Prepared in cooperation with the Missouri River Recovery—Integrated Science Program
U.S. Army Corps of Engineers, Yankton, South Dakota

Development of a Channel Classification to Evaluate Potential for Cottonwood Restoration, Lower Segments of the Middle Missouri River, South Dakota and Nebraska

Scientific Investigations Report 2010–5208

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

Cover photograph: Landsat 5 imagery of Big Bend in Lake Sharpe segment, Middle Missouri River, acquired on 9/17/2009. U.S. Geological Survey, Earth Resources Observation and Science Data Center.

Development of a Channel Classification to Evaluate Potential for Cottonwood Restoration, Lower Segments of the Middle Missouri River, South Dakota and Nebraska

By Robert B. Jacobson, Caroline M. Elliott, and Brittany L. Huhmann

Prepared in cooperation with the Missouri River Recovery—Integrated Science Program
U.S. Army Corps of Engineers, Yankton, South Dakota

Scientific Investigations Report 2010–5208

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

Suggested citation:
Jacobson, R.B., Elliott, C.M., and Huhmann, B.L., 2010, Development of a channel classification to evaluate potential for cottonwood restoration, lower segments of the Middle Missouri River, South Dakota and Nebraska: U.S. Geological Survey Scientific Investigations Report 2010–5208, 38 p.

Contents

Figures

Tables

Conversion Factors, Abbreviations, and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)

To communicate effectively with stakeholders, managers, and other scientists working on the Lower Missouri River, this report uses a mix of U.S. customary units and International System of Units (SI) units of measure. Distances along the Missouri River are given in river miles upstream from the junction with the Mississippi River at St. Louis, Missouri, as measured by the U.S. Army Corps of Engineers in 1960. Discharges are provided in the customary units of cubic feet per second. Reach-scale hydraulic variables—velocity and depth—are in SI units of meters per second and meters.

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Development of a Channel Classification to Evaluate Potential for Cottonwood Restoration, Lower Segments of the Middle Missouri River, South Dakota and Nebraska

By Robert B. Jacobson, Caroline M. Elliott, and Brittany L. Huhmann

Abstract

This report documents development of a spatially explicit river and flood-plain classification to evaluate potential for cottonwood restoration along the Sharpe and Fort Randall segments of the Middle Missouri River. This project involved evaluating existing topographic, water-surface elevation, and soils data to determine if they were sufficient to create a classification similar to the Land Capability Potential Index (LCPI) developed by Jacobson and others (U.S. Geological Survey Scientific Investigations Report 2007–5256) and developing a geomorphically based classification to apply to evaluating restoration potential.

Existing topographic, water-surface elevation, and soils data for the Middle Missouri River were not sufficient to replicate the LCPI. The 1/3-arc-second National Elevation Dataset delineated most of the topographic complexity and produced cumulative frequency distributions similar to a high-resolution 5-meter topographic dataset developed for the Lower Missouri River. However, lack of bathymetry in the National Elevation Dataset produces a potentially critical bias in evaluation of frequently flooded surfaces close to the river. High-resolution soils data alone were insufficient to replace the information content of the LCPI. In test reaches in the Lower Missouri River, soil drainage classes from the Soil Survey Geographic Database database correctly classified 0.8–98.9 percent of the flood-plain area at or below the 5-year return interval flood stage depending on state of channel incision; on average for river miles 423–811, soil drainage class correctly classified only 30.2 percent of the flood-plain area at or below the 5-year return interval flood stage. Lack of congruence between soil characteristics and present-day hydrology results from relatively rapid incision and aggradation of segments of the Missouri River resulting from impoundments and engineering. The most sparsely available data in the Middle Missouri River were water-surface elevations. Whereas hydraulically modeled water-surface elevations were available at 1.6-kilometer intervals in the Lower Missouri River, water-surface elevations in the Middle Missouri River had to be interpolated between streamflow-gaging stations spaced 3–116 kilometers. Lack of high-resolution water-surface elevation data precludes development of LCPI-like classification maps.

An hierarchical river classification framework is proposed to provide structure for a multiscale river classification. The segment-scale classification presented in this report is deductive and based on presumed effects of dams, significant tributaries, and geological (and engineered) channel constraints. An inductive reach-scale classification, nested within the segment scale, is based on multivariate statistical clustering of geomorphic data collected at 500-meter intervals along the river. Cluster-based classifications delineate reaches of the river with similar channel and flood-plain geomorphology, and presumably, similar geomorphic and hydrologic processes. The dominant variables in the clustering process were channel width (Fort Randall) and valley width (Sharpe), followed by braiding index (both segments).

Clusters with multithread and highly sinuous channels are likely to be associated with dynamic channel migration and deposition of fresh, bare sediment conducive to natural cottonwood germination. However, restoration potential within these reaches is likely to be mitigated by interaction of cottonwood life stages with the highly altered flow regime.

Introduction

Riparian cottonwood communities have been in general decline in rivers of the Great Plains because of lack of reproduction and recruitment. Causes for recruitment failures typically have been linked to river-management actions that have decreased channel-migration processes that would naturally provide bare mineral soils for seedling germination or actions that promote hydrologic conditions that give a competitive advantage to invasive species.

Lack of cottonwood recruitment on the Missouri River has been recognized as a threat to habitat needed by the threatened bald eagle (*Haliaeetus leucocehpalus*). A 2000 Biological Opinion recommended that the U.S. Army Corps of Engineers implement reasonable and prudent alternatives to maintain cottonwood communities by avoiding bank stabilization and purchasing land where cottonwood could be restored (U.S. Fish and Wildlife Service, 2000). Implementation of this goal requires an understanding of hydrologic and geomorphic processes that promote natural cottonwood regeneration or that would support active restoration efforts. The objective of the study described here was to provide a spatially explicit river and flood-plain classification that resolves differences in biophysical capacity for cottonwood restoration along the Middle Missouri River.

Background

Riparian cottonwood communities are considered to be in decline along the Missouri River as a result of bank stabilization and flow-regime regulation (U.S. Fish and Wildlife Service, 2000). Bank stabilization prevents channel migration and consequent formation of cottonwood regeneration sites in freshly deposited sediment in point bars. Flow regulation that decreases magnitude and frequency of flood peaks decreases nutrient deposition in flood plains, may decrease soil moisture, and further diminishes potential for channel migration. Flow regulation may also result in germination of seedlings in places where they will be subject to scour; flow regulation may also change flood-recession rates and thereby alter root growth patterns (Scott and others, 1997; Auble and Scott, 1998; Mahoney and Rood, 1998; Kalischuk and others, 2001). As a result, regeneration has not been sustained in many places and cottonwood communities have become senescent or invaded by nonnative species (U.S. Fish and Wildlife Service, 2000; National Research Council, 2002).

Lack of cottonwood regeneration has been considered a factor in continuing concern for the status of the bald eagle. Large, old cottonwood trees have been identified as important nesting habitat for bald eagles along the Missouri River, and lack of cottonwood regeneration threatens habitat availability. Although the bald eagle was delisted as an endangered species in 2007 the U.S. Fish and Wildlife Service recognized the value of cottonwood communities and their role in providing habitat for the bald eagle in a 2000 Biological Opinion (U.S. Fish and Wildlife Service, 2000). To avoid take (harm or destruction) of bald eagles from loss of cottonwood community habitat, the U.S. Fish and Wildlife Service stipulated three reasonable and prudent measures:

- Map and evaluate current health of cottonwood forests on the Missouri River;
- Develop a management plan to allow for natural regeneration, seed germination, and seedling establishment to maintain populations;
- Implement management actions to ensure that no more than 10 percent of cottonwood habitat suitable for bald eagles is lost.

This report addresses the physical processes and geomorphic framework that define river flood-plain ecosystems in part of the Middle Missouri River. The objective is to develop a classification system that delineates relatively discrete reaches with common suites of geomorphic processes and rates [process domains, in the sense of (Montgomery, 1999)]. Similar process domains are inferred to have similar potential for natural cottonwood regeneration or active mechanical restoration.

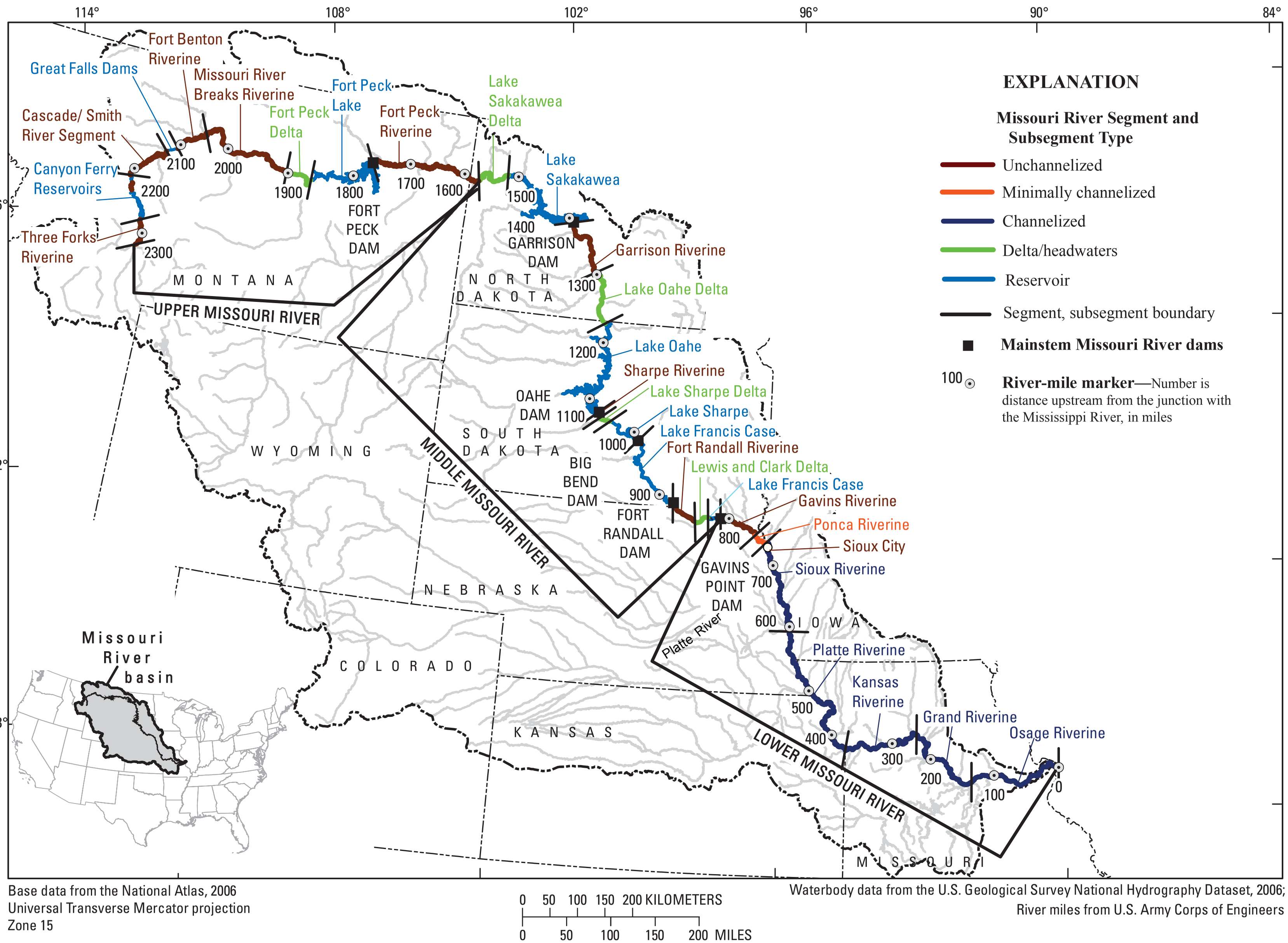
Previous classification work on the Lower Missouri River has delineated the river based on specific project needs. The broadest classification has been into segments generally delineated at major tributaries or geologic or engineering boundaries (Laustrup and LeValley, 1998; U.S. Fish and Wildlife Service, 2000). Segment-scale classifications have been used to describe broad variation in hydrology and channel hydraulics (Galat and Lipkin, 2000; Pegg and others, 2003; Reuter and others, 2008; Reuter and others, 2009) and have not explicitly considered adjacent flood plains.

Classifications that expand laterally from the channel to address adjacent flood plain and valley-bottom terraces generally require relative elevation data, soils data, or both. Classification schemes for parts of the Lower Missouri River flood plain have been based on surficial geology (Holbrook and others, 2006; Ghimire and others, 2007) and hydrogeomorphic classifications that combine relative elevation, measures of soils wetness, topography, and soil moisture retention (Jacobson and others, 2007). Other approaches to flood-plain classification have been based on existing vegetation classes (Rieman and others, 2001) or vegetation and mappable water bodies [National Wetlands Inventory Program, (U.S. Fish and Wildlife Service, 1994–2000)].

Classifications of the Missouri River at finer scales include reach scale (10s of kilometers), bend scale (bend-crossover units or channel units, 100s to 1,000s of meters), and macro-, meso-, and micro-scale units (ranging from 100s of meters to millimeter scale). At finer scales, classifications are more specific to particular intended uses. Reach-scale classifications have been developed for part of the Missouri River between Gavins Point Dam and Sioux City, Iowa (Elliott and Jacobson, 2006) and parts of the adjacent Platte River in Nebraska (Elliott and others, 2009b); these classifications have been intended to resolve geomorphically similar reaches that would have similar channel dynamics and suites of channel and sandbar habitats. Macro- and mesoscale classifications on the Missouri River have been used to define areas with similar depth, velocity, and substrate characteristics and for which specific gear types would be used in fishery studies (Welker and Drobish, 2009). Mesoscale aquatic habitat classifications of the Lower Missouri River also have been defined using species-specific criteria to subdivide spatially continuous maps of derivative hydraulic variables (Reuter and others, 2008; Jacobson and others, 2009b; Reuter and others, 2009)

Scope and Objectives

This report documents development of a channel flood-plain classification for the Sharpe and Fort Randall segments of the Middle Missouri River. The Middle Missouri River generally is defined as segments between Gavins Point Dam, South Dakota, and the headwaters of Lake Sakakawea in North Dakota (fig. 1). This section of the Missouri River is



Base data from the National Atlas, 2006
Universal Transverse Mercator projection
Zone 15

Waterbody data from the U.S. Geological Survey National Hydrography Dataset, 2006;
River miles from U.S. Army Corps of Engineers

Figure 1. Missouri River Basin and segment-scale classification of the mainstem.

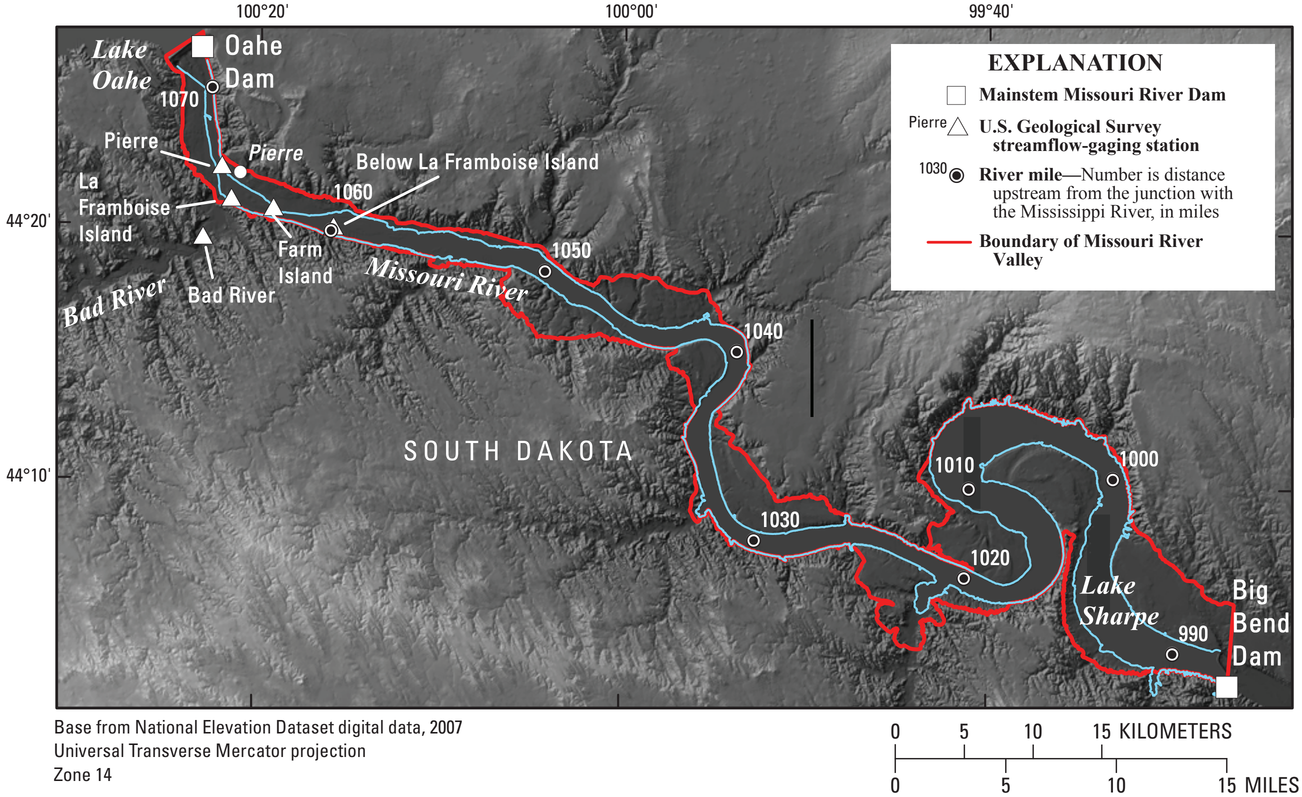


Figure 2. The Sharpe segment of the Missouri River.

characterized by five large reservoirs separated by relatively free-flowing segments. This report concentrates on segments of the river downstream from Oahe Dam, South Dakota, and upstream from Lewis and Clark Lake, South Dakota (figs. 1–3, table 1). These are interreservoir segments Oahe Dam to Big Bend Dam, Fort Randall Dam to the Niobrara River, and Niobrara River to the headwaters of Lewis and Clark Lake. The segment defined by Lake Francis Case is not considered in this report because it is unlikely to provide cottonwood habitat.

The primary objective is to develop a classification system similar to the Land Capability Potential Index (LCPI) that has been applied to the Lower Missouri River downstream from Gavins Point Dam (Jacobson and others, 2007). Because the LPCI was developed in an area where high-resolution elevation and water-surface profile data were available, it was not clear whether a similar classification could be developed in the Middle Missouri River where data were more sparse. Therefore, two subobjectives were identified. The first was to evaluate the utility of existing low-resolution data in development of an alternative LCPI by comparing LCPI metrics in areas with high-resolution and low-resolution data. The second was to develop a classification system based on available geomorphic data that would serve as the alternative LCPI as well as a general classification for the Middle Missouri channel and flood plain.

Approach and Methods

We first assessed the information content of generally available, low-resolution datasets relative to the LCPI to identify which, if any, physical variables in low-resolution datasets are useful in classifying the potential for cottonwood regeneration. In particular, we were interested in the ability of soils data alone to classify sites similar to classifications from LCPI datasets, and whether low-resolution, national elevation data (NED) adds significantly to our ability to classify these sites.

Based on the limitations in using low-resolution data to develop an LCPI-like classification, we then developed a general geomorphic reach-scale classification that would capture many of the salient geomorphic processes of the Middle Missouri River. Although not as detailed or directly relevant to cottonwood regeneration as the LCPI, the geomorphic process domains delineated in the reach-scale classification approach should provide useful information for guiding restoration efforts.

The approach to geomorphic classification is to employ generally available geospatial data arrayed in a longitudinal framework to develop quantitative classification indices. Many river classifications exist, but utility of a classification system rests on its ability to discriminate characteristics that are important for specific uses (Kondolf and others, 2003). To achieve the most utility, we applied the continuous

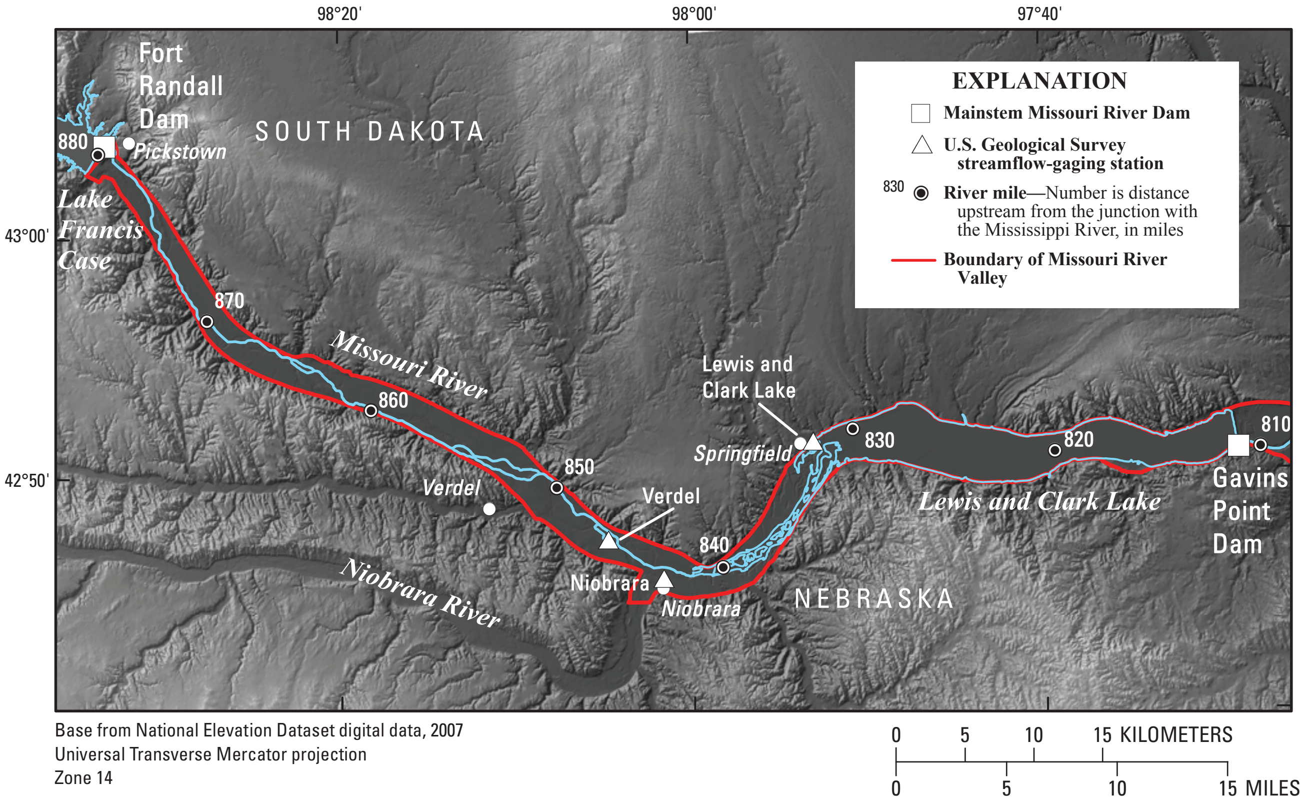


Figure 3. The Fort Randall segment of the Missouri River.

longitudinal classification method of Elliott and Jacobson (2006) to develop a general classification of USACE segments 6, 8, and 9 (table 1) in a manner consistent with previous classifications.

