri River Commission maps (Missouri River Commission, 1894; Miller, 2002). Sand bars were not digitized from the 1894 maps because their importance or persistence could not be established from available hydrologic information. The channel, sand bars, and vegetated bars were also digitized from georeferenced 1941 imagery. Several photographs were missing from the 1941 dataset; thus channel and bar boundaries were interpolated between missing photos. It was difficult to differentiate between bars and islands in the black-and-white predam maps and imagery; therefore, all vegetated bars and islands were digitized as vegetated bars. Chutes were prominent features of the flood plain in predam 1941 imagery and in the 1894 maps. Chute boundaries and centerlines were digitized, and length and sinuosity were calculated from centerlines. Chute width was calculated every 100 m along the chute, and mainstem width was measured at chute inlets and outlets.

Statistical Classification

Previous work has illustrated the broad framework of statistical approaches to river classification (Kondolf and others, 2003). Much of the existing literature focuses on classification of drainage basins (Higgins and others, 2005; Keaton and others, 2005) or valley segments (Rabeni and Sowa, 2002) rather than the reach scale addressed in this study. The objective of this study was to define naturally occurring clusters of geomorphic characteristics that would be indicative of discrete sets of geomorphic processes (process domains).

Within clustering approaches, there are two general strategies. In the first, a large suite of potentially applicable variables is assembled and subjected to an ordination procedure (such as principal component analysis) to explore relations among potentially redundant variables and to reduce variables to factor scores. The factor scores are then clustered, after which assigned clusters can be used as the basis for a discriminant analysis to define the mathematical functions that best describe the clusters.

We followed a second approach, a variation on the general clustering strategy, in which we explored variables and reduced them using scientific judgment of which variables contained the most useful, physically relevant information. In effect, this approach is a hybrid of deductive and inductive classification methods because physical understanding is used to select the relevant variables. Variables chosen in this fashion may not have as much statistical power to define individual clusters, but they are more useful for physical interpretation compared to multivariate factor scores that would reflect complex loadings of several variables.

A key step in variable selection is to define which variables are potentially controlling, or independent variables, and which are adjustable, or dependent. Geomorphic variables might be considered dependent or independent, depending on the time frame and spatial extent of interest (Schumm and Lichty, 1963; Piégay and Schumm, 2003). To scale the analysis to management issues, our emphasis was on variables that could be considered dependent over decadal time scales and 1–100 km spatial scales. In this context, valley width, bedrock interactions, bank revetment, and broad-scale sinuosity could be considered independent variables. Channel width, extent of sand and vegetated bars, number of channels, and reach-scale sinuosity can be considered dependent variables as they can

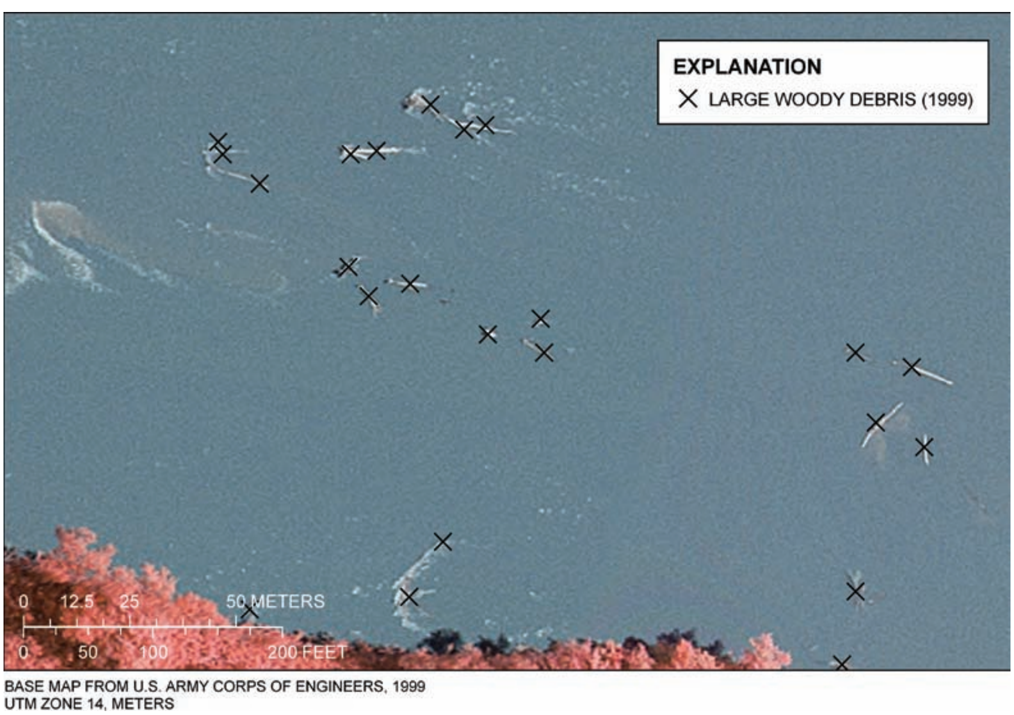


Figure 13. An example of large woody debris locations mapped from 1999 orthophotographs in the 59-mile segment of the Missouri National Recreational River.

adjust to changes in flow regime, sediment regime, broad-scale flow patterns, and bank erodibility on annual to decadal time frames. Of the remotely sensed variables measured in this study, locations of large woody debris can probably be considered the most dependent of variables.

Results

Longitudinal Variation of Geomorphic Characteristics

Longitudinal analysis of geomorphic characteristics provides a systematic approach to assessing variation of processes at the segment scale. In general, the longitudinal distribution of geomorphic characteristics of the MNRR is clustered rather than being uniform or having monotonic trends.

Valley and Channel Widths

Valley width is narrowest in the 39-mile segment of the MNRR, ranging from about 1,500 to 4,300 m (fig. 3; table 3). Channel widths are more variable. Upstream of the Niobrara River in the 39-mile segment, channel width ranges from 317 to 2,337 m with a mean of 952 m (figs. 3, 5, 14; table 3). Narrow and wide reaches are juxtaposed in an oscillating pattern. Channel width increases substantially (mean width is 2,550 m) and becomes more uniform downstream of the Niobrara River in the Lewis and Clark Lake delta.

The valley widens considerably in the 59-mile segment approximately six river miles below Gavins Point Dam near Yankton, South Dakota, ranging between 2,700 and 17,000 m (fig. 3, 6; table 3), and the right bank of the river is frequently close to the right valley wall (fig. 6). Channel widths in the 59-mile segment also vary widely, ranging from 202 to 1,835 m, with an average of 868 m.

The valley is also relatively wide in the Kensler's Bend segment, ranging from about 8,000 to 15,700 m (figs. 3, 7, 14; table 3). This moderately engineered segment consists of a high proportion of narrow channel widths when compared to the rest of the Missouri River segments. Average channel width in the Kensler's Bend Segment is 264 m, and widths range from 173 to 793 m.

The oscillating pattern in channel widths also was a feature of the predam river (fig.15; table 3). Wide reaches (channel widths greater than 2,000 m) were present in the 59-mile segment during the predam era, but are not present in the river today. The river has more narrow reaches today (widths less than 300 m) compared to the predam era although narrow channel segments also occurred on the Missouri River before impoundment.

Bank Material

A considerable amount of the MNRR channel is bordered by bedrock or revetment (table 4). Nearly half of the bankline in the 39-mile segment is within 50 m of a valley wall and is therefore presumed to be stabilized to some extent by bedrock. An additional 12.4 percent of the bankline in this segment is armored with revetment or hard points. The 59-mile segment has about 5 percent of the bank within 50 m of bedrock, but a third of the banks in the segment have been protected with engineering structures. The banks in the Kensler's Bend segment are almost entirely (95.4 percent) protected with engineered bank structures. There is a small amount of bank (3.5 percent) that is not protected with engineering structures but is instead stabilized by bedrock.

Table 3. General segment characteristics for the Missouri National Recreational River and adjacent Missouri River segments.

Segment	River miles (1960)[1]		Centerline distance	Valley width (1999, meters)		Channel width (1999, meters)		Channel's percent of valley width (1999, 1894)		Channel width (1894, meters)	
	Begin	End	Kilometers	Range	Mean	Range	Mean	Mean	Mean	Range	Mean
39-mile, free-flowing reach	879.8	843.7	57.0	1,467–3,091	2,377	317–2,337	952	40.3	33.06	269–1,950	786
39-mile, delta reach	843.7	827.6	26.4	2,198–4,280	2,846	1,679–4,208	2,549	89.5	28.92	353–1,694	823
Reservoir	827.6	811.9	25.4	2,145–4,631	3,327	2,063–4,585	3,216	96.6	30.18	137–2,140	1,004
59-mile	811.9	752.8	87.6	2,704–16,998	9,842	202–1,835	868	10.5	10.66	136–2,625	1,049
Kensler's Bend	752.8	727.8	39.2	8,041–15,730	12,026	173–793	264	2.3	10.27	263–3,276	1,235

[1] River miles are referenced to the river position in 1960. The Missouri River channel has changed position considerably in some places since 1960. The distance between river miles has been taken from the 1999 centerline.

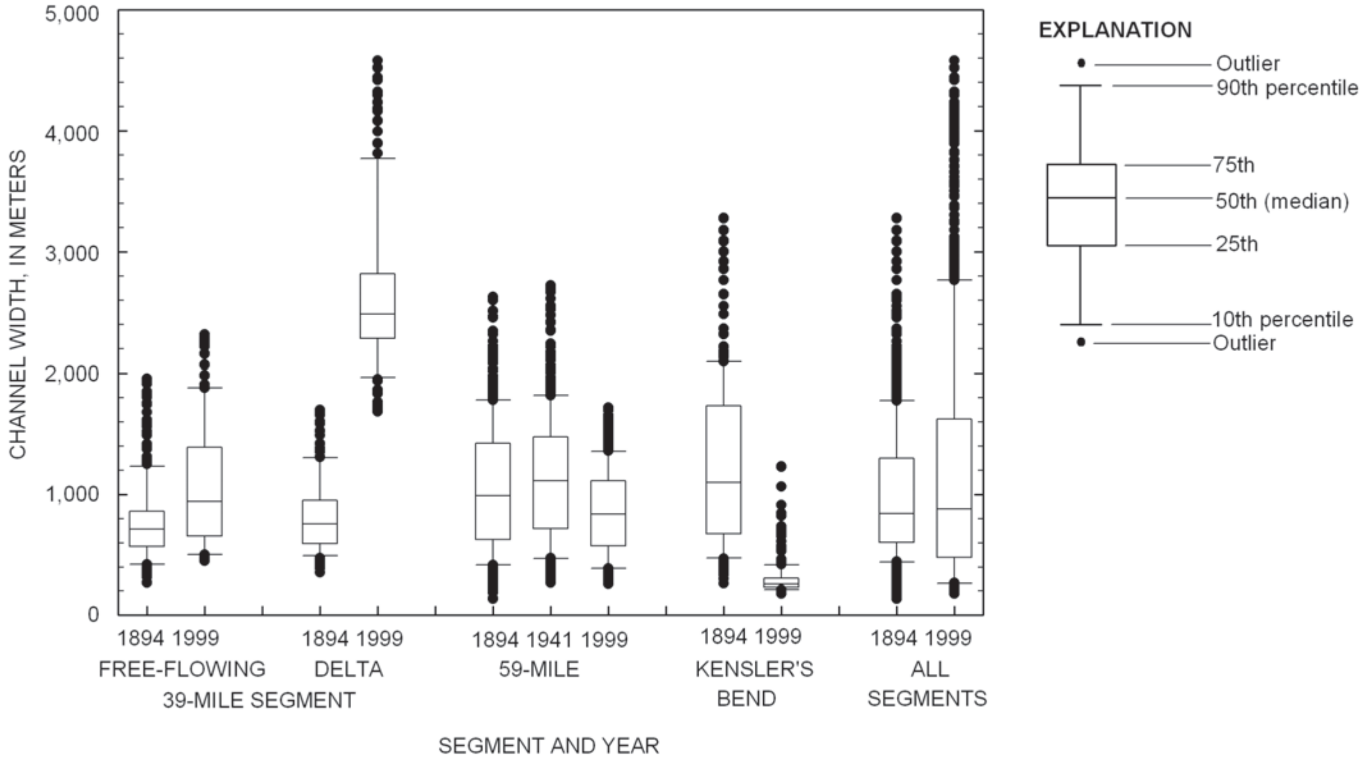


Figure 14. Channel-width statistics in the Missouri National Recreational River and adjacent Missouri River segments in the predam and postdam eras.

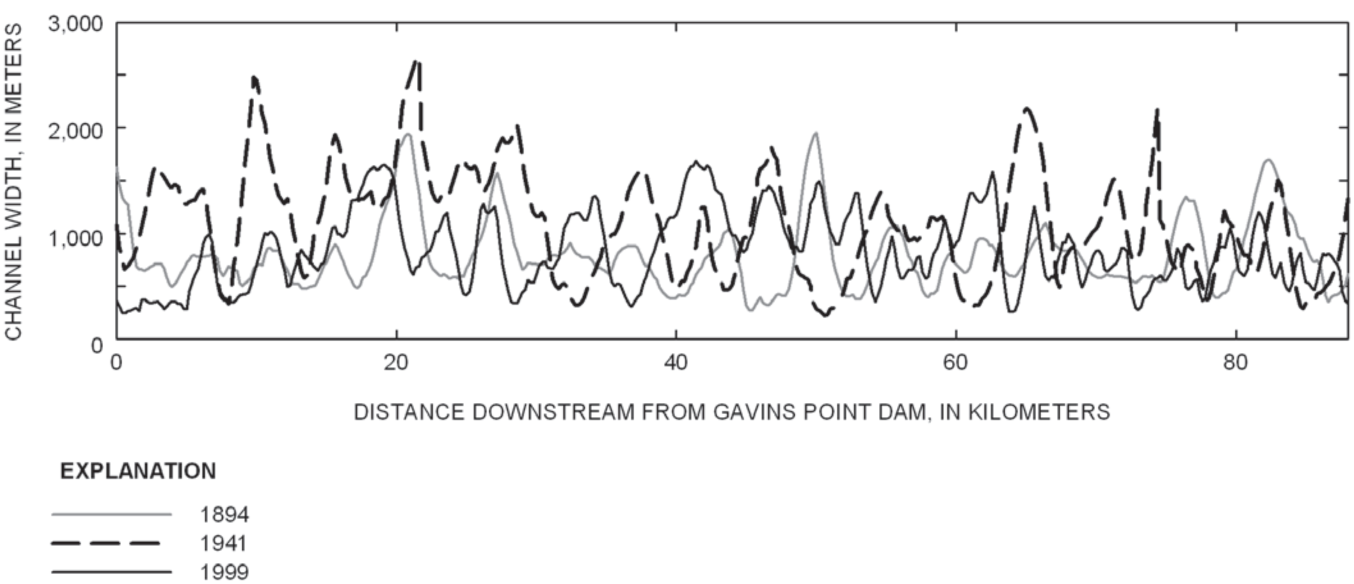


Figure 15. Channel width in the 59-mile segment from 1894, 1941, and 1999. Width measurements are every 200 m along each year's centerline and are shown in kilometers downstream from Gavins Point Dam.

Table 4. Bank material for the Missouri National Recreational River and Kensler's Bend segments, 1999.

[m, meters; **bold** numbers indicate totals]

Bank material		Percent of total bankline		
		39-mile segment	59-mile segment	Kensler's Bend segment
Natural bank material	Natural alluvial banks	37.2	61.9	0.0
	Banks with bedrock within 50 m	48.7	5.2	3.5
	Total	**85.8**	**67.1**	**3.5**
Revetment/protected banks[1]	Revetment/ rock protected banks	12.4	31.5	94.3
	Bedrock and revetment	1.8	1.4	1.1
	Total	**14.2**	**32.9**	**95.4**
	Total unerodible bankline[2]	62.9	38.1	100.0

[1]Protected bankline includes unarmored banks that is between hard points in a protected reach of river.

[2]Total percent unerodible bankline is equal to the total percent bedrock added to the total percent revetment/protected bank.

Sinuosity

Sinuosity was measured at a variety of distances from the segment level to 400 m (fig. 16; table 5). At the segment scale, sinuosity is lowest in the 39-mile segment of the MNRR, particularly in the Lewis and Clark Lake delta. This is also the segment with the narrowest valley widths, and valley width is probably a limiting factor to meandering, especially in the straight reaches immediately downstream of Fort Randall Dam. Where the valley widens in the 59-mile segment, segment-scale sinuosity also increases. Segment-scale sinuosity is highest in the Kensler's Bend segment where the channel has been engineered into large bends.

All segments have experienced a reduction in sinuosity since 1894 although the segment scale sinuosity in the 59-mile segment was the same before and after regulation in 1941 and 1999. The overall reduction in sinuosity for the entire section of the Missouri River has resulted in a shorter river: in 1894 the channel length from the present-day location of Fort Randall Dam to what is now river mile 729 was 256.9 km whereas in 1999 the channel length was only 235.9 km. Most of the length lost is due to loss of a meandering channel in the present day location of Lewis and Clark Lake.

Table 5. Segment-scale sinuosity for the Missouri National Recreational River and adjacent Missouri River segments.

[--, no data]

Segment	Segment-scale sinuosity		
	1894	1941	1999
39-mile, free-flowing reach	1.09	--	1.04
39-mile, delta reach	1.09	--	1.02
Lewis and Clark Lake	1.17	--	1.02
59-mile	1.20	1.1	1.10
Kensler's Bend	1.62	--	1.42
Average	1.23	--	1.11

Sinuosity measurements change with the distance over which they are measured. Over the range of scales used in this study, sinuosity generally increased with scale of measurement (fig. 16). Sinuosity is lowest in the 39-mile segment, with average 400 m to 8 km sinuosity values ranging from 1.004 to 1.044. Sinuosity values at 400 m to 8 km in the 59-mile and Kensler's Bend segments are substantially greater, ranging from 1.007 to 1.154 and 1.004 to 1.148, respectively.

Bars

More than 1,700 bars were mapped on the 1999 orthophotography from Fort Randall Dam to Sioux City (table 6). Nearly 65 percent of these bars consisted of vegetated bars and islands. Both of the MNRR reaches have several large and persistent high-elevation islands. It was difficult to differentiate between the elevation of islands and vegetated bars systematically from aerial orthophotography; therefore, the islands have been included with vegetated bars in the total values for each segment. Vegetated bars and islands are commonly found in wider reaches in the MNRR segments (fig. 17).

In the 39-mile segment, vegetated bar area increases downstream into the Lewis and Clark Lake delta. In the 1999 orthophotography there was an average of 5.6 vegetated bars per kilometer upstream of the mouth of the Niobrara River and 26.6 bars per kilometer in the Lewis and Clark Lake delta downstream of the Niobrara River confluence. There were 1.4 bare sand bars per kilometer in the 39-mile segment upstream of the Niobrara River, and 4.2 bare sand bars per kilometer downstream of the Niobrara River. In the delta reach, bare sand bars are generally smaller and present only in the former Missouri River thalweg.

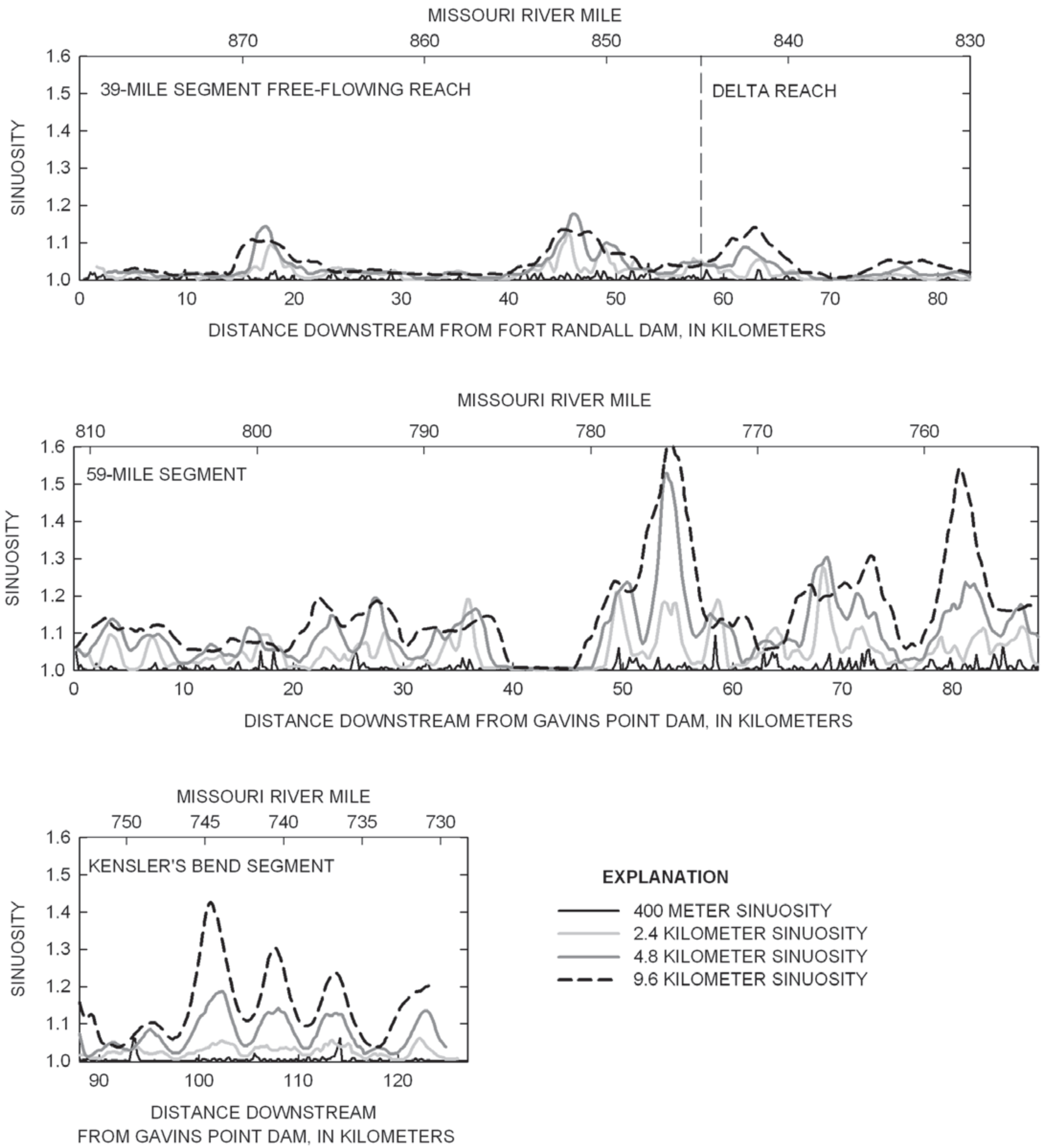


Figure 16. Sinuosity at 400 m, 2.4, 4.8, and 9.6 km in the 39-mile, 59-mile, and Kensler's Bend Missouri River segments based on 1999 channel position.

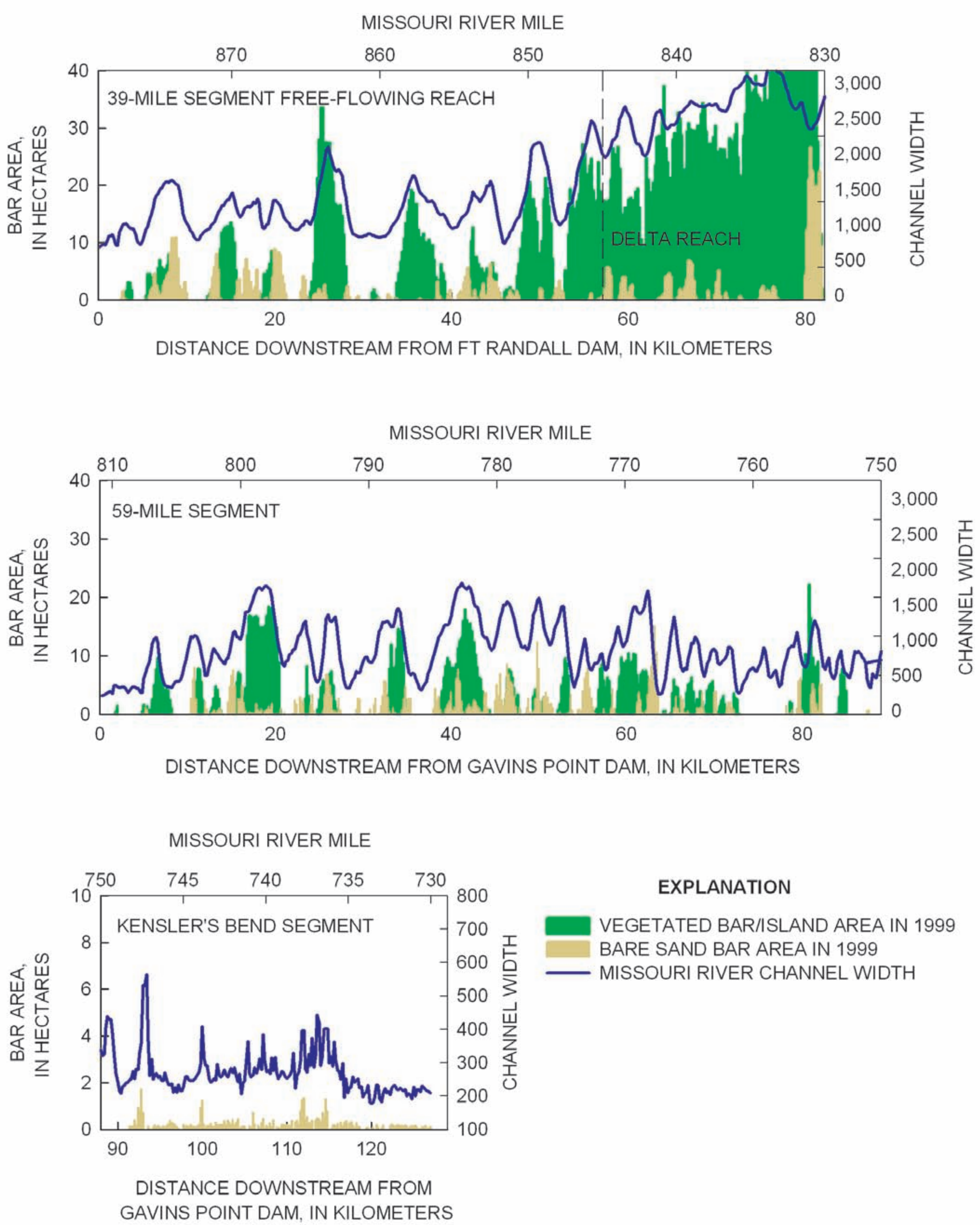


Figure 17. Channel width and bar locations for the 39-mile, 59-mile, and Kensler's Bend Missouri River segments.

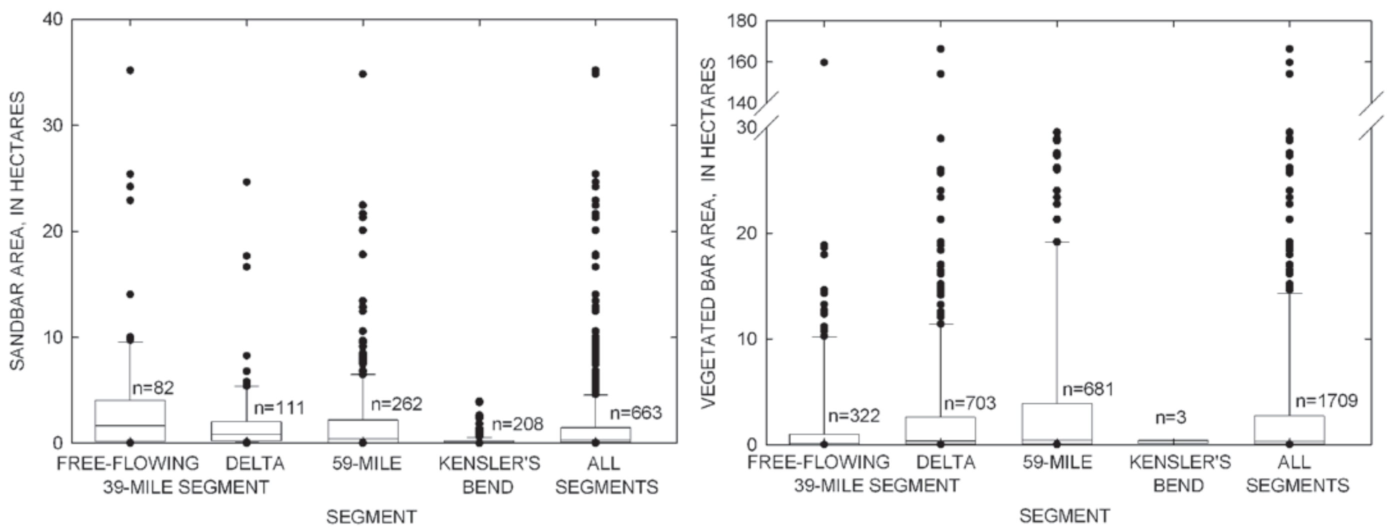
In 1999, the 59-mile segment had fewer vegetated bars than the 39-mile segment, with an average of one vegetated bar per kilometer. The 59-mile segment had three bare sand bars per kilometer. Bare sand bars were almost three times more numerous than vegetated bars/islands in 1999 when the mean size of bare sand bars was about an eighth of the mean bar size of vegetated bars. Two prominent high-elevation islands are present in the 59-mile reach—Rush Island located between river miles 800.5 and 797.8, and Goat Island located between river miles 786 and 782.6. Both Rush Island and Goat Island are large, 230 and 300 ha respectively, and both islands were present at dam closure according to 1955 USACE degradation ranges (West Consultants, 2002).

Vegetated bars and islands are rare downstream of Ponca State Park; there is an average of 0.1 vegetated bars per kilometer in the Kensler's Bend segment. Bare sand bars in the segment average 5.3 bars per kilometer, but these bars on average are much smaller than the bars in the 39-mile and 59-mile segments (fig. 18). Nearly all of the sand bars in the Kensler's Bend segment are associated directly with zones of recirculation behind wing-dikes, with 88 percent of the bars falling within 30 m of a wing dike. In addition, nearly all of the bare sand bars in the Kensler's Bend segment are attached to the bank, with little backwater-channel or side-channel habitat. This is a marked difference from the 39-mile and 59-mile segments where a high proportion of bars are mid-channel bars. The few bare sand bars not attached to the bank in the Kensler's Bend segment are small and generally appear to be related to an adjacent bar that is much larger and attached to the bank.

Table 6. Bar statistics for the Missouri River National Recreational River and adjacent Missouri River segments in 1999.

[km, kilometer; ha, hectares; **bold** indicates totals and means]

Segment	Number	Bars per km	Total bar area (ha)	Bar area per km (ha)	Mean bar area (ha)
Vegetated bars (including islands)					
39-mile, free-flowing reach	322	5.6	1,749	31	5.4
39-mile, Delta reach	703	26.6	4,414	167	6.3
59-mile	90	1.0	1,423	36	15.6
Kensler's Bend	3	0.1	1	0	0.3
Total	**1,118**	**-**	**7,587**	**234**	
Mean	**280**	**5.3**	**1,896**	**59**	**6.9**
Bare sandbars					
39-mile, free flowing reach	82	1.4	302	5	3.7
39-mile, Delta reach	111	4.2	232	9	2.1
59-mile	262	3.0	532	6	2.0
Kensler's Bend	208	5.3	60	2	0.3
Total	**663**	**-**	**1,126**	**22**	
Mean	**166**	**3.2**	**563**	**5**	**2.0**



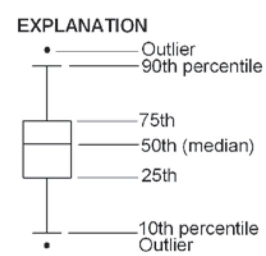


Figure 18. Sand-bar and vegetated-bar (including islands) statistics for the 39-mile, 59-mile, and Kensler's Bend Missouri River segments.

Bars where a coarse substrate of gravel or cobbles was present (particle size distribution 64 mm or greater) were mapped in 31 locations between Gavins Point Dam and Sioux City for a related project (M. Laustrup, U.S. Geological Survey, oral commun, 2006; fig. 19). Eighty percent of the gravel-cobble bars occur in the first 12 km downstream of the dam. The coarse substrate deposits in the combined 59-mile and Kensler's Bend segments comprise nine percent of the total number of coarse-substrate deposits mapped over the 1,300 km of the lower Missouri River downstream of Gavins Point Dam (M. Laustrup, U.S. Geological Survey, oral commun., 2006).

Braiding

Braiding index was defined in this study as the number of channels at a given location (fig. 20). The average braiding index for the 39-mile segment in 1999 was 2.5 channels per location and was highest in the delta reach of the 39-mile segment in the upper reaches of Lewis and Clark Lake where it was 7.2 channels per location. In 1999, the 59-mile segment of the MNRR had a braiding index ranging from 1 to 7 channels per location with an average of 1.9 channels per location. The channelized Kensler's Bend segment was primarily a single-thread channel, with an average braiding index of 1.14 channels per location. Predam data from 1941 indicated a braiding index of 2.83 channels per location in the 59-mile segment.

Large Woody Debris

Large woody debris is a common channel element in the MNRR segments (fig. 13, 21). More than 12,000 pieces of large woody debris were mapped from the 1999 orthophotography in the 39-mile, 59-mile, and Kensler's Bend segments. The overall average was 51.7 pieces per kilometer. The free-flowing reach of the 39-mile segment had 38.1 pieces per km. Nearly half of the large woody debris (43 percent) was mapped within 50 m of the bank and 27 percent was within 20 m of the bank. The Lewis and Clark Lake delta had somewhat lower rates of large woody debris abundance, with 29.2 pieces per kilometer.

Large woody debris was most common in the 59-mile segment, with an average of 96.2 pieces per kilometer. Similar to the 39-mile segment, almost half of the large woody debris in the system (46 percent) was mapped within 50 m of the bank. Of the total number of pieces of large woody debris in the river, 26 percent were within 10 m of the bank. In the 59-mile segment clusters of large woody debris tended to occur adjacent to and immediately downstream of regions where bank erosion was occurring.

The Kensler's Bend segment had 21.6 pieces of large woody debris per kilometer, with 90 percent within 50 m of the bank and 26 percent within 10 m of the bank. Nearly all of the large woody debris visible in the Kensler's Bend segment occurred on inside bends within zones of recirculation near wing dikes and sand bars. Dikes and similar in-channel structures may have acted to trap or collect wood in recirculation zones. This trapping may explain the high loading of large woody debris near wing dikes in the Kensler's Bend segment.

Average numbers of 21.3 large woody debris pieces per kilometer were reported for the Missouri River segment from river miles 1,390 to 1,300 below Garrison Dam in North Dakota (Angradi and others, 2004). This average is much lower than the large woody debris per kilometer in the 39-mile and 59-mile segments. In the Garrison study, large woody debris occurrence and distribution were mapped in detail by field surveys (Angradi and others, 2004). Angradi and others found similarly high occurrences (39 percent) near banks and reported large woody debris loading to be much higher along unstabilized, forested, and alluvial shorelines compared to stabilized banks. No clear relation between bank stabilization and large woody debris was found in our study. On a broad scale, however, the segment with the highest rates of bank erosion, the 59-mile segment, had over twice the large woody debris per kilometer compared to other segments. The Kensler's Bend segment had the highest amount of bank revetment and the lowest amount of large woody debris at 21.6 pieces per kilometer.

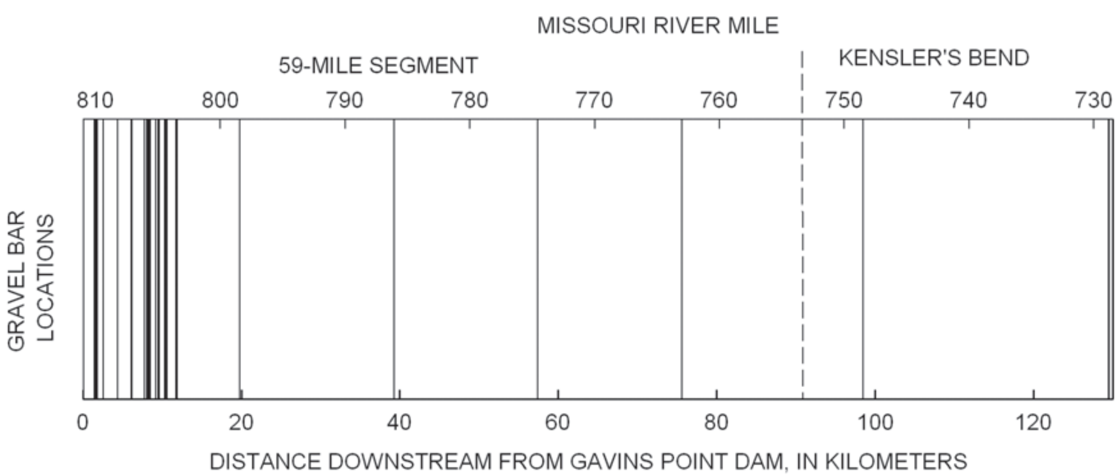


Figure 19. Gravel bar locations for 59-mile and Kensler's Bend segments (Laustrup, oral commun., 2006).

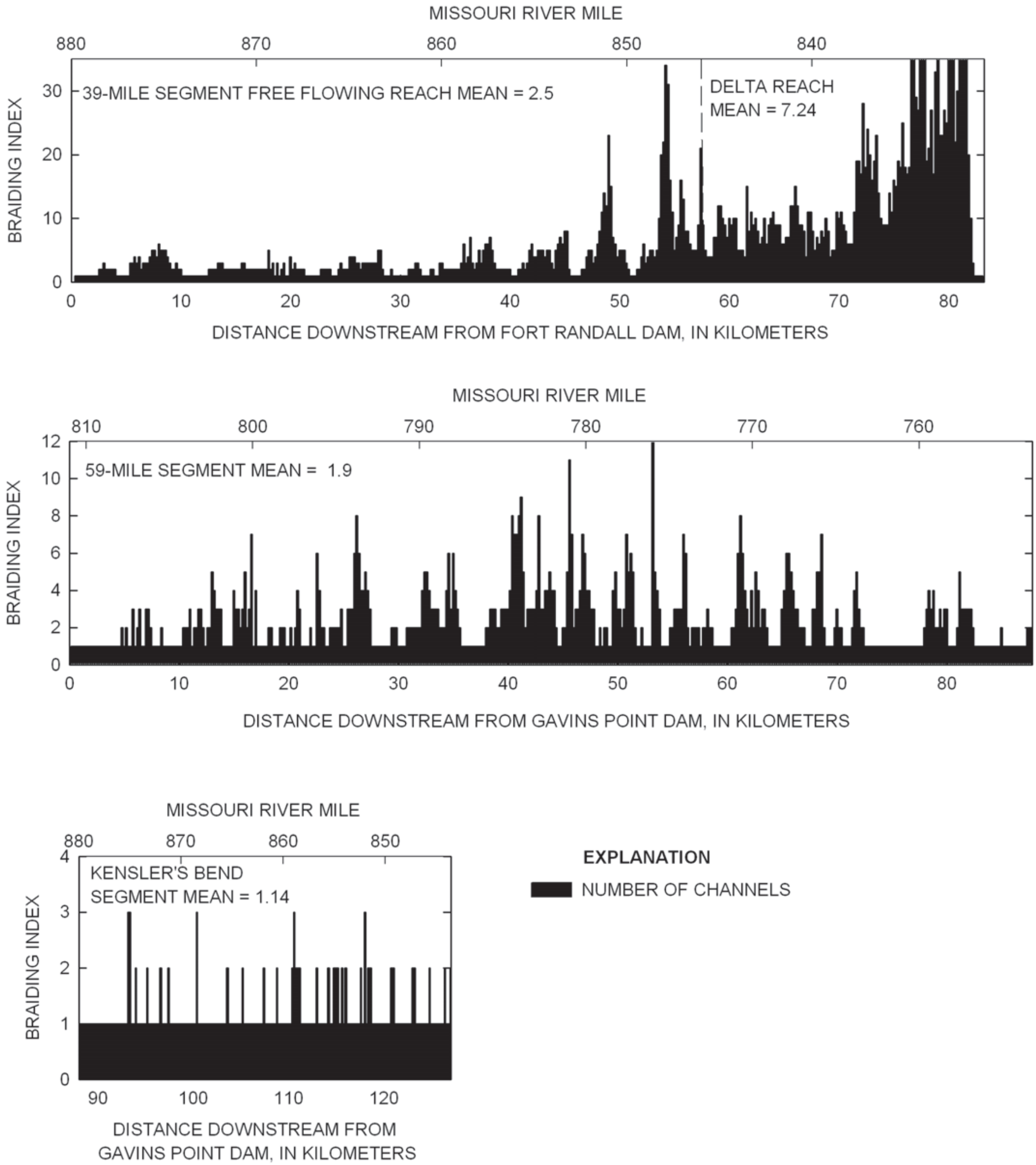


Figure 20. Braiding index for the free-flowing and delta reaches of the 39-mile, 59-mile, and Kensler's Bend Missouri River segments.

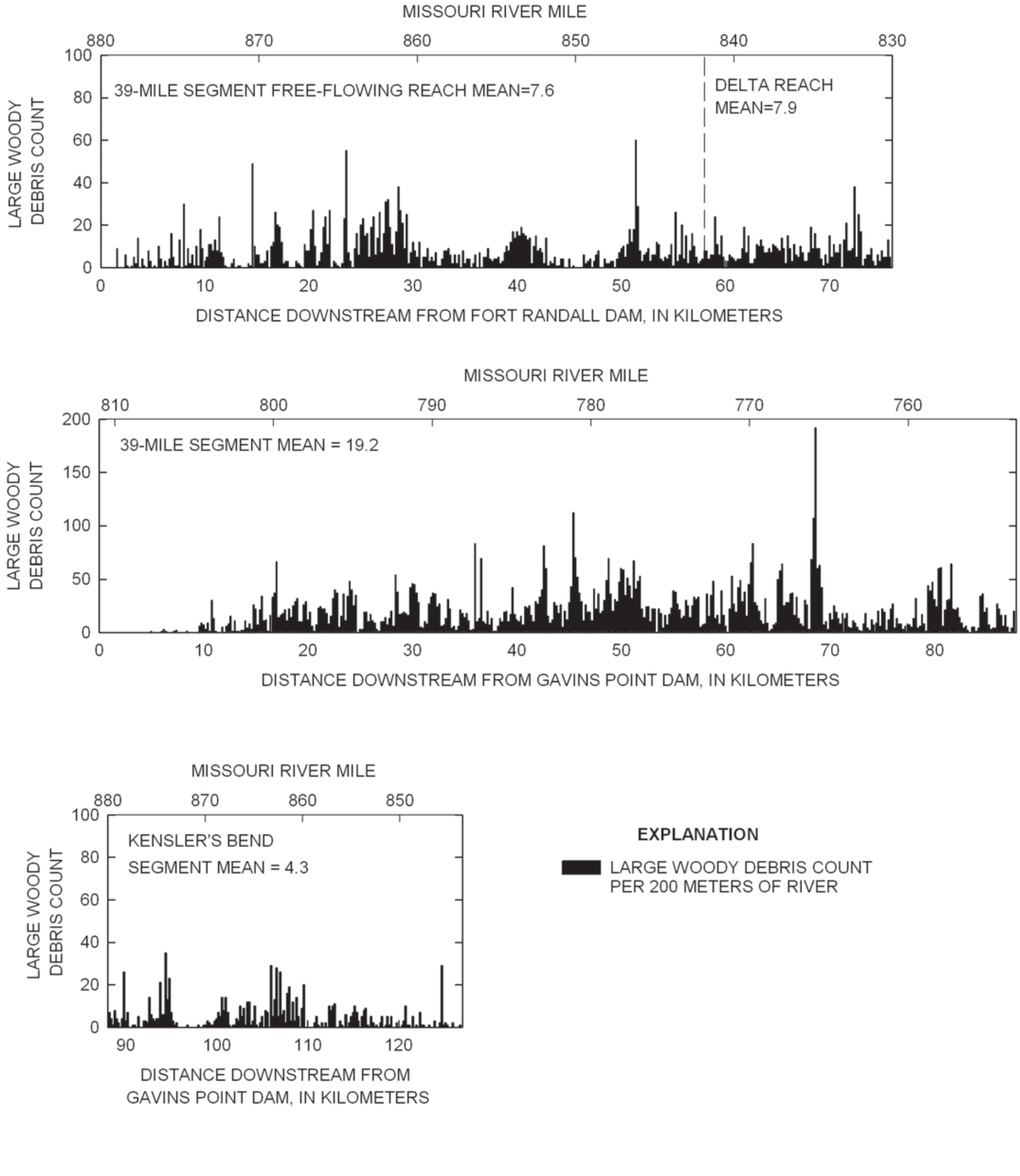


Figure 21. Large woody debris per 200 longitudinal meters of channel in the 39-mile, 59-mile, and Kensler's Bend Missouri River segments.

Temporal Variability

Bank Erosion and Error

In general, bank erosion is spatially variable within and among segments. During the time period addressed in this project, bank erosion was much lower in the 39-mile segment than in the 59-mile segment of the MNRR (fig. 22). We did not attempt to quantify bank erosion in the deltaic part of the 39-mile segment in Lewis and Clark Lake, or in the stabilized Kensler's Bend segment.

The error margin on these totals was based on error buffers placed on the banklines with variable widths corresponding to orthophotograph accuracy. Because of this implicit uncertainty, erosion can be difficult to detect over short time frames. These results are consistent with Hughes and others (2006) who found that error buffer size strongly affected change detection resulting in an inverse relation between buffer size and measurable lateral channel movement. Where there has been a large amount of bank erosion, error-buffer size does not necessarily affect change detection; however, when bank erosion rates are low, bankline erosion detection may become overwhelmed by buffer size. For example, from 2003 to 2004 in the 59-mile segment, the mean-bank-erosion rate was 0.62 lateral meters per longitudinal meter (m/m), but uncertainty was ± 2.37 m/m of channel; therefore, the sum of individual years of bank erosion calculated by using this method did not equal the total amount of bank erosion for the entire time.

In the 39-mile segment, bank erosion totaled 5.7 ha from 1993 to 2003, or 0.99 m/m; table 7). In this segment, erosion rates were much higher, 6.2 ha, from 1993 to 1999 than from 1999 to 2003, 0.3 ha. Because of low rates of detectible bank erosion and high error margins on measurements in the 39-mile segment, rates were not calculated for as many individual year pairs compared to the 59-mile segment. There was no detectible erosion on the right bank in the 39-mile segment during 1993–2003.

In the 59-mile segment, there were 206 ha, or 22.08 m/m (±5.71 m/m) of bank erosion from 1993 to 2004 and the yearly average erosion rate was 19 ha/yr, or 2.01 m/m (fig. 23; table 7). During this time, 2003–04 had the lowest rate of bank erosion at 6 ha/yr. The highest period of bank erosion measured was 37 ha/yr from 1996 to 1997, coinciding with the high-flow events that occurred during the same time (fig. 2). These results are considerably lower when compared to the USACE yearly average estimates for bank erosion for the 59-mile segment from 1995 to 1997 of 100 ha/yr (table 1). It is difficult to compare erosion rates directly because of varying definitions of bankline, different methods of erosion detection and data collection, and different periods of data collection.

Erosion almost always occurs on banks composed of alluvial sediments. Banks that are made up of bedrock, or that have been protected with rock or other materials, are usually not associated with regions of rapid erosion. In the 59-mile segment, 43 percent of the unprotected bankline did not erode within detectible limits from 1993 to 2004. Conversely, 57 percent of unprotected banks had detectable bank erosion. Small areas of erosion also occasionally occur within reaches with bank protection. Typically this erosion occurs as "scallops" in unarmored areas between hard points. These individual areas are generally small (< 0.5 ha in area).

Bank erosion did not occur in the same locations over every time period (fig. 24). A detailed sequence of bank erosion from 1993 to 2004 near river mile 779 (51.2 km below Gavins Point Dam) illustrated the nature and magnitude of changes in bank erosion. On the right bank, substantial erosion was measured for every year of data. The yearly average bank erosion rate in the segment has slowed since 1996 and no erosion occurred in 2003 on the left river bank. This change likely was due to the deposition of a large sand bar near the left bank associated with a shift in the channel thalweg after the 1997 high flow event.

Table 7. Total erosion areas with error calculations for the 39-mile and 59-mile segments of the Missouri National Recreational River.