Definitions

We use "segment" to denote lengths of the river having similar flow regime and valley-scale geologic constraints on form and process (Frissell and others, 1986). Segments usually are defined at major tributary junctions where flow regime or water quality might be expected to change river processes substantially. Segments also are defined by bedrock or engineering changes that might exert strong effects on channel morphology. In the Middle Missouri River, segments are clearly defined by dams. Downstream from dams, the free-flowing parts of the river typically undergo a gradual transition into the headwaters of the next downstream reservoir incorporating riverine, deltaic, and lacustrine conditions. Conceptually, lengths of river characterized by each of these three conditions can be considered subsegments, although the transitions vary in position within and among years. In this report, the three subsegments between Oahe Dam and Big Bend Dam are referred to collectively as the *Sharpe segment* and the three subsegments of river between Fort Randall Dam and Gavins Point Dam are referred to collectively as the *Fort Randall segment*.

Segments generally contain multiple "reaches" or lengths of river characterized by uniform multiples of channel units or bend-crossover units (Frissell and others, 1986). The concept of reaches is used less precisely than segments. It is meant to describe varying lengths of channel with at least one bend-crossover sequence. Typically, a reach is defined with multiple, similar bend-crossover sequences.

Data Resources

Several types of widely available sources of data are used for this analysis including U.S. Department of Agriculture National Aerial Imagery Program (NAIP) digital aerial othophotography and National Elevation Dataset (NED) digital elevation models. Hydrologic information was synthesized using U.S. Geological Survey (USGS) streamflow-gaging stage and discharge records, supplemented with U.S. Army Corps of Engineers (USACE) records for Oahe Dam upstream from the Sharpe segment and for the Fort Randall Dam at the upstream end of the Fort Randall segment.

Hydrologic Data

Hydrologic data were used to assess variation within the aerial photography datasets and to develop stage frequency analyses. Big Bend and Fort Randall Dams are managed for

Table 1. Geomorphic segments of the Missouri River.

[River mile, distance upstream from the Junction with the Mississippi River, in miles; MOREAP, Missouri River Environmental Assessment Program; USACE, U.S. Army Corps of Engineers]

River mile start	River mile end	Length, miles	Segment Number from MOREAP document[2]	USACE Segment	Pallid Sturgeon Population Assessment (Welker and Drobish, 2009)	Segment number, this document	Segment	Segment names	Type/class/environment
Upper Missouri River									
2,320	2,278.3	41.7	--	--	--	28	Confluence of Gallatin, Madison, and Jefferson Rivers to Canyon Ferry Lake	Three Forks Riverine	Unchannelized River
2,278.3	2,211.1	67.2	--	--	--	27	Canyon Ferry Lake to Holter Dam	Canyon Ferry Reservoirs	Series of dams and run-of-river reservoirs
2,211.1	2,121	90.1	--	--	--	26	Holter Dam to Black Eagle Reservoir	Cascade/Smith River	Unchannelized River
2,121	2,105.7	15.3	--	--	--	25	Black Eagle Reservoir to Morony Dam	Great Falls Dams	Series of dams and run-of-river reservoirs
2,105.7	2,052	53.7	--	--	--	24	Morony Dam to Marias River	Fort Benton Riverine	Unchannelized River
2,052	1,9051	147	1	--	--	23	Marias River to Fort Peck Delta	Missouri River Breaks Riverine	Unchannelized River
1,905[1]	1,858[1]	47	2	1	--	22	Fort Peck Delta to Fort Peck Lake	Fort Peck Delta	Delta/Headwaters
1,858[1]	1,771.5	86.5	2	1	--	21	Fort Peck Lake to Fort Peck Dam	Fort Peck Lake	Reservoir
1,771.5	1,568[1]	203.5	3	2	1,2,3,4	20	Fort Peck Dam to Lake Sakakawea Delta	Fort Peck Riverine	Inter-Reservoir/Unchannelized River
Middle Missouri River									
1,568[1]	1,512[1]	56	--	2	4	19	Lake Sakakawea Delta to Lake Sakakawea	Lake Sakakawea Delta	Delta/Headwaters
1,512[1]	1,389.9	122.1	5	3	--	18	Lake Sakakawea to Garrison Dam	Lake Sakakawea	Reservoir
1,389.9	1,304[1]	85.9	6	4	--	17	Garrison Dam to Lake Oahe Delta	Garrison Riverine	Inter-Reservoir/Unchannelized River
1,304[1]	1,228[1]	76	7	4	--	16	Lake Oahe Delta to Lake Oahe	Lake Oahe Delta	Delta/Headwaters
1,228[1]	1,072.3	155.7	7	5	--	15	Lake Oahe to Oahe Dam	Lake Oahe	Reservoir
1,072.3	1,065.2[1]	7.1	8	6	--	14	Oahe Dam to Bad River	Sharpe Riverine	Inter-Reservoir/Unchannelized River
1,065.2[1]	1,052.5[1]	12.7	8	6		13	Bad River to Lake Sharpe	Lake Sharpe Delta	Delta/Headwaters

Table 1. Geomorphic segments of the Missouri River.—Continued

[River mile, distance upstream from the Junction with the Mississippi River, in miles; MOREAP, Missouri River Environmental Assessment Program; USACE, U.S. Army Corps of Engineers]

River mile start	River mile end	Length, miles	Segment Number from MOREAP document[2]	USACE Segment	Pallid Sturgeon Population Assessment (Welker and Drobish, 2009)	Segment number, this document	Segment	Segment names	Type/class/environment
					Middle Missouri River—Continued				
1,052.5[1]	987	65.5	8	6	--	12	Lake Sharpe to Big Bend Dam	Lake Sharpe	Reservoir
987	880	107	9	7	--	11	Big Bend Dam to Fort Randall Dam	Lake Francis Case	Reservoir
880	844[1]	36	10	8	5	10	Fort Randall Dam to Niobrara River	39-mile MNRR; Fort Randall Riverine	Inter-Reservoir
8,44[1]	826[1]	18	11	9	6	9	Niobrara River to Lewis and Clark Lake	Lewis and Clark Delta	Delta/Headwaters
8,26[1]	811.1	14.9	12	9	--	8	Lewis and Clark Lake to Gavins Point Dam	Lewis and Clark Lake	Reservoir
					Lower Missouri River				
811.1	753	58.1	13	10	7	7	Gavins Point Dam to Ponca, Nebraska	59-mile Missouri National Recreational River; Gavins	Unchannelized River
753	734	19	14	11	8	6	Ponca, Nebraska to Big Sioux River	Ponca	Minimally Channelized
734	594.5	139.5	15	12	8	5	Big Sioux River to Platte River	Sioux	Channelized River
594.5	367.5	227	16	13	9	4	Platte River to Kansas River	Platte	Channelized River
367.5	250	117.5	17	14	10	3	Kansas River to Grand River	Kansas	Channelized River
250	130.4	119.6	18	14	13	2	Grand River to Osage River	Grand	Channelized River
130.4	0	130.4	19	15	14	1	Osage River to Mississippi River	Osage	Channelized River

[1] River miles marking the beginning and end of delta/reservoir headwater reaches are approximate because of fluctuating water levels in the reservoirs.

[2] Laustrup and LeValley (1998).

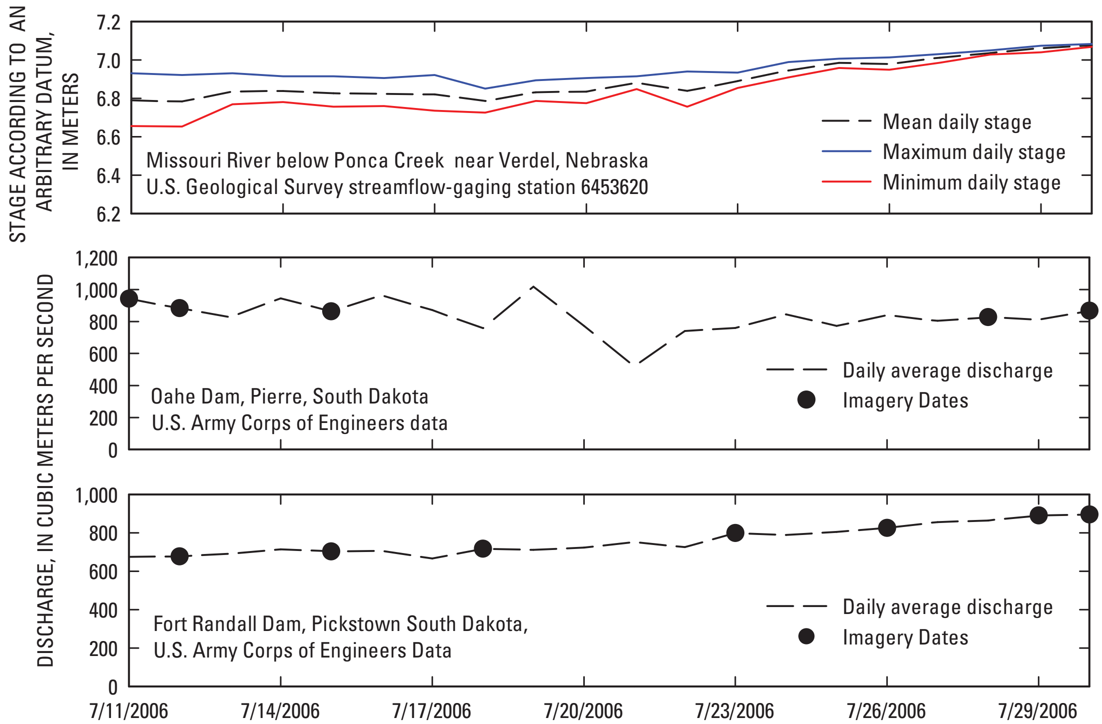


Figure 4. Stage, discharge, and aerial photography acquisition data for the Missouri River in the Sharpe and Fort Randall segments.

load-following power production causing discharges downstream from these dams to fluctuate daily. Aerial orthophotography is indexed by the date but not the time of day the photography was taken, therefore, we use daily average discharges downstream from these dams for reference. Daily fluctuations in discharge exist within the imagery data sets illustrated by the differences in daily minimum, maximum, and mean stage in the Fort Randall segment (fig. 4, table 2). Such hydrologic variation may result in nonuniform mapping of geomorphic features that are dependent on water levels, although our focus on geomorphic features rather than waterlines minimized this effect. Mean daily stage data are available from four USGS streamflow-gaging stations in the Sharpe segment and three locations in the Fort Randall segment of the river (table 3). Midnight tailwater elevations were compiled from USACE gaging stations at Oahe Dam and Big Bend Dam. USGS gage heights were converted to elevations using the individual gage datums, and both USGS and USACE elevations were converted from National Geodetic Vertical Datum of 1929 (NGVD 29) to North American Vertical Datum of 1988 (NAVD 88) for consistency with the National Elevation Dataset. Mean daily stage data were available for the past 10 years from the Sharpe gaging stations and 13 years from the Fort Randall gaging stations.

Determination of the elevations of floods with expected 2-, 5-, and 10-year recurrence interval floods was completed for each gaging station along the Fort Randall and Sharpe segments. From the daily stage data, an annual exceedance series was identified, consisting of the top n independent high flow events within the n years of available data. For the Fort Randall segment n=13, and for the Sharpe segment n=10. The events for each gaging station were ranked in order of magnitude, with the highest elevation event receiving a rank

Table 2. Discharges for National Aerial Imagery Program (NAIP) digital aerial orthophotography used in this study.

[USACE, U.S. Army Corps of Engineers; m^3/s, cubic meters per second]

NAIP aerial photography dates (month/day/year)	Discharge at Oahe Dam, USACE data (m^3/s)	NAIP aerial photography dates (month/day/year)	Discharge at Fort Randall Dam, USACE data (m^3/s)
Sharpe segment		Fort Randall segment	
7/11/2006	943.0	7/12/2006	676.8
7/12/2006	883.5	7/15/2006	702.3
7/15/2006	863.7	7/18/2006	716.4
7/28/2006	826.9	7/23/2006	798.5
7/30 2006	866.5	7/26/2006	824.0
7/10/2008	39.6	7/29/2006	889.1
7/11/2008	218.0	7/30/2006	894.8
7/12/2008	212.4	7/6/2007	563.5
		7/7/2007	594.7
		7/15/2007	625.8
		7/16/2007	625.8
		7/17/2007	597.5

Table 3. Sources for stage infomation used in this study.

[USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey]

Gaging station	Source	River mile
Sharpe segment		
Oahe Dam	USACE	1,071.8
Missouri River at Pierre, South Dakota	USGS	1,066.4
Missouri River at LaFramboise Island at Pierre, South Dakota	USGS	1,064.8
Missouri River Below La Framboise Island at Pierre, South Dakota	USGS	1,062.8
Missouri River at Farm Island near Pierre, Dakota	USGS	1,060.0
Fort Randall segment		
Fort Randall Dam	USACE	880.1
Missouri River below Ponca Creek near Verdel, Nebraska	USGS	846.3
Missouri River at Niobrara, Nebraska	USGS	842.8
Lewis and Clark Lake at Springfiled, South Dakota	USGS	832.0

of 1 and the lowest elevation event receiving a rank of n. The average recurrence interval for each event was then calculated as $T = (n+1)/m$, where n = number of years of record and m = event rank. Elevations for floods with recurrence intervals of 2, 5, and 10 years were determined directly as a result of these calculations or were found by linearly interpolating between the two events with recurrence intervals most closely bracketing the desired interval.

Aerial Orthophotography

We used two-meter (m) resolution digital natural-color orthophotography quarter-quadrangles (DOQQ) from 2006, 2007, and 2008 taken by the Farm Service Agency's National Agricultural Imagery Program (FSA/NAIP). The 2008 NAIP imagery was used for digitizing channel boundaries in the Sharpe segment and 2007 NAIP imagery was used for channel boundary determination in the Fort Randall segment (table 2). All in-channel features were digitized from 2006 imagery (table 2). The photographs were compiled in a geographic information system (GIS) using the ArcGIS software package (ESRI, Redlands, Calif.). All data derived from the orthophotography have the horizontal datum North American Datum of 1983 (NAD 83). The projection used for all data associated with this report is Universal Transverse Mercator Zone 14, Meters (UTM 14).

Land-Surface Elevations

We used 1/3-arc-second (approximately 6.5-m cell size) resolution digital elevation models from the NED to assess elevations within the Sharpe and Fort Randall segments (U.S. Geological Survey, 2009). The data are provided using North American Datum of 1983 (NAD 83) as a horizontal reference and North American Vertical Datum of 1988 (NAVD 88) as a vertical reference. The raster maps were mosaicked and compiled using the ArcGIS software package (ESRI, Redlands, Calif.). To evaluate information content of different available elevation data, we also used 1-arc-second (approximately 26-m cell size) and a high-resolution, 5-m dataset (Jacobson and others, 2007).

The following sections provide detail on methods used in the two subobjectives—assessment of information content for LCPI-like classification and geomorphic classification of the channel and flood plain. The first objective is addressed through exploratory statistical evaluations of available topographic, water-surface elevation, and soils data, and the second objective is addressed through multivariate statistical clustering of geomorphic data compiled in a longitudinal GIS framework.

Information Content Assessment

We used graphical and tabular statistical assessments to evaluate information content of datasets readily available in the Middle Missouri River relative to those used to construct the LCPI for the Lower Missouri River (Jacobson and others, 2007). Geomorphic adjustments of channels in regulated rivers generally result in channel incision or widening directly downstream from dams (Williams and Wolman, 1984); channel aggradation generally occurs upstream from reservoirs in headwaters and can potentially occur far downstream from dams if sediment delivered by tributaries cannot be transported by regulated flows. These changes in local channel geometry can combine with changes to the natural flow regime to alter the magnitude, frequency, duration, and timing for flood events that connect the channel and flood-plain surfaces. In the LCPI approach, modern flood-elevation profiles were available to assess connectivity between the channel and flood-plain; similar flood profiles were not available for the area of interest on the Middle Missouri River.

To explore the information content of soils and NED elevation data relative to the high resolution LCPI datasets (Jacobson and others, 2007), we identified three comparison flood-plain reaches in the Lower Missouri River downstream from Gavins Point Dam (fig. 5). The upstream-most reach (river mile 770) is incising; the middle reach (river mile 672) has water-surface elevations nearly the same as those that existed before Gavins Point Dam was closed; and the downstream-most reach (river mile 560) is stable to slightly aggrading (U.S. Army Corps of Engineers, 2007; Jacobson and others, 2009a). These three flood-plain reaches were selected to document the range of geomorphic adjustments expected because of impoundments on the Missouri River. The reaches were each defined by 1 km length of the river channel and the valley bottom from bluff to bluff.

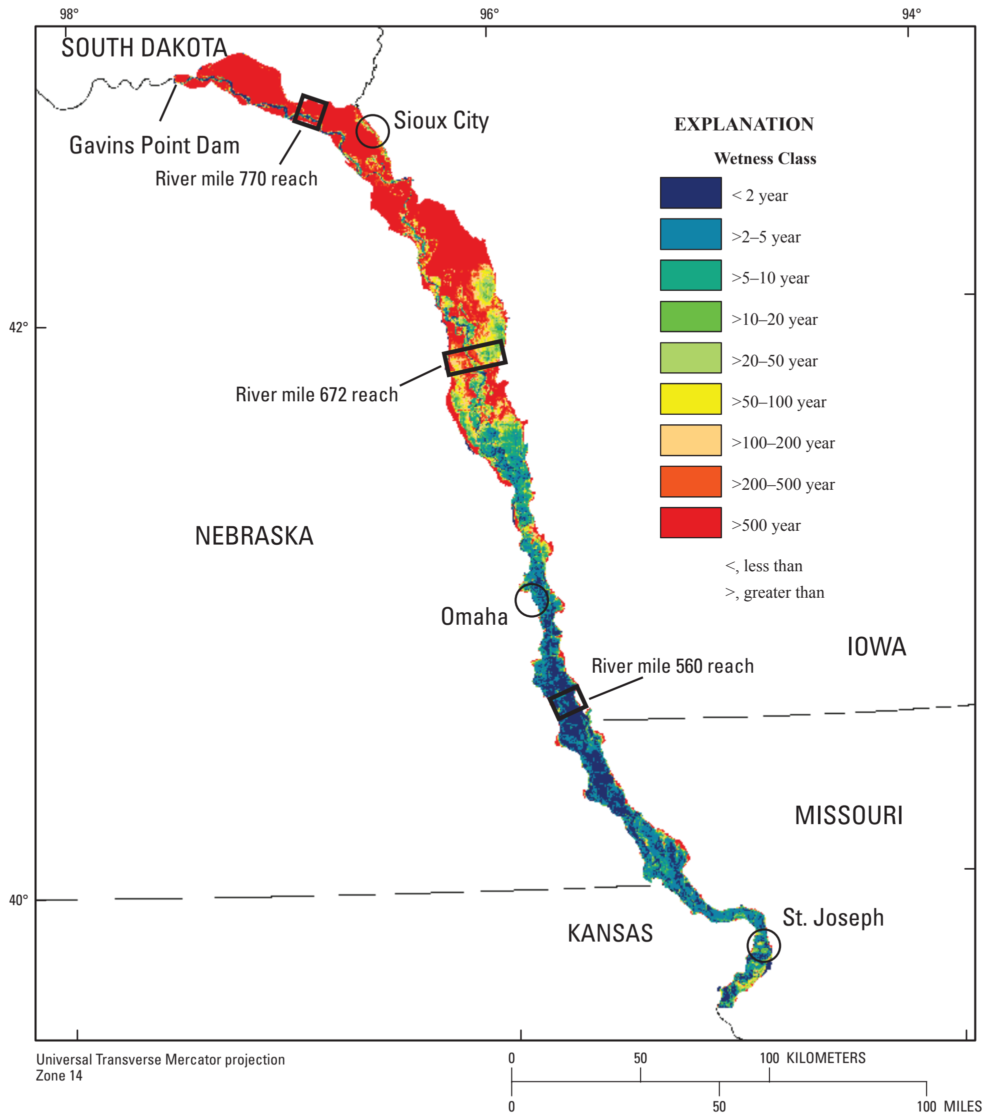


Figure 5. Locations of comparison reaches on Lower Missouri River and distribution of wetness classes. Wetness classes are indices based on hydraulically modeled flood return intervals (U.S. Army Corps of Engineers, 2004). Map development is detailed in Jacobson and others (2007).

The information contents of different elevation source data were assessed by comparing cumulative frequency distributions of elevations relative to water-surface elevations. The information content of soils data was evaluated by calculating how well soil characteristics correctly classify the area of the flood plain within the 5-year return flood stage.

Geomorphic Measurements

Geomorphic channel attributes were extracted from the maps using automated procedures and scripts within ArcMap (ESRI, Redlands, Calif.). The geomorphic information was attributed to address points at 500-m spacing along the channel and analyzed statistically for naturally occurring classification units.

Channel and Valley Boundary Determinations

The river channel boundary was manually digitized on a computer screen at a 1:3,000 scale using the most recent NAIP imagery—2008 for the Sharpe segment and 2007 for the Fort Randall segment. All areas of the river that appeared to be “active channel” were digitized as part of the channel. The active channel was identified by steep slope breaks on banks, presence of open water, and geomorphic and sedimentological features indicative of frequent sediment transport. In contrast to defining the channel boundary by water’s edge, this method allowed for comparison of channel and bank position between orthophotographs with different discharges. The river valley boundary was digitized at a 1:10,000 on the 2007 and 2008 NAIP orthophotography. Geologic maps and NED digital elevation models aided in determining the valley boundary.

Longitudinal Addressing System

The 2007 and 2008 NAIP orthophotography was also used to establish a longitudinal address system for the collection of geomorphic data. To establish the address system, the channel centerline was drawn between the digitized channel boundaries using a computer-automated method. Address points were defined along this centerline with 500-m spacing, and a polygon address system was created by using generally perpendicular transects drawn through the address points to divide the channel into quadrilateral polygons as described in Elliott and Jacobson (2006) and Elliott and others, (2009b). Address polygons were intersected with polygon datasets to assign attributes to address points.

Channel and Valley Width

The digitized channel boundary lines were converted to closely-spaced points (1 m) to calculate river width. A distance function was then used to measure the distance from each address point to the closest channel boundary point on the right and left banks. These values were added together to calculate total channel width. Channel width, therefore, measures the width of the active channel, including all midchannel bars and islands, as well as bars along the sides of the channel. The same process was used to calculate valley width for both segments.

Sinuosity Index

Sinuosity is calculated by dividing the distance between points as measured along the thalweg by the straight-line distance between points. It was not possible in some reaches to map the thalweg accurately solely from aerial photographs. We therefore used the channel centerline as the basis for calculating a modified channel sinuosity index. This effectively defines a minimum scale of sinuosity resolution. Additionally, because sinuosity can vary greatly with the scale of measurement, we calculated sinuosity values for 1-kilometer (km), 2-km, 4-km, 8-km, and 16-km reaches of the river in both segments.

Braiding Index and Bar Count

Bars (islands and sandbars surrounded by inundated channels) were manually digitized from the 2006 NAIP aerial orthophotography in both segments at a scale of 1:5,000 or less. The dominant surface material was used to classify each bar as "vegetated" or "bare sand," with vegetated bars having 50 percent or greater vegetation coverage. A braiding index representing the total number of channels was calculated at each address point. Perpendicular transects running through each address point were intersected with the bar polygons, such that gaps were created in the transects when they overlapped the bars. An automated count was made of the number of resultant line segments for each transect to define the braiding index.

The number of vegetated and bare sand bars within each address polygon and bar area as a percentage of address polygon area were also calculated. Bar number was tabulated by counting the number of bar polygon centroids within an address polygon. Percent area was calculated by tabulating the total area of all bars or portions of bars within each address polygon and dividing this number by the address polygon area.

Statistical Classification

Statistical classification involved an exploratory analysis of the entire set of address point variables and a cluster classification based on a selected, reduced dataset. Methods are similar to those of Elliott and others (2009b).

Variables collected at each address point considered for analysis included valley and channel width, braiding index, the number of vegetated and bare sand bars, and sinuosity at 2,000, 4,000, and 8,000 m. In each of the two segments, the variable data were examined for normality and for correlations using bivariate scatterplots and principal component analysis (PCA).

To simplify the classification process, a reduced number of variables was determined from the original dataset. The chosen variables were valley width, channel width, braiding index, and 2,000-m sinuosity. One-third of the address points was randomly selected for clustering analysis to minimize dependence among spatially adjacent data points in the initial clustering process. Variables were standardized by the range of values and examined for normality, which is not critical for cluster analysis but is a fundamental assumption of discriminant analysis. Nonnormality is not critical for useful analysis (Hill and Lewicki, 2006), and the variables used in this analysis were not considered critically nonnormal.

Hierarchical cluster analysis was used to examine the clustering structure of the standardized, randomly selected datasets in the two Missouri River segments. K-means analysis was applied to the standardized, randomly selected datasets separately for each segment. This type of cluster analysis begins with a predefined number of clusters (K) and divides the data into K mutually exclusive groups by maximizing the between-group variation (Wilkinson and others, 2004). Euclidean distance was applied as the distance metric, and between-group sum of square differences were plotted with within-group sum of square differences for the K-means analysis of 2 to 10 clusters. Similar to a "scree" plot, slope breaks in these curves can be interpreted as numbers of clusters where the information content of the clustering process changed. Cluster parallel plots were used to assess influences of variables in defining clusters. Cluster parallel plots show standardized values (z scores) of selected variables relative to the mean for each cluster, with the most influential variable at the top and least influential at the bottom.

Discriminant analysis was used to inspect data fit within defined clusters and to classify the remaining, nonrandomly selected address points. Classification into clusters was cross-validated using a jackknife procedure.

Results

The following sections provide results of the information content assessment for three reaches of the Lower Missouri River, river miles 420–811, and for the statistical classification of the channel flood-plain complexes for the lower segments of the Middle Missouri River. The information content assessment demonstrates the dependence of LCPI classification on well-constrained flood profiles and indicates that existing, low-resolution data lack the ability to resolve LCPI classes in the Middle Missouri River. The statistical classification presents an alternative to LCPI that delineates the main geomorphic process domains along the Middle Missouri River and thereby provides some guidance to cottonwood restoration planning.

Information Content Analysis

The component data sources for the LCPI are hydraulically modeled water-surface elevation profiles for floods of a range of return intervals, high-resolution elevation data amenable to gridding at 5-m cell size, and detailed soils maps (Jacobson and others, 2007). Of these, only the soils maps are presently available for the Middle Missouri River at a resolution equal to that used in the original LCPI. The following sections present results of evaluations of alternative elevation data, soils data, and water-surface elevation data in creating LCPI-type classifications.

Elevation Data

On the Lower Missouri River, elevation data gridded at 5 m were available with root-mean square vertical error of approximately 0.2 m (U.S. Army Corps of Engineers, 2004; Jacobson and others, 2007). In contrast, the two generally available elevation datasets for the Middle Missouri River are the NED 1-arc-second and 1/3-arc-second. The

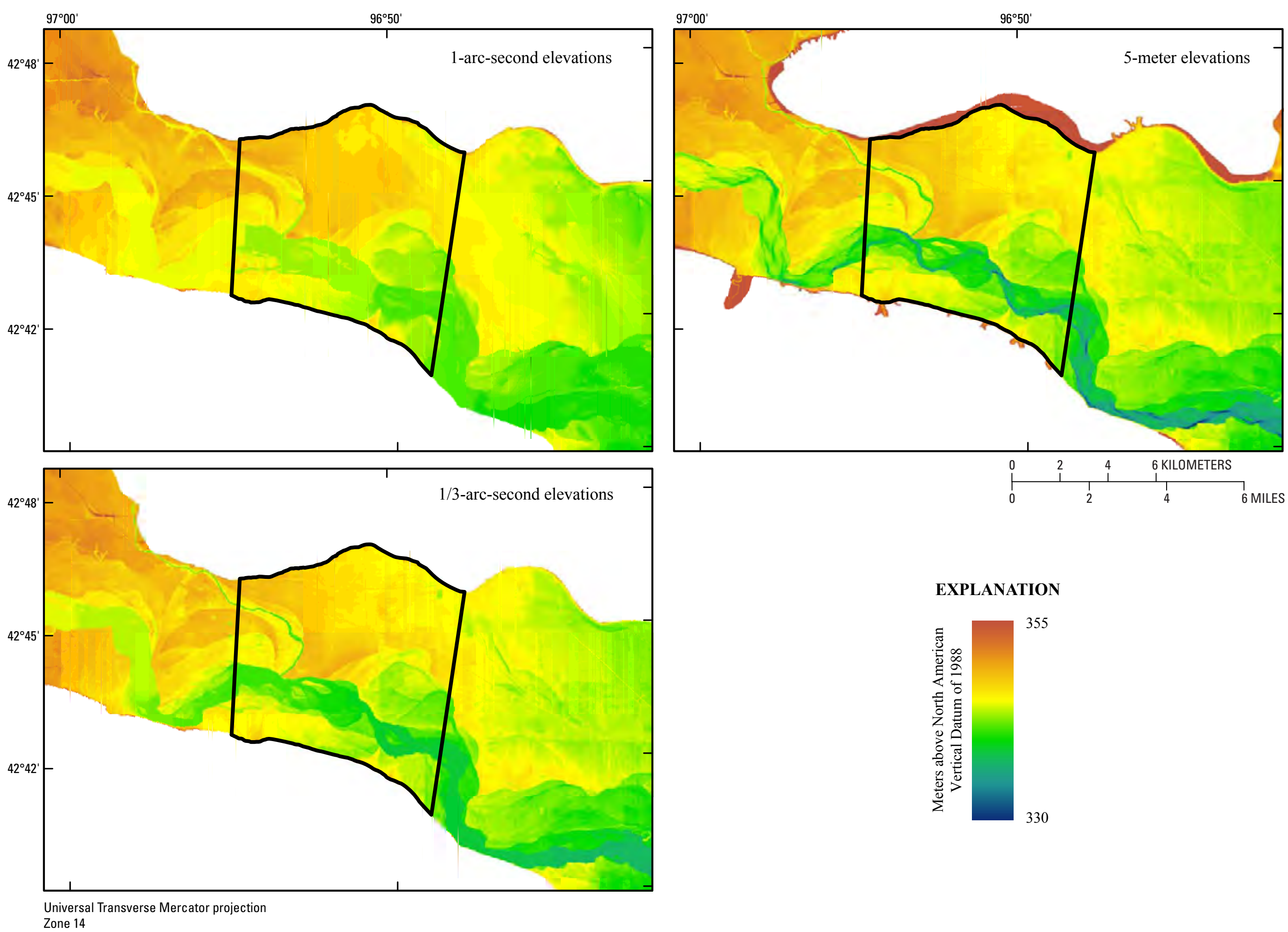


Figure 6. Elevation maps of comparison reach at river mile 770 using 1-arc-second, 1/3-arc-second, and 5-meter datasets.

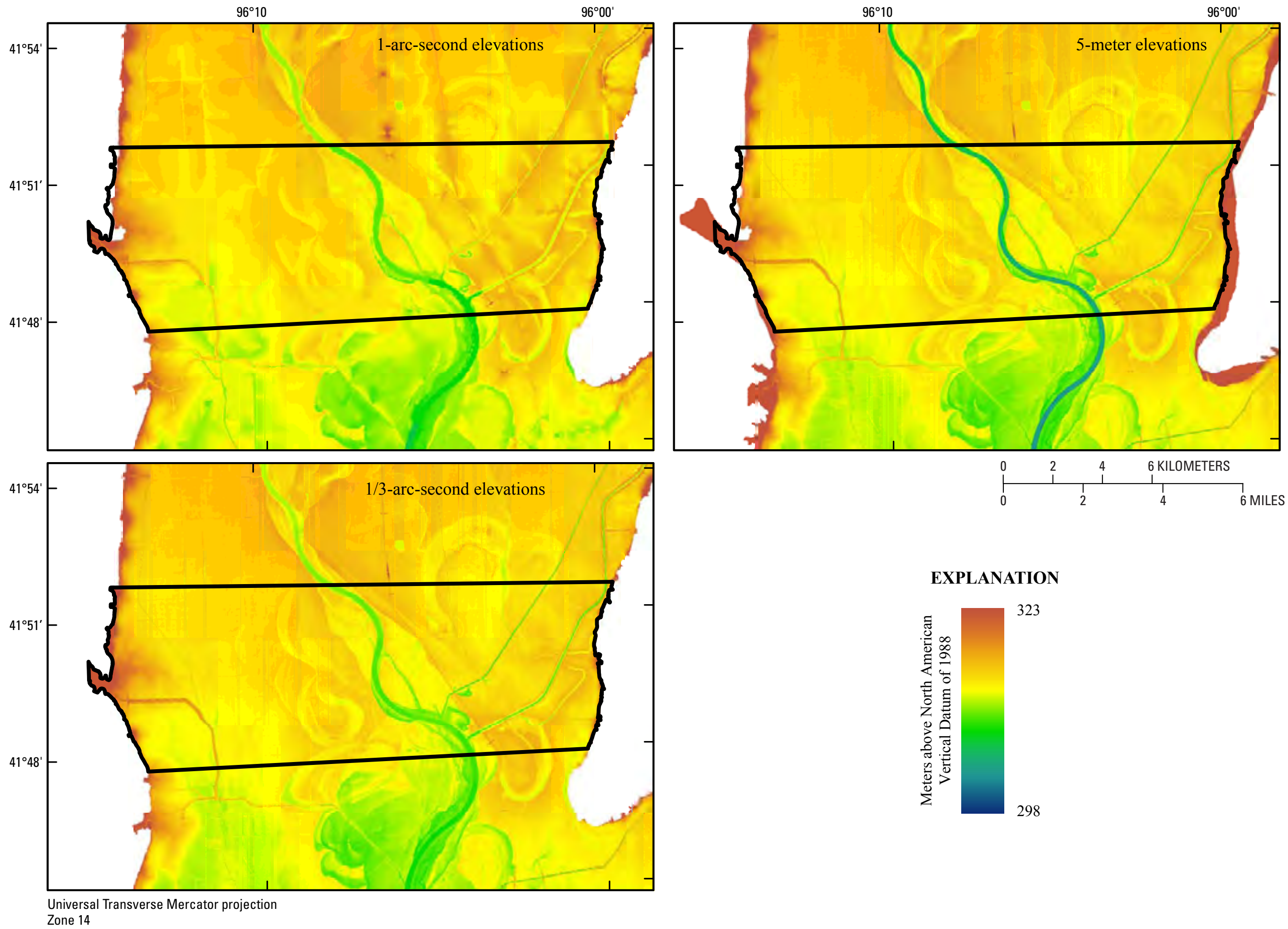


Figure 7. Elevation maps of comparison reach at river mile 672 using 1-arc-second, 1/3-arc-second, and 5-meter datasets.

1-arc-second dataset has a grid-cell size of approximately 26 m and a vertical root-mean square error of approximately 2.44 m; the 1/3-arc-second dataset has a grid-cell size of approximately 6.5 m and shares the vertical root-mean square error of approximately 2.44 m.

Maps of the Lower Missouri River comparison reaches illustrate the qualitative differences among the datasets (figs. 6–8). In all three comparison reaches, the 1-arc-second elevation map shows substantially less topographic detail. Differences between the 1/3-arc-second and 5-m elevation maps are less discernible except near the channel where the 5-m dataset shows more detail because of the inclusion of bathymetric data. Lack of topographic information near the channel in the 1-arc-second and 1/3-arc-second datasets may be attributable to high water stages during acquisition of the topographic data.

Cumulative distribution functions of elevations from these examples document that the 1/3-arc-second data conform better to the 5-m data than the 1-arc-second data (fig. 9). Differences in the distributions are most apparent in the tails, especially the lower elevations. Because the 5-m data were gridded with added bathymetric data (Jacobson and others, 2007), they more accurately represent low elevations near the channel. Differences among elevation datasets are especially important for frequent floods in the river mile 770 comparison reach; for example, the 5-m dataset indicates that 11 percent of the valley bottom is at or below the elevation of the 2-year return interval flood, whereas the 1/3-arc-second dataset indicates 7 percent, and the 1-arc-second dataset indicates 0 percent.

The cumulative distribution functions illustrate the general differences in the relations between floods and flood-plain elevations among the three reaches. In the unchannelized, incised reach at river mile 770, there is a broad distribution of low elevations, but because of incision and flow regulation much of the distribution of elevations is not inundated by even 100- to 500-year return-interval floods. In contrast, the channelized reaches at river mile 672 and 560 have a narrow distribution of available valley-bottom elevations. In the stable-incising reach at river mile 560 over 90 percent of the valley bottom is within the range of elevations associated with 10- to 25-year return-interval floods. The reach at river mile 672 is intermediate with less than 10 percent of the valley bottom within the elevation of 25-year return-interval floods.

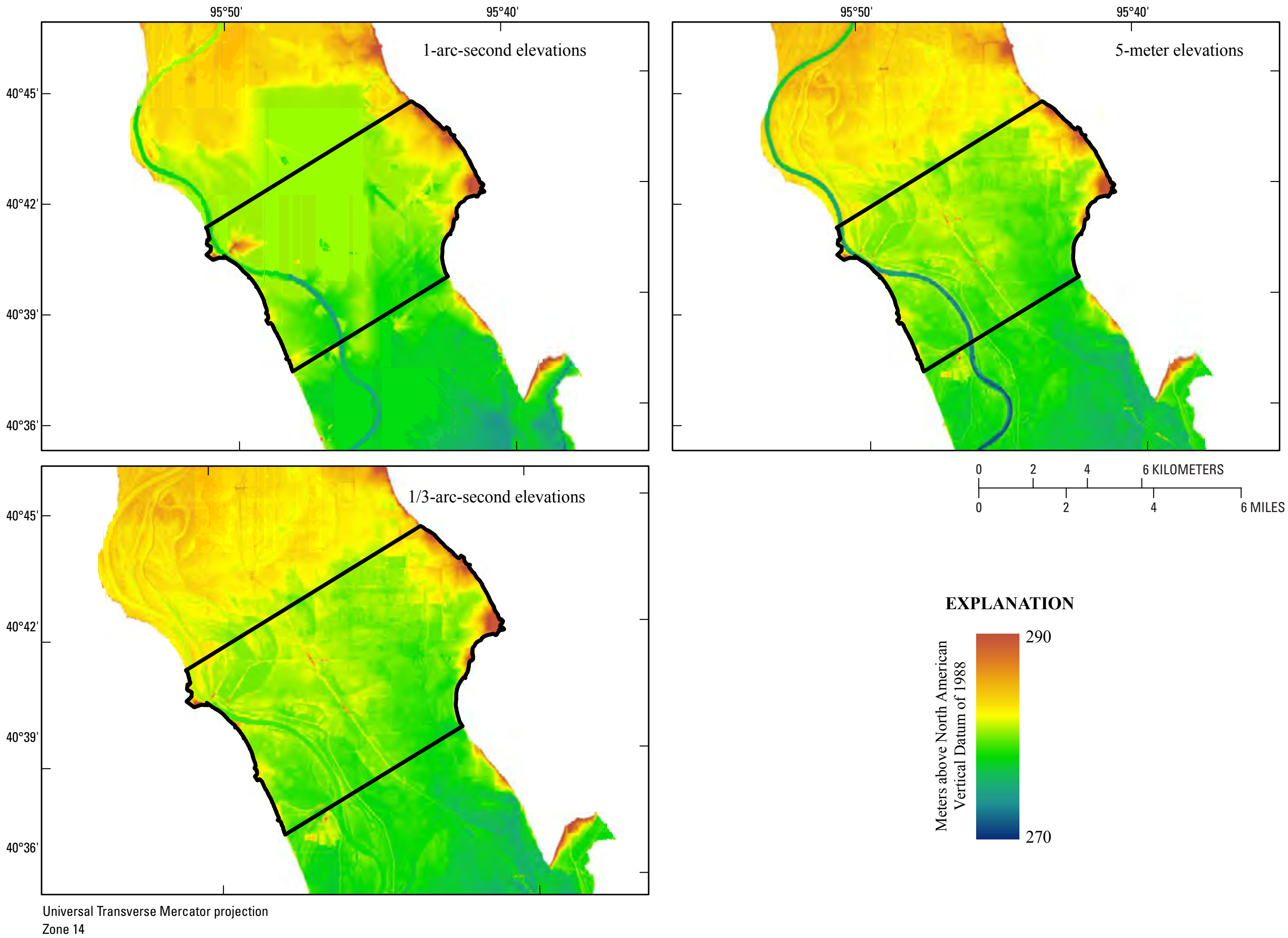


Figure 8. Elevation maps of comparison reach at river mile 560 using 1-arc-second, 1/3-arc-second, and 5-meter datasets.

Soils Data

The utility of using high-resolution soils data as a surrogate for the combination of water-surface elevations and high-resolution topography was explored by calculating how well soil attributes corresponded with modern flood classes. The question is: If only soils data were available, could accurate predictions be made for areas of good potential for cottonwood regeneration? In this case, we assumed that nonirrigated cottonwood regeneration required relatively wet conditions as indicated by LCPI classes with elevations within the 5-year return-interval flood (0- to 5-year wet area). Table 4 indicates the information content of soils data relative to known wetness conditions.

Table 4. Percent correct classification of 0–5 year wet area based on known soil characteristics.

River mile	Drainage classes[1]		Wetland classes[2]		Entisols	
	Percent of class actually wet	Percent of wet correctly classified	Percent of class actually wet	Percent of wet correctly classified	Percent of class actually wet	Percent of wet correctly classified
560	98.9	62.6	97.8	52.6	89.6	49.6
672	.8	23.2	3.4	22.9	4.2	96.2
770	2.8	34.7	3.5	32.6	4.8	100
All	30.2	66.3	18.8	51.1	33.5	61.6

[1] Combined somewhat poorly, poorly, and very poorly drained classes.

[2] Good wetland class.