[ha, hectares; m/m, lateral meters per longitudinal meters; no., number; ha/yr, hectares per year; m/m/yr, meters per meter per year; **bold** indicates mean]

Period	Total erosion area[1] (ha)	Total erosion area[1] (m/m)	Error (from buffer area)[1] (ha)	Error (from buffer area)[1] (m/m)	Years (no.)	Erosion rate[1] (ha/yr)	Erosion rate[1] (m/m/yr)
39-mile segment							
1993–99	6.2	1.08	±6.8	±1.19	6	1.0	0.18
1999–2003	0.3	0.05	±1.2	±0.22	4	0.1	0.01
Mean			±4.0	±0.71		**0.5**	**0.09**
1993–2003	5.7	0.99	±7.2	±1.26	10	0.6	0.10
59-mile segment							
1993–96	59	6.30	±28	±5.71	3	20	2.10
1996–97	37	3.96	±33	±3.52	1	37	3.96
1997–98	14	1.55	±30	±3.26	1	14	1.55
1998–99	17	1.82	±22	±2.38	1	17	1.82
1999–2001	27	2.84	±21	±2.27	2	13	1.42
2001–03	15	1.65	±29	±3.15	2	8	0.83
2003–04	6	0.62	±22	±2.37	1	6	0.62
Mean			**±27**	**±3.24**		**16**	**1.76**
1993–2004	206	22.08	±53	±5.71	11	19	2.01

[1] Due to the method used to calculate error, the sum of bank erosion for each individual time period does not equal the total erosion calculations for the entire time period.

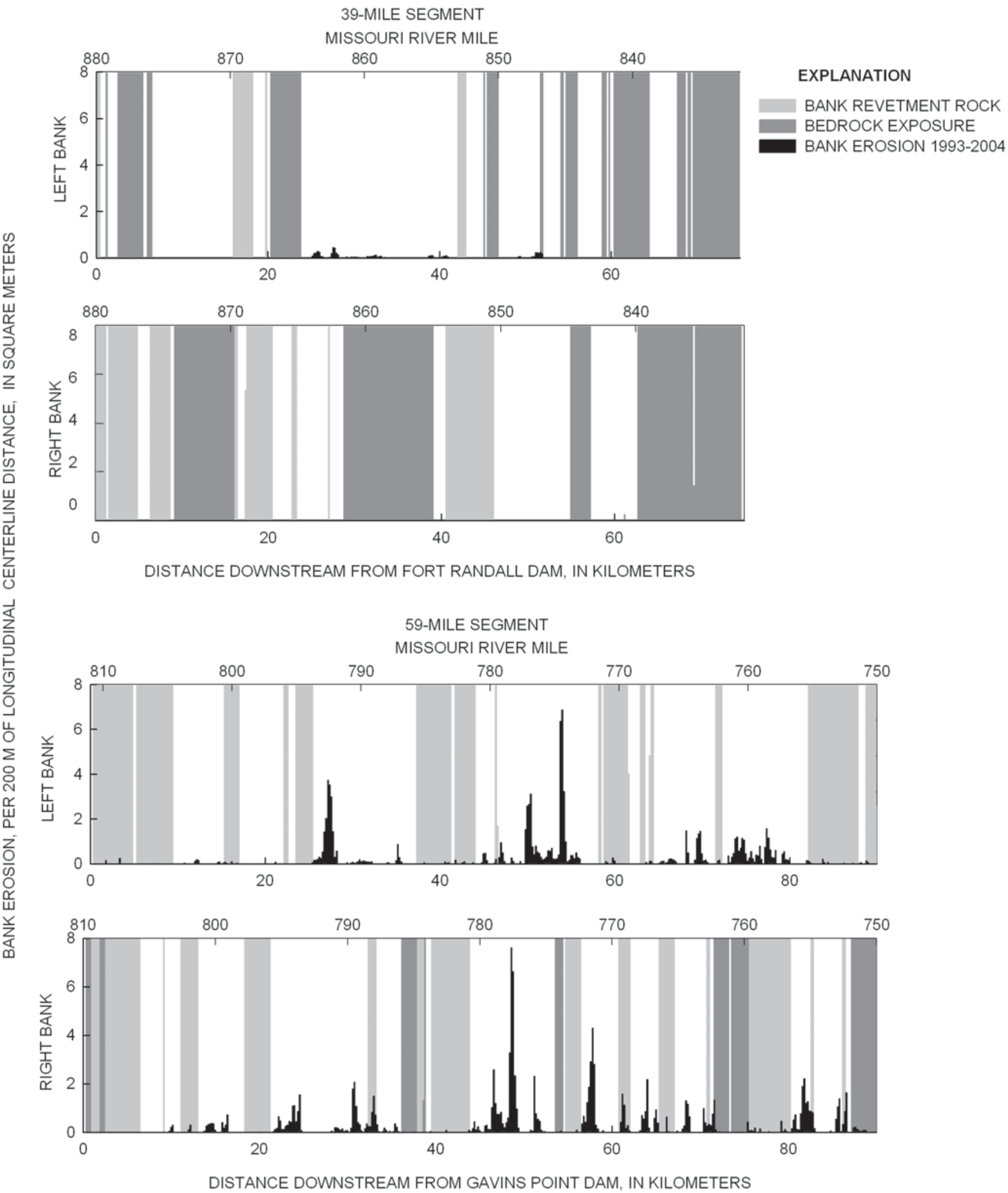


Figure 22. Erosion per 200 m of longitudinal channel by centerline for the 1993–2004 period in the 39-mile and 59-mile Missouri River segments. Bank revetment and banks within 50 m of bedrock exposures are also indicated. The left and right bank refer to the river left and right banks when facing downstream.

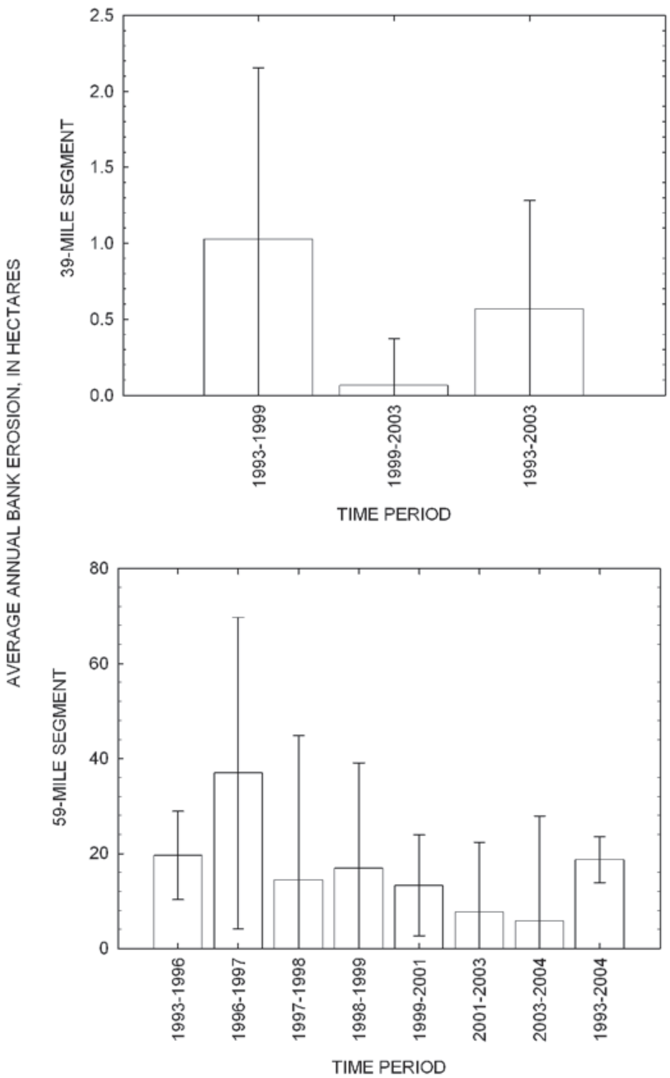


Figure 23. Erosion results for the 39-mile and 59-mile segments by year with error bars.

Bank erosion is much higher in the 59-mile segment than the 39-mile segment (table 7). Historical USACE bank and bed erosion data also verify that postdam erosion rates are considerably lower in the 39-mile segment than the 59-mile segment (Pokrefke and others, 1998; Biedenharn and others, 2001; table 1). This difference in erosion rates likely is due to two primary factors. First, about 50 percent of the banks of the 39-mile segment are within 50 m of the valley wall (table 4), and are presumably protected by stable bedrock. In addition, the downstream end of the 39-mile segment is aggrading, and reservoir backwater effects are seen well upstream of the Niobrara River. There is a much smaller percentage of bankline in the 39-mile segment affected by erosional fluvial processes.

Bar Changes Over Time: Multiyear Analysis

Because bar area is sensitive to discharge and the orthophotography used in this analysis had discharges varying from 662 to 1,862 m^3/s, it is impossible to quantify bar changes over time directly based on area. A more robust analysis of change over time is to focus on bar counts (frequencies, rather than area). Bar area change over time can be assessed indirectly by compiling regression models of discharge and bar area and then examining the trend of residuals over time.

In the free-flowing reach of the 39-mile segment, there were 5.6 and 2.9 vegetated bars per kilometer mapped in 1999 and 2004 (322 and 164 bars total; fig. 25, table 8). In the delta reach of the 39-mile segment, there was a similar decrease in total number of mapped vegetated bars (703 to 465). The numbers of bare sand bars in the free-flowing reach of the 39-mile segment were 1.4 per kilometer in 1999 and 1.5 per kilometer in 2004. In the delta, there were 4.2 bars per kilometer mapped in 1999 and 2.9 bars per kilometer mapped in 2004. Because discharges were dissimilar for the two dates and only two dates of imagery were available, it was not possible to evaluate trends over time and area.

Table 8. Multiyear bar analysis in the 39-mile segment of the Missouri National Recreational River.

[m^3/s, cubic meters per second; km, kilometer; ha, hectares]

Segment and year	Discharge (m^3/s)[1]	Number of bars	Bars per km	Total bar area (ha)	Mean bar area (ha)
Vegetated bars (including islands)					
39-mile, free-flowing reach					
1999	680	322	5.6	1,749	5.4
2004	735	164	2.9	1,902	12.0
39-mile, delta reach					
1999[2]	680	703	26.9	4,414	6.3
2004	735	465	17.6	4,177	9.0
Bare sand bars					
39-mile, free-flowing reach					
1999	680	82	1.4	302	3.7
2004	735	85	1.5	351	4.0
39-mile, delta reach					
1999[2]	680	111	4.2	232	2.1
2004	735	77	2.9	237	3.0

[1] Discharge at Fort Randall Dam. Several orthophotograph sets were taken over a range of dates; discharge is the mean within the range of discharges for the orthophotograph set.

[2] Full coverage of the delta reach was not available from U.S. Army Corps of Engineers 1999 orthophotographs; the downstream most 2 km of the delta were supplemented with 1999 U.S. Geological Survey Digital Orthophoto Quarter Quadrangles.

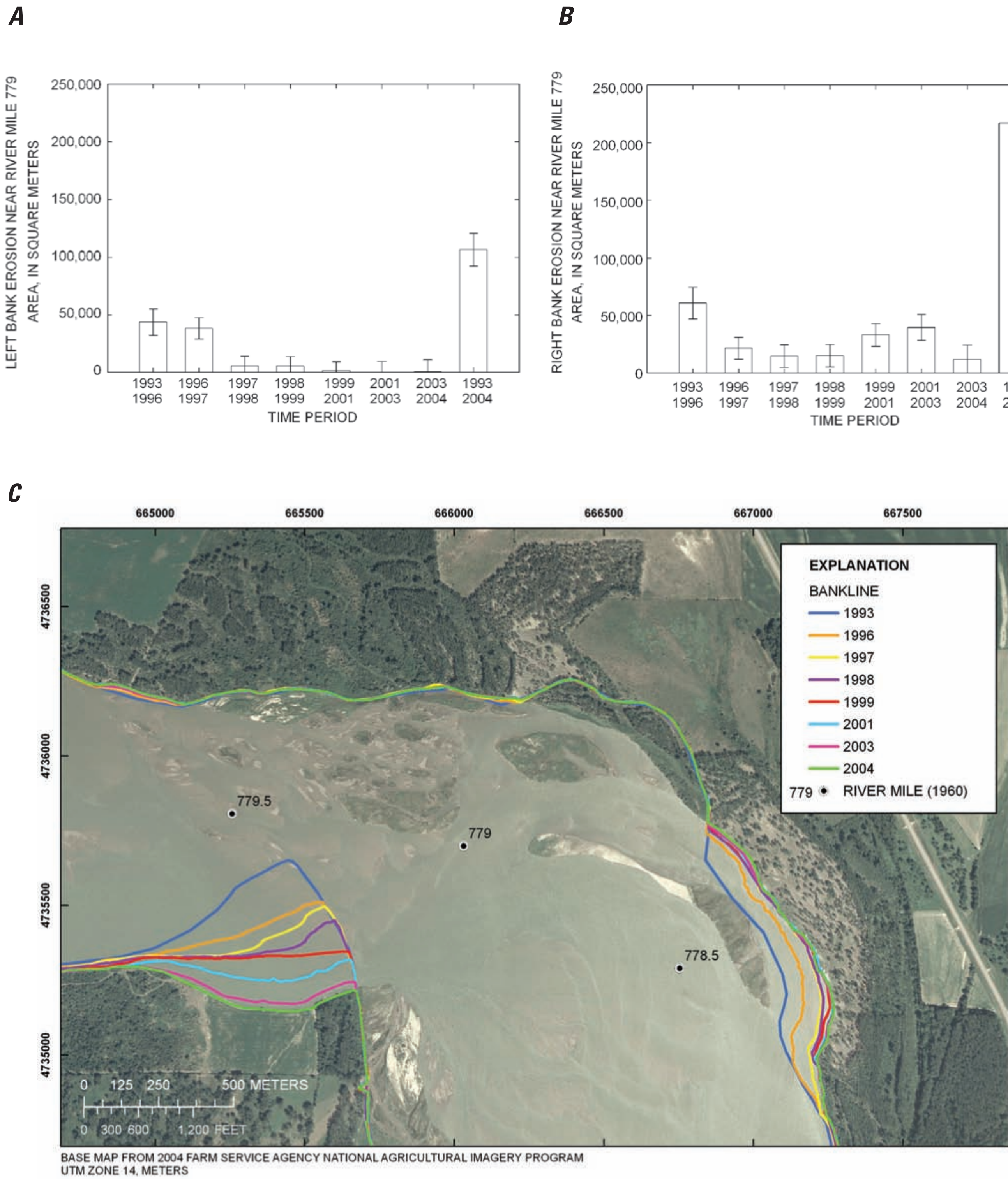


Figure 24. Bank erosion in the 59-mile segment at river mile 779. *A,* Erosion areas at left descending bank near river mile 779. *B,* Erosion areas at right descending bank near river mile 779. *C,* Map view of erosion history near river mile 779. On the right descending bank, erosion occurred every year the banklines were measured. On the left descending bank, erosion only occurred from 1993 to 1999 when growth of a midchannel sand bar caused the thalweg to shift and protected the bank from further erosion.

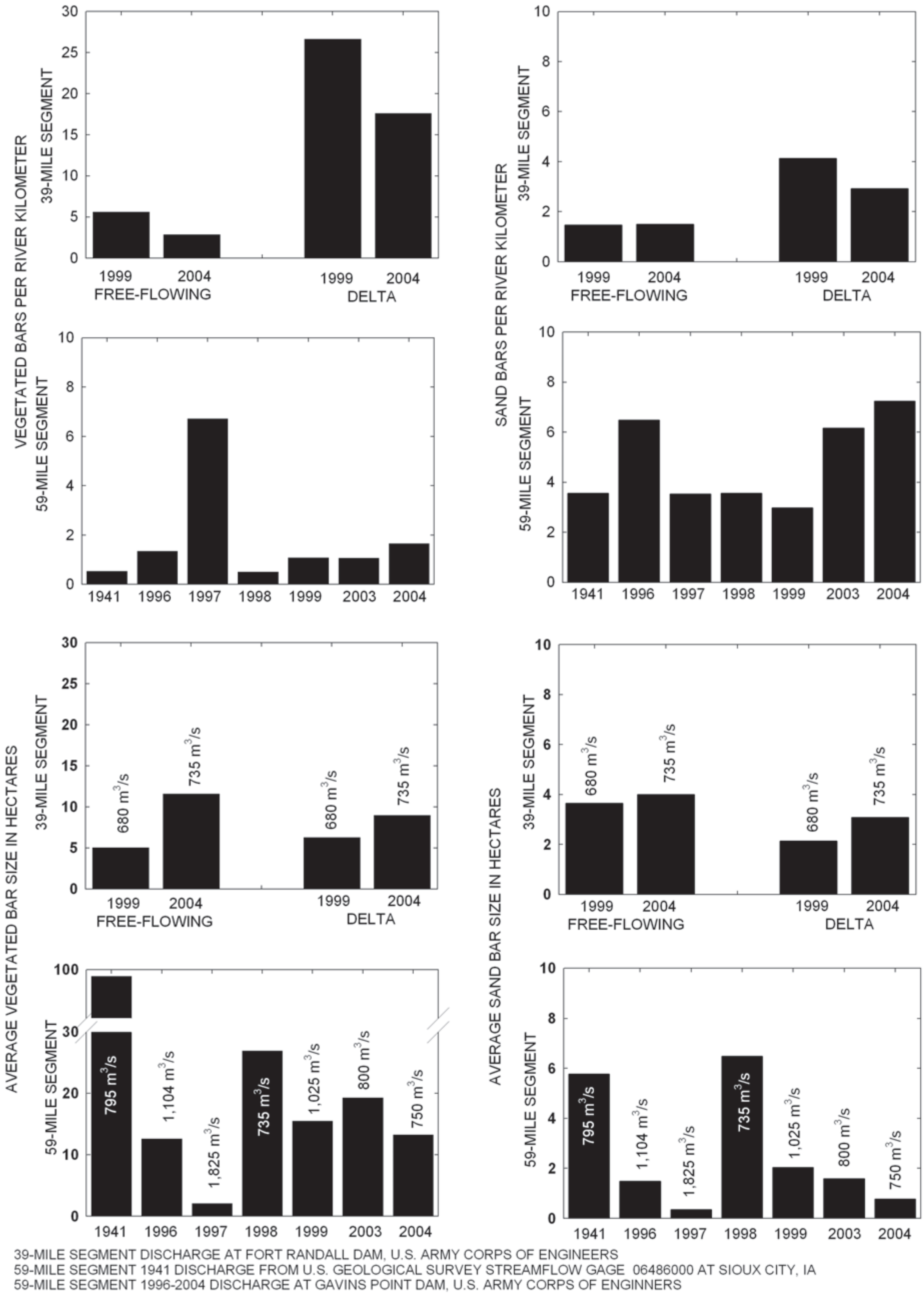


Figure 25. Changes in number and mean area of sand bars and vegetated bars over time in the 39-mile and 59-mile segments of the Missouri National Recreational River. Discharge, in cubic meters per second (m^3/s) is indicated for each year.

In the 59-mile segment, vegetated bars were most numerous in orthophotography acquired during the 1997 sustained high-flow period at average discharge of 1,826 m^3/s from Gavins Point Dam (fig. 25; table 9). During this relatively high-flow event, there were 589 vegetated bars, or 6.7 bars per kilometer. The average vegetated bar size was very small (mean = 2.0 ha), however, and the high number of vegetated bars mapped is likely due to flows that dissected existing bar-sand islands at this discharge. The number of vegetated bars in 1998 was relatively low, 45 bars, or 0.8 bars/km, yet their sizes were relatively large (mean = 26 ha). This variance is likely because vegetation was scoured from many of the smaller bars and many of the relatively large bars were not dissected by channels at the discharge captured in the orthophotography.

The number of bare sand bars per kilometer has remained fairly stable in the 59-mile segment in recent years: 6.2 bars per kilometer in 2003 and 7.2 per kilometer in 2004. These numbers are similar to the pre-1997 bar density of 6 per kilometer in 1996 (table 9). Most bare sand bars were submerged during the high flows in 1997. There were fewer bars per kilometer during the 1998–99 period (3.6 bars per kilometer, 3 bars per kilometer) compared to pre-1997 (6.5 bars per kilometer in 1996), but mean bar area was relatively high in 1998 (mean area = 6 ha) and remained fairly high in 1999 (mean area = 2 ha). From 2003 to 2004 there was an increase of roughly 100 sand bars in the segment, yet an overall decrease in bar area and mean bar area (mean bar area = 2 ha in 2003 and 1 ha in 2004). Although discharge was variable during this period, some of the loss of bar size and increase in number seems to be due to bar erosion and dissection.

Table 9. Multiyear bar analysis in the 59-mile segment of the Missouri National Recreational River.

[m^3/s, cubic meters per second; km, kilometer; ha, hectares]

Year	Discharge (m^3/s)[1]	Number of bars	Bars per km	Total bar area (ha)	Mean bar area (ha)
Vegetated bars (including islands)					
1941[2]	795[3]	46	0.5	4,534	99
1996	1,104	118	1.3	1,486	13
1997	1,826	589	6.7	1,212	2
1998	736	45	0.5	1,209	27
1999	1,025	90	1.0	1,420	16
2003	800	93	1.1	1,793	19
2004	747	145	1.7	1,921	13
Bare sand bars					
1941[2]	795[3]	312	3.6	1,804	6
1996	1,105	568	6.5	840	1
1997	1,825	309	3.5	108	0.4
1998	735	312	3.6	2,022	6
1999	1,025	262	3.0	532	2
2003	800	540	6.2	858	2
2004	750	634	7.2	492	1

[1] Discharge at the U.S. Army Corps of Engineer's gage at Gavins Point Dam. Several photograph sets were taken over a range of dates, discharge is the mean within the range of discharges for the orthophotograph set.

[2] 1941 discharge at U.S. Geological Survey streamflow gage 06486000 at Sioux City.

[3] Some 1941 photographs were missing; bar areas were estimated between missing photographs.

We assessed trends in bar area for the 59-mile segment by modeling bar area as a linear function of discharge. The residuals of this regression, plotted by year, indicated trends in bar areas that account for variable discharge (fig. 26). Vegetated bar residuals reflected the effect of the 1997 high discharges as very low values in 1998 (the average relation of discharge and vegetated bar area severely over-predicted bar area in 1998). Apart from the 1998 outlier, the relation of residuals indicated an increasing trend in vegetated bar areas for 1997 to 2004, independent of discharge variation. This trend was consistent with vegetation encroachment on bars created during 1997. Conversely, residuals for sand bars indicated that 1998 had sand bars far in excess of the area that would be predicted based on the average area-discharge relation alone. The overall trend in sand-bar area residuals is negative, indicating loss of sand bars independent of discharge variation, probably as a result of vegetation encroachment and erosion. The trend in all bar area residuals by year was also negative, indicating that loss of sand-bar area dominated loss of bars and associated habitat complexity.

In the 1941 predam dataset for the 59-mile segment, there were fewer vegetated bars, 0.53 bars per kilometer, than in the postdam period, but vegetated bar area was very high (fig. 25, table 9). This difference resulted from the large number of off-channel chutes that defined large vegetated islands. Bare sand bars numbered 3.6 per kilometer in 1941, a number equal to the 3.6 sand bars per kilometer in 1998, following the 1997 high-flow event. High flow events were common in the flow regime of the predam era (fig. 2) and such events were likely capable of creating new sand bars and scouring vegetation from existing low-lying bars.

Growth of the Lewis and Clark Lake Delta

The delta of Lewis and Clark Lake has grown an average of 105 m longitudinally each year from 1993 to 2003 (fig. 27), indicating an average growth rate of 1.05 kilometers per decade. Based on topographic maps from 1978 (USGS 1978 digital raster graphic quadrangles for Springfield, South Dakota, and Santee, Nebraska) the total delta growth for the 25-year time period is 4.98 km with an average of 199 m per year. Although contributing to loss of storage capacity in the reservoir, loss of waterfront access, and increasing groundwater levels, the growth of the delta has produced abundant backwater and wetland habitat.

Multiple-Year Bar-Persistence Analysis

In both the 39-mile and 59-mile MNRR segments, vegetated bar locations are much more persistent over time than bare sand bars. In the 39-mile segment, bar persistence was measured by compiling bar occurrence in 1999 and 2004. In the free-flowing reach of the 39-mile segment, 83.3 percent of 10-m grid cells were mapped as vegetated bars in the same location in 1999 and 2004 (table 10). In the delta reach of the 39-mile segment, 73.9 percent of bars were present in the same location in both years. Vegetated-bar changes from 1999 to 2004 occurred primarily in the delta as bar interiors remained stable, margins generally increased in size, and the total number of bars grew.