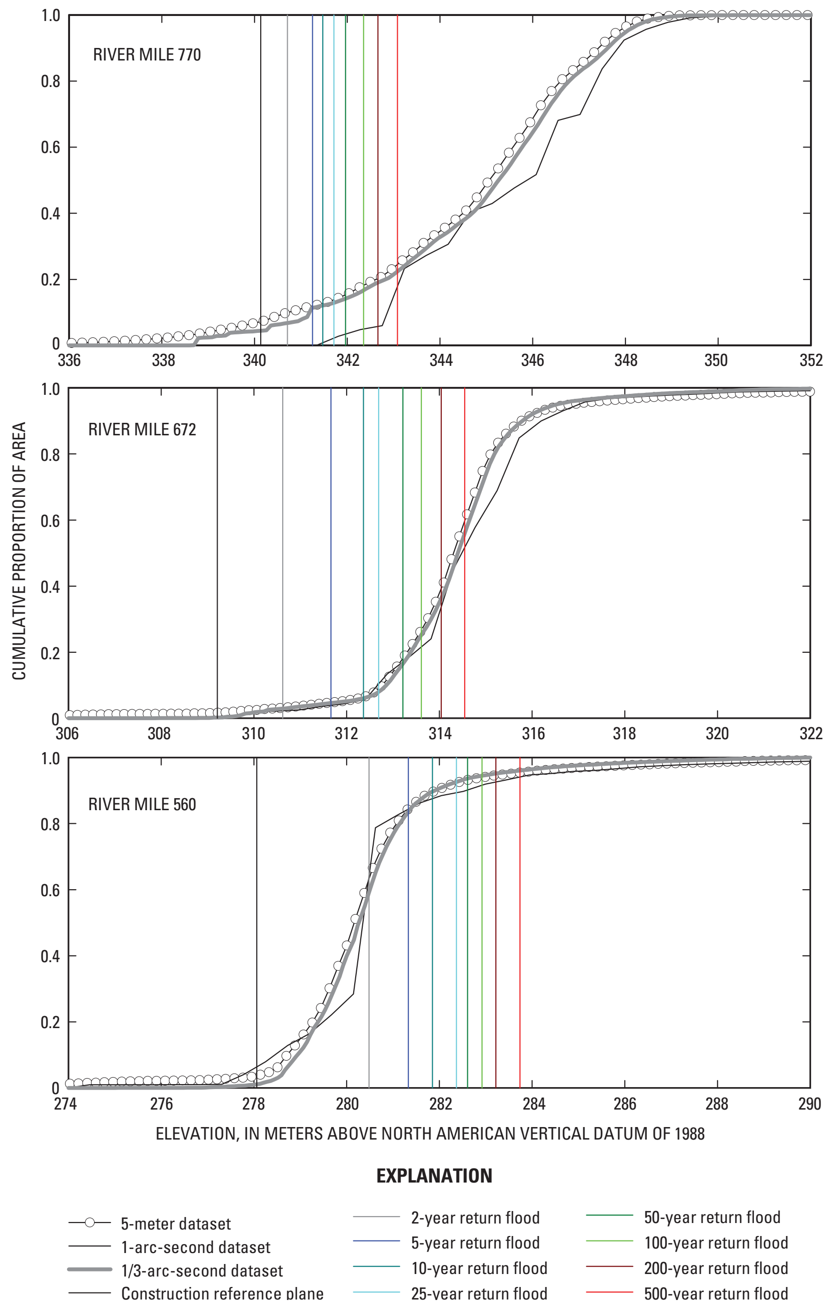


Figure 9. Cumulative frequency distributions of floodplain topography and water-surface elevations in comparison reaches at river mile 770,river mile 672, and river mile 560. The construction reference plane is a datum used by the U.S. Army Corps of Engineers to indicate water-surface elevation at approximately 75 percent flow exceedance.

Soil drainage classes integrate saturated hydraulic conductivity of the soil and underlying geologic materials, and to some extent, contain information related to surface topography (Soil Survey Staff, 1993). At river mile 560, 98.9 percent of the soil area classed as poorly, somewhat poorly, or very poorly drained was within the 0–5 year wet area. Moreover, 62.6 percent of the wet area was comprised of these drainage classes. These data indicate that in stable to aggrading reaches of the river, knowledge of soil drainage classes is useful for classifying wetness. However, in upstream reaches that are characterized by ongoing incision, such as river mile 672 and 770, the percentage of poorly drained classes that is actually wet is quite small (0.8 and 2.8 percent, respectively), and the percentage of these classes within the wet area is only 23.2 and 34.7 percent, respectively. For river miles 423 to 811, 30.2 percent of poorly drained class area is actually wet, and

66.3 percent of the wet area is underlain by soils in the poorly drained classes. These data indicate that the utility for soil drainage classes to predict actual wetness in the flood plain depends on the state of geomorphic adjustment of the channel; drainage class is less predictive of wetness in reaches undergoing channel incision.

The wetland index and shallow water index are wildlife habitat interpretations that rate the soil as good, fair, poor, or very poor for wetland restoration purposes (Soil Survey Staff, 1993). A *good* rating indicates the habitat is easily established; *fair* indicates that the habitat can be established in most places with moderate management effort; *poor* indicates that limitations on the habitat development are severe; and *very poor* indicates that restrictions on habitat development are very severe and unsatisfactory results can be expected. The wetland and shallow-water habitat indices produce practically identical results so only wetland index is shown in table 4.

Wetland suitability classes show relations similar to drainage classes. Soils with wetland suitability in the good category predict wetness relatively well at river mile 560, but do poorly at river miles 672 and 770 where only 3.4 and 3.5 percent, respectively, of the good classes are coincident with the wet area. On average, through river miles 423 to 811, 18.8 percent of good wetland suitability is coincident with wet areas and 51.1 percent of the wet area has soils rated as good wetland suitability.

We also explored whether soils classified as entisols would be a useful indicator of wetness, as they are typically developed in recently deposited alluvium. Although 89.6 percent of soil area classified as entisols was wet at river mile 560, only 49.6 percent of the wet area was comprised of entisols; the remainder was dominantly mollisols. The ability of entisols to predict wetness was poor at river mile 672 and 770, with only 4.2 and 4.8 percent, respectively, of the entisols coincident with wet areas. In contrast, the wet areas in these reaches were dominated by entisols because channel incision has resulted in only very young, sandy sediments being deposited at elevations coincident with 0- to 5-year return- interval floods.

Soil attributes are highly variable in their ability to predict wet areas conducive to cottonwood restoration in these segments of the Lower Missouri River. At river mile 560, soil attributes predict wetness very well, but this is because aggradation in this reach has put nearly all of the flood plain in this reach in the 0- to 5-year wet area. In upstream reaches that are stable or incising, soil attributes do not perform as well because soils with pedogenic characteristics indicative of wetness have been stranded at elevations where they are infrequently inundated because of recent incision.

Water-Surface Elevation Data

The LCPI benefitted from hydraulically modeled water-surface elevations for floods with return intervals from 2 to 500 years (U.S. Army Corps of Engineers, 2004). Hydraulic flood models generally were not available for the Middle Missouri River. The next best source of information for water-surface elevations is from a sparse network of streamflow-gaging stations maintained by the U.S. Geological Survey and the U.S. Army Corps of Engineers. Water-surface elevations for stages attained with return intervals of 2, 5, and 10 years show little differences because of the highly regulated flows (fig. 10). Because of long distances between gages (3–116 km) water-surface elevations would have to be interpolated extensively to model water-surface elevations similar to the LCPI. In areas where water- surface elevations change rapidly, such as the deltas at the junctions of the Niobrara and Bad Rivers (fig. 10), these interpolations would not be valid.

Longitudinal Classification

Although the LCPI process cannot be replicated in the Middle Missouri River, longitudinal classification of the channel and flood plain can be used to inform understanding of cottonwood restoration potential. The longitudinal classification is based on quantifiable geomorphic characteristics that are indicative of channel and flood-plain form and process.

Flood-Plain Elevations

Comparison of existing water-surface elevation data and the range of elevations of adjacent flood plain and valley bottom indicate the strong effect of reservoirs and headwater deltas in the Middle Missouri River (fig. 10). Figure 10 shows the water-surface elevations of 2-, 5-, and 10-year floods compared to percentiles of the adjacent valley bottom elevations. The colored bands indicate 0–2, greater than 2–5, greater than 5–8, and greater than 8–10 percent of the adjacent valley bottom exists at the indicated range of elevations. Because these are subaerial, 1/3-arc-second data derived from photogrammetric measures, the lowermost extent of elevation data may be limited by the water-surface elevation that existed on the day of the data acquisition.

Water-surface elevations in the Sharpe segment are very flat because the effects of Big Bend Dam extend nearly to the base of the next upstream dam (Oahe Dam, figs. 2, 10). Most of the segment has 2–5 percent of the adjacent land subject to inundation by the 2-, 5-, and 10-year floods. High longitudinal variation results from juxtaposition of reaches where nearly the entire valley is inundated by the lake and reaches where flood plain and terraces flank the river (for example, 28–35 km, 45–47 km, 77–84 km, and 105–115 km upstream from Big Bend Dam, fig. 10). The flood-plain and terrace reaches have as much as 5–10 percent of the adjacent land within the 2-, 5-, and 10-year flood elevations.

In the reservoir part of the Fort Randall segment, the 2-, 5-, and 10-year water-surface elevations intersect the 8–10th percentile of elevations, indicating that 8–10 percent of the adjacent valley bottom would be potentially inundated by the 2-, 5-, and 10-year floods (fig. 10). Upstream, the water-surface elevations intersect smaller percentiles indicating that

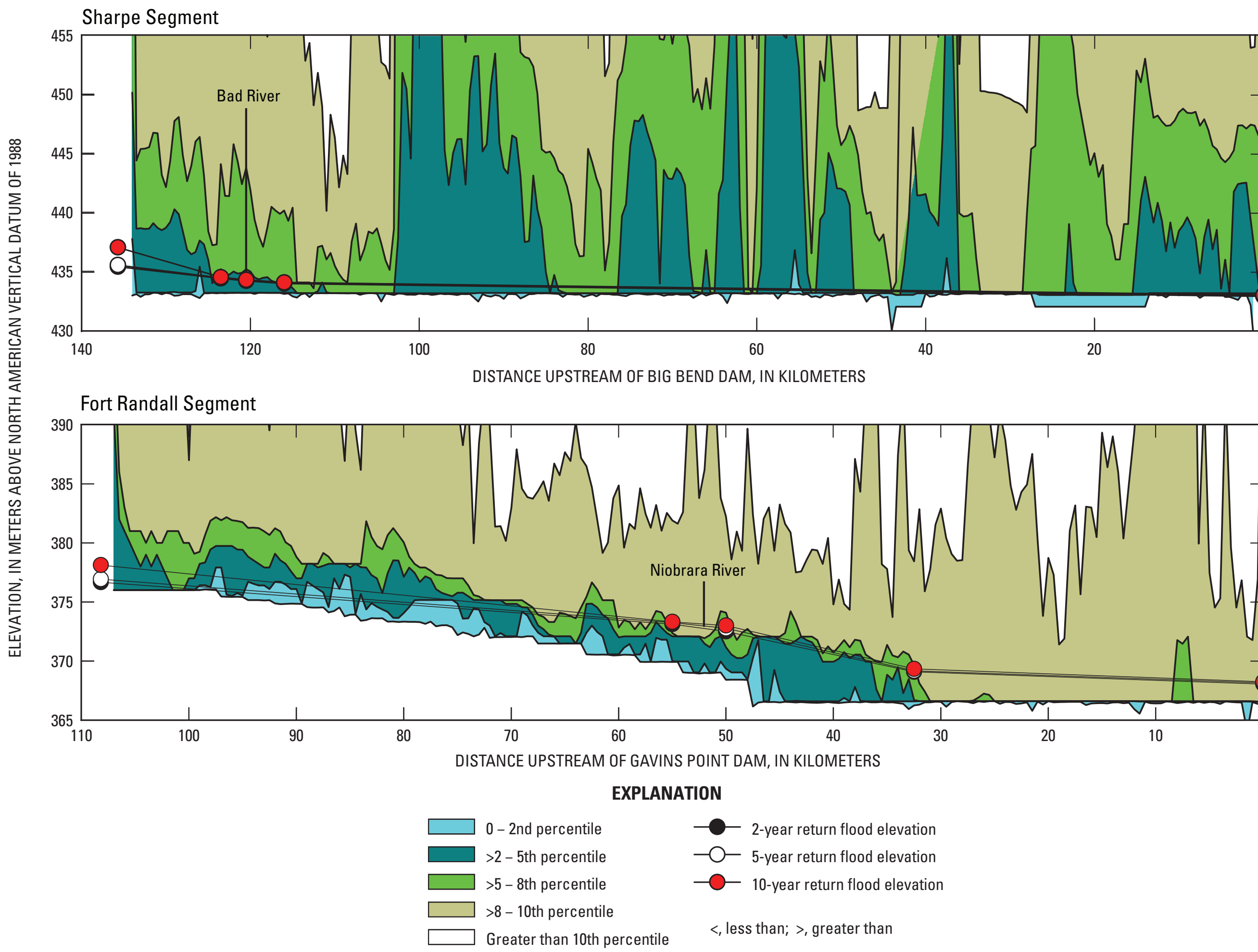


Figure 10. Longitudinal profiles of water surface elevations for 2-, 5-, and 10-year return floods, and distributions of flood-plain elevations on the Sharpe and Fort Randall segments.

smaller areas of the adjacent flood plain would be inundated. In the reaches 70–95 km upstream from Gavins Point Dam, these water-surface elevations would affect only 0–2 percent of the adjacent flood plain.

Geomorphic Characteristics

Geomorphic characteristics are illustrated in a longitudinal framework for the Sharpe and Fort Randall segments (figs. 11, 12). Valley width, channel width, sandbar frequency, and sinuosity vary substantially within both segments. Both segments have reservoirs at their downstream ends that fluctuate in water level and influence the base level of the riverine reaches. Both segments also have zones of sediment deposition, or deltas, between their riverine and reservoir reaches.

Sharpe Segment

The reach between Oahe Dam and the headwaters of Lake Sharpe occurs in a fairly narrow valley that range from about 1,960 to 2,740 m (fig. 11, table 5). The valley widens to as much as 11,630 m in the Lake Sharpe reservoir reach (figs. 2, 11) where there are large bends in the bedrock valley of the Missouri River. The reservoir itself occupies an average of 36 percent of the valley width in the reservoir segment. Channel widths generally increase in a downstream direction as the short riverine segment transitions to delta and then to reservoir (fig. 11).

The Bad River enters the Missouri River near Fort Pierre, South Dakota, on the right descending bank at river mile 1,065.2 (fig. 2). The Bad River generally contributes a small percentage of flow to the Missouri River (less than 1 percent of mean annual discharge), although infrequent flood events have contributed considerably more discharge. Five Bad River floods in the last 83 years have been 1.2 to 3.0 times the annual mean discharge of the Missouri River.). Sediment from the Bad River is primarily fine material and enough sediment has been deposited downstream from the confluence with the Missouri River/Lake Sharpe to form a large delta (U.S. Army Corps of Engineers, 2006). The effects of the delta are evident in increasing sandbar frequency downstream from river mile 1,065.2 (fig. 11). Because of reservoir level fluctuations, exact

Table 5. Geomorphic characteristics of reaches within the Sharpe and Fort Randall Missouri River segments.

[%, percent]

Sharpe segment	Oahe Dam to Bad River			Bad River to Lake Sharpe (Delta)			Lake Sharpe			Oahe Dam to Big Bend Dam (entire segment)		
River mile start	1,072.3			1,065.2			1,052.5			1,072.3		
River mile end	1,065.2			1,052.5			987.0			987.0		
total distance (miles)	7.1			12.7			65.5			85.3		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Valley width (meters)	2,017	2,745	2,331	1,962	2,646	2,295	1,434	11,627	5,378	1,434	11,627	4,691
Channel width (meters)	426	1,746	846	545	1,854	1,369	961	3,973	1,911	426	3,973	1,749
Percent channel width of valley width	21%	64%	36%	28%	70%	60%	67%	34%	36%	30%	34%	37%
Braiding index (number of individual channels)	1.0	2.0	1.2	1.0	6.0	2.9	1.0	2.0	1.0	1.0	6.0	1.3
Number of sandbars in a channel address polygon	0	0	0	0	7.0	1.3	0	0	0	0	7.0	0.2
Sandbar percent area in a channel address polygon	0	0	0	0	5.7	0.9	0	0	0	0	5.7	0.1
Number of vegetated bars in a channel address polygon	0	2.0	0.4	0	20	3.4	0	1.0	0	0	20	0.5
Vegetated bar percent area in a channel address polygon	0	55.9	5.1	0	59.6	24.2	0	0.6	0	0	59.6	3.8
Total number of bars in a channel address polygon	0	2.0	0.4	0	21.0	4.7	0	1.0	0	0	21.0	0.7
Total percent of bars in a channel address polygon	0	55.9	5.1	0	59.6	25.1	0	0.6	0	0	59.6	3.9
Channel sinuosity calculated over a 1,000 meter-ruler	1.00	1.06	1.01	1.00	1.03	1.00	1.00	1.07	1.01	1.00	1.07	1.01
Channel sinuosity calculated over a 2,000 meter-ruler	1.00	1.06	1.02	1.00	1.03	1.01	1.00	1.10	1.01	1.00	1.10	1.01
Channel sinuosity calculated over a 4,000 meter-ruler	1.01	1.05	1.03	1.00	1.05	1.01	1.00	1.21	1.04	1.00	1.21	1.03
Channel sinuosity calculated over a 8,000 meter-ruler	1.03	1.10	1.06	1.00	1.09	1.02	1.00	1.64	1.12	1.00	1.64	1.10
Channel sinuosity calculated over a 16,000 meter-ruler	1.15	1.20	1.18	1.02	1.20	1.07	1.04	2.69	1.39	1.02	2.69	1.33

Table 5. Geomorphic characteristics of reaches within the Sharpe and Fort Randall Missouri River segments.—Continued

[%, percent]

Fort Randall segment	Fort Randall Dam to Niobrara River			Niobrara River to Lewis and Clark Lake (Delta)			Lewis and Clark Lake			Fort Randall Dam to Gavins Point Dam		
River mile start	880			844.0			826.0			880		
River mile end	844.0			826.0			811.1			811.1		
Total distance (miles)	36.0			18.0			14.9			68.9		
	Minimum	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**
Valley width (meters)	1,488	3,075	2,379	2,199	4,600	2,972	2,143	4,239	3,171	1,488	4,600	2,710
Channel width (meters)	372	2,297	954	1,694	4,564	2,738	2,138	4,223	3,078	372	4,564	1,893
Percent channel width of valley width	25%	75%	40%	77%	99%	92%	100%	100%	97%	25%	99%	70%
Braiding index (number of individual channels)	1.0	16.0	2.5	3.0	29.0	8.5	1.0	1.0	1.0	1.0	29.0	3.7
Number of sandbars in a channel address polygon	0	8.0	0.9	0	18.0	1.4	0	0	0	0	18.0	0.8
Sandbar percent area in a channel address polygon	0	25.7	2.3	0	11.5	0.7	0	0	0	0	25.7	1.4
Number of vegetated bars in a channel address polygon	0	66.0	4.2	0	70	21.4	0	0	0	0	70	7.7
Vegetated bar percent area in a channel address polygon	0	0.7	0.2	0	0.8	0.6	0	0	0	0	0.8	0.3
Total number of bars in a channel address polygon	0	66.0	5.1	0	70	22.8	0	0	0	0	70	8.6
Total percent of bars in a channel address polygon	0	69.6	25.1	0	80.5	56.4	0	0	0	0	80.5	27.6
Channel sinuosity calculated over a 1,000 meter-ruler	0.99	1.08	1.01	0.99	1.04	1.01	0.99	1.02	1.00	0.99	1.08	1.00
Channel sinuosity calculated over a 2,000 meter-ruler	1.00	1.10	1.10	1.00	1.04	1.01	0.99	1.02	1.00	0.99	1.10	1.01
Channel sinuosity calculated over a 4,000 meter-ruler	1.00	1.17	1.17	1.00	1.06	1.02	0.99	1.02	1.01	0.99	1.17	1.02
Channel sinuosity calculated over a 8,000 meter-ruler	1.00	1.12	1.12	1.01	1.14	1.05	1.00	1.04	1.01	1.00	1.14	1.04
Channel sinuosity calculated over a 16,000 meter-ruler	1.01	1.01	1.01	1.03	1.23	1.13	1.02	1.03	1.02	1.01	1.23	1.07

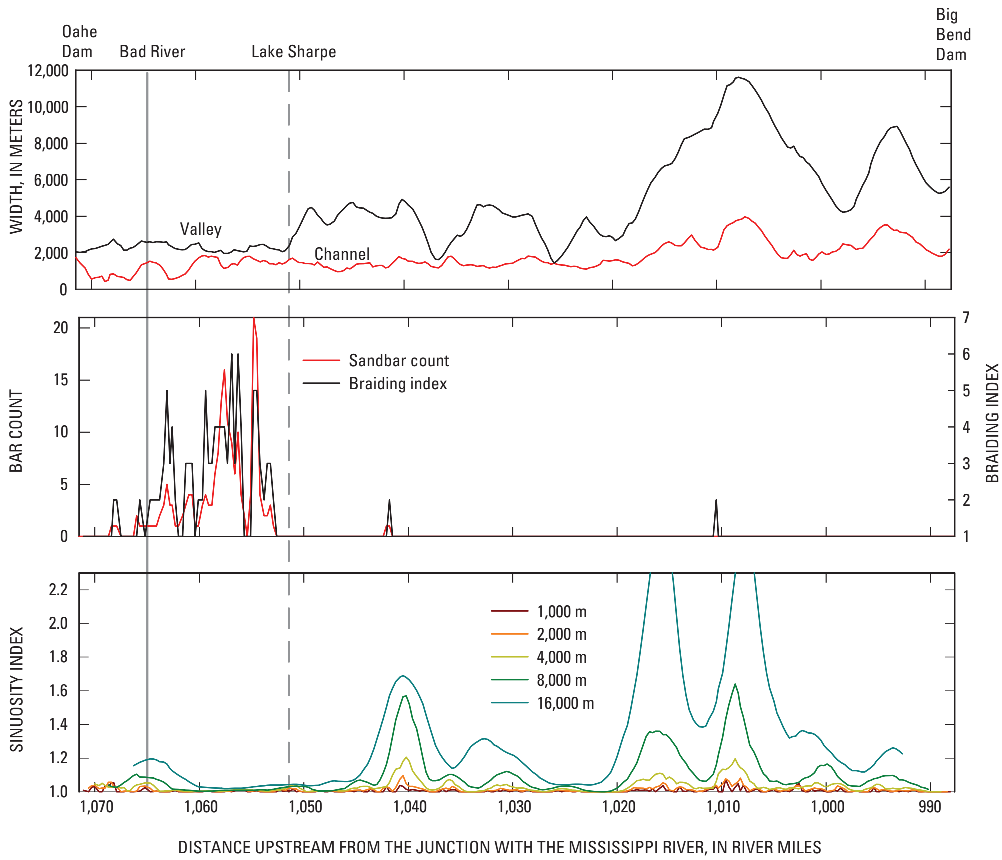


Figure 11. Longitudinal geomorphic characteristics for the Sharpe segment of the Missouri River.

delineation of the boundary between lake and riverine subsegments is not possible. Substantial decreases in sandbar occurrence downstream from river mile 1,052.5 are apparent in aerial photography in 2004, 2005, 2006, and 2008, indicating that river mile 1,052.5 is a reasonable downstream boundary of the Lake Sharpe delta.

Sinuosity generally increases with scale in the Sharpe segment of the Missouri River because sinuosity measured over longer lengths picks up the large bends of the bedrock valley. Meander bends in Lake Sharpe have sinuosity values measured over scales of 8,000 and 16,000 m ranging up to 1.6 and greater than 2.2 (fig. 11).

Fort Randall Segment

Valley widths in the Fort Randall segment are quite narrow ranging from about 1,490 to 4,600 m (fig. 12, table 5). Channel widths vary in the riverine subsegment including narrow and wider reaches ranging from about 380 to 2,300 m wide upstream from the Niobrara River confluence and become increasingly wide (about 1,690 to 4,560 m) in the delta and reservoir subsegments (fig. 12, table 5). The river occupies an average of 92 and 97 percent of the valley width in the delta and reservoir subsegments of the Fort Randall segment (table 5).

In the Fort Randall segment, the sand-bedded Niobrara River enters the Missouri River at river mile 843. The Niobrara River contributes about 6.4 percent of the Missouri River discharge on a mean annual basis but as much as 55 percent of the sediment load to the Missouri River and Lewis and Clark Lake (Engineering and Hydrosystems Inc., 2002). Consequently, a large delta has formed at the headwaters of Lewis and Clark Lake (Elliott and Jacobson, 2006; U.S. Army Corps of Engineers, 2006). The rapid increase in braiding index at approximately river mile 850 defines the upstream boundary of the delta. This delta has grown at a rate of approximately 105 meters per year from 1993–2003 and as of 2006 was located near river mile 826 (Elliott and Jacobson, 2006). Downstream from river mile 826 to Gavins Point Dam at river mile 811.1 is Lewis and Clark Lake where the reservoir fills nearly the entire bedrock-defined valley (figs. 3, 12).

Statistical Classification

In the Sharpe segment, channel width and valley width are interrelated (fig. 13) and positively loaded on factor 1 in the PCA (fig. 14). Sinuosity at all scales is interrelated and positively loaded on factor 1 as well. In-channel characteristics such as the number of vegetated bars, sand bars, and braid index are related and negatively loaded on factor 2 (fig. 14).

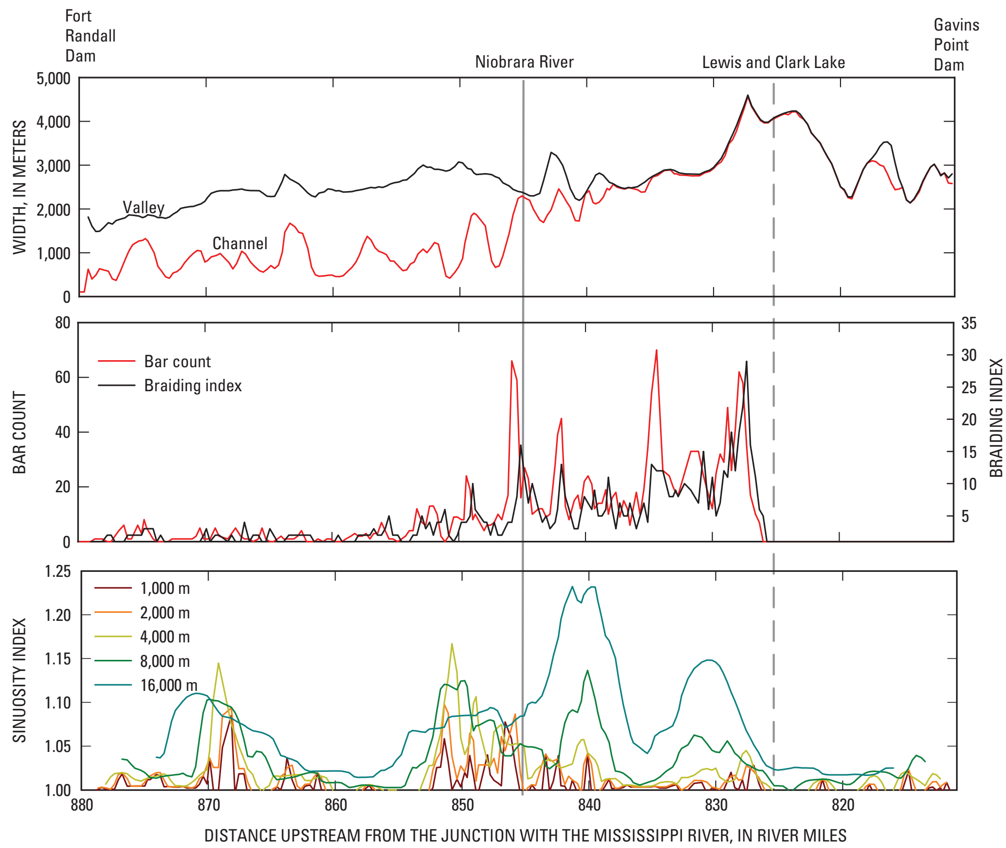


Figure 12. Longitudinal geomorphic characteristics for the Fort Randall segment of the Missouri River.

In the Fort Randall segment, there is also a strong relation between valley width and channel width as seen in the scatterplots (fig. 15), and these variables are positively loaded on factor 2 in the PCA (fig. 16). As seen in the Sharpe segment, sinuosity at all scales is interrelated and positively loaded on factor 1 (figs. 15, 16) Characteristics related to channel complexity (the number of sand and vegetated bars and braiding index) are positively loaded on factor 1, although the number of sand bars and vegetated bars are less related than in the Sharpe reach (figs. 15, 16).

Based on correlations among variables evident in the scatterplots and PCA (figs. 13–16), we selected a reduced set of variables to be used in cluster analysis (figs. 17, 18). A subset of all address points was randomly selected and standardized to act as a training classification set. Hierarchical cluster analysis of the standardized, randomly selected data indicated four to five distinct clusters in the Sharpe segment (fig. 19). In the Fort Randall segment hierarchical cluster analysis supported the identification of four clusters (fig. 20).

K-means analysis supported the hierarchical clustering analysis. Breaks in slope of the "scree" plots occur in both of the Missouri River segment datasets at four clusters (figs. 21 and 22) . Cluster parallel plots support the understanding that valley width, braiding index, and channel width are the most

Table 6. Result of jackknife validation of discriminant function classifications for the Sharpe segment.

	Classification	Classification 1	2	3	4	Percent correct
		Four-cluster classification				
Classified by jackknife	**1**	51	1	0	0	100
	2	1	23	0	0	100
	3	0	0	10	5	100
	4	0	0	0	5	100
	Total	**51**	**23**	**10**	**10**	**100**

Table 7. Result of jackknife validation of discriminant function classifications for the Fort Randall segment.

	Classification	Classification				Percent correct
		1	2	3	4	
		Four-cluster classification				
Classified by jackknife	**1**	25	1	0	0	96
	2	0	11	0	0	100
	3	1	0	10	2	77
	4	0	1	0	13	93
	Total	**26**	**13**	**10**	**15**	**92**

influential variables defining clusters in the Sharpe segment whereas channel width, braiding index, and sinuosity are the most influential variables in the Fort Randall segment (figs. 23, 24).

Discriminant plots show distinct groupings of cluster classes (figs. 25, 26). A five-cluster plot in the Sharpe segment indicated two clusters with nearly complete overlap, therefore a four-cluster classification was determined to be more appropriate (fig. 25). The remaining points that were not randomly selected were classified by discriminant functions into the best fit cluster (figs. 27, 28). Cross validation of classifications using a jackknife procedure indicated that 100 percent of all points were classified correctly in the Sharpe segment (table 6), and 77–100 percent of points were classified correctly in the Fort Randall segment (table 7).

Discussion

This report addressed two objectives related to understanding and prioritizing restoration of cottonwood communities along the Middle Missouri River. The first objective was to assess the utility of available soils, topography, and water-surface elevation data in defining a Land Capability Potential Index (LCPI) similar to that developed for the Lower Missouri River (Jacobson and others, 2007). The second objective was to develop a geomorphic classification for the Sharpe and Fort Randall segments of the Middle Missouri River using existing GIS data. The following section presents discussion about the prospects for developing a LCPI-like index from relatively low-resolution data, development of the longitudinal classification, and application of the classification to assess potential for cottonwood restoration.

Data Availability and An Alternative LCPI

The original LCPI combined county-level soils data (SSURGO) (Jacobson and others, 2007; Soil Survey Staff, 2009) high-resolution topographic data (U.S. Army Corps of Engineers, 2004), and hydraulically modeled floodwater-surface elevations (U.S. Army Corps of Engineers, 2004) to create the LCPI for the Lower Missouri River. Of these data sources, only the SSURGO data are readily available for the Middle Missouri River segments considered in this report. Hence, a specific objective of this study was to determine whether the soils data could be used alone or in combination with other sources of topography and water-surface elevations to create an LCPI-like classification for the Middle Missouri River.

Flood-Plain Elevation Data

Alternative elevation data available in the Middle Missouri River are the 1-arc-second and 1/3-arc-second digital elevation models from the National Elevation Dataset (Gesch and others, 2009; U.S. Geological Survey, 2009). The 1-arc-second data have a cell size of approximately 26 m and the 1/3-arc-second data have a cell size of approximately 6.5 m in this region. Compared to the 5-m cell size dataset developed for the LCPI, the 1-arc-second data poorly represent elevation cumulative frequency distributions (fig. 9). One can infer from the stepped distributions that the 1-arc-second data fail to capture details of the actual distribution of elevations on the flood plain. The lack of correspondence to the 5-m data in the low-elevation tail of the distribution also indicates that frequently flooded areas near the channel are underrepresented in the data. This is an important bias in the incised reach at river mile 770 where water-surface elevations of a wide range of floods occur in this range of elevations. The 1-arc-second data match better with the 5-m data in the upper parts of the flood plain (fig. 9).

The 1/3-arc-second topographic data generally conform better to the frequency distribution of the 5-m data compared to the 1-arc-second data. Small potential deviations from the 5-m distribution occur at the lowest elevations, probably because the 1/3-arc-second data lack the bathymetric data included with the 5-m data. NED datasets typically are derived by methods confined to subaerial data collection (for example, photogrammetry) that are limited to the water-surface elevations existing at the time of data collection. If the original data are collected at relatively high water, less flood-plain elevation will be present in the NED. Nevertheless, good general

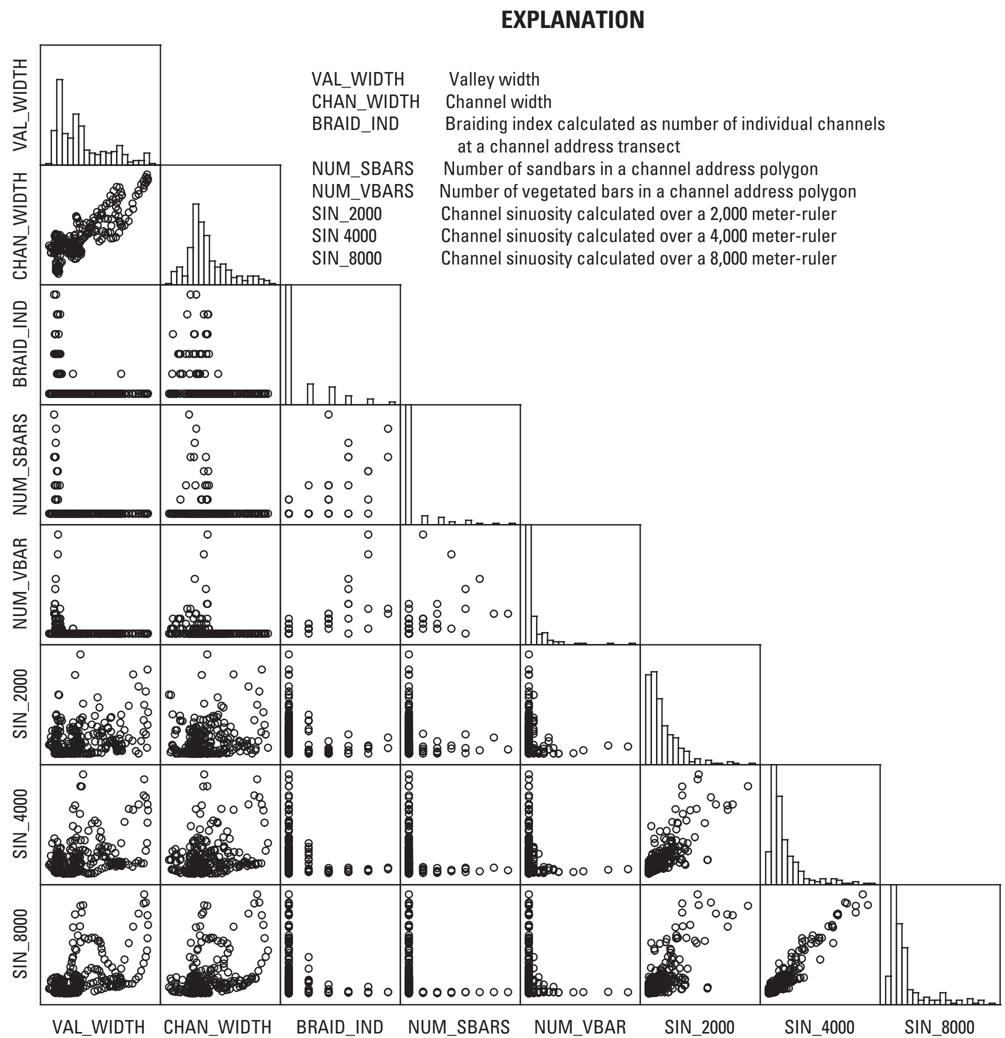


Figure 13. Bivariate and frequency plots of selected, non-transformed classification variables for the Sharpe segment of the Missouri River.

correspondence between the 1/3-arc-second and the 5-m data frequency distributions indicates that 1/3-arc-second data should be sufficient for LCPI-like classifications for much of the flood plain. Exceptions would exist if the 1/3-arc-second data were collected during high flow events or if the flow stages of interest are concentrated in a small range of elevations where the data are obscured by high water, or if both conditions existed. Concentration of flow stages in a narrow range is typical of highly regulated systems downstream of dams and is typified by the narrow range shown at river mile 770 (fig. 9).

Soil Characteristics as Indicators for Cottonwood Restoration

The Middle Missouri River is composed of reservoir and interreservoir river segments. Missouri River mainstem reservoirs were not designed to pass sediment (Ferrell, 1993; Engineering and Hydrosystems Inc., 2002) and, consequently sediment tends to accumulate in the reservoir headwaters while sediment deficits in the tailwaters downstream from dams tend to lead to channel incision (Williams and Wolman, 1984; Schmidt and Wilcock, 2008; Jacobson and others, 2009a). The general model of channel incision downstream from dams and channel aggradation in headwaters can be modified by tributary inputs. For example, sediment input from the Bad River causes moderate aggradation in the reach downstream from Oahe Dam, which might otherwise be expected to be affected by incision. Similarly, bed aggradation in the headwaters of Lewis and Clark Lake is accelerated because of sediment influxes from the Niobrara River (U.S. Army Corps of Engineers, 2007).

Without recent geomorphic adjustments, it would be expected that characteristics and spatial arrangements of flood-plain soils would relate to an equilibrium among prevailing rates of flood-plain erosion, flood-plain deposition,

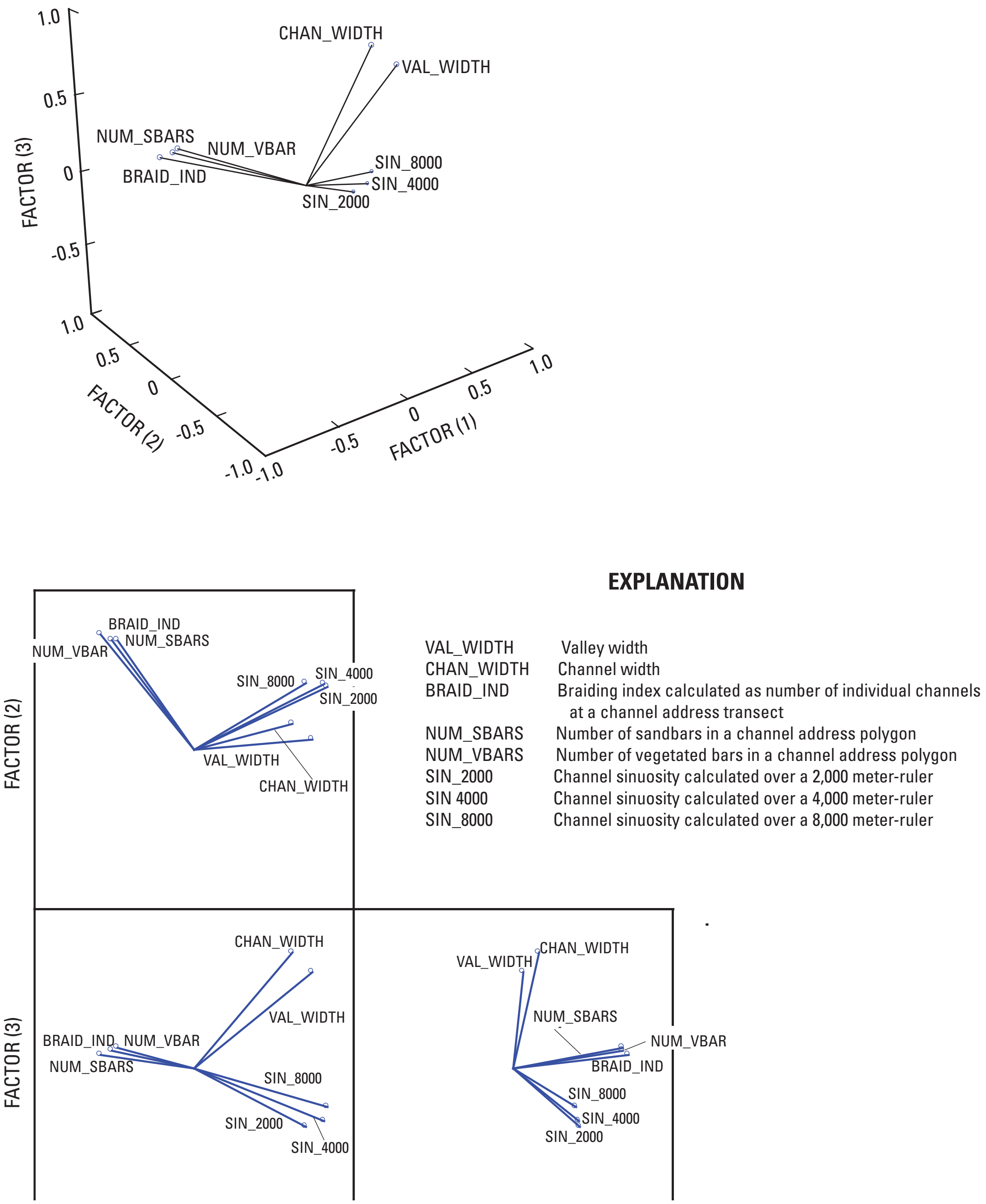


Figure 14. Principal components analysis of selected variables of for the Sharpe segment of the Missouri River. All variables have been standardized to the range.

and flood-plain inundation. Fragmentation of the sediment transport system by dams alters that equilibrium to the point where soil characteristics may no longer be reliable indicators of prevailing hydrology or geomorphic processes. In incising reaches, former flood plains become terraces that are no longer inundated by floods of 1- to 2-year return interval. Soils on the former flood plain will retain pedogenic and sedimentologic characteristics indicative of their origin in an active flood plain, slowly evolving to characteristics adjusted to their new hydrologic and geomorphic regimes (Chadwick and Chorover, 2001; Cornu and others, 2009). Hence, soils with pedogenic features indicative of water saturation and reducing geochemical conditions (redoximorphic features; Soil Survey Staff, 1993) may be found in landscape positions where soil saturation is now rare. In contrast, channel reaches characterized by rapid aggradation tend to have soils dominated by deposition of fine, organic-rich sediments, frequent inundation, and high water tables. Rapid aggradation of organic rich alluvial

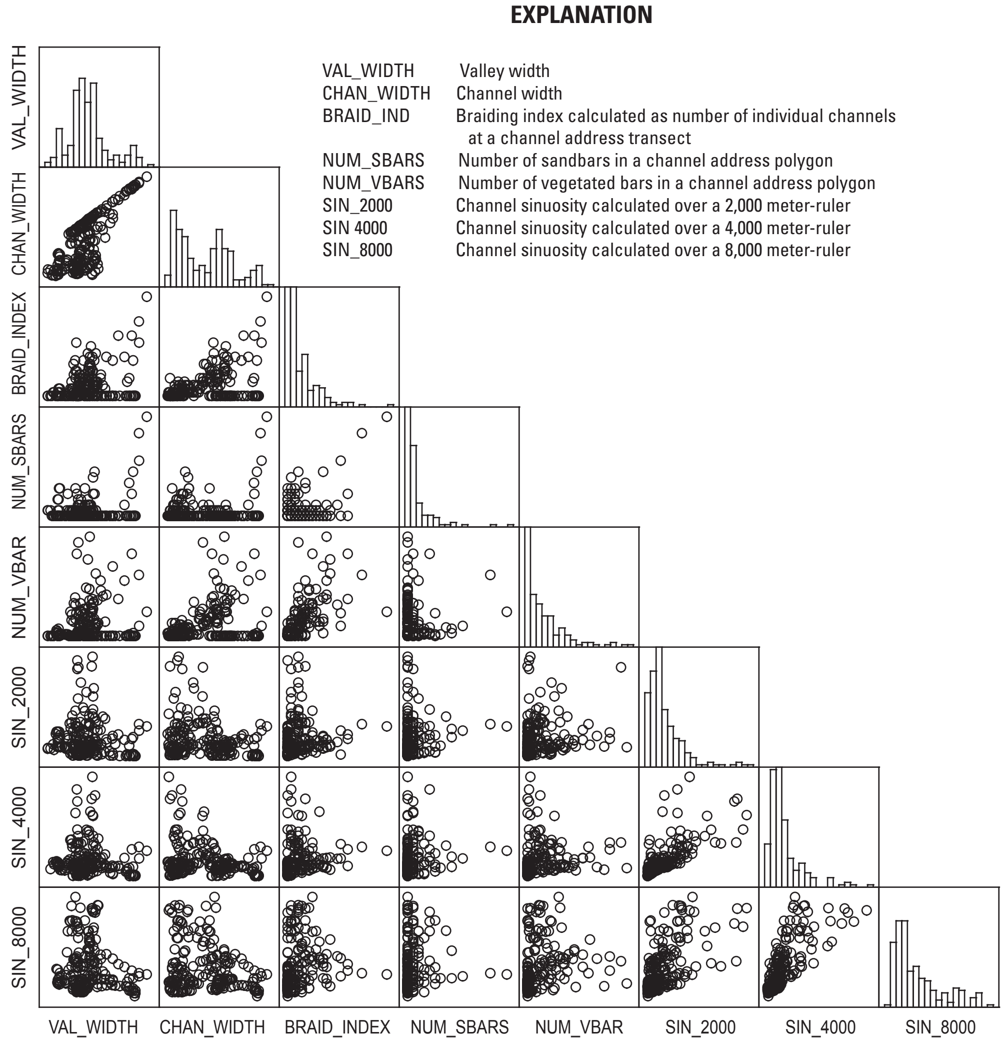


Figure 15. Bivariate and frequency plots of selected, non-transformed classification variables for the Fort Randall segment of the Missouri River.

sediments leads to cumulative A-horizons in soils that consequently classify as mollisols (Jacobson and others, 2003); these soils retain their sedimentologic characteristics and may not develop redoximorphic pedogenic characteristics related to their frequent inundation until years to decades have passed (Cornu and others, 2009).