In the 59-mile segment bar persistence was measured over 6 photograph years: 1996, 1997, 1998, 1999, 2003, and 2004. Vegetated bars were also much more persistent in location than bare sand bars. Nearly half (42.7 percent) of the 10-m grid cells mapped as vegetated bars in this segment were mapped as vegetated bars in all 6 years. Only 0.1 percent of cells mapped as bare sand bars were present in all 6 years; however, this figure is biased by high flows in 1997 when there was very little sand exposed. Eighteen percent of cells mapped as bare sand bars were located in the same place for 3 years or more.

Table 10. Bar persistence in the 39-mile and 59-mile segments of the Missouri National Recreational River.

Segment	Number of years present	Vegetated bars (percent of total)[3]	Bare sand bars (percent of total)[3]
39-mile, free-flowing reach[1]	1	16.7	67.2
	2	83.3	32.8
39-mile, delta reach[1]	1	26.1	96.4
	2	73.9	3.6
59-mile[2]	1	15.7	59.1
	2	17.8	22.9
	3	5.3	11.4
	4	8.9	5.3
	5	9.6	1.2
	6	42.7	0.1

[1]Orthophotograph years 1999, 2004.

[2]Orthophotograph years 1996, 1997, 1998, 1999, 2003, and 2004.

[3]These values refer to the total percent of sand or vegetated bars that occur in a given location. For instance, in the 39-mile free flowing reach, 16.7 percent of the vegetated bars were present in 1 of the 2 years, 1999 or 2004, and 83.3 percent were present in both years 1999 and 2004. Therefore, in this reach of the river, 83.3 percent of vegetated bars were persistent over the measurement period.

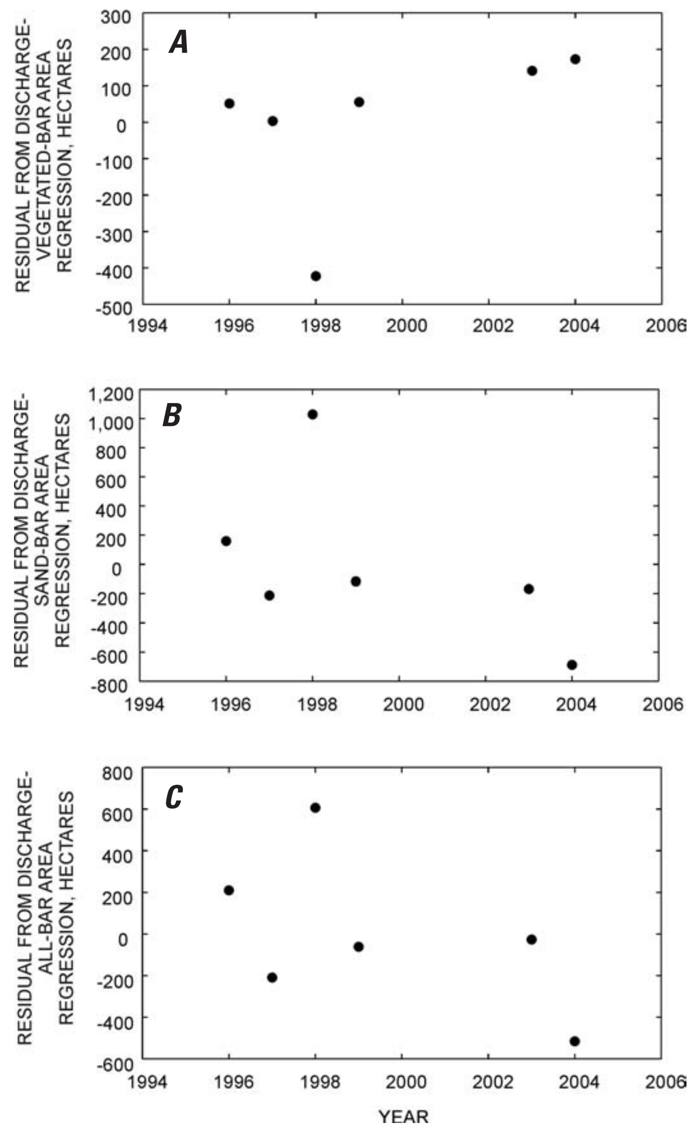


Figure 26. Residuals from bar area-discharge regressions plotted against year indicate trends in bar area that are independent of discharge in all three segments. *A,* Vegetated-bar area shows an increase. *B,* Sand-bar area shows a decrease. *C,* All-bar area shows a decrease. Note that large sand-bar area and small vegetated-bar area in 1998 resulted from scour of vegetation and bar-building during high flows in 1997.

Spatial Controls and Temporal Change

This section addresses spatial controls on changes in river features over time, from the predam era where data were available to a recent decade. Predam conditions provide a potential reference for management and restoration planning.

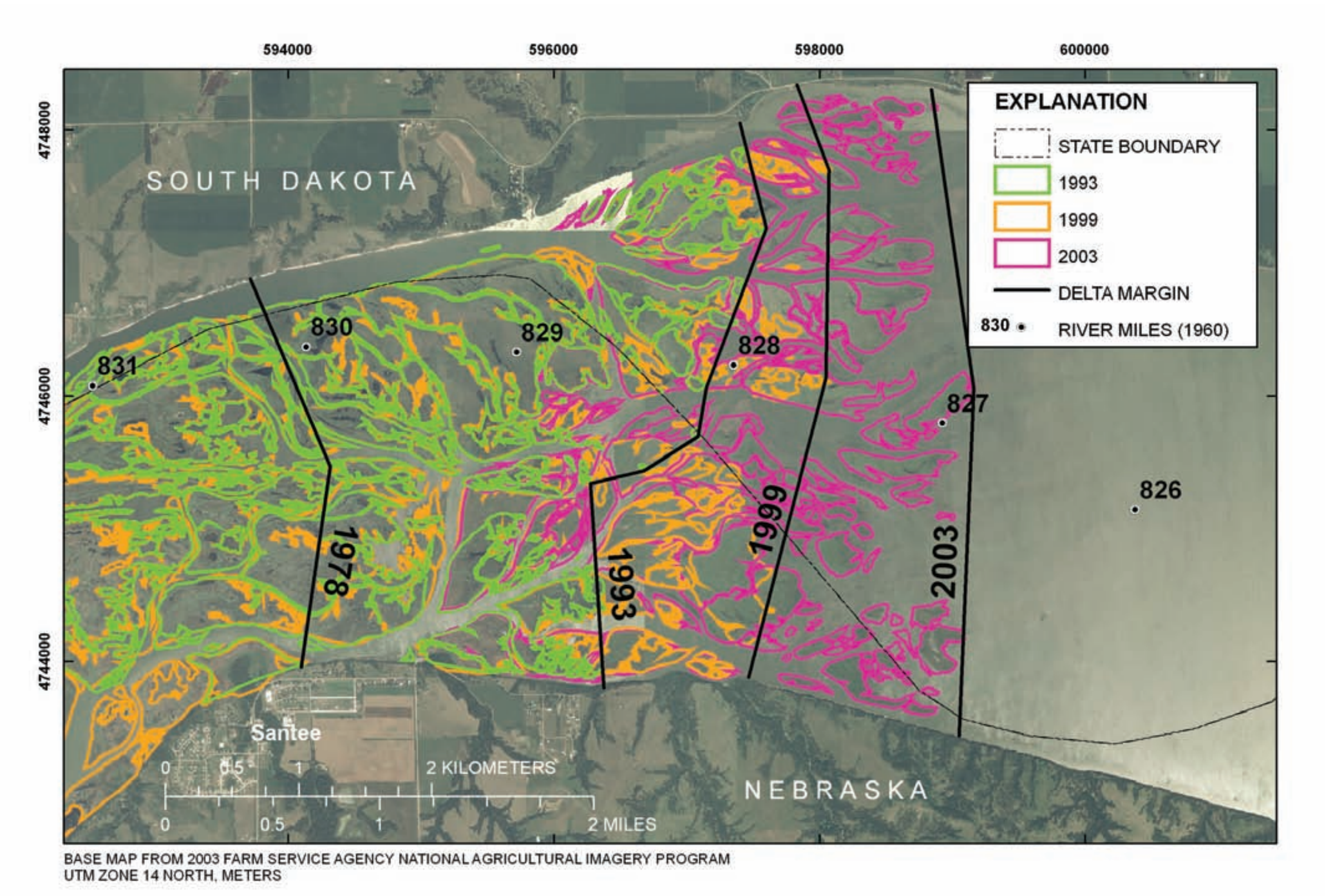


Figure 27. Delta-bar progression in the headwaters of Lewis and Clark Lake.

Bar Persistence and Channel Width

In the 39-mile segment, bare sand bars occur primarily in relatively narrow channel settings between 600 and 1,500 m wide (fig. 28). Vegetated bars are common with channel widths around 1,200 to 2,500 m.

In the 59-mile segment, bare sand bars and vegetated bars do not frequently occur at channel widths less than 700 m; most sand bars occur where the channel is 600 to 1,500 m wide (fig. 28). Vegetated bars occur in channels with similar widths compared to bare sand bars. Reaches with both bare and vegetated bars are generally more than 700 m wide.

These results differ slightly from a previous study (Biedenharn and others, 2001), which found 500 m to be the threshold width for bar formation in the 59-mile segment. The Biedenharn study, however, used a presence/absence analysis at 0.8 km increments, and only 2 years of photos, 1977 and 1983, with unspecified discharges. The present analysis used more robust data: a presence/absence of bars over 6 years of photography (discharges ranging between 662 and 1,862 m^3/s) and a 200 m sampling interval.

The threshold width for sand bar persistence presumably resulted from the hydraulics of flow expansion. Where the channel was relatively narrow, sand bedload moved through the reach. Where channel width expanded, transport capacity decreased and sand deposited as bars. The upstream part of the expansion zones would tend to experience both erosional and depositional events, depending on the range of discharges, and would therefore maintain more bare sand bars. Farther downstream in the expanded zone, vegetation scouring flows would be less common and vegetated bars would therefore persist.

Historical Channel Positions

Channel positions from the 1894 Missouri River Commission maps, digital raster graphics from the 1960s and 1970s, and digital orthophotography from 1993 to 2005 show that the 39-mile channel has occupied nearly the same position for much of this history. In contrast, the wide flood plain of the 59-mile and Kensler's Bend segments contain numerous channel migration scars, wetlands, oxbow lakes, and abandoned chutes, attesting to a dynamic history of channel change. Downstream of Gavins Point Dam, the meanders of the river have changed position substantially during the historical period except for two reaches that the river has occupied

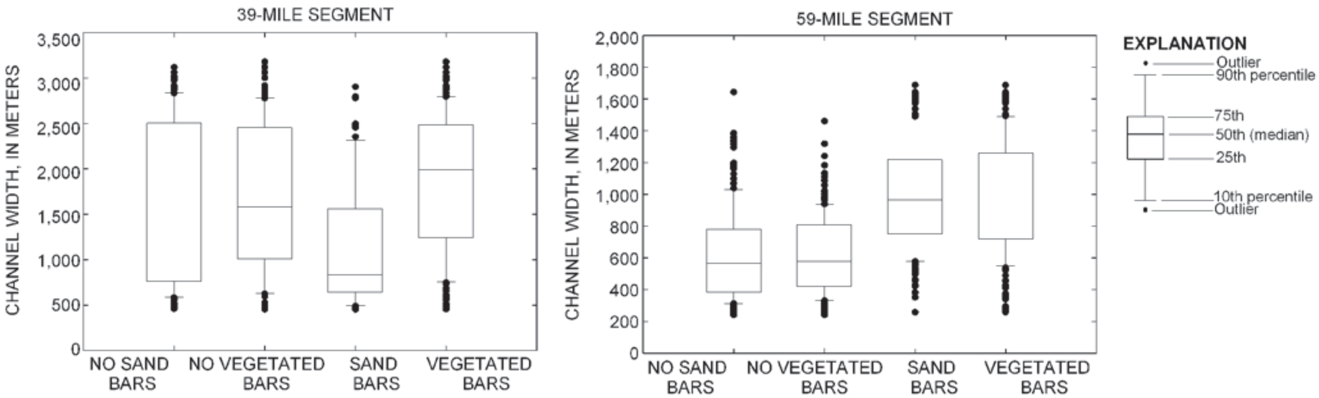


Figure 28. Bar persistence and channel width for the 39-mile and 59-mile segments for locations with and without bare sand bars and vegetated bars. The 39-mile segment analysis is based on 2 years of bar locations and the 59-mile segment on 6 years.

continuously since 1894 at river miles 787–83 in the 59-mile segment (fig. 29) and river miles 746–42 in the Kensler's Bend segment. Both of these reaches are bordered by bedrock on the right bank.

The pattern of alternating wide and narrow reaches was evident during both the predam and postdam time periods, but in many cases the positions of wide and narrow reaches have shifted (figs. 15, 30–32). Based on channel positions from 1894 to 2004 and degradation range data from 1955 to 2002 in the 59-mile segment, it appears that channel migration rates were higher in the predam era than they are today (West Consultants, 2002). Predam erosion-rate estimates by the USACE documented that predam bank erosion rates were higher than the postdam rates, with an erosion rate from 1930 to 1956 of 80 ha/yr, and a postdam rate from 1956 to 1997 of 50 ha/yr (West Consultants, 2002).

The 59-mile segment has a much wider flood plain than the 39-mile segment. The active channel of the river takes up, on average, 40 percent of the flood plain upstream of the Niobrara River in the 39-mile segment. In the delta reach, the river has aggraded and expanded so the active channel averages 90 percent of the flood plain. The 59-mile segment occupies, on average, 10.5 percent of the valley, but this percent ranges considerably from 1.3 to 66 percent. The Kensler's Bend segment occupies an average of 2.3 percent of the Missouri River valley. The most dramatic changes from the predam, prechannelization era are seen in the Lewis and Clark Lake delta reach and Kensler's Bend segment. The Missouri River in what is now the Lewis and Clark Lake delta occupied between 16 and 40 percent of the space in the valley with an average value of 29 percent. Before channelization in the Kensler's Bend segment the channel occupied between 3 to 20 percent of the valley and averaged 10 percent.

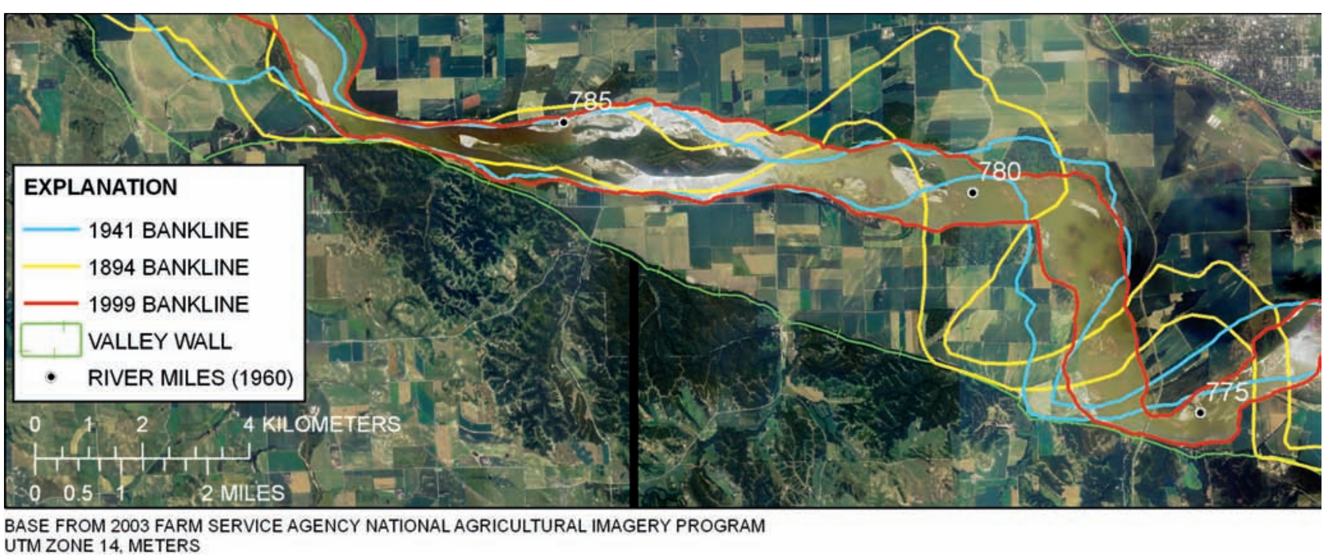


Figure 29. Channel position for a reach of the 59-mile segment from1894 to 1999. Bank positions have remained remarkably stable in some places, but have meandered many kilometers in adjacent reaches.

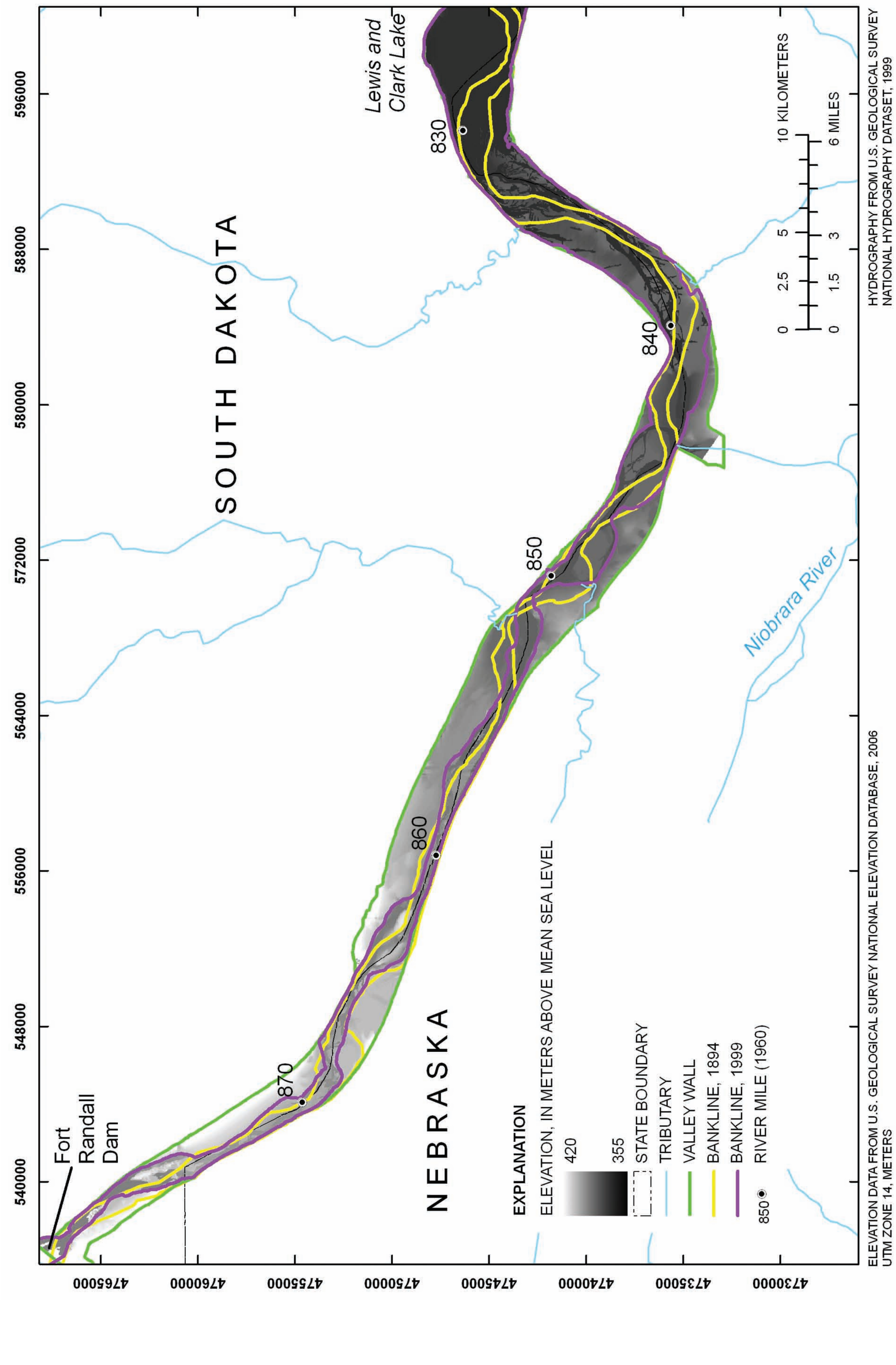


Figure 30. Historical channel positions and flood-plain topography in the 39-mile segment of the Missouri National Recreational River.

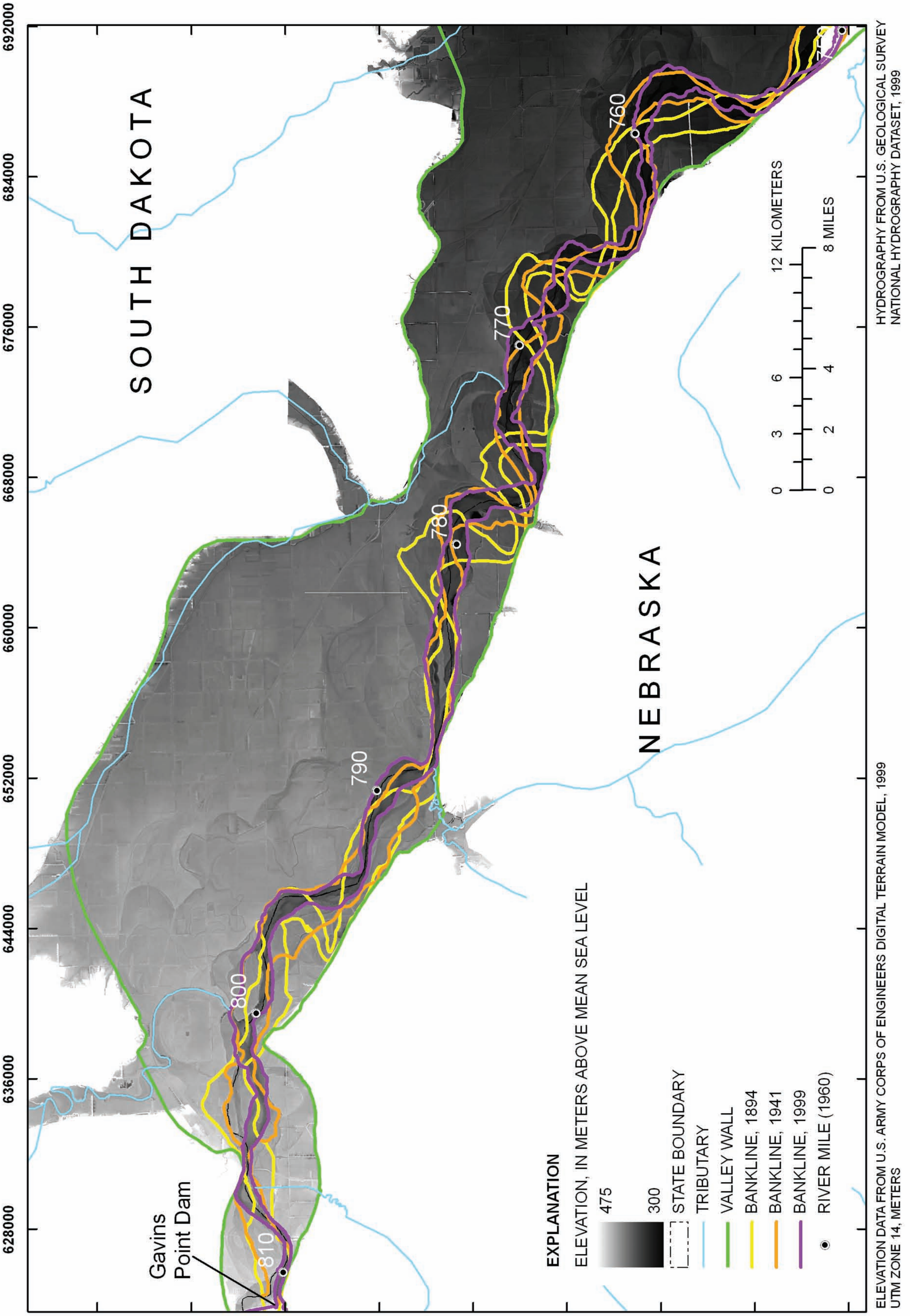


Figure 31. Historical channel positions and flood-plain topography in the 59-mile segment of the Missouri National Recreational River.