Distributions of soil characteristics among comparison reaches along the Lower Missouri River support the idea that soil characteristics may be poor indicators of hydrologic condition in a geomorphically active river. In the incising reach at river mile 770, the 0–5 year wet area was dominated by relatively well-drained entisols, but a large area of entisols existed within the valley bottom outside of the 0- to 5-year wet area, resulting in entisols predicting only 4.2 percent of the 0- to 5-year wet area (table 4). The 0- to 5-year wet area in the stable-aggrading reach at river mile 560 was slightly dominated by mollisols, but mollisols were also dominant throughout the entire valley bottom resulting in only 45.1 percent correct classification of the 0- to 5-year wet area. Similar rates of classification errors occurred with other soil characteristics (table 4). In general, soil characteristics were better at classifying wet areas in aggradational reaches, with up to 98.9 percent correct classification rate.

Longitudinal variation in classification performance relative to the LCPI identification of wet areas indicates that soils alone are not robust indicators of wetness conditions along the reaches of the Missouri River affected by reservoirs. Independent assessment of hydrologic condition, like that afforded through modeled water-surface elevations, is necessary to assess the hydrologic condition of flood plains along geomorphically active rivers.

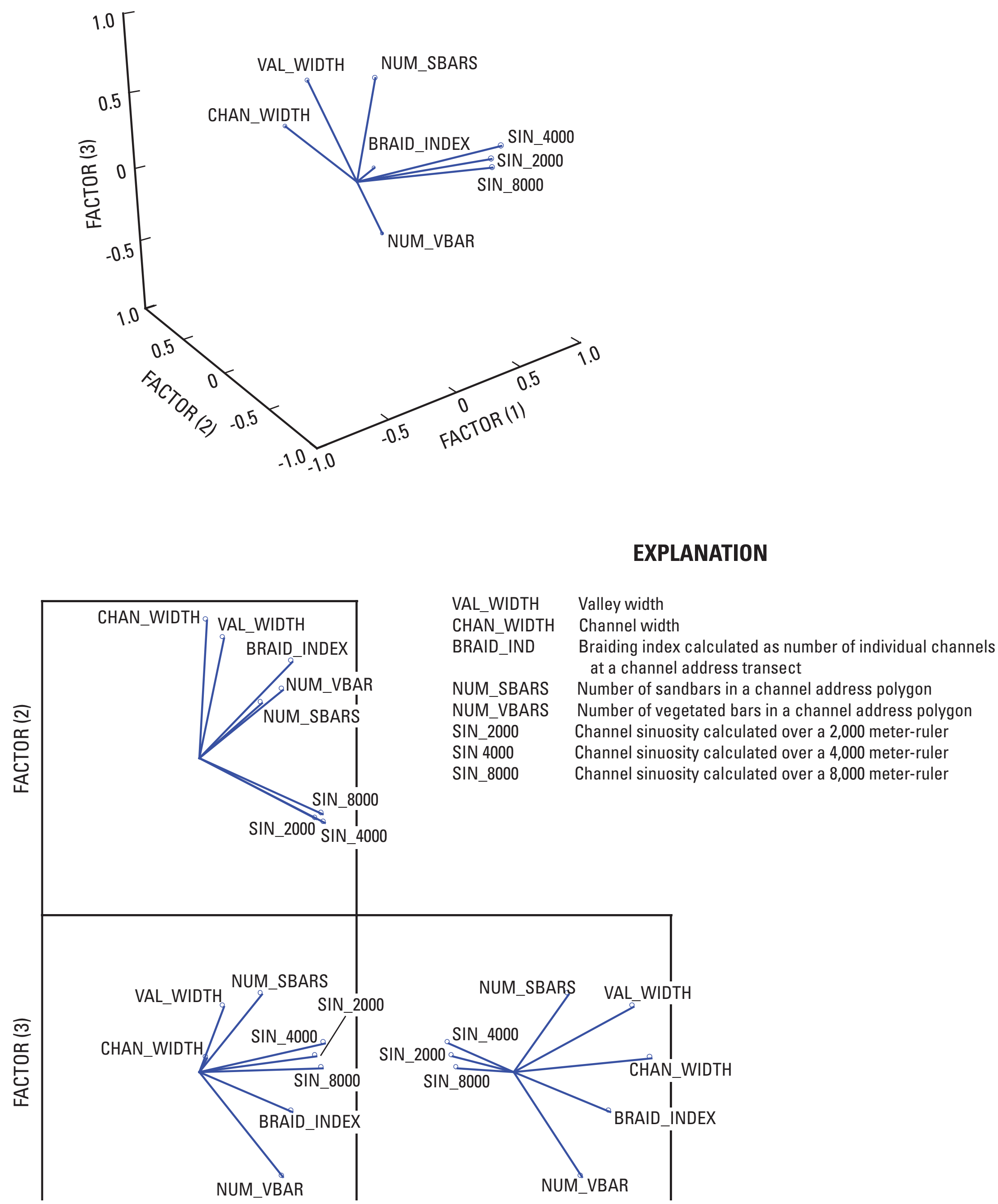


Figure 16. Principal components analysis of selected variables of for the Fort Randall segment of the Missouri River. All variables have been standardized to the range.

Water-Surface Elevations Compared to Flood-Plain Elevations

Whereas hydraulic models provided estimates of water-surface elevations for floods at intervals of 1.6 km on the Lower Missouri River (U.S. Army Corps of Engineers, 2004), streamgage spacings on the Sharpe and Fort Randall segments of the Middle Missouri River range from 3 to 116 km, and average 30.5 km (fig. 10). The long interpolations of water-surface elevations between streamgages challenges the validity of applying an LCPI-like intersection of water-surface elevations and topography to delineate wetness classes. Interpolation of water-surface elevations over long distances may be more valid in reservoir segments where water-surface elevations can be assumed to be flat to gently sloping.

The longitudinal inventory of elevation and interpolated water-surface elevations of 2-, 5-, or 10-year floods (fig. 10) provides some limited information on where land exists at elevations that can be inundated by these floods. Reaches where the water-surface elevations intersect higher percentiles

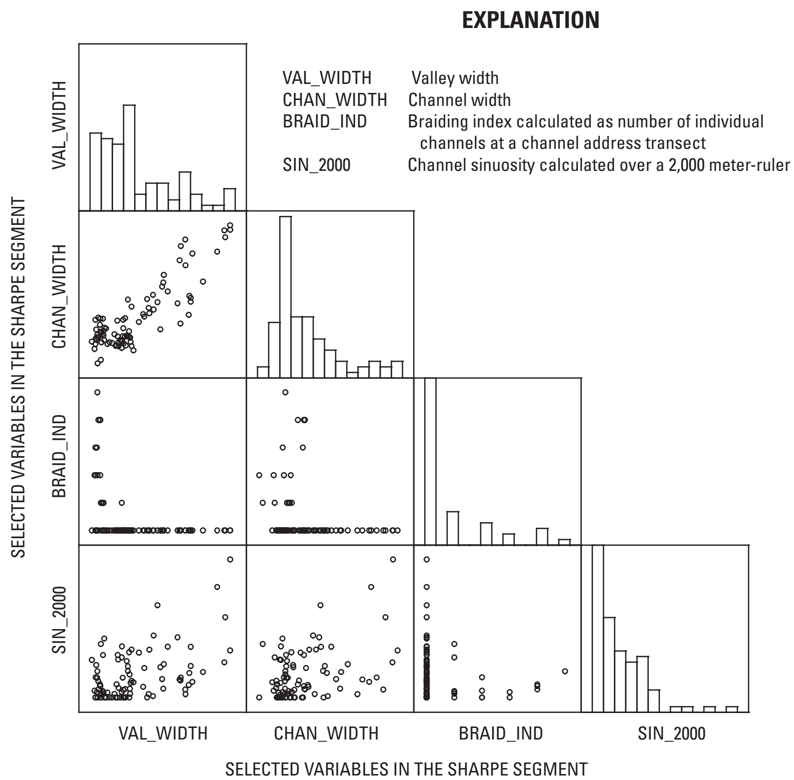


Figure 17. Bivariate and frequency plots of a reduced set of selected classification variables for the Sharpe segment of the Missouri River.

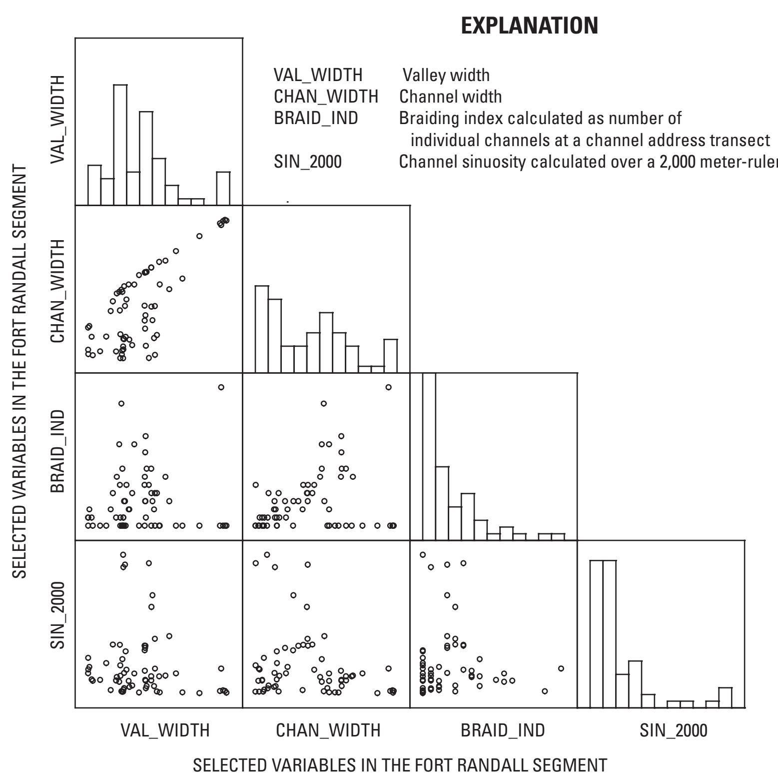


Figure 18. Bivariate and frequency plots of a reduced set of selected classification variables for the Fort Randall segment of the Missouri River.

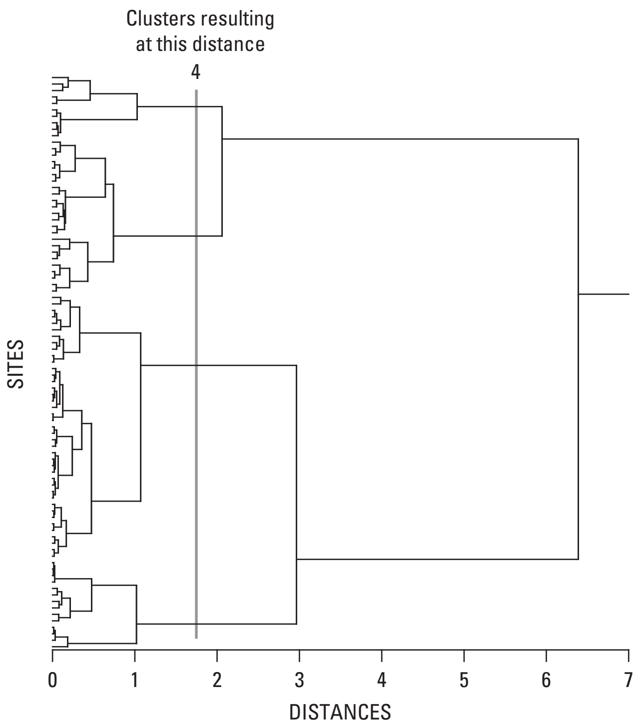


Figure 19. Hierarchical cluster dendogram of the reduced dataset for the Sharpe segment of the Missouri River. Selected variables were standardized for this analysis.

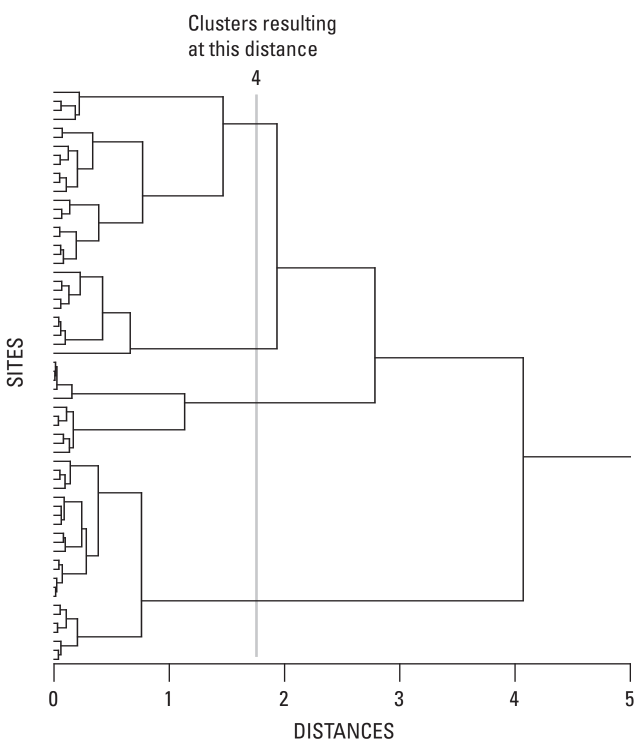


Figure 20. Hierarchical cluster dendogram of the reduced dataset for the Fort Randall segment of the Missouri River. Selected variables were standardized for this analysis.

indicate more land is available at elevations where wetness conditions may favor cottonwood restoration. Examples from the Sharpe segment are reaches at 28–35 km, 45–47 km, 77–84 km, and 105–115 km upstream from Big Bend Dam where 2-, 5-, and 10-year flood elevations affect 5–10 percent of the valley bottom.

Longitudinal Geomorphic Classification of the Middle Missouri River

Rivers can be classified in many ways, but a generally accepted criterion is that a classification should be developed to address specific applications (Kondolf and others, 2003). In this project, our objective was to develop a classification for the Middle Missouri River and its flood plain that would delineate units useful for cottonwood restoration. As discussed in the previous sections, available data were not of sufficient resolution to replicate the LCPI classification developed for the Lower Missouri River. This section of the report discusses a longitudinal geomorphic classification of the Middle Missouri River and its application to cottonwood restoration.

Segment Scale Classification

River classifications fall into two broad categories: *deductive* and *inductive*. Deductive classification systems are based on assumptions that well-understood processes determine channel form, and that the channel form is indicative of geomorphic processes. The most frequently cited example of deductive reach-scale classification is the Rosgen classification that places river reaches in predetermined classes based on channel planform, slope, and cross-sectional morphology (Rosgen, 1996).

In contrast, an inductive approach measures a suite of geomorphic variables and uses statistical clustering techniques to determine naturally occurring geomorphic sections of the river (Kondolf and others, 2003; Elliott and Jacobson, 2006; Elliott and others, 2009a). The inductive approach can be hierarchical depending on the number of criteria and number of clusters desired, and can, therefore, be used to define subreaches, reaches, or segments. For example, Elliott and Jacobson (2006) identified nested 2, 4, and 10-cluster classifications for the Missouri National Recreational River segment of the Lower Missouri River.

A combination of deductive and inductive approaches may be justified in a hierarchical approach. Elliott and Jacobson (2006) defined broad-scale features that clearly delineate physically distinct parts of the river and the flood plain at the segment scale. These features included boundaries imposed by dams, tributary junctions, and headwaters of lakes. A similar segment-scale classification is used in this report (figs. 1, 29, table 1), with segments delineated either by tributary junctions where flow regime and material fluxes change abruptly, or by hard structures such as dams. In the inter-reservoir reaches, we define riverine, deltaic, and lacustrine subsegments. The

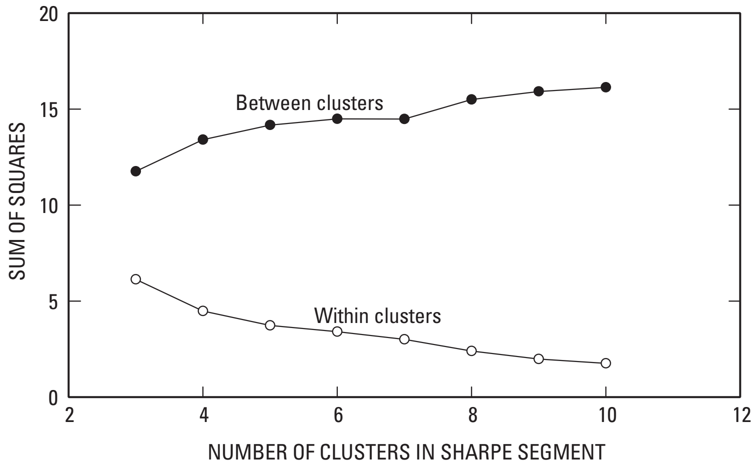


Figure 21. Changes in sum of square differences within and among clusters as number of clusters changes for the Sharpe segment of the Missouri River.

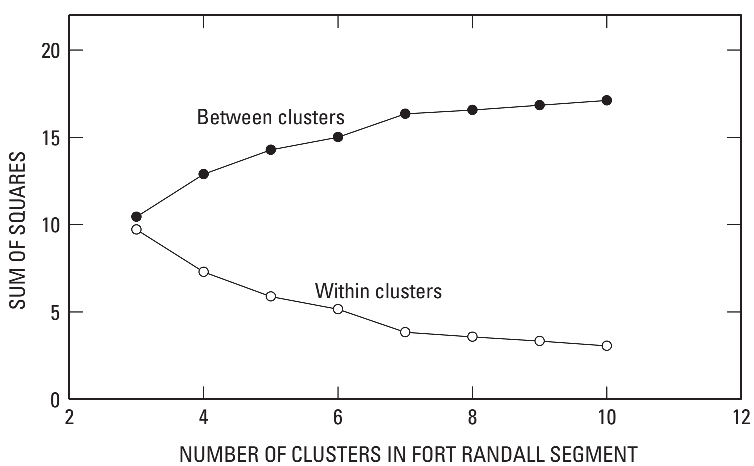


Figure 22. Changes in sum of square differences within and among clusters as number of clusters changes for the Fort Randall segment of the Missouri River.

transitions between subsegments are not clearly delineated because they vary with seasonal variation in water levels and with decadal variation in channel incision and aggradation.

The proposed inductive, reach-scale classification of the Middle Missouri River is nested within the deductive, segment-scale classification (figs. 1, 29, table 1). Other segment-scale classifications have been proposed for the Missouri River, and the proliferation of classifications, numbering protocols, and naming systems has caused some confusion (table 1). The numbering system proposed in our classification starts with 1 in the downstream segment (Osage River to Mississippi River) and counts up in the upstream direction. The logic for upstream incremental counting is that the upstream limit of the mainstem segments doesn't need to be defined, allowing segment numbering to continue to successively smaller channels. If the numbering system starts with 1 upstream and counts down, then some arbitrary starting place needs to be defined, and if there is subsequent interest in smaller channels upstream, the system has to be revised or negative numbers need to be used. An alternative to numbering systems is to use names as also proposed in table 1.