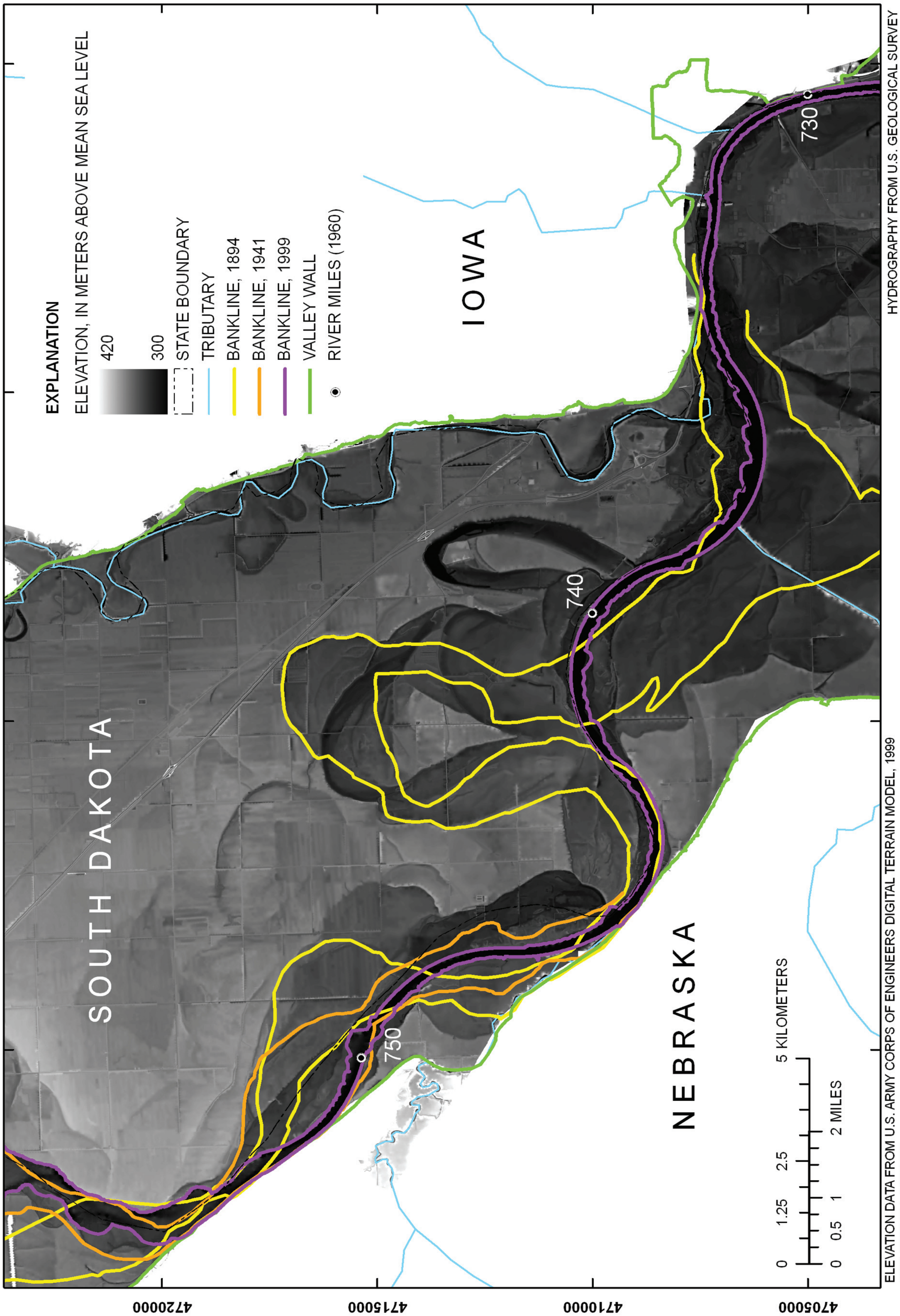


Figure 32. Historical channel positions and flood-plain topography in the Kensler's Bend segment of the Missouri River.

Channel Changes Since the Predam Era in the 59-mile Segment

Changes in bars since the predam era were assessed by comparing 1941 aerial orthophotography (available for the 59-mile segment only) to bars mapped from 1999 orthophotography. In the predam era, there were fewer vegetated bars (46 compared to 95 in 1999 at a comparable discharge), but the total bar area was higher than at any point in recent years (table 9). The average bar area was three times greater in 1941 compared to 1999. This difference results from the prevalence of long, off-channel chutes in the predam river. There were only 3.6 sand bars per kilometer in 1941 as compared to the 1993–2004 range of 3.0–7.2 bars per kilometer. The average sand bar size in 1941, however, was quite large at 6 ha. This size is comparable to the mean areas of emergent bars in 1998 of 6 ha. Braiding has decreased considerably since 1941 when there was an average of 2.82 channels at any given point. In 1999, there were 1.89 channels at any given point.

Mean channel width has decreased in the 59-mile segment since 1941 when the predam widths varied between 232 and 2,717 m with an average channel width of 1,132 m. In 1999, the widths ranged from 240 to 1,686 m with an average channel width of 830 m.

Side-Channel Chutes

Side-channel chutes were a major part of the predam river landscape (fig. 33). Chutes were identified as secondary channels that were much narrower than the main, or primary channel, within the active channel width of the river. There were 13 chutes mapped in the 59-mile segment in the 1941 predam photographs. Two more chutes were present in the upper end of the Kensler's Bend segment before channelization. The chutes ranged in length from 0.57 to 13.50 km, with an average length of 3.67 km. Some of the channels were quite sinuous, with sinuosity varying from 1.02 to 1.53 and an average of 1.16. These sinuous channels were generally narrow ranging from 16 to 96 m, with average width of 55 m. Channel widths of the mainstem Missouri River at chute inlets were highly variable, from 593 to 2,166 m; however, these chutes at the 1941 discharge of approximately 800 m^3/s represented only 1–24 percent of the mainstem Missouri River width at their inlets and were 7 percent of the width of the main channel on average. Many chutes acted as secondary flow cut-offs at higher discharges and were shorter than the path of the main channel. In the 1941 photographs, 11 (73 percent) of the chutes were shorter than the path of the Missouri River main channel, ranging from 0.05 to 1.03 km shorter. Three chutes (20 percent) were about the same length as the main channel. One chute was considerably longer (by 700 m) than the main channel. Not all chutes contained water at the 1941 river stage suggesting that chutes had developed at various discharges in this segment.

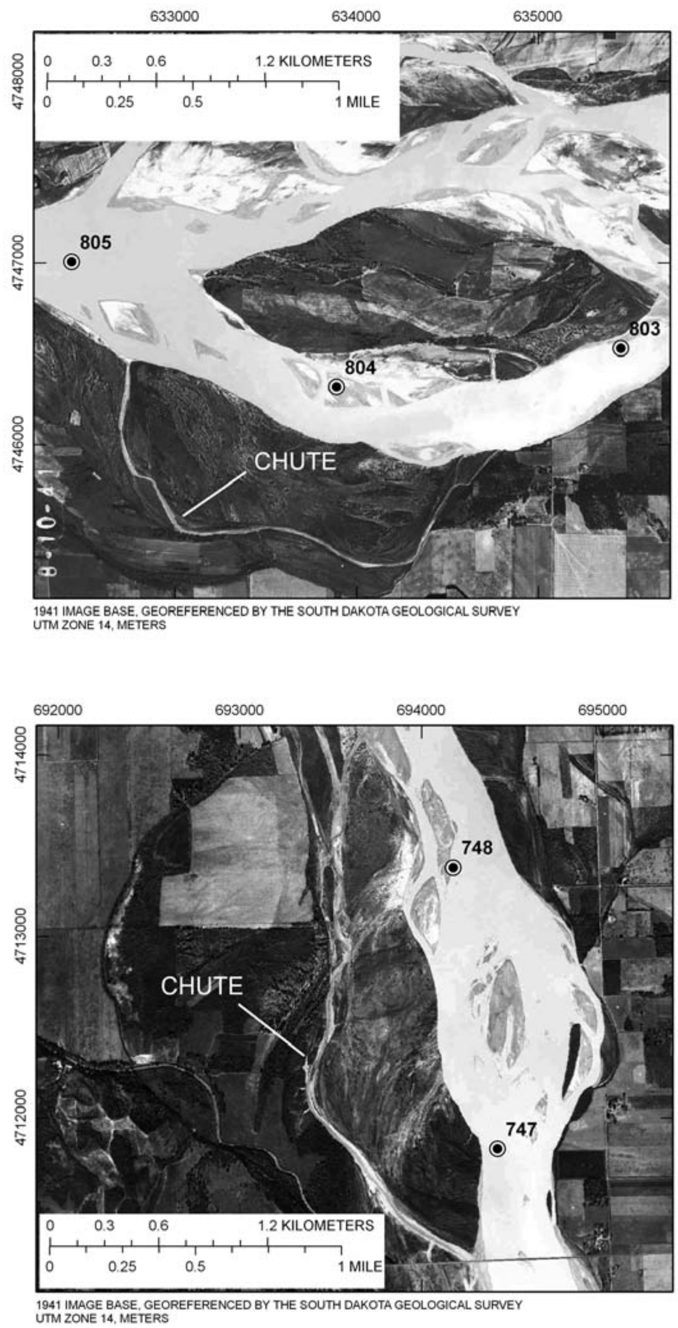


Figure 33. Examples of chutes from 1941 photography in the 59-mile segment of the Missouri National Recreational River.

There were considerably fewer off-channel chutes in the 59-mile segment of the post-dam river, probably because of an altered hydrograph and lower flood peaks as well as bed degradation and subsequent water table lowering. Together, these factors have cut chutes off from the main channel. An example that was clearly visible in the modern flood plain was a meandering, 13.5 km chute that cuts through the flood plain on the Nebraska side from river miles 798.3 to 789.1. It was visible on the 1941 photography, and was about 100 m longer than the main channel. The chute was labeled on the 1994

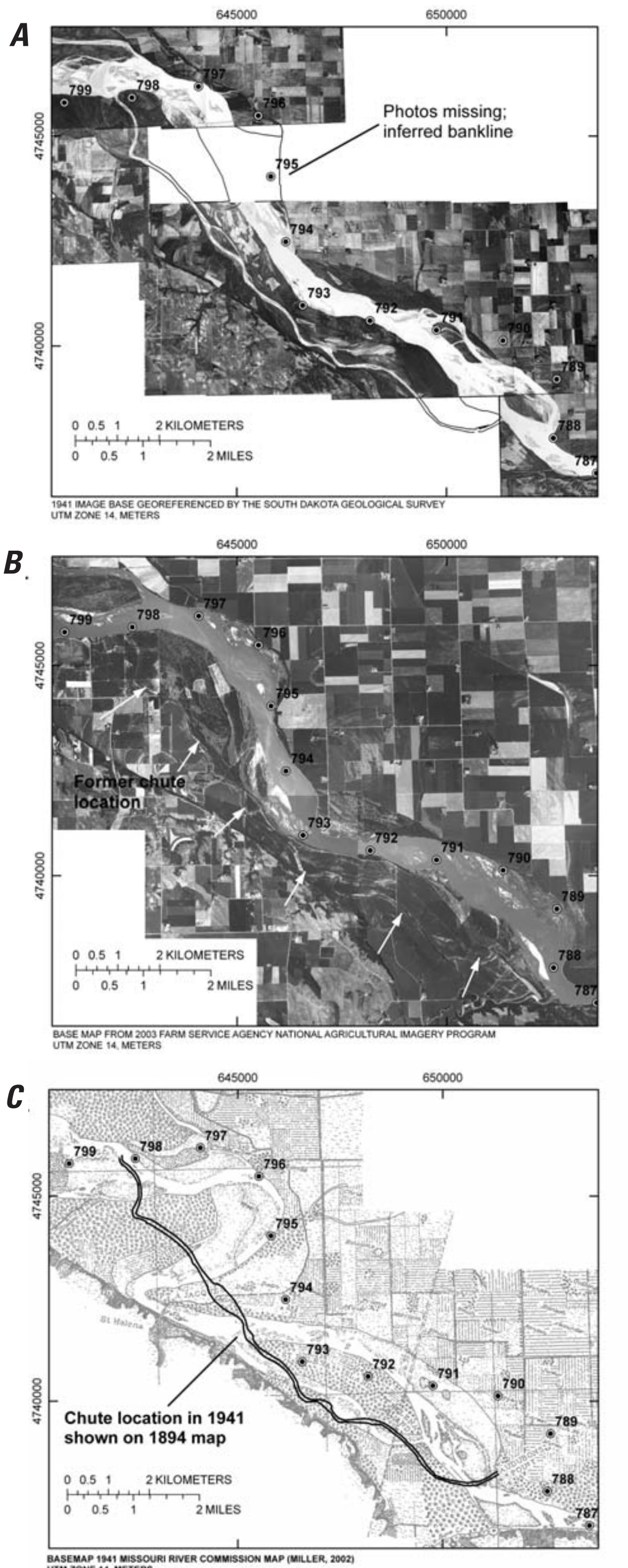


Figure 34. Chute progression at river mile 798–89 in the 59-mile segment of the Missouri National Recreational River. *A,* The 13.5-km chute cuts through the flood plain in 1941. *B,* The chute is still visible in 2004. *C,* Though not present in 1894, the chute follows a similar path to the mainstem and another chute (Missouri River Commission Maps, 1894; Miller, 2002).

USGS topographic maps as “The Chute” and is still visible in recent air photos and in high-resolution digital elevation models (fig. 34) but, “The Chute” is clearly no longer connected to the river (1997, 2004 imagery). It has become vegetated, contains off-channel ponds and wetlands, and in some places is under cultivation. In places this relic chute is still more than 5 m deeper than the surrounding flood plain. This chute occupies some of what was the main channel position and a part of a previous chute in 1894 and was likely a product of channel migration, abandonment, infilling, and narrowing due to vegetative encroachment.

Statistical Classification

The following sections combine methods and results for the statistical analysis and classification. We combined the methods and results because of the strong interdependence between the two. All statistical analyses were performed by using Systat software version 11 (Systat Software Inc., 2006).

Cluster Analysis

Remotely measured geomorphic channel attributes from 1999 were used for the clustering analysis (table 11). Use of measurements from GIS datasets and imagery generally limits analysis to planform variables, but has the advantage of providing nearly continuous data along the river. Effects of variable discharge were minimized by basing the classification and validation on datasets with average discharge and by measuring channel-related variables relative to well-defined bank lines rather than waters’ edge.

The 1999 geomorphic channel attribute data were calculated in the GIS and spatially joined in the GIS to the address points. The resultant data were analyzed for correlation and to assess normality of distributions. Some of the variables (table 12) were interrelated, as shown by principal component analysis (fig. 35) and scatterplots (fig. 36). The principal component analysis showed that variables related to channel complexity (bar number, vegetated bar area, and channel width) are related and are negatively loaded on factor 1. Importantly, bare sand area was insensitive to factor 1, indicating that conditions associated with vegetated bars are not necessarily those associated with bare sand bars. Sinuosity at 9,600 m, valley width, and total revetment—all relatively independent variables—are positively associated with factor 1. Two factors that might have similar influence on geomorphic processes—banks protected by bedrock and banks protected by revetment—plot in opposite directions on factors 1 and 3.

After considering the results of principal component analysis, we focused on four key variables that were judged to be dependent, geomorphically-adjustable variables. The four variables were channel width, bare sand bar area, vegetated bar area, and number of channels. The use of bar area is justified in this case because all data were collected at a fairly narrow range of discharges in 1999. To minimize dependence

Table 11. Variable names, abbreviations, and definitions for multivariate classification.

Variable name	Abbreviation	Definition
Channel width	CHAN_W	Width of channel, high-bank to high bank, in meters perpendicular to the centerline
Variability of channel width	CHAN_STD	Standard deviation of channel width calculated on a running basis over 1 kilometers
Valley width	VAL_W	Valley width perpendicular to the channel center line, in meters
Sinuosity at 800 meters	S800	Ratio of distance along the channel centerline over 800 meters to the straightline distance between the two end points
Sinuosity at 2,400 meters	S2400	Ratio of distance along the channel centerline over 2,400 meters to the straight line distance between the two end points
Sinuosity at 9,600 meters	S9600	Ratio of distance along the channel centerline over 9,600 meters to the straight line distance between the two end points
Sand bar area	SAND_AR	Area of bare sand bar associated with the address point, in square meters
Vegetated bar area	VEG_AR	Area of vegetated bar associated with the address point, in square meters
Number of bars	BAR_NUM	Number of bars, bare sand or vegetated, associated with the address point; equal to number of channels minus one
Total revetment length	TTL_RVT	Length of revetted bank, both sides of river, associated with the address point, in meters
Number of pieces of large woody debris	LWD_NUM	Number of pieces of large woody debris identifiable on high-resolution imagery
Bank affected by bedrock	BANK_BR	Length of bank line associated with address point, within 50 meters of bedrock exposure

among spatially adjacent sample points, we randomly selected one third of the points for initial clustering and analysis. We also eliminated address points in Lewis and Clark Lake so the extreme channel widths would not bias the results.

The four variables were transformed to achieve better normality (fig. 37). Normality is not critical for cluster analysis but is a fundamental assumption for the subsequent discriminant analysis. Violation of normality in discriminant analysis, however, is not considered critical to obtaining useful results (Hill and Lewicki, 2006).

Hierarchical cluster analysis (using Ward linkage and Euclidean distance, Wilkinson and others, 2004) yielded evidence of distinct clusters in the dataset (fig. 38). Hierarchical cluster analysis generally defines nested clusters based on combining observations into increasingly larger, similar, and exclusive clusters (Wilkinson and others, 2004). The hierarchical cluster dendrogram showed that reasonably distinct clusters could be defined in 4, 5, and 10 groups (fig. 38).

The normalized and standardized dataset was subsequently analyzed with K-means cluster analysis stipulating 2–12 clusters. K-means cluster analysis starts with a predefined number of clusters (K) and divides the data into K mutually exclusive groups by maximizing the between-group variance (Wilkinson and others, 2004). We used Euclidean distance as the distance metric and developed a plot of between-group sum of square differences and within-group sum of square differences by cluster number (fig. 39). Similar to a "scree" plot, breaks in the slopes of these curves were interpreted as numbers of clusters at which information content of the clustering process changed. Consistent with the hierarchical analysis, prominent inflections appear to occur at 4 and 10 clusters.

K-means clustering also provided two types of diagnostic plots to show how values of the variables group within the cluster. These plots were very useful for interpreting the physical meaning of the clusters (figs. 40, 41). These plots were arranged with the variable having the highest discrimination capability at the top of the plot and that with the least at the bottom. Cluster parallel plots depict standardized values (z scores) of the variables (relative to mean) for each cluster. The variables are arranged generally from most to least influential, from top to bottom. Cluster profile plots show the mean and standard deviation of each variable for each cluster, with a vertical dashed line showing the mean of all values for all clusters. The variables are arranged generally from most to least influential, from top to bottom. K-means cluster classes for 4 and 10 clusters were assigned to the normalized, standardized data.

After assigning classes for 4 and 10 clusters, we used discriminant analysis to develop classification functions for the clusters. Discriminant analysis plots (figs. 42, 43) showed distinct groupings of cluster classes along the first two factored axes. In addition, the discriminant classifications were cross validated by using a jackknife procedure which indicated that 95 to 97 percent of all points were correctly classified (table 13). Success in classification was least for clusters with small representation, such as cluster 5 in the 10-cluster dataset, for which only 67 percent were correctly classified in the jackknife procedure.

Table 12. Pearson product-moment correlation coefficients and probabilities. *A,* Pearson product-moment correlation coefficients between variables. *B,* Bonferroni corrected probabilities that correlation coefficients in A are actually 0.

[CHAN_W, channel width; CHAN_STD, standard deviation of channel width over 1 km; VAL_W, valley width; S800, sinuosity of channel centerline at 800 m along centerline; S2400, sinuosity of channel centerline at 2400 m along centerline; S9600, sinuosity of channel centerline at 9600 m along centerline; SAND_AR, area of sand bar; VEG_AR, area of vegetated bar; BAR_NUM, number of unattached bars; TTL_RVT, total length of revetted bank; LWD_NUM, number of pieces of large woody debris; BANK_BR, length of bank within 50 m of bedrock wall]

A	CHAN_W	CHAN_STD	VAL_W	S800	S2400	S9600	SAND_AR	VEG_AR	BAR_NUM	TTL_RVT	LWD_NUM	BANK_BR
CHAN_W	1.000											
CHAN_STD	0.143	1.000										
VAL_W	-0.393	-0.024	1.000									
S800	-0.086	0.323	0.164	1.000								
S2400	-0.153	0.273	0.232	0.625	1.000							
S9600	-0.285	0.081	0.478	0.213	0.379	1.000						
SAND_AR	0.174	0.128	-0.094	0.154	0.071	0.007	1.000					
VEG_AR	0.700	0.080	-0.347	-0.106	-0.157	-0.235	-0.025	1.000				
BAR_NUM	0.697	0.066	-0.300	-0.085	-0.151	-0.215	0.144	0.950	1.000			
TTL_RVT	-0.336	-0.085	0.287	-0.038	0.026	0.152	-0.018	-0.264	-0.188	1.000		
LWD_NUM	0.052	0.206	0.245	0.144	0.221	0.219	0.175	-0.132	-0.077	-0.054	1.000	.
BANK_BR	0.396	-0.178	-0.428	-0.163	-0.258	-0.293	-0.049	0.420	0.365	-0.384	-0.286	1.000
B												
CHAN_W	0.000											
CHAN_STD	0.747	0.000										
VAL_W	0.000	1.000	0.000									
S800	1.000	0.000	0.240	0.000								
S2400	0.455	0.000	0.002	0.000	0.000							
S9600	0.000	1.000	0.000	0.010	0.000	0.000						
SAND_AR	0.138	1.000	1.000	0.432	1.000	1.000	0.000					
VEG_AR	0.000	1.000	0.000	1.000	0.360	0.002	1.000	0.000				
BAR_NUM	0.000	1.000	0.000	1.000	0.493	0.009	0.708	0.000	0.000			
TTL_RVT	0.000	1.000	0.000	1.000	1.000	0.472	1.000	0.000	0.057	0.000		
LWD_NUM	1.000	0.016	0.001	0.715	0.006	0.006	0.125	1.000	1.000	1.000	0.000	
BANK_BR	0.000	0.106	0.000	0.260	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000

Classification Validation

Ultimately, validation of the classification needed to be established by evaluating its physical reality. To address this, we classified the previously non-selected two-thirds of the data points by using the discriminant functions for the 4- and 10-cluster cases and transferred the classifications back to the address GIS dataset. By examining the cluster parallel and profile plots, and the physical context of the river, we assigned descriptive categories to the classes (figs. 44, 45; table 14).

In general, the classifications provided physically realistic and distinct classes for the 1999 channel (figs. 44, 45). Channel number was the most influential variable in the 4-cluster classification, followed by vegetated-bar area, channel width, and bare-sand-bar area. In the 10-cluster classification, the order of importance of variables was changed to vegetated-bar area, channel width, channel number, and bare-sand-bar area. Although the K-means cluster analysis did not necessarily result in hierarchical nesting of clusters, the 10-cluster classes tend to fit within the 4-cluster classes (tables 14, 15), and the 10-cluster classes can be generally described as subunits of the 4-cluster classes.

In addition, we combined classes 2 to 4 of the 4-cluster classification to divide address points into two simple classes: simple (single-thread) channels and complex (multi-thread) channels (figs. 44, 45). This simple classification delineated complex channel reaches regardless of degree of complexity or dominance of vegetated or bare sand bars.