The definition of river segment originally proposed by Frissell and others (1986) was intended to indicate longitudinal parts of a stream system between substantial tributaries and with relatively uniform properties of bedrock and valley physiography. This definition leaves some latitude in determining substantive hydrologic and physiographic variation. Clearly, segments should be defined where large storage reservoirs, like those on the mainstem Missouri River, impose substantive hydrologic change on downstream channels. Impounded sections of the river also typically have a combination of lacustrine, deltaic, and riverine conditions. Because

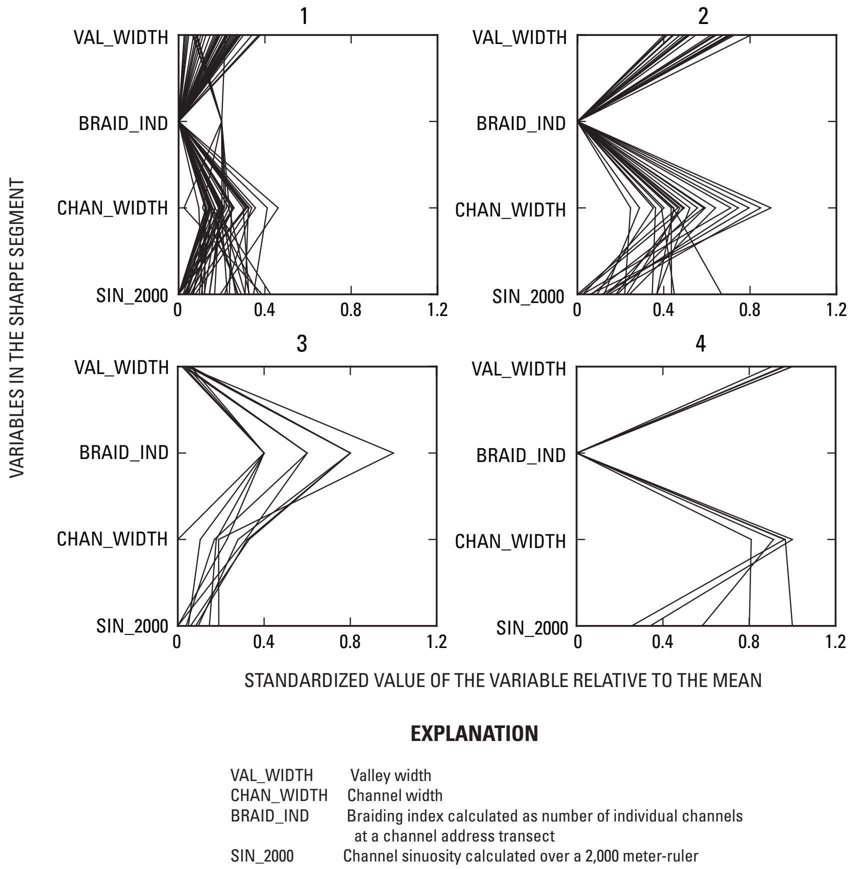


Figure 23. Cluster-parallel plots from the K-means procedure for the Sharpe segment of the Missouri River.

these conditions have a substantial effect on the distributions of water, sediment, and nutrients over time and space, they are important delimiters of riverine habitat and appropriate to define as subsegments. However, the locations and characteristics of the transitions between these conditions are highly dynamic. The transitions vary with seasonal to multiyear variations in lake levels and over longer periods as channel incision and deltaic sedimentation change channel-floodplain geomorphology. Consequently, lakes, deltas, and riverine parts of the Missouri River can be defined as separate subsegments, but transitions among them are dynamic.

Reach-Scale Classification

Reaches within segments are characterized conceptually as uniform lengths of river with similar channel and flood-plain morphology generally containing multiples of channel units or bend-crossover units (Frissell and others, 1986). Our statistical classification attempts to define naturally occurring clusters of uniform channel and flood-plain geomorphology at the reach scale (table 8). Because reaches are defined at a substantially finer scale compared to segments, statistically defined reaches may cluster within identified segments or subsegments or they may occur in multiple segments. In inter-reservoir reaches where subsegment boundaries are difficult to define, the spatial distribution of statistically defined reaches provides an independent basis for delineating riverine, deltaic, and lacustrine subsegments (figs. 27, 28).

The number of clusters used in the classification is a matter of judgment that is based on a combination of physical understanding of the river, the structure of the hierarchical clustering (figs. 19, 20) and the shape of the “scree” plots from the K-means clustering (figs. 21, 22). More than four clusters could be used in the Sharpe and Fort Randall segments but it is unclear whether subdivided clusters would result in increased ability to interpret and apply the classification.

Because the Sharpe and Fort Randall segments were clustered separately, the numbering and the characteristics of the clusters are not the same in the two segments. In the Sharpe segment, valley width was the most influential variable in the K-means cluster procedure, followed by braiding index, channel width, and sinuosity (fig. 23). In contrast, channel width was most influential in the Fort Randall segment, followed by braiding index, sinuosity, and valley width (fig. 24). The influence of valley width in the Sharpe segment results from the greater variability, especially relative to channel width, within the segment (fig. 11). In contrast, channel width was more variable than valley width in the Fort Randall segment (fig. 12). Valley width can be of considerable importance in riverine habitat assessments because it is a measure of total valley

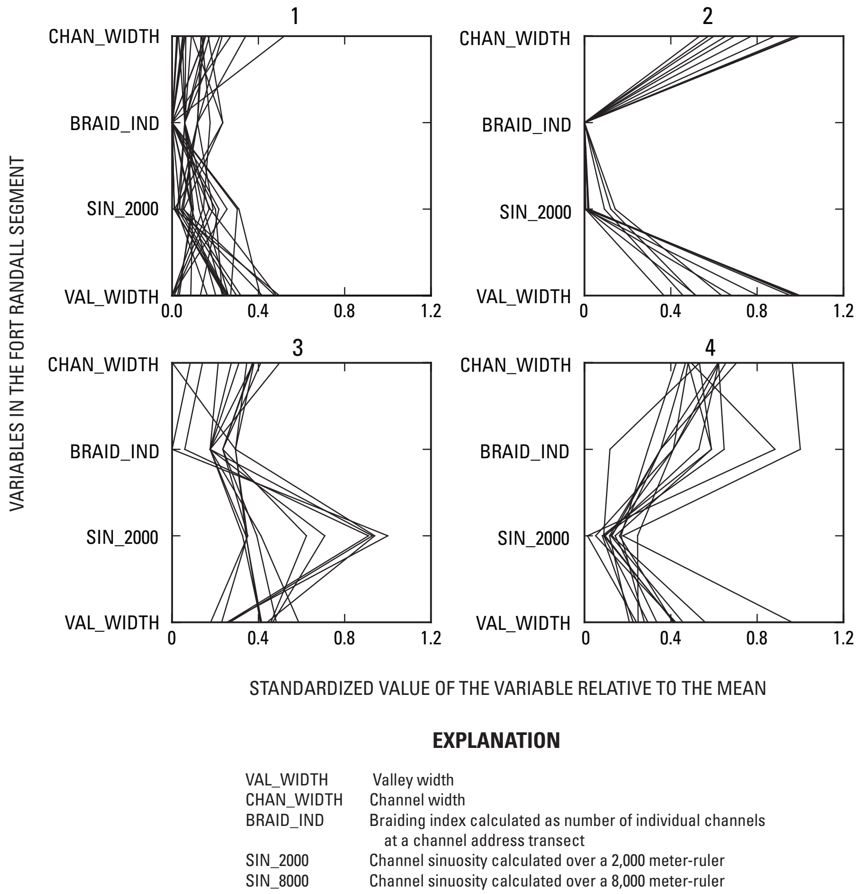


Figure 24. Cluster-parallel plots from the K-means procedure for the Fort Randall segment of the Missouri River.

Table 8. Names and interpreted physical significance of the clustered classes in the Sharpe and Fort Randall segments.

Classification	Descriptive name	Physical process interpretation
		Sharpe segment
1	No braiding, variable valley width, channel width, and sinuosity	This unit occurs in multiple settings within the Sharpe segment, including the reaches above and below the Bad River. It is associated with variable valley and channel widths, no braiding and variable sinuosity.
2	Wide valley, no braiding, medium channel width	This unit occurs entirely within Lake Sharpe and is characterized by a wide valley, medium channel widths, and no braiding consistent with a reservoir environment.
3	Medium to highly braided, narrow valley	This unit occurs downstream from the Bad River in the delta region of the Sharpe segment and is characterized by braiding and a narrow valley.
4	Wide valley and channel, no braiding	This unit is restricted to Lake Sharpe and is characterized by wide valley and channel widths and no braiding consistent with a reservoir environement.
		Fort Randall segment
1	Low to medium channel and valley width, variable braiding	This unit is made up primarily of the riverine reaches of the Missouri River below Fort Randall Dam and its occurrence is limited downstream from the Niobrara River.
2	Low braiding index, low sinousity, high channel and valley width	This unit is restricted to the reservoir and delta of Lewis and Clark Lake characterized by wide valley and channel widths, low braiding and sinuosity consistent with a reservoir environment.
3	Lower channel widths, medium braiding high sinuosity	This unit occurs in the riverine reach mostly upstream from the Niobrara River and is characterized by measures of channel complexity such as braiding, high sinuosity and lower channel widths.
4	High channel width, medium to high braiding, low sinuosity	This unit occurs in the highly braided delta primarily downstream from the Niobrara River. There is some occurance in the reaches with high channel complexity immediately upstream from the Niobrara River.

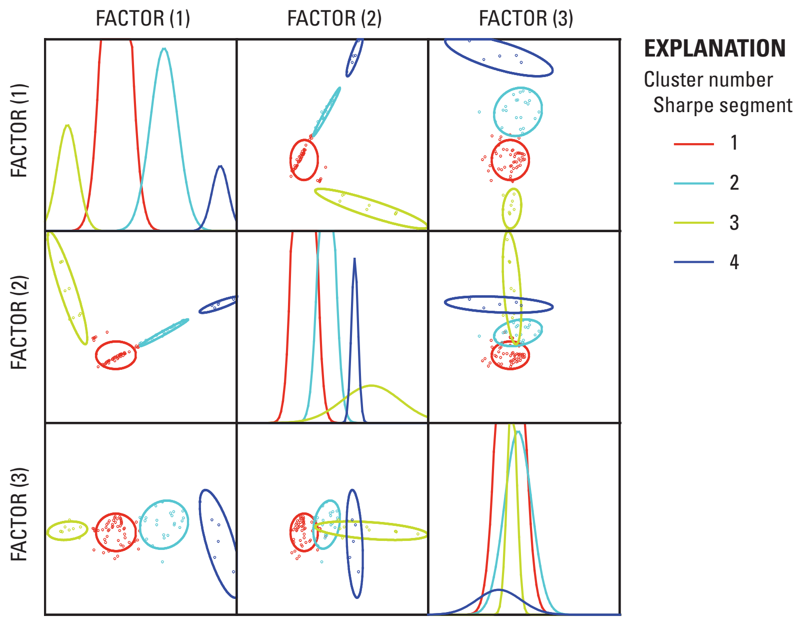


Figure 25. Canonical scores plot for the four-cluster classification, Sharpe segment.

bottom area available for riparian restoration. The relation of

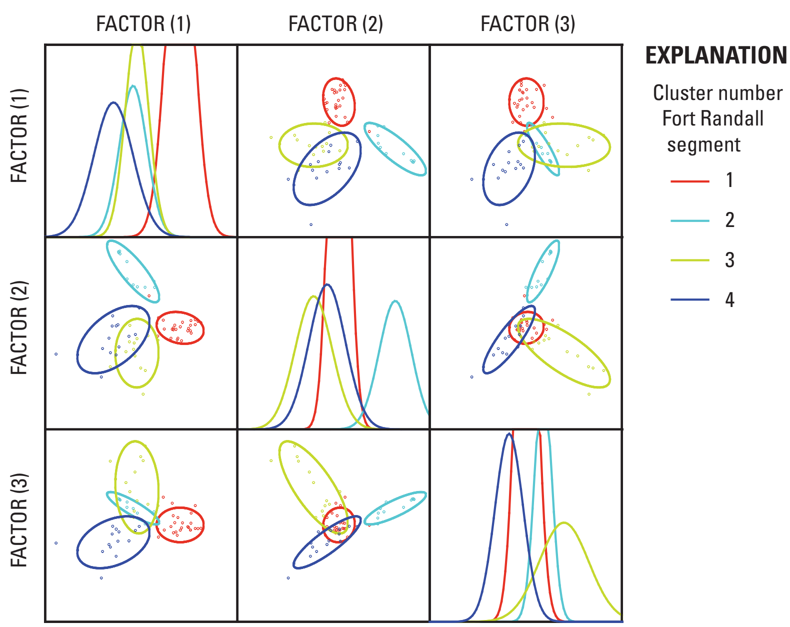


Figure 26 Canonical scores plot for the four-cluster classification, Fort Randall segment.

channel width to valley width also determines interactions of the channel with the valley wall, which can be associated with bedrock substrate availability and convergent flow hydraulics (Laustrup and others, 2007; Jacobson and others, 2009b).

Braiding index is the second most influential variable in both segments (figs. 23, 24). Braiding index is calculated from the number of channels and is useful for distinguishing between single-thread and multithread channels. Braiding index can be sensitive to prevailing discharge when aerial photography is obtained, especially for reaches with many low-elevation sand bars. Discharges during aerial photographs used in this analysis varied little among dates (fig. 4) and ranged from approximately 25 to 50 percent flow exceedance. Therefore, braiding indices were measured under fairly consistent conditions that represent typical discharge conditions.

Braiding index is a useful measure of complexity of aquatic habitats and is an indicator of channel dynamics in the Missouri River (Elliott and Jacobson, 2006). The index was influential in defining cluster 3 in the Sharpe segment in the riverine section upstream from the Bad River junction, and it was influential in defining clusters 3 and 4 in the Fort Randall reach. Cluster 3 is characterized by multithread channels in the riverine part of the segment upstream from the Niobrara River junction and cluster 4 is characterized by the multithread, distributary channels of the Lewis and Clark Lake delta.

Sinuosity is a measure of the curviness of the centerline of the channel and an index of aquatic habitat complexity. Sinuosity also is related directly to channel migration rates (Johannesson and Parker, 1989). Sinuosity was least influential in the Sharpe reach because it tended to co vary with valley width at all scales (figs. 11, 23). In the Fort Randall segment, sinuosity was the third most influential variable and helped define cluster 3 (fig. 24). Cluster 3 occurs in a complex part of the channel at river miles 860–870 and in the riverine segment upstream from the Niobrara junction.

Implications for Cottonwood Restoration

Under natural conditions, cottonwoods germinate after seeds are deposited by water on freshly deposited sediment, usually on point bars created by channel migration (Johnson, 1992; Scott and others, 1996; Scott and others, 1997; Johnson, 2000). If the seeds are deposited high enough to avoid subsequent scour by water or ice (Friedman and others, 1995; Auble and Scott, 1998) and groundwater does not decline so rapidly that root growth cannot keep pace during the summer and fall (Mahoney and Rood, 1998), seedlings may survive to the next year. High

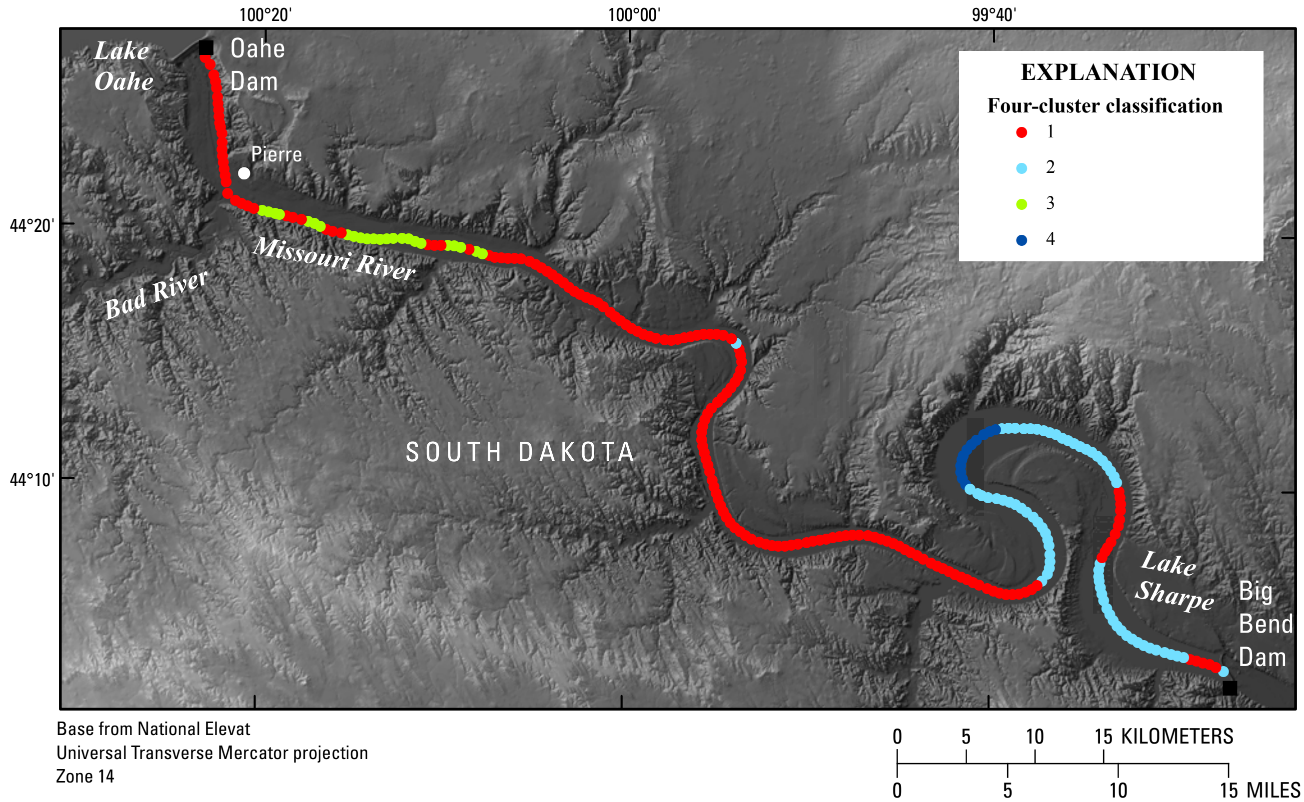


Figure 27. Reach-scale cluster classifcations for the Sharpe segment of the Missouri River.

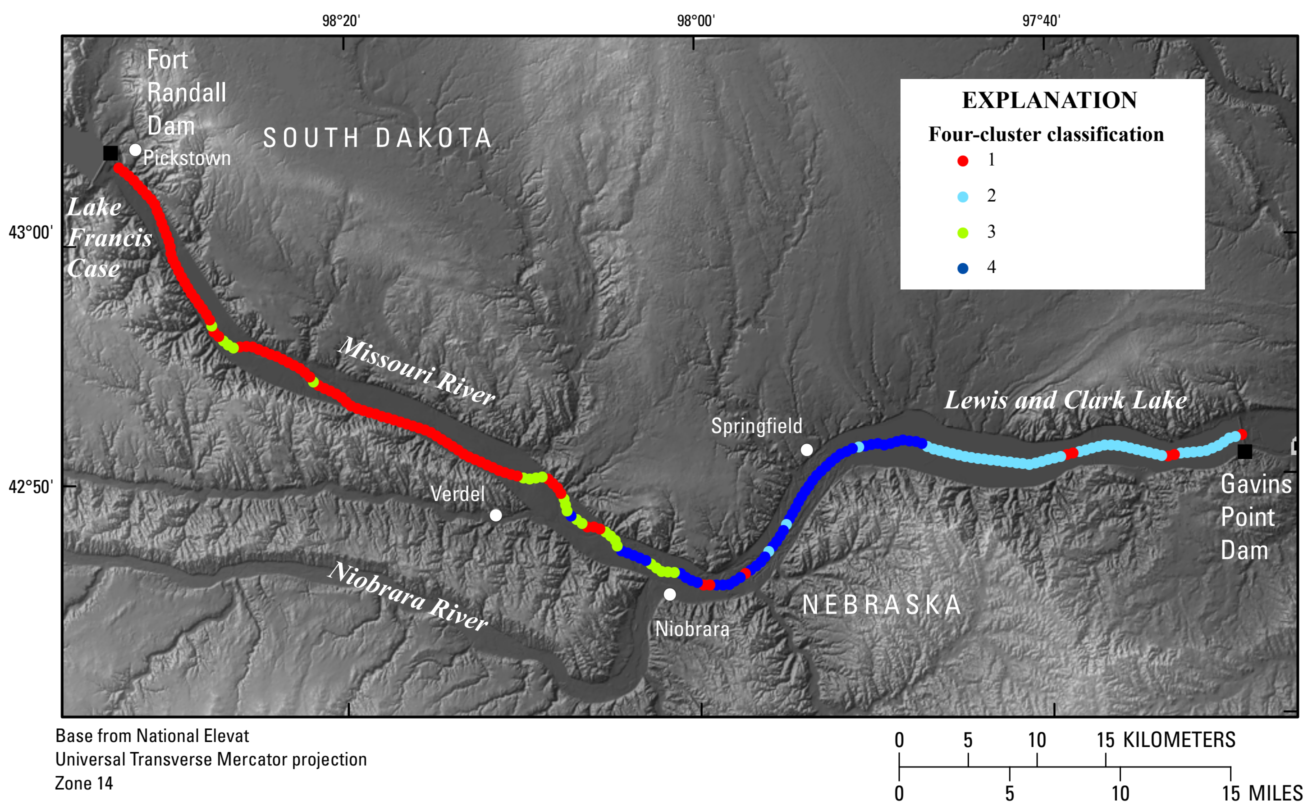


Figure 28. Reach-scale cluster classifcations for the Fort Randall segment of the Missouri River.