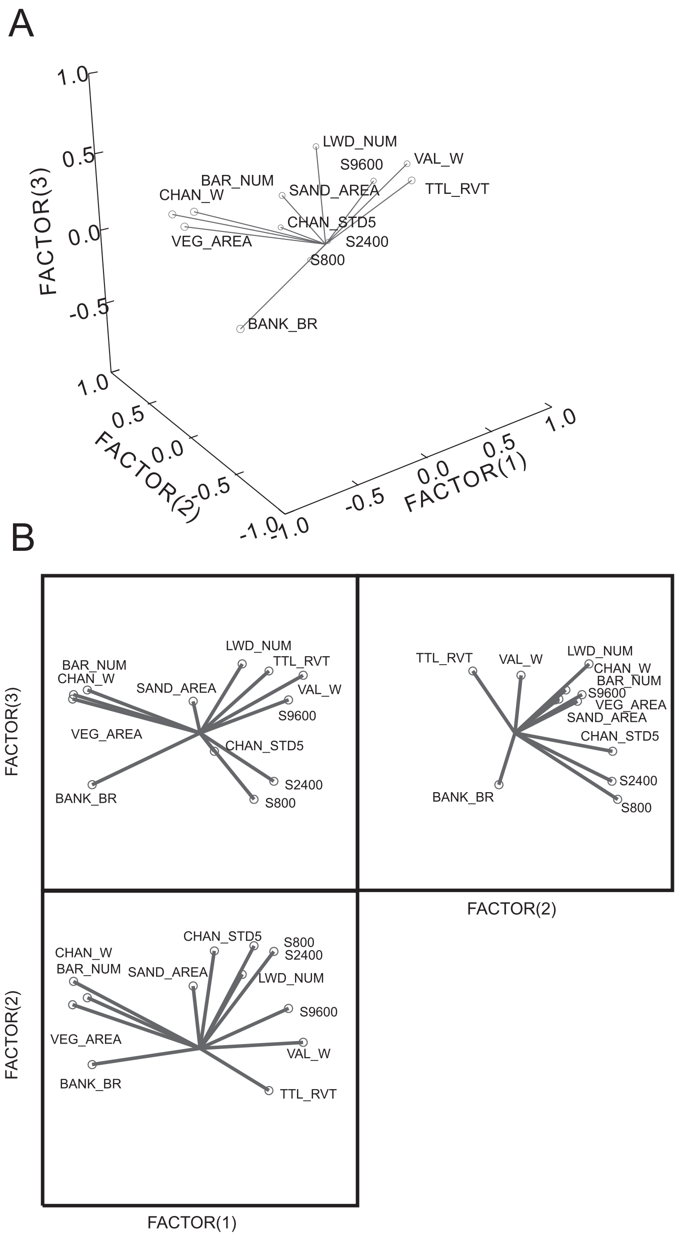


Figure 35. Principal component analysis plot showing loading of selected variables on three principal components. *A,* Three-dimensional plot of first three axes. *B,* Component comparison plots. [CHAN_W, channel width; CHAN_STD, standard deviation of channel width over 1 km; VAL_W, valley width; S800, sinuosity of channel centerline at 800 m along centerline; S2400, sinuosity of channel centerline at 2,400 m along centerline; S9600, sinuosity of channel centerline at 9,600 m along centerline; SAND_AR, area of sand bars; VEG_AR, area of vegetated bar; BAR_NUM, number of unattached bars; TTL_RVT, total length of revetted bank; LWD_NUM, number of pieces of large woody debris; BANK_BR, length of bank within 50 m of bedrock wall]

Temporal Persistence of Assigned Classes

Persistence of the classes from year to year was evaluated by classifying channel characteristics in 2003 and 2004 by using the 1999 discriminant functions. Channel characteristics from 2003 and 2004 imagery were merged into one dataset because of limitations of finding usable orthophotography at discharges comparable to that of the 1999 imagery used for the original classification for all segments of the river. In the 4-cluster classification, address classes were consistent between the two dates for classes 1 and 4 (86 percent and 95 percent consistency), and somewhat less consistent for classes 2 and 3 (67 percent and 57 percent; table 16). Seventeen percent of the class 2 addresses in 1999 were classified as class 3 in 2003–04 and 11 percent of the class 2 became class 4. Thirty-four percent of the class 3 addresses changed to class 2. The 2 to 3 class change can be interpreted as a transition from reaches dominated by vegetated bars to reaches dominated by bare sand bars. The 2 to 4 change can be interpreted as an increase in channel complexity, with or without an increase in bare sand bars. The 3 to 2 transition is interpreted as a transition from reaches dominated by bare sand bars to reaches dominated by vegetated bars. Eleven percent of the class 1 addresses changed to class 3, a transition that can be interpreted as increasing channel complexity and deposition of sand bars.

Judging persistence and class transitions from the 10-cluster classification was considerably more complex (table 16). The more restricted definition of class 1 (simple narrow channels mostly downstream of Ponca State Park) resulted in strong persistence at 97 percent. The next most stable was class 2 at 60 percent; however, class 2 was still fairly volatile: 21 percent of class 2 changed to class 3, a transition interpreted as increasing complexity and bare-sand-bar area. Twenty-six percent of class 4 changed to class 6, interpreted as a decrease in bare sand bars due to vegetation encroachment. Eighty-nine percent of class 5 changed to class 7, a transition from sand (and mud) bars to vegetated bars in the complex, lower delta plain of the Lewis and Clark Lake. Twenty-eight percent of class 6 changed to class 4, indicating increased bare sand bars in complex reaches. Sixty-seven percent of class 7 addresses changed to class 9; this transition indicated a loss of vegetated-bar area and probably results from vegetated bars connecting to the flood-plain surface. Twenty-nine percent of class 8 changed to class 6, indicating changes of bare sand bars to vegetated bars in that class. Fifty-one percent of class 9 changed to class 10, indicating additional conversion of bare sand bars to vegetated bars.

The temporal changes in classes of the MNRR indicate the dynamic nature of the river. The time period covered was one of relatively low flows following the large 1997 event; hence, this was a time of geomorphic recovery characterized largely by conversion of bare sand bars to vegetated bars in the free-flowing river, and continued increase in channel and habitat complexity in the deltaic reach.

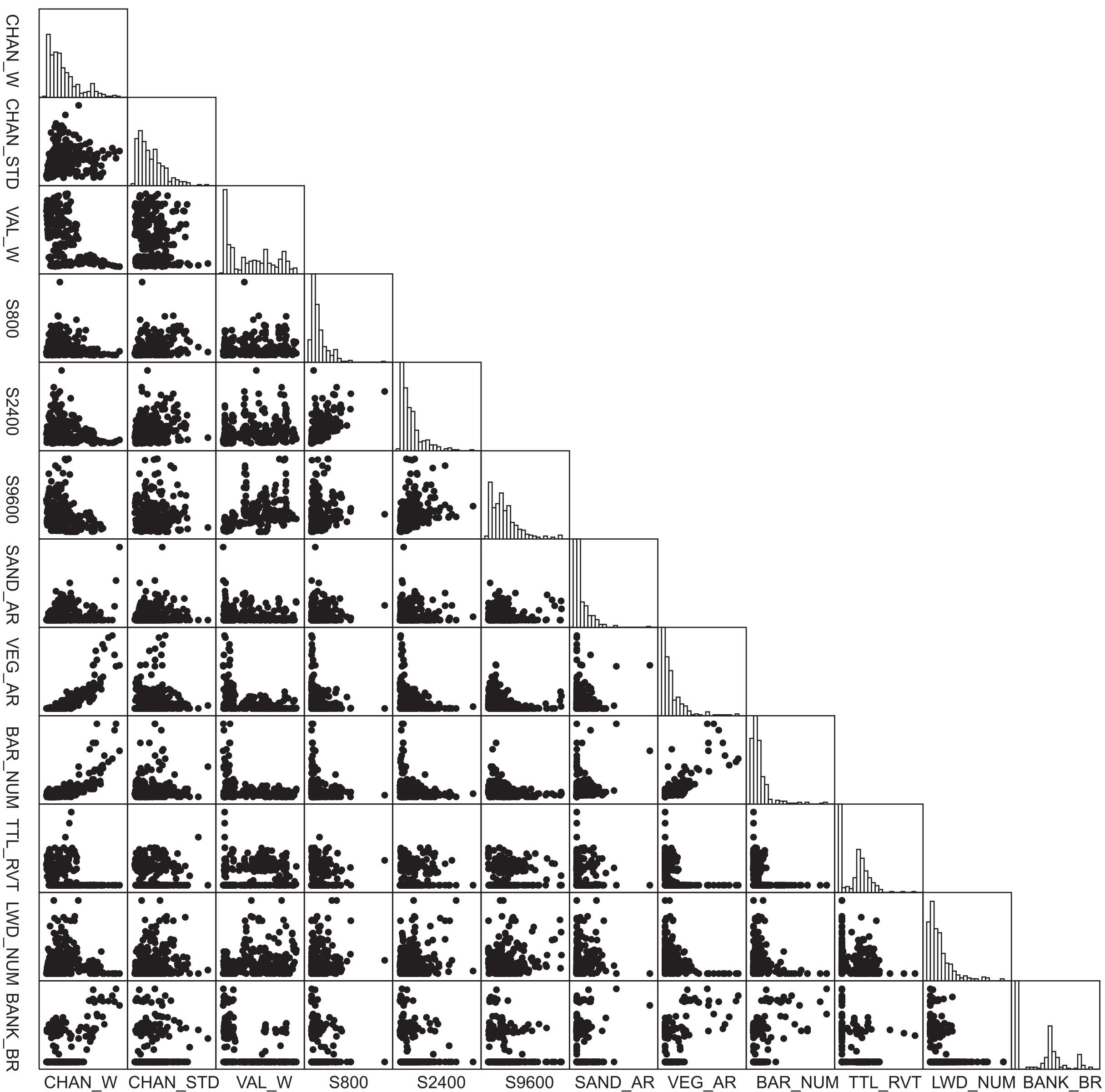


Figure 36. Scatterplots and histograms among selected, nontransformed classification variables. Most relations are nonlinear and nonnormal. [CHAN_W, channel width; CHAN_STD, standard deviation of channel width over 1 km; VAL_W, valley width; S800, sinuosity of channel centerline at 800 m along centerline; S2400, sinuosity of channel centerline at 2,400 m along centerline; S9600, sinuosity of channel centerline at 9,600 m along centerline; SAND_AR, area of sand bars; VEG_AR, area of vegetated bar; BAR_NUM, number of unattached bars; TTL_RVT, total length of revetted bank; LWD_NUM, number of pieces of large woody debris; BANK_BR, length of bank within 50 m of bedrock wall]

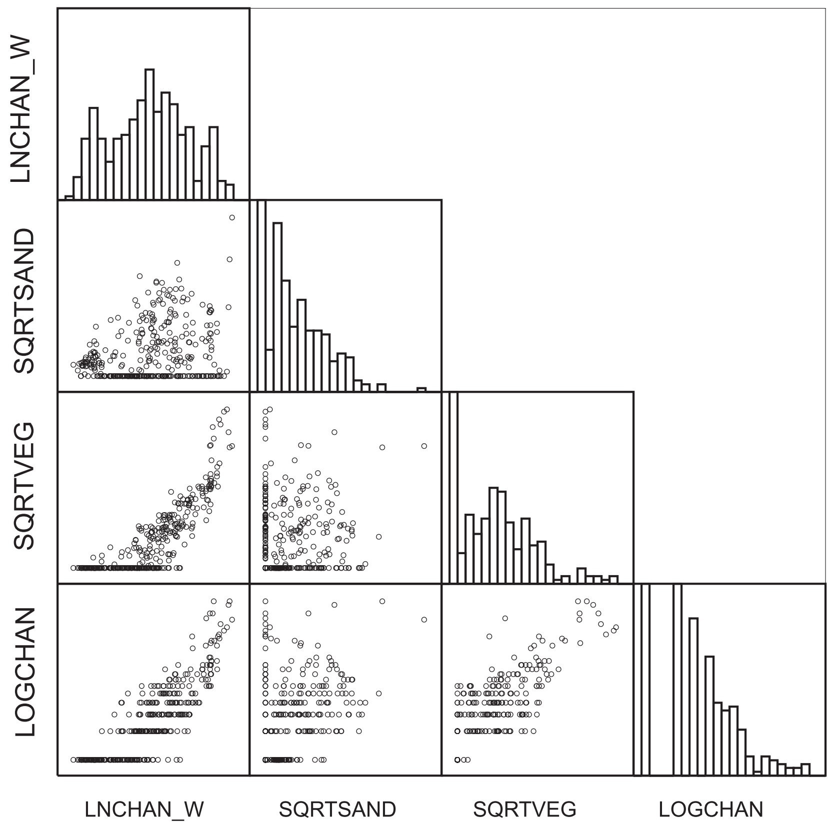


Figure 37. Scatterplots and histograms among the reduced set of selected, transformed classification variables. Normality has improved but is only reasonably validated for LNCHAN_W. [LNCHAN_W, natural log of channel width; SQRTSAND, square root of area of sand bar; SQRTVEG, square root area of vegetated bar; LOGCHAN, log base 10 of number of channels]

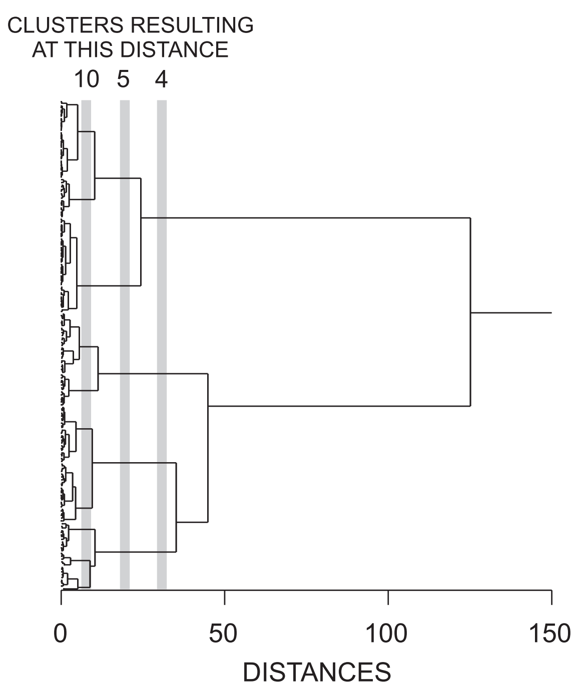


Figure 38. Hierarchical cluster dendrogram of the reduced dataset. Transformed variables were also standardized for this analysis. Gray vertical lines indicate prominent breaks at 4, 5, and 10 clusters.

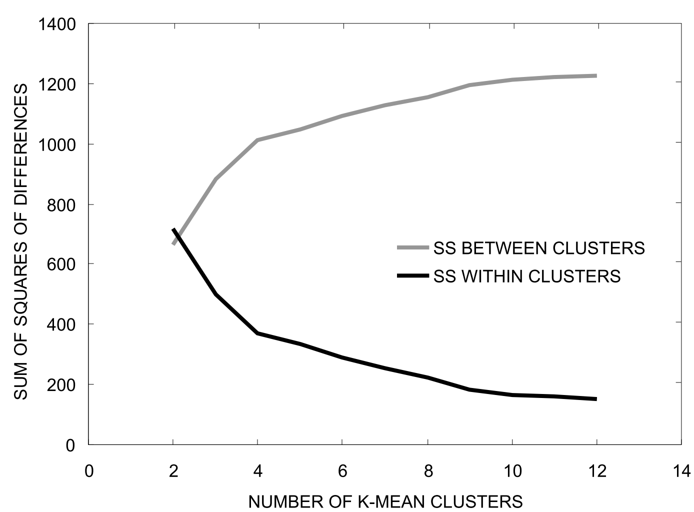


Figure 39. "Scree" plot showing changes in sum of square differences within and among clusters as number of clusters changes. Breaks in slope at 4 and 10 clusters indicate changes in ability to describe natural clusters.

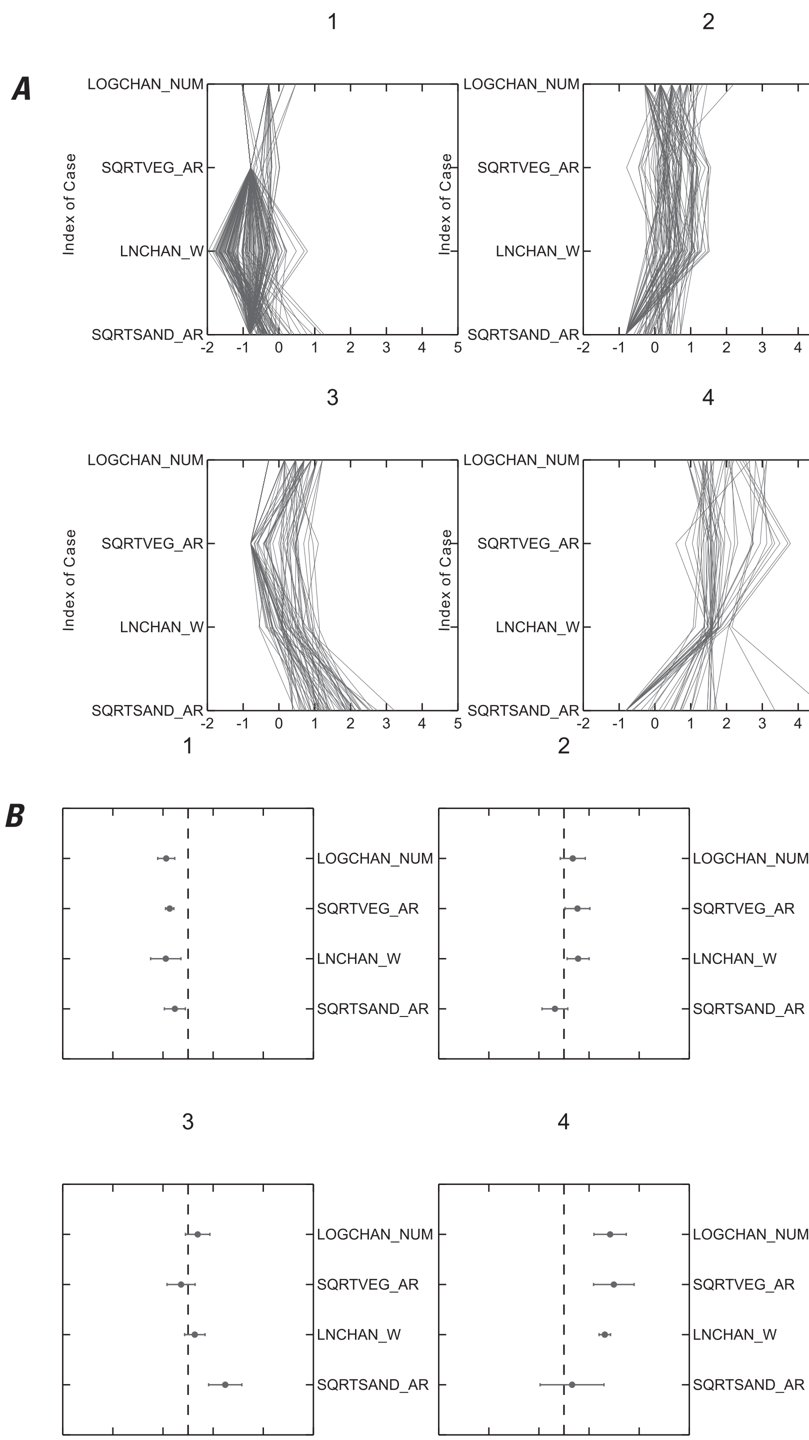


Figure 40. Clustering results from the K-means procedure for 4 clusters. *A,* Cluster parallel plots showing standardized values of the variables (relative to mean) for each cluster. The variables are arranged generally from most to least influential, from top to bottom. *B,* Cluster profile plots showing the mean and standard deviation of each variable for each cluster. The vertical dashed line is the mean of all values for all clusters. The variables are arranged generally from most to least influential, from top to bottom.

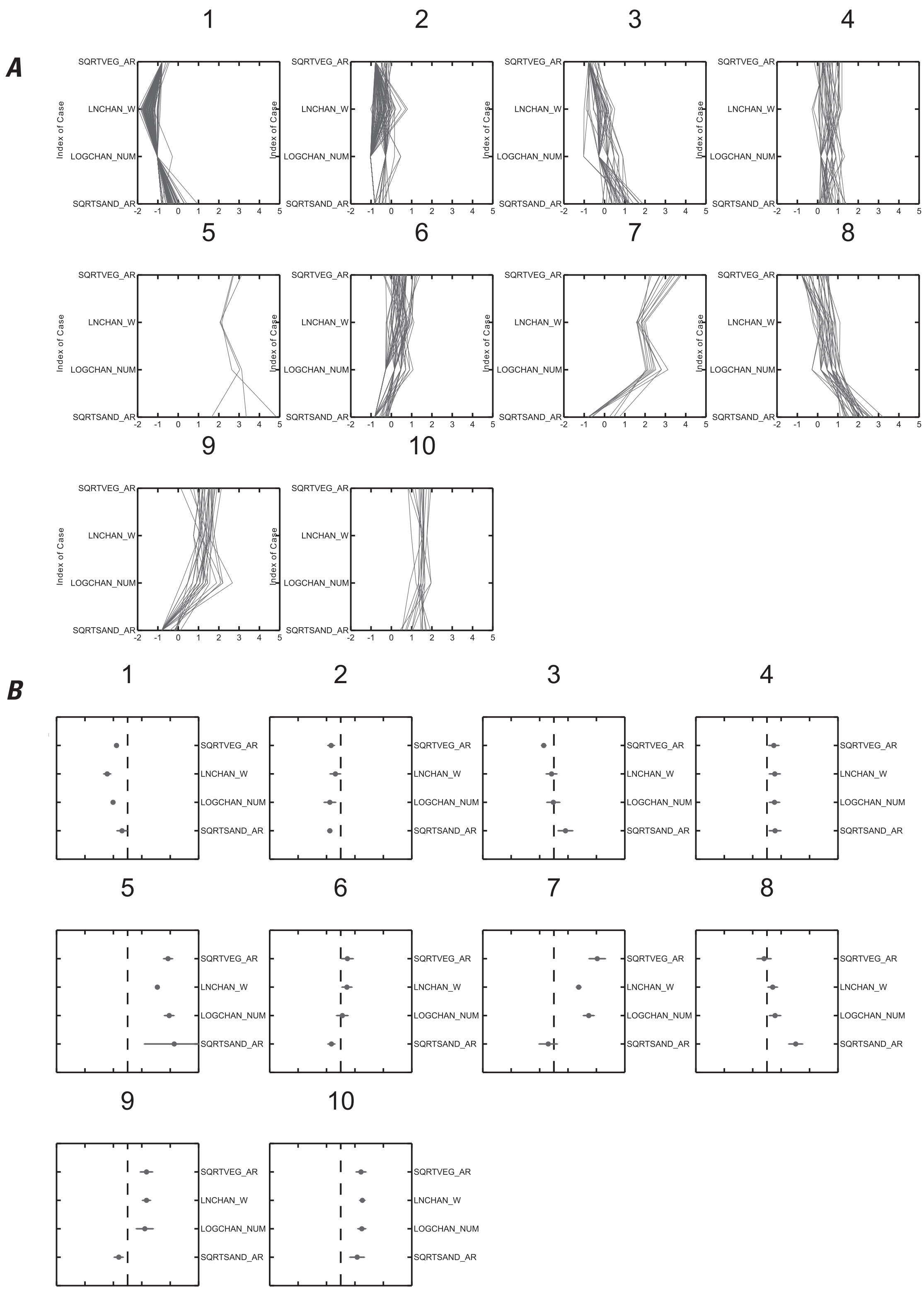


Figure 41. Clustering results from the K-means procedure for 10 clusters. *A,* Cluster parallel plots showing standardized values of the variables (relative to mean) for each cluster. The variables are arranged generally from most to least influential, from top to bottom. *B,* Cluster profile plots showing the mean and standard deviation of each variable for each cluster. The vertical dashed line is the mean of all values for all clusters. The variables are arranged generally from most to least influential, from top to bottom.

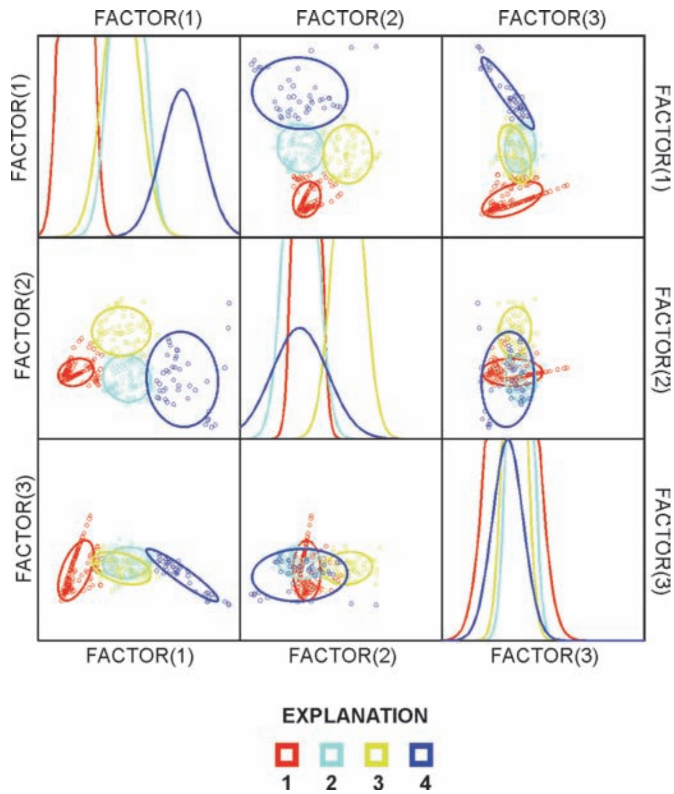


Figure 42. Canonical scores plot for the 4-cluster classification showing elliptical clusters used for classification.