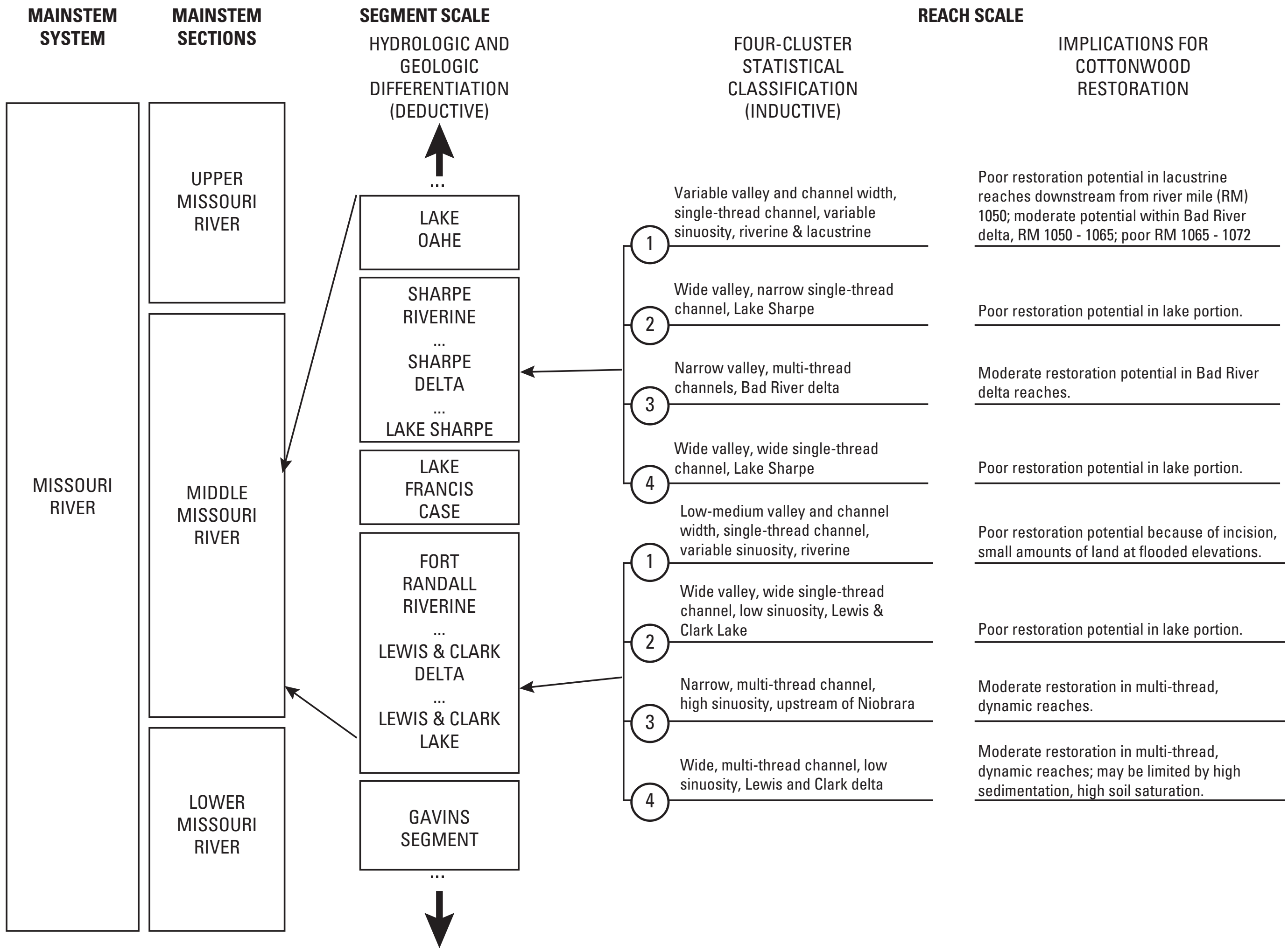


Figure 29. Schematic summary of classification of the lower segments and reaches of the Middle Missouri River, with interpreted implications for cottonwood restoration.

water tables also may limit cottonwood growth and survival by contributing to root hypoxia or encouraging shallow root distributions (Kozlowski, 2009).

Restoration strategies for cottonwoods have focused on restoring the natural hydrologic and geomorphic dynamics of river reaches (Scott and others, 1997; Johnson, 2000; Shafroth and others, 2002) or on artificial mechanisms (Friedman and others, 1995). In artificial regeneration experiments, Friedman and others (1995) found that natural seed sources on disturbed or irrigated ground increased cottonwood seedling density by a factor of more than 10 over nondisturbed, nonirrigated ground (0.03 seedlings/ square meter (m^2). Irrigation and disturbance increased seedling density by another order of magnitude to 10.3 seedlings/m^2. These results indicate that artificial regeneration of cottonwoods is possible if costs of plowing and irrigation are acceptable.

For natural or artificial regeneration of cottonwoods, flow regime and relative elevation of ground above water-surface elevations are critical factors for germination and survival. For natural regeneration, a dynamically migrating channel is also critical. While lacking the detail of the LCPI, the distribution of elevations along the Sharpe and Fort Randall segments provides an indication of the interaction of flow regime and ground-surface elevations (fig. 10). The base of the shaded bands on this figure indicates approximate river level on the day that the topographic elevations were recorded, presumably a relatively frequent flow exceedance. The elevation difference between the river level and the 2, 5, and 10-year recurrence stages indicates the range of relatively frequent floods. The intersection of the floodwater-surface elevations with the colored bands indicates what percentage of the valley bottom would be affected by stages of that magnitude. Sections of the profile where the floodwater-surface elevations intersect bands indicating 8 to 10 percent of the valley bottom is at or below that elevation present more restoration opportunity than sections where intersecting bands indicate that 0 to 2 percent of the valley bottom is at or below that elevation. It should be noted that the valley-bottom elevations are in percentiles of elevations associated with address points along the river and do not show absolute area. Moreover, some of the current land uses in the valley bottom at appropriate elevations may be incompatible with cottonwood restoration activities; much of the wider flood plain of the Sharpe segment is occupied by intensive, irrigated agriculture (fig. 2). Also, areas where valley-bottom lands are relatively close to the floodwater-surface elevations may too wet for successful cottonwood restoration. Excessively wet conditions may apply to flood plain bordering the Lewis and Clark delta where high groundwater levels may limit cottonwood growth and survival.

The reach-scale channel classification presented in this report provides guidance for evaluating where natural cottonwood restoration may be most successful. Clusters with multithread and highly sinuous channels (cluster 3 in the Sharpe segment and clusters 3 and 4 in the Fort Randall segment) are likely to be associated with dynamic channel migration and deposition of fresh, bare sediment conducive to cottonwood germination (fig. 29). Channel migration and sediment deposition rates are likely reduced from natural conditions that existed prior to flow regulation. Nevertheless, ongoing channel migration in these reaches is expected to continue to create new surfaces for germination, although less extensive and at a slower rate (Elliott and Jacobson, 2006).

It is less clear whether the current flow regime would be conducive for regeneration on these new surfaces. In particular, pulsed discharges would need to be large enough to deposit seeds at elevations where seedlings will survive winter ice, and groundwater-recession rates would need to be fast enough to encourage deep root growth but not so fast as to create water stress. Lack of groundwater recession may be a limiting factor in deltaic segments affected by lake levels or in riverine reaches affected by unnaturally high discharges during summer months.

The classification presented in this report is not definitive about potential for cottonwood restoration in the Sharpe and Fort Randall segments but does provide a filter to prioritize and evaluate reaches within these segments. Increased accuracy in classifying restoration potential could be achieved by acquiring improved topographic data that would resolve bathymetry and low-elevation surfaces near the water surface and by developing hydraulic models to provide high-resolution flood profiles. This would provide data sufficient to replicate the LCPI used in the Lower Missouri River (Jacobson and others, 2007). Development of channel migration models would provide another useful tool for evaluating the quality and extent of cottonwood regeneration under naturally occurring conditions without mechanical disturbance, seeding, and irrigation. The classification presented in this report could be used to target these science investments in specific reaches or segments that would be considered to have the highest restoration potential.

Conclusions

The objective of this study was to develop a spatially explicit river and flood-plain classification to apply to evaluation of the potential for cottonwood restoration along the Sharpe and Fort Randall segments of the Middle Missouri River. Two subobjectives were (1) to evaluate whether existing topographic, water-surface elevation, and soils data were sufficient to create an index classification similar to the LCPI of Jacobson and others (2007), and (2) if an LCPI-like classification was not possible, to develop a geomorphically based classification that would provide a framework for evaluating restoration potential.

Assessment of topographic, water-surface elevation, and soils data available for the Middle Missouri River indicated that they were not sufficient to replicate the LCPI. Relatively high-resolution topographic data from the 1/3-arc-second NED largely delineated most of the topographic complexity and produced cumulative frequency distributions similar to the high-resolution 5-m topographic dataset developed for the Lower Missouri River. However, because the 1/3-arc-second NED does not include bathymetry, topographic data are only available for areas that were subaerially exposed when the original data were collected. This presents a potentially critical bias in evaluation of frequently flooded surfaces close to the river.

We explored the idea that soil data alone would be sufficient to provide most or all of the information content of the LCPI. Comparison reaches were identified along the Lower Missouri River where high-resolution LCPI data were available to delineate areas presently at or below the 5-year return interval flood elevation. The comparison reaches of the Lower Missouri River also were characterized by a range of channel incision. In these reaches, soil characteristics from the SSURGO database correctly classified only 2 to 98 percent of the area at or below the 5-year return interval flood stage, depending on reach and soil parameters used. The incongruence between mapped soil characteristics and present-day hydrology over much of the flood plain is explained by the relatively rapid geomorphic evolution of the Lower Missouri River. Like many impounded rivers, the regulated segments of the Missouri River have been variably affected by incision, thereby altering the relation between present-day hydrology, geomorphology, and flood-plain soils. We concluded that it was unlikely soils would be useful as a sole classification guide in the reservoir and interreservoir segments of the Middle Missouri River.

The most sparsely available data in the Middle Missouri River were water-surface elevations. Compared to the Lower Missouri River where water-surface elevations for 2- to 500-year return interval floods were modeled every 1.6 km along the river, water-surface elevations in the Middle Missouri River had to be obtained from current streamflow gaging stations spaced at 3–116 km intervals. Although water surfaces for some of the segments are very flat because of reservoir lake levels, lack of high-resolution data in riverine sections precludes development of an LCPI-like intersection of topography with water-surface elevations to map indices of wetness.

An hierarchical river classification framework provides structure for combining deductive and inductive, statistical classifications at a range of scales. The segment-scale classification presented in this report is deductive and based on the concept that dams, significant tributaries, and geological (and engineered) channel constraints present primary controls on the biophysical capacity of the river system, including flow regime, material fluxes, and channel dynamics.

An inductive reach-scale classification is nested within the segment scale. The reach-scale classification is based on multivariate statistical clustering of geomorphic data collected at 500-m intervals along the Sharpe and Fort Randall segments. Separate, four-cluster classifications for the two segments delineate reaches of the river with similar channel flood-plain geomorphology, and presumably, similar geomorphic and hydrologic processes that would affect cottonwood restoration in similar ways. The dominant variables in the clustering process were channel width (Fort Randall) and valley width (Sharpe), followed by braiding index (both segments).

The classification provides a useful tool for evaluating cottonwood restoration potential. Clusters with multithread and highly sinuous channels are likely to be associated with dynamic channel migration and deposition of fresh, bare sediment conducive to natural cottonwood germination. However, restoration potential within these reaches is likely to be mitigated by the highly regulated flow regime and lake levels that may be out of phase with cottonwood life cycles. In particular, multithread reaches in the Lewis and Clark delta probably have high sedimentation rates and high groundwater levels that will limit growth and survival. Steady summer-fall flows in riverine reaches may not produce groundwater-recession rates sufficient to support adequate root growth.

The reach-scale classification of the Sharpe and Fort Randall segments provides a tool to prioritize and evaluate reaches for cottonwood restoration. Development of high-resolution topographic data to resolve bathymetry and low-elevation surfaces near the water surface, and development of hydraulic models to provide high-resolution flood profiles, would provide data sufficient to replicate the LCPI used in the Lower Missouri River (Jacobson and others, 2007). In addition, channel migration models would provide a useful tool for evaluating the quality and extent of natural cottonwood regeneration. The reach-scale classification presented in this report provides a framework to focus science and management investments in reaches with the highest restoration potential.

References Cited

Auble, G.T., and Scott, M.L., 1998, Fluvial disturbance patches and cottonwood recruitment along the upper Missouri River, Montana: Wetlands, v. 18, no. 4, p. 546–556.

Chadwick, O.A., and Chorover, J., 2001, The chemistry of pedogenic thresholds: Geoderma, v. 100, no. 3–4, p. 321–353.

Cornu, S., Montagne, D., and Vasconcelos, P.M., 2009, Dating constituent formation in soils to determine rates of soil processes: A review: Geoderma, v. 153, no. 3-4, p. 293–303.

Elliott, C.M., Huhmann, B.L., and Jacobson, R.B., 2009a, Geomorphic classification of the Lower Platte River, Nebraska: U.S. Geological Survey Scientific Investigations Report 2009–5198, 29 p.

Elliott, C.M., and Jacobson, R.B., 2006, Geomorphic classification and assessment of channel dynamics in the Missouri National Recreational River, South Dakota and Nebraska: U.S. Geological Survey Scientific Investigations Report 2006–5313, 66 p.

Elliott, C.M., Reuter, J.M., and Jacobson, R.B., 2009b, Channel morphodynamics in four reaches of the Lower Missouri River, 2006–07: U.S. Geological Survey Scientific Investigations Report 2009–5074, 258 p.

Engineering and Hydrosystems Inc., 2002, Conceptual analysis of sedimentation issues on the Niobrara and Missouri Rivers, South Dakota and Nebraska: Omaha, Nebr., U.S. Army Corps of Engineers, 19 p.

Ferrell, J., 1993, Big dam era—A legislative history of the Pick-Sloan Missouri River Basin Program: Omaha, U.S. Army Corps of Engineers, 228 p.

Friedman, J.M., Scott, M.L., and Lewis, W.M., 1995, Restoration of riparian forest using irrigation, artificial disturbance, and natural seedfall: Environmental Management, v. 19, no. 4, p. 547–557.

Frissell, C.A., Liss, W.J., Warren, C.E., and Hurley, M.D., 1986, A hierarchical framework for stream habitat classification—Viewing streams in a watershed context: Environmental Management, v. 10, no. 2, p. 199–214.

Galat, D.L., and Lipkin, R., 2000, Restoring ecological integrity of great rivers—historical hydrographs aid in defining reference conditions for the Missouri River: Hydrobiologia, v. 422/423, p. 29–48.

Gesch, D.B., Evans, G., Mauck, J., Hutchinson, J., and Carswell, W.J., 2009, The National Map—Elevation: U.S. Geological Survey Fact Sheet 2009–3053, 4 p.

Ghimire, M.K., Bondy, A.K., Cordova, A.J., Noah, D., and Holbrook, J., 2007, Surficial material geologic map of the Arrow Rock 7.5’ quadrangle: Missouri Department of Natural Resources, Division of Geology and Land Survey, Geological Survey Program, OFM-05-XXX-GS, scale 1:24,000.

Hill, T., and Lewicki, P., 2006, Statistics—Methods and applications: Tusla, Oklahoma, StatSoft, Inc., 831 p.

Holbrook, J., Kliem, G., Nzewunwah, C., Jobe, Z., and Goble, R., 2006, Surficial alluvium and topography of the Overton Bottom North Unit, Big Muddy National Fish and Wildlife Refuge in the Missouri River valley and its potential influence on environmental management, *in* Jacobson, R.B., ed., Science to support adaptive habitat management, Overton Bottoms North Unit, Big Muddy National Fish and Wildlife Refuge, Missouri: U.S. Geological Survey Scientific Investigations Report 2006–5086, p. 17–32.

Jacobson, R.B., Blevins, D.W., and Bitner, C.J., 2009a, Sediment regime constraints on river restoration–An example from the Lower Missouri River, *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., Management and restoration of fluvial systems with broad historical changes and human impacts: Denver, Colo., Geological Society of America Special Paper 451, p. 1–22.

Jacobson, R.B., Chojnacki, K.A., and Reuter, J.M., 2007, Land capability potential index (LCPI) for the Lower Missouri River valley: U.S. Geological Survey Scientific Investigations Report 2007–5256, 19 p.

Jacobson, R.B., Johnson, H.E., III, and Dietsch, B.J., 2009b, Hydrodynamic simulations of physical aquatic habitat availability for pallid sturgeon in the Lower Missouri River, at Yankton, South Dakota, Kenslers Bend, Nebraska, Little Sioux, Iowa, and Miami, Missouri, 2006–07: U.S. Geological Survey Scientific Investigations Report 2009–5058, 67 p.

Jacobson, R.B., O’Connor, J.E., and Oguchi, T., 2003, Surficial geologic tools in fluvial geomorphology, *in* Kondolf, G.M., and Piégay, H., eds., Tools in Fluvial Geomorphology: Chichester, England, John Wiley and sons, p. 25–57.

Johannesson, H., and Parker, G., 1989, Linear theory of river meanders, *in* Ikeda, S., and Parker, G., eds., River Meandering, Water Resources Monograph 12: Washington, D.C., American Geophysical Union, p. 181–213.

Johnson, W.C., 1992, Dams and riparian forests: case study from the upper Missouri River: Rivers, v. 3, p. 229–242.

Johnson, W.C., 2000, Tree recruitment and survival in rivers: influence of hydrological processes: Hydrological Processes, v. 14, no. 16-17, p. 3,051–3,074.

Kalischuk, A.R., Rood, S.B., and Mahoney, J.M., 2001, Environmental influences on seedling growth of cottonwood species following a major flood: Forest Ecology and Management, v. 144, no. 1-3, p. 75–89.

Kondolf, G.M., Montogomery, D.M., Piégay, H., and Schmitt, L., 2003, Geomorphic classification of rivers and streams, *in* Kondolf, G.M., and Piégay, H., eds., Tools in fluvial geomorphology: Chichester, England, John Wiley and Sons, p. 171–204.

Kozlowski, T.T., 2009, Pjysiological-ecological impacts of flooding on riparian forest ecosystems: Wetlands, v. 22, no. 3, p. 550–561.

Laustrup, M.S., Jacobson, R.B., and Simpkins, D.G., 2007, Distribution of potential spawning habitat for sturgeon in the Lower Missouri River, 2003–06: U.S. Geological Survey Open-File Report 2007–1192, 26 p.

Laustrup, M.S., and LeValley, M., 1998, Missouri River Environmental Assessment Program: Columbia, Mo, U.S. Geological Survey, Missouri National Resources Committee, p. 33.

Mahoney, J.M., and Rood, S.B., 1998, Streamflow requirements for cottonwood seedling requirement—an integrative model: Wetlands, v. 18, p. 634–638.

Montgomery, D.R., 1999, Process domains and the river continuum: Journal of the American Water Resources Association, v. 35, p. 397–410.

National Research Council, 2002, The Missouri River ecosystem, exploring the prospects for recovery: Washington, D.C., National Academy Press, 176 p.

Pegg, M.A., Pierce, C.L., and Roy, A., 2003, Hydrological alteration along the Missouri River Basin—a time series approach: Aquatic Sciences, v. 65, p. 63–72.

Reuter, J.M., Jacobson, R.B., Elliott, C.M., and DeLonay, A.J., 2009, Assessment of Lower Missouri River physical aquatic habitat and its use by adult sturgeon (genus *Scaphirhynchus*) 2005–07: U.S. Geological Survey Scientific Investigations Report 2009–5121, 81 p.

Reuter, J.M., Jacobson, R.B., Elliott, C.M., Johnson, H.E., III, and DeLonay, A.J., 2008, Hydraulic and substrate maps of reaches used by sturgeon (genus *Scaphirhynchus*) in the Lower Missouri River, 2005–07: U.S. Geological Survey Data Series Report 386, 442 p.

Rieman, B., Peterson, J.T., Clayton, J., P., H., Thurow, R., Thompson, W., and Lee, D., 2001, Evaluation of potential effects of federal land management alternatives on trends of salmonids and their habitats in the interior Columbia River basin: Forest Ecology and Management, v. 153, p. 43–62.

Rosgen, D., 1996, Applied River Morphology, Wildland Hydrology, Pagosa Springs, Colorado, 352 p.

Schmidt, J.C., and Wilcock, P.R., 2008, Metrics for assessing the downstream effects of dams: Water Resources Research, v. 44, p. 1–19.

Scott, M.L., Auble, G.T., and Friedman, J.M., 1997, Flood dependency of cottonwood establishment along the Missouri River, Montana, USA: Ecological Applications, v. 7, no. 2, p. 677–690.

Scott, M.L., Friedman, J.M., and Auble, G.T., 1996, Fuvial process and the establishment of bottomland trees: Geomorphology, v. 14, p. 327–339.

Shafroth, P.B., Friedman, J.M., Auble, G.T., Scott, M.L., and Braatne, J.H., 2002, Potential responses of riparian vegetation to dam removal: Bioscience, v. 52, no. 8, p. 703–712.

Soil Survey Staff, 1993, Soil survey manual: Washington, D.C., United States Department of Agriculture, Soil Conservation Service, Agricultural Handbook No. 18, available at: URL *http://soils.usda.gov/technical/manual/.*

Soil Survey Staff, 2009, Spatial and tabular data of soil surveys for counties in Iowa, Nebraska, and South Dakota, Soil Survey Geographic (SSURGO) database: U.S. Department of Agriculture, Natural Resources Conservation Service, available at: URL *http://SoilDataMart.nrcs.usda.gov/.*

U.S. Army Corps of Engineers, 2004, Upper Mississippi River system flow frequency study: U.S. Army Corps of Engineers, 33 p.

U.S. Army Corps of Engineers, 2006, Missouri River Mainstem Reservoir System - Master Water Control Manual, Missouri River Basin: Omaha, Nebraska, Northwestern Division, Missouri River Basin, Water Management Division, 431 p.

U.S. Army Corps of Engineers, 2007, Missouri River Stage Trends: U.S. Army Corps of Engineers, Northwestern Division, Reservoir Control Center Technical Report Ja-07, 43 p.

U.S. Fish and Wildlife Service, 1994–2000, National Wetlands Inventory website: U.S. Department of the Interior, Fish and Wildlife Service, *http://www.fws.gov/wetlands/.*

U.S. Fish and Wildlife Service, 2000, Biological opinion on the operation of the Missouri River main stem reservoir system, operation and maintenance of the Missouri River bank stabilization and navigation project, and operation of the Kansas River reservoir system: U.S. Fish and Wildlife Service, 308 p.

U.S. Geological Survey, 2009, National elevation dataset: U.S. Geological Survey, available online at: URL *http://gisdata.usgs.net/ned.*

Welker, T.L., and Drobish, M.R., 2009, Missouri River standard operating procedures for fish sampling and data collection, volume 1.4: U.S. Army Corps of Engineers, Omaha District, Yankton, SD, 209 p.

Wilkinson, L., Engelman, L., Corter, J., and Coward, M., 2004, Cluster analysis: Statistics I: Richmond, California, Systat Inc., 57–91 p.

Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: US Geological Survey Professional Paper 1286, 83 p.

Prepared by:
Rolla Publishing Service Center

For more information concerning this publication, contact:
Director, U.S. Geological Survey
Columbia Environmental Research Center
4200 New Haven Road
Columbia, MO 65201
(573) 875–5399

Or visit the Columbia Environmental Research Center website at:
http://www.cerc.usgs.gov

USGS

R.B. Jacobson and others—**Development of a Channel Classification to Evaluate Potential for Cottonwood Restoration**—Scientific Investigations Report 2010–5208