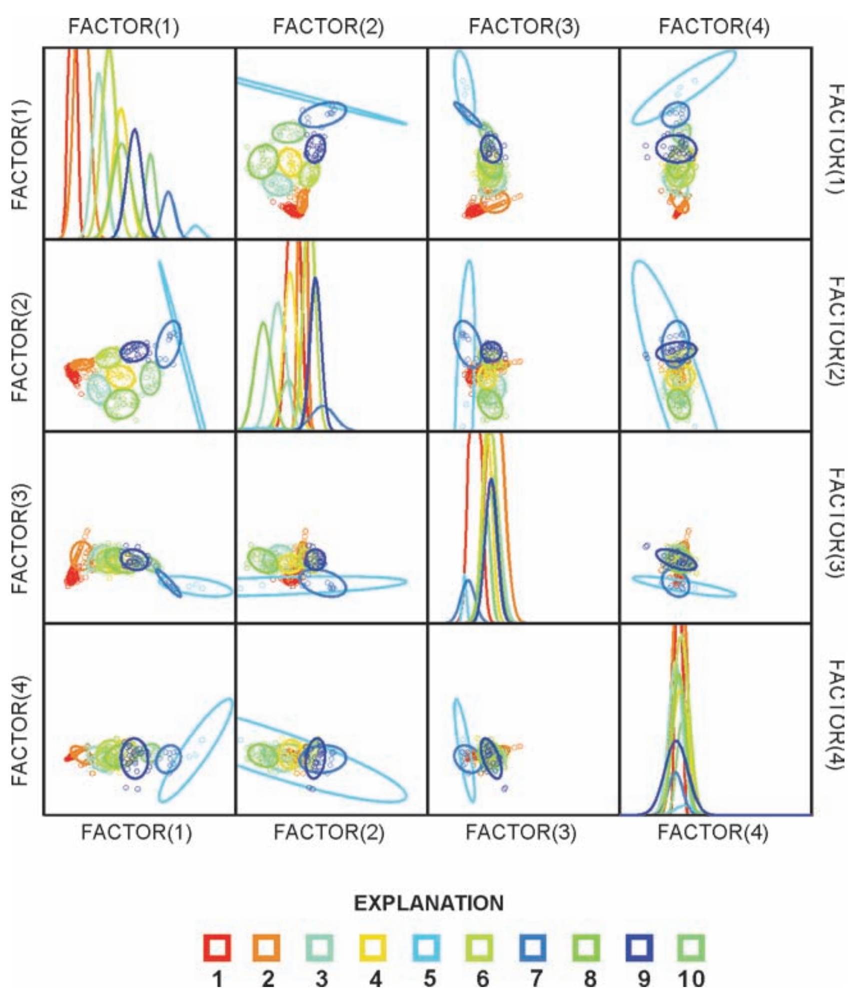


Figure 43. Canonical scores plot using the first 4 factors for the 10-cluster classification. Ellipses show the groupings used for classification.

Table 13. Result of jackknife validation of discriminant function classification of 4- and 10-cluster classifications.

Classified by jackknife	4-cluster class 1	2	3	4	Percent correct
1	151	0	0	0	100
2	3	83	2	0	94
3	1	4	61	0	92
4	0	5	1	35	85
Total	155	92	64	35	95

Classified by jackknife	10-cluster class 1	2	3	4	5	6	7	8	9	10	Percent correct
1	70	1	0	0	0	0	0	0	0	0	99
2	1	73	0	0	0	0	0	0	0	0	99
3	1	1	33	0	0	0	0	0	0	0	94
4	0	0	0	34	0	0	0	0	0	0	100
5	0	0	0	0	2	0	1	0	0	0	67
6	0	1	0	0	0	45	0	0	0	0	98
7	0	0	0	0	0	0	9	0	1	0	90
8	0	0	0	2	0	0	0	28	0	0	93
9	0	0	0	0	0	0	0	0	28	0	100
10	0	0	0	0	0	0	0	0	0	15	100
Total	72	76	33	36	2	45	10	28	29	15	97

Bank Erosion and Classification

Erosion rates were compiled to evaluate whether erosion was preferentially associated with particular classes. For the 39-mile segment, erosion rates were calculated as the total area of movement of both primary banks from 1993 to 2003. For the 59-mile segment, erosion rates were calculated as the total area of movement of both primary banks from 1993 to 2004; both were expressed as an annual average for each address point (fig. 46). The values associated with each addressed point were areas within the address polygons (fig. 47) averaged over two sides of the river. Each address point assesses approximately 400 m of bank; therefore, areal rates can be converted to estimate linear bank retreat by dividing by 400.

Erosion rates were extremely variable when compiled by classification unit (table 17). Nevertheless, class 3 stood out as having substantially higher erosion rates in the 4-cluster classification and classes 3 and 8 stand out in the 10-cluster classification. All of these classes were associated with reaches that were relatively wide, and had both greater than average bare sand bar area and complex channels. Pairwise analysis of variance (table 18) confirmed that the mean annual erosion in class 3 of the 4-cluster classification was significantly greater than the other 3 classes (p = 0.000). For the 10-cluster classification, class 3 was significantly greater than classes 1, 4, 9, and 10 at the p = 0.01 level, and significantly greater than classes 2 and 6 at the p = 0.05 level. Although class 8 had substantially greater mean erosion than other classes, it only approached significance relative to class 1 (p = 0.100) and class 9 (p = 0.266). Erosion rates between classes 3 and 8 were not significantly different (p = 0.409).

Discussion

Geomorphic Classification and Channel Dynamics

The objective of this study was to develop a geomorphic classification of the MNRR that would identify and delineate process domains. The following sections address how this classification relates to others in the geomorphology literature, the timescales over which this classification may be expected to be valid, and some implications for management decisions.

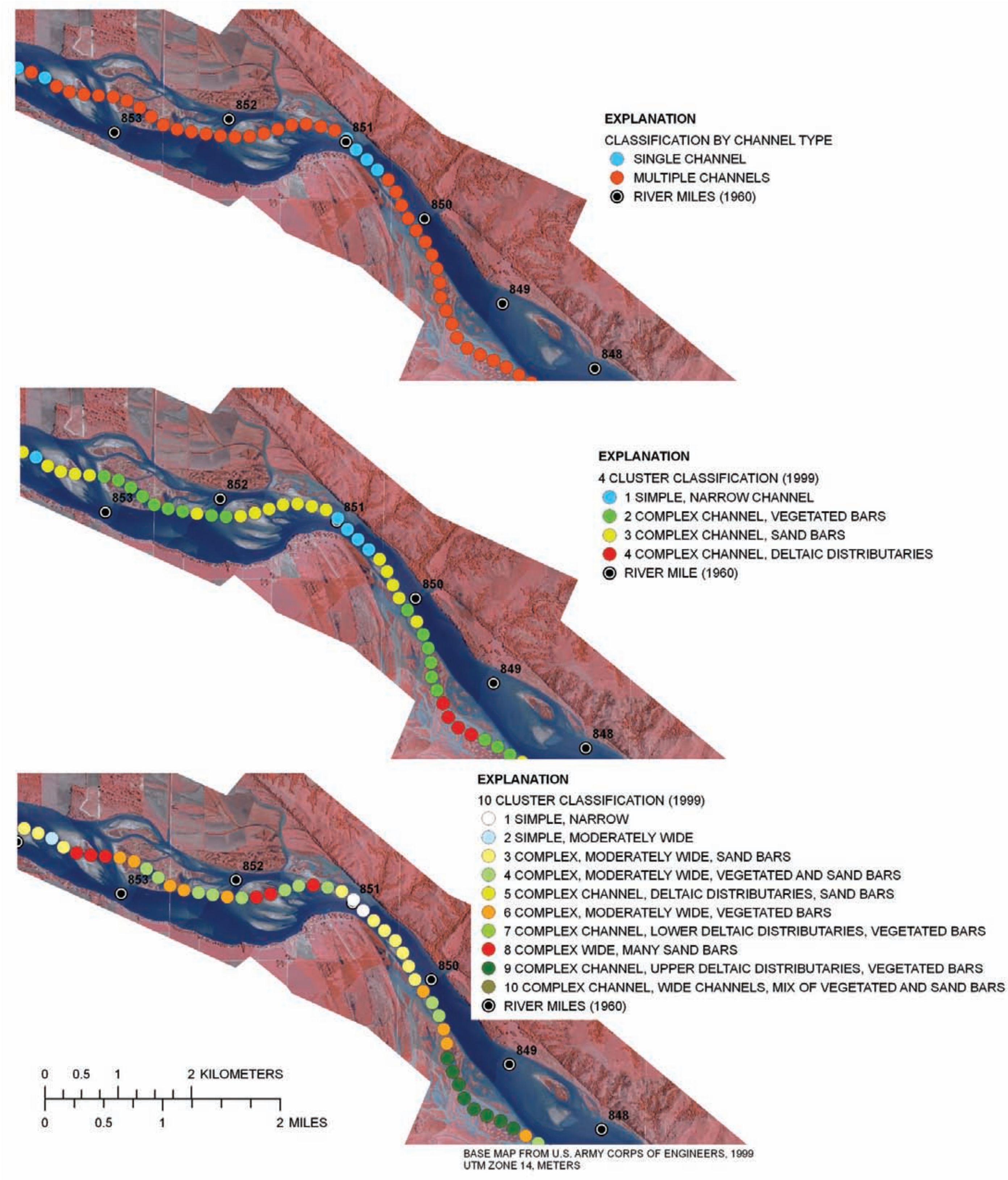


Figure 44. Channel-type, 4-cluster, and 10-cluster classifications in the 39-mile segment free-flowing reach of the Missouri National Recreational River.

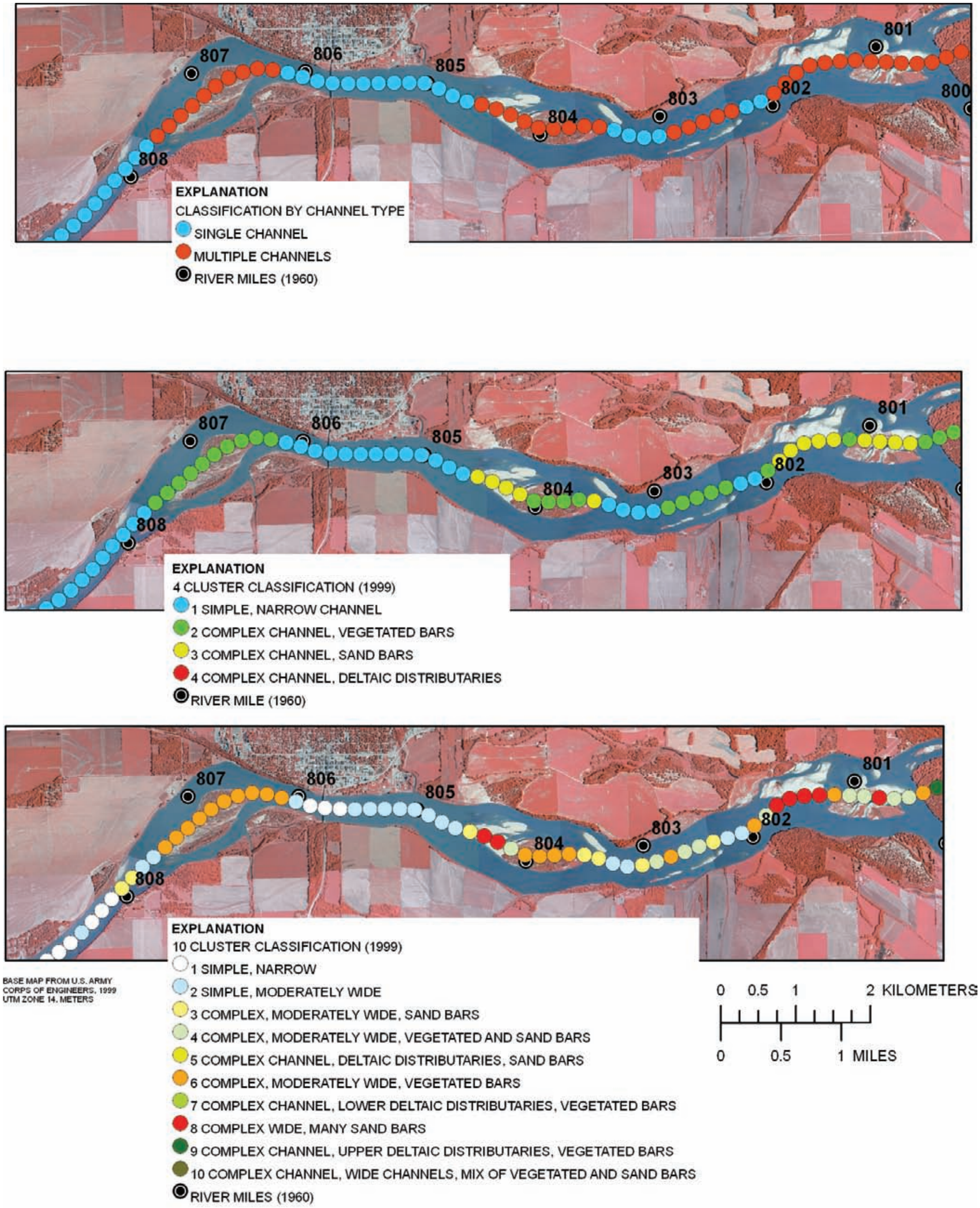


Figure 45. Channel-type, 4-cluster, and 10-cluster classifications in the 59-mile segment of the MIssouri National Recreational River.

Table 14. Names and interpreted physical significance of clustered classes.

	Relation to 4-cluster (see table 15)	Descriptive name	Physical process and form interpretation
A. 4-cluster classification			
1	NA	Simple, narrow	Simple, single, narrow channel, very little bare sand or vegetated bars; much of this class occurs downstream of Ponca State Park and is stabilized by revetment.
2	NA	Complex channel, vegetated bars	Complex channels, dominated by vegetated bars.
3	NA	Complex channel, bare sand bars	Complex channels, dominated by bare sand bars. This unit has the highest lateral erosion rates.
4	NA	Very complex channel, deltaic distributaries	This unit has the fewest members. It represents complex reaches with more than three channels and many vegetated and bare sand bars. It is best expressed in the Lewis and Clark Lake delta.
B. 10-cluster classification			
1	1	Simple, narrow	Simple, single, narrow channel, very little bare sand or vegetated bars; much of this class occurs downstream of Ponca State Park and is stabilized by revetment.
2	1	Simple, moderately wide	Mostly similar to class 1 only somewhat wider. Punctuated by short lengths with bare sand bars and multiple channels. Commonly occur downstream of Ponca State Park as eroded areas downstream of wing dikes.
3	3	Complex, moderately wide, bare sand bars	Complex channels, dominated by bare sand bars. This unit shares the highest lateral erosion rates with unit 8. Somewhat narrower channel, smaller area of vegetated and bare sand bars than unit 8.
4	2	Complex, moderately wide, vegetated and bare sand bars.	This unit has moderate occurrence of vegetated bars, channel widths, number of channels, and bare sand bars. It is similar to units 6 and 9 but has more bare sand bars than either and less channel complexity than 9.
5	4	Complex channel, deltaic distributaries, bare sand bars	This unit has the fewest members. It represents complex reaches with a relatively large number of channels and bare sand bars. It is limited to areas of fresh deposition in the Lewis and Clark Lake delta. No measurable erosion of the high bank is associated with this unit.
6	2	Complex, moderately wide, vegetated bars.	This unit has moderate occurrence of vegetated bars, channel widths, and number of channels, but few bare sand bars. It is similar to units 4 and 9 but has fewer bare sand bars than 4 and more channel complexity than 9.
7	4	Complex channel, lower deltaic distributaries, vegetated bars	This unit has relatively few members. It represents complex reaches with a relatively large number of channels and vegetated bars. It is mostly found in the downstream one half of the Lewis and Clark Lake delta. No measurable erosion of the high bank is associated with this unit.
8	3	Complex, wide, many bare sand bars	Complex channels, dominated by bare sand bars. This unit shares the highest lateral erosion rates with unit 3. It has a somewhat wider channel and somewhat larger area of vegetated bars, and a substantially larger area of bare sand bars compared to unit 3.
9	52% in class 2 and 48% in class 4	Complex channel, upper deltaic distributaries, vegetated bars	This unit represents complex reaches with a relatively large number of channels and vegetated bars. It is mostly found in the upstream one half of the Lewis and Clark Lake delta.
10	4	Complex, wide channel, mix of vegetated and bare sand bars	This unit is found in moderately wide channel segments with a mix of vegetated and bare sand bars. It is well represented in the upper one half of the Lewis and Clark Lake delta.

Table 15. Correspondence between 4-cluster and 10-cluster classifications, showing how refined 10-cluster classes from 1999 are distributed within and among 4-cluster classes.

	10-cluster classification										
4-cluster classification	1	2	3	4	5	6	7	8	9	10	Total 4-cluster
1	230	201	27			5					463
2		6	1	66		159			50		282
3			84	27	1			77		2	191
4					8		21		45	32	106
Total 10-cluster	230	207	112	93	9	164	21	77	95	34	1,042

Continuous Longitudinal Classification and Geomorphic Process Domains

The clustered distribution of geomorphic characteristics along the MNRR indicated a nonuniform distribution of geomorphic processes. The punctuated distribution of processes was similar to the juxtaposition of disturbance reaches and stable reaches documented in smaller, single-thread channels (Church, 1983; Saucier, 1983; Jacobson and Pugh, 1997; Jacobson and Gran, 1999). This type of instability phenomenon occurs at longer channel distances than riffle/pool sequences and appears to relate to factors like channel interactions with the valley wall (Jacobson and Pugh, 1997), interactions with tributary junctions (Church, 1983), or instability related to loss of sediment transport capacity at sites of flow divergence. This last mechanism is similar to thresholds of channel braiding related to stalled central bars (Knighton, 1998). In this mechanism, once braiding is initiated because of loss of sediment transport capacity, flow divergence around central bars creates a positive feedback that maintains the complex channel (Ashmore, 1991).

Although the mechanisms responsible for juxtaposition of simple and complex channels may not be well understood, the data indicate the phenomenon exists and persists over time. The simple reaches fit the model of a meandering channel that would be characterized mostly by point and lateral bars. Complex reaches fit the model of braided channels characterized by multiple channels and midchannel sand bars.

Divergence of flow around midchannel bars and episodic shifting of channels in the complex reaches would result in erosional, depositional, and disturbance processes substantially different from the simple reaches. The subclasses identified in our clustering process presumably have discrete suites of processes associated with them. For example, classes dominated by complex flow and bare sand bars have less flow and erosional resistance, greater disturbance frequency, and less nutrient exchange compared to classes dominated by complex flow and vegetated bars. Generalized dominant processes associated with the 4-cluster classification are given in table 19. Physical interpretation of geomorphic processes, rather than depending on form alone, addresses some of the pitfalls identified with form-based fluvial classifications (Goodwin, 1999; Juracek and Fitzpatrick, 2003).

The distinct morphological and process classes recognized along the MNRR are similar in concept to the process domains defined by Montgomery (1999). The process-domain concept was built on the observation that geomorphic and ecological processes vary discontinuously with hydrologic, geologic, and topographic controls within a drainage basin, resulting in discrete domains where some processes are dominant over others. Results of our analysis in the MNRR indicate that the process-domain concept can be extrapolated usefully to the river-reach scale. Distinct clusters of river-reach types support the concept that each type has distinct suites of geomorphic and ecologic processes. At the channel-network scale investigated by Montgomery (1999), most of the differentiation of domains results from variables that are clearly independent: rock type, network position, and topography. In contrast, process domains at the river-reach scale may include differentiation due to instability phenomena (for example, the transition from meandering to braided, an internal threshold) in addition to the effects of external, independent controls (for example, bedrock, bank stabilization, or tributary junctions).

Our reach-scale classes fit well within the concept of fluvial-process zones (FPZ) or hydrogeomorphic patches defined by Thorp and others (2006). This concept couples ecogeomorphology with patch-dynamics concepts to present a nested, hierarchical system of patches within a river system. As scale was not explicit in their definition, the concept generally includes reach-scale classes within the FPZ concept. Thorp and others (2006) asserted that physical and chemical differences among FPZ patches will correlate with ecological processes such as productivity, organic-matter dynamics, nutrient cycles, and community structure.

Multiscale Classification of the Missouri National Recreational River

Channel classes identified for the MNRR can be arranged in a hierarchy that defines clusters of geomorphic processes at a range of scales and resolution. At the coarsest scale of reso-

Table 16. Comparison of persistence of classification groups between the 1999 classification and 2003 data for the 39-mile segment and 2004 data for the 59-mile segment. *A,* Two cluster classification. *B,* Four cluster classification. *C,* Ten cluster classification.

[**Bold** numbers indicate same class in both years. ***Italicized bold*** numbers indicate transition to a different class of 20% or more]

A. Proportion of addresses in the 1999 2-cluster classification that classified the same or in other classes in 2003–04.

1999 4-cluster classification	Simple	Complex	Total in 1999
Simple	0.86	0.14	463
Complex	0.05	0.95	579
Total in 2003–04	428	614	1,042

B. Proportion of addresses in the 1999 4-cluster classification that classified the same or in other classes in 2003–04.

	2003–04 4-cluster classification				
1999 4-cluster classification	1	2	3	4	Total in 1999
1	**0.86**	0.03	0.11		463
2	0.05	**0.67**	0.17	0.11	282
3	0.08	***0.34***	**0.57**	0.01	191
4		0.02	0.03	**0.95**	106
Total in 2003–04	428	270	210	134	1,042

C. Proportion of addresses in the 1999 10-cluster classification that classified the same or in other classes in 2003–04.

	2003–04 10-cluster classification										
1999 10-cluster classification	1	2	3	4	5	6	7	8	9	10	Total in 1999
1	**0.97**	0.01	0.01								230
2	0.06	**0.60**	0.21	0.03		0.05		0.04			207
3	0.05	0.14	**0.45**	0.09		0.16		0.11			112
4			0.03	**0.46**		0.26		0.12	0.05	0.08	93
5							***0.89***		0.11		9
6		0.02	0.01	***0.28***		**0.60**		0.04	0.04	0.01	164
7							**0.33**		***0.67***		21
8			0.03	0.18		***0.29***		**0.47**	0.03	0.01	77
9				0.01		0.04	0.04	0.01	**0.39**	***0.51***	95
10					0.03		0.09	0.06	0.24	**0.59**	34
Total in 2003–04	242	147	104	121	1	176	22	78	74	77	1,042

lution, we have applied a deductive classification to delineate the broad segments of the MNRR and adjacent parts of the river corridor (fig. 48). Segments are defined based on sections of the river that have clearly different hydrologic regimes or channel constraints (Frissell and others, 1986). In this case, because of different storage and reservoir management guidelines for the Fort Randall and Gavins Point Dams, hydrologic regimes of the two segments are very different. Lewis and Clark Lake, while not a part of the MNRR, would clearly qualify as another hydrologically-distinct segment. The delineation between the lake and the 39-mile segment, however, is variable because of progradation of the delta over the long term, and backwater hydraulic effects over the short term. Distinct morphologic changes associated with backwater and the upper deltaic plain support additional segmentation of the 39-mile segment into free-flowing and deltaic reaches approximately at the Niobrara River junction. The Kensler's Bend segment has generally similar hydrology to the 59-mile segment. Because

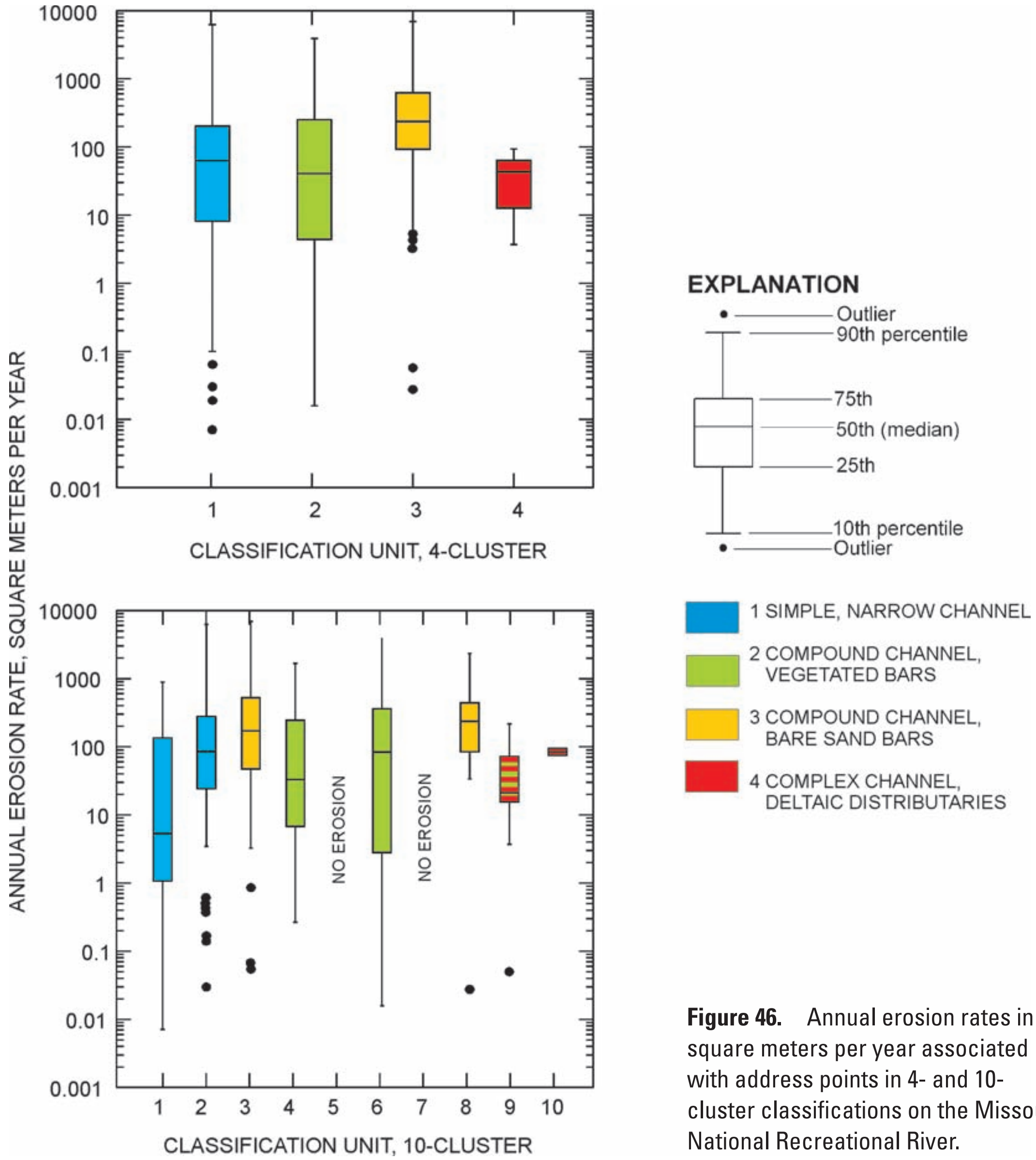


Figure 46. Annual erosion rates in square meters per year associated with address points in 4- and 10-cluster classifications on the Missouri National Recreational River.

channel engineering structures fundamentally alter the relation between flow and geomorphic form, Kensler's Bend qualifies as a separate segment.

At finer resolution in the hierarchy, we applied a statistical clustering analysis to identify naturally occurring groups of geomorphic characteristics at the reach scale. The coarsest of these simply differentiates reaches with complex and simple channels. The finest of these subdivides the reaches based on relative variations of channel width, vegetated-bar area, and bare-sand-bar area.

The hierarchical classification presented here delineates hydrologically and geomorphically distinct parts of the river at scales ranging from 200 m to tens of kilometers. Units with even finer resolution (mesohabitat and microhabitat scales) could be accommodated within the classification structure if data become available. The hierarchical, multiscale structure allows the classification to be used at scales optimized for specific questions. For example, if used as a template for stratified sampling design of fish or birds, the strata could be defined narrowly or broadly to select for different ranges of variation.

Temporal Persistence of Spatial Patterns

The long-term history of the Missouri River indicated by late-19th century maps and mid-20th century aerial orthophotography provides an understanding of historical reference condition, especially in illustrating how reach-scale geomorphic complexity has diminished over time. With the construction of the dams, the Missouri River in what today is the MNRR began a practically irreversible adjustment of channel form to the altered hydrologic and sediment regimes.

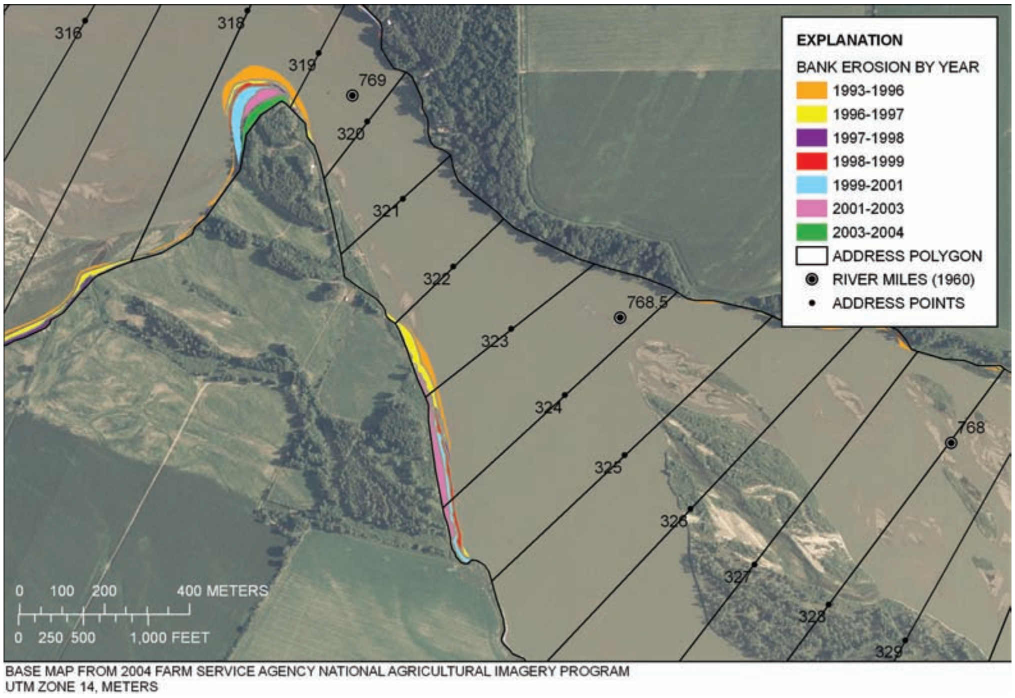


Figure 47. Address polygons used for collecting bank-erosion values. Eroded areas are associated with polygons immediately downstream of address points.

Cross-sectional monitoring data presented by the USACE (2004b) indicated that the rate of channel incision is slowing 50 years after the dams were closed but is still measurable. The classification developed in this study was based on recent channel characteristics. It probably would not be optimal for the historical river and may have a finite lifetime in application to the present river as it continues to adjust.

Notwithstanding ongoing adjustments and year-to-year hydrologic variability, classified reaches in the MNRR showed persistence over multiyear time frames. The classification developed here was based on channel conditions in 1999 and used to classify conditions in 2003–04. At the broadest level of the reach-scale classification hierarchy, persistence of classes between time periods was 86–95 percent. At finer levels of the hierarchy, persistence was as low as 33 percent, reflecting the more dynamic processes resolved at the finer scales.

Decadal-average bank erosion rates also varied systematically by geomorphic classes, although they were highly variable. Variability of erosion rates within classes probably resulted from erosion being concentrated at the upstream and downstream margins of the complex reaches. These parts of the channel are characterized by flow expansions and contraction, and erosion in such areas could be attributed to multiple classes.

Implications for Management

The classification system and supporting data illustrate a river that is characterized by relatively discrete reaches with naturally clustering sets of geomorphic characteristics. River morphology is generally indicative of geomorphic processes as a channel's morphology adjusts to hydrologic regime, sediment regime, and physiographic conditions of the valley (Leopold and others, 1964). Morphology is therefore a general indicator of geomorphic processes and the morphological units identified in this classification are inferred to have specific sets of geomorphic processes.

Understanding of the spatial distribution of processes should provide guidance for river-management decisions. For example, two prominent management decisions on the MNRR have involved regulation of bank-stabilization structures and design of engineered sand-bar habitat.

In 2006, 12.5 percent of the banks in the 39-mile segment, and 32 percent of the banks in the 59-mile segment were revetted or stabilized by hard points (Biedenharn and others, 2001; Wilson, 2005). The future of bank stabilization in the MNRR is likely to continue as a contentious issue because of differing perceptions of benefits and costs. Acknowledging the ecological benefits of channel migration (Trush and others, 2000), management agencies can prioritize where bank stabilization projects are permitted to maximize social benefits of bank stability while minimizing ecological costs. Planning processes could use geomorphic classes identified in this study as a framework for determining where bank stabilization is warranted or where bank instability could be controlled at socially acceptable rates. For example, the distribution of classes identified with high-erosion rates could be compared with maps of land uses, historical structures, archeological sites, and infrastructure to prioritize stabilization projects. Conversely, classes associated with low-erosion rates could be identified as low priority for stabilization and perhaps be allowed to erode at a socially acceptable rate and thereby potentially provide ecologically beneficial habitat dynamics.

Classification also may aid in design of stabilization projects, as the reach classification is broadly indicative of the intensity of erosional energy. For example, the same design that would stabilize banks in a simple channel may be inadequate in a complex reach with divergent flow and a shifting thalweg. Such reaches may require additional investment to achieve stabilization goals. Moreover, stabilization designs in complex reaches may need to be more longitudinally extensive because of the capacity of the channel to shift erosional energy from place to place. Application of the “self-organized criticality” theory to bank instability indicates that measures that prevent small-scale bank erosion locally may act to increase the overall instability and the risk of larger scale, low-frequency bank failures (Fonstad and Marcus, 2003). Shifting of erosional energy from stabilized banks may require that stabilization projects are designed to stabilize entire reaches, rather than small sections within a reach.

Classification and a historical understanding of bank erosion also can contribute to application of the erodible corridor concept (Piégay and others, 2005). Under this concept, the decision is made to allow the river to erode freely within a defined corridor of land without erosion-control structures. The extent of the corridor would be designed based on historical bank-erosion rates and where bank erosion would be socially and economically acceptable. Piégay and others (2005) indicated that design widths for the corridor should take into account spatially explicit erosion rates and controls on channel migration; hence a geomorphic classification is a prerequisite to the design process. Such a corridor might be defined for the MNRR by using the results of this classification and a cost-benefit analysis of existing property and infrastructure within prospective corridors. Development of design-corridor widths would benefit from combining historical analysis of where the channel has been with numerical modeling of channel migration (Piégay and others, 2005; Wallick and others, 2006).

In addition to bank stabilization, construction of sand-bar habitat is another management process that could benefit from the geomorphic classification. To maximize persistence of emergent sand-bar habitat, projects could be located in reaches of the river that would be minimally erosive, yet would also experience periodic scouring flows that would remove vegetation. The documentary evidence provided, and the classification system defined in this report, indicate where sand bars are naturally persistent (complex channel reaches), but the temporal data showed that in the absence of scouring flows, vegetation is encroaching on most of these bars. Whereas complex channel reaches would not develop scouring shear stresses and thereby allow encroachment to continue, simple channel reaches are more likely to transport sand through them, as they lack the flow divergence that would lead to bar formation. These observations indicate that geomorphic processes may favor sand-bar persistence at the upstream end of complex reaches. At these interfaces between simple and complex channels, flow divergence could be achieved and maintained with relatively small engineering investment, but flows will be more concentrated, and more likely to scour vegetation from bars, than in the downstream portions of complex reaches.

A final application for the geomorphic classification presented here could be for structuring scientific monitoring and assessment efforts. Many of the biological indicators used to assess success of river-management efforts depend in

Table 17. Descriptive statistics for annual erosion rates by class.

[m^2, square meters]

Classification	Class	Mean (m^2)	Standard deviation (m^2)	Coefficient of variation	Number	Total annual erosion (percent)
4-cluster	1	80.6	424.6	5.3	463	28.1
	2	113.8	415.1	3.6	282	24.1
	3	331.9	922.9	2.8	191	47.7
	4	1.3	10.0	7.5	106	0.1
10-cluster	1	7.2	63.1	8.8	230	1.2
	2	165.4	619.3	3.7	207	25.8
	3	388.9	1,133.1	2.9	112	32.8
	4	118.0	290.1	2.5	93	8.3
	5	0.0	0.0	n/a	9	0.0
	6	155.1	511.3	3.3	164	19.1
	7	0.0	0.0	n/a	21	0.0
	8	210.8	474.0	2.2	77	12.2
	9	7.3	31.3	4.3	95	0.5
	10	5.0	20.2	4.1	34	0.1

Table 18. Pairwise comparison of means of erosion rates by using analysis of variance and the Tukey method for pairwise comparisons (Wilkinson and others, 2004). Values in the table are the probability of means being equal. *A,* 4-cluster comparison. *B,* 10-cluster comparison.

[Significant differences at the 0.05 level are indicated in **bold;** differences at the 0.01 level are indicated in ***bold italic.***]

A. Overall analysis of variance, p = 0.000				
	4-cluster classification			
	1	2	3	4
1	1.000			
2	0.842	1.000		
3	***0.000***	***0.000***	1.000	
4	0.509	0.247	***0.000***	1.000

B. Overall analysis of variance, p = 0.000										
	10-cluster classification									
	1	2	3	4	5	6	7	8	9	10
1	1.000									
2	0.057	1.000								
3	***0.000***	**0.012**	1.000							
4	0.795	0.999	***0.010***	1.000						
5	1.000	0.996	0.515	1.000	1.000					
6	0.162	1.000	**0.012**	1.000	0.998	1.000				
7	1.000	0.938	0.063	0.996	1.000	0.962	1.000			
8	0.100	1.000	0.409	0.981	0.982	0.999	0.841	1.000		
9	1.000	0.321	***0.000***	0.917	1.000	0.483	1.000	0.266	1.000	
10	1.000	0.830	***0.008***	0.988	1.000	0.892	1.000	0.679	1.000	1.000

Table 19. Names and interpreted physical significance of clustered classes.

4-cluster classification	Descriptive name	Dominant physical process
1	Simple, narrow	Meandering-type channel. Sediment transport with minimal deposition or erosion. Occasional point bar accretion and lateral bank erosion. Low sediment accretion and lateral erosion rates. Low disturbance frequency.
2	Complex channel, vegetated bars	Flow divergence upstream of midchannel bars; flow convergence downstream of midchannel bars. Overbank sedimentation on low-lying vegetated bars at higher flows. Lower disturbance frequency.
3	Complex channel, sand bars	Flow divergence upstream of midchannel bars; flow convergence downstream from midchannel bars. Sediment scour and deposition. Frequent shifting of channel positions. Lateral bank erosion. High disturbance frequency.
4	Very complex channel, deltaic distributaries	Flow divergence upstream of midchannel bars; flow convergence downstream from midchannel bars. Deposition and subsequent bar growth. No bank erosion. Low rates of bar erosion. Sediment transport rates decrease as slope decreases in the reservoir.

large part on the template of physical habitat available to the organism. Randomized sampling of river segments without recognition of the clustered nature of geomorphic processes risks incorporating large, unnecessary variance due to the variability of the underlying habitat template. Stratification based on homogeneous physical-habitat units, defined at the appropriate hierarchical level for the indicator in question, can improve sampling designs by minimizing variance (Vos and others, 2000). Recognition of a physical habitat classification structure can also be used in poststratification of a randomized survey when prestratification is thought to decrease precision (Hughes and others, 2000).

Summary

The multiscale geomorphic classification presented here provides a physically-based framework for understanding spatial distributions of geomorphic processes within the MNRR in South Dakota and Nebraska. Longitudinal assessment of channel geomorphic characteristics illustrates the discontinuous, clustered distribution of channel morphology, suggesting the underlying discontinuous distribution of geomorphic processes. Statistically identified clusters are therefore treated as process domains, or lengths of channel with characteristic sets of geomorphic processes.

The first level of classification of the MNRR recognizes deductively the importance of hydrologic variation due to reservoir operations at Fort Randall and Gavins Point Dams, the overriding influence of inundation in Lewis and Clark Lake, and the independent control of bank stabilization and channelization in Kensler's Bend. These controls define the broad scale segmentation into the 39-mile segment (Fort Randall Dam to Lewis and Clark Lake), the 59-mile segment (Gavins Point Dam to Ponca State Park), and the Kensler's Bend segment (Ponca State Park to Sioux City, Iowa). In addition, the profound change of the 39-mile segment where it transitions from a relatively free-flowing reach to the Lewis and Clark Lake delta indicates a useful division of reaches at the Niobrara River.

Channel characteristics collected nearly continuously (200-m intervals) illustrate spatial variability along the channel and provide data for the statistical analysis. Channel widths are highly variable in all segments except Kensler's Bend and are distributed in juxtaposed wide and narrow clusters. Channel morphology is controlled by bedrock along substantial portions of the MNRR, from about 50 percent in the 39-mile segment to nearly 5 percent of the 59-mile segment. Channel morphology also is strongly controlled by bank stabilization structures, ranging from 12.4 percent of the 39-mile segment to about 32 percent of the 59-mile segment, and about 95 percent of the Kensler's Bend segment. Reach-scale sinuosity

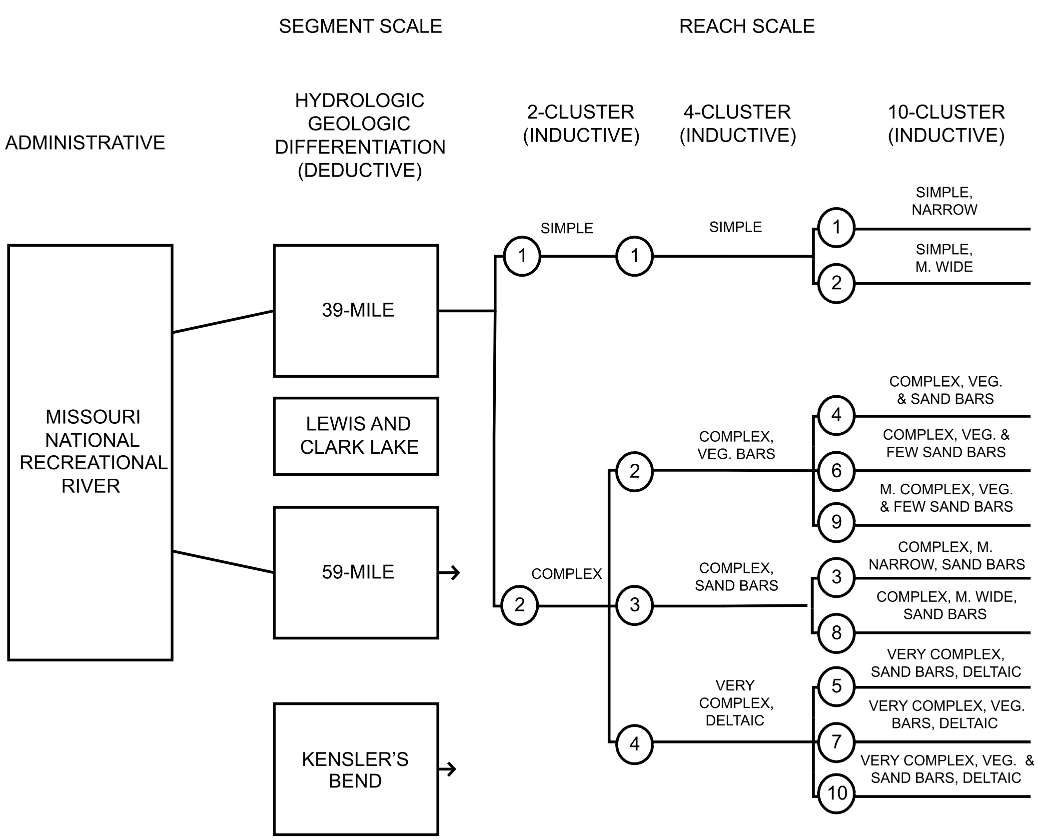


Figure 48. Multiscale classification concept for the Missouri National Recreational River and adjacent Missouri River segments. Segments were classified deductively to delineate sections of the river with manifestly different hydrologic regimes and channel constraints. Reach-scale classes were derived inductively by cluster analysis to define naturally occurring groups of geomorphic characteristics. The reach-scale hierarchy applies to the 59-mile and Kensler's Bend segments as well. [veg. = vegetation; m. = moderately]

is lowest in the 39-mile segment and achieves values as high as 1.6 in the 59-mile segment. Although often a strong indicator of channel complexity, sinuosity was not used in statistical classifications because the thalweg could not be mapped with certainty from aerial imagery.

Over 1,700 bare sand bars and vegetated bars were mapped in the MNRR in 1999. Vegetated bars were most common in the Lewis and Clark Lake delta (26.6 bars per kilometer). In the free-flowing portion of the 39-mile segment there was an average of 5.6 bars per kilometer and in the 59-mile segment vegetated bars averaged 1.0 bar per kilometer. Bare sand bars were more numerous in the 59-mile segment (2.98 sand bars per kilometer) compared to the free-flowing part of the 39-mile segment (1.46 sand bars per kilometer). Presence of bars also was indicative of channel complexity. Large woody debris was considered the most dependent of physical variables that could be measured from remotely sensed imagery. Over 12,000 pieces of large woody debris were mapped, with 38.2 pieces per kilometer in the 39-mile segment, 96 pieces per kilometer in the 59-mile segment, and 22 pieces per kilometer in the Kensler's Bend segment. Ninety percent of the large woody debris in the Kensler's Bend segment was mapped within 50 m of the bank, 26 percent was within 10 m, and nearly all was located on the inside of bends within recirculation zones downstream of wing dikes. Within the channelized segment, wing dike orientation appeared to be a critical factor in retaining large woody debris.

Bank erosion was highly variable in space and over time. The 39-mile segment averaged 0.99 m/m from 1993 to 2003 whereas the 59-mile segment averaged over 22 m/m from the 1993 to 2004 period. Bank erosion in Kensler's Bend was effectively zero. Within the 59-mile segment, the 1996-97 period recorded the highest bank erosion rate at 3.96 m/m/year.

Assessment of changes in bar area is confounded by sensitivity to discharge. Analysis of bar frequencies, rather than areas, indicate that vegetated bars and bare sand bars are tending to decrease slightly in frequency over time in the 39-mile segment whereas they are both increasing slightly over time in the 59-mile segment. In both, numbers of bars have been highly variable, especially as a result of high flows in 1997. Linear regression models of bar area and discharge in the 59-mile segment provide an indirect assessment of changes in bar area; residuals from these models plotted against year indicate that, controlling for discharge, vegetated bars are tending to increase in area and bare sand bars are tending to decrease in area. Persistence analysis confirmed that vegetated bars were more likely to be found in the same position from year to year, whereas 60 percent of areas identified as sand bars contained sand only 1 out of 6 years. Mapping of the Lewis and Clark Lake delta also provided estimates of rates of progradation of the delta front. Based on 25 years of data, the progradation of the delta was calculated at 199 m/yr.

Comparisons of modern (1993 to 2004) channel characteristics with those from 1941 to 1894 confirm that the MNRR is narrower and has a simpler planform than its predam reference condition. In particular, in the predam era, the MNRR had fewer vegetated bars but the bars were much larger. The vegetated bar/islands were defined by long, narrow, and sinuous chutes that are no longer connected to the mainstem channel. In 1941 there were 3.6 bare sand bars per kilometer in the 59-mile segment, whereas the range from 1993 to 2004 was 3.0 to 7.2 bare sand bars per kilometer. The average size (at prevailing discharge) in 1941, however, was very large compared to the modern channel.

The statistical classification was developed from geomorphic characteristics of the river collected from high-resolution digital aerial photography acquired in 1999, and it was tested by comparison with similar datasets from 2003 and 2004. The simplest level of the classification hierarchy divided the river into discrete reaches characterized by single and multithread channels. More detailed hierarchical levels established 4-part and 10-part classifications. The classifications were validated by exploring persistence of classified units over time and by evaluating variation of bank erosion rates by geomorphic class. Persistence of classified units varied with hierarchical level; units classified with the 2-part system were most persistent, and those with the 10-part system were least. Transitions between classes of the 4-part and 10-part systems were consistent with simplification of the channel and increasing vegetation encroachment from 1999 to 2004. Although bank erosion rates were highly variable along the river, the classification successfully identified classes that were significantly less stable compared to others.

The classification system presented here establishes a physical framework that can provide useful information for river-management decisions. Delineation of discrete-process domains at the reach scale should be useful for tailoring design and extent of bank-stabilization projects to river characteristics, for placement and design of habitat-rehabilitation projects, and for design of monitoring and assessment programs.

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