Geomorphic Change on the Missouri River During the Flood of 2011

Chapter I of
2011 Floods of the Central United States

Professional Paper 1798–I

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

Front cover. Top photograph: View of flooding from Nebraska City, Nebraska, looking east across the Missouri River, August 2, 2011. Photograph by Robert Swanson, U.S. Geological Survey (USGS).
Lower right photograph: View of damaged home properties and an extensive sand splay upstream from Bismark-Mandan, North Dakota. Photograph by Joel Galloway, USGS.

Back cover. Flood debris and related bank erosion downstream from Bismark-Mandan, North Dakota. Photograph by Edward Schenk, USGS.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Contents

Flooding of agricultural fields, roads, and properties. Photograph by Joel Galloway, U.S. Geological Survey.

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	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	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

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

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

Acknowledgments

Collaborative assistance on the Garrison Reach is being provided by Dr. Larry Strong at the U.S. Geological Survey (USGS) Northern Prairie Wildlife Research Center (satellite imagery and sandbar data).

External assistance includes collaboration with Dr. Mark Dixon and Victoria Albers at the University of South Dakota (forest and vegetation distribution data). Funding for research on the Garrison Reach is provided by the U.S. Army Corps of Engineers, the North Dakota State Water Commission, the North Dakota Department of Transportation, the North Dakota Game and Fish Department, the North Dakota Department of Health, the City of Bismarck, the City of Mandan, the Burleigh County Water Resources Board (WRB), the Morton County WRB, and the Lower Heart WRB.

A U.S. Geological Survey (USGS) employee near extensive bank erosion caused by the flood of 2011 at the confluence of the Missouri and Knife Rivers. Photograph by Edward Schenk, USGS.

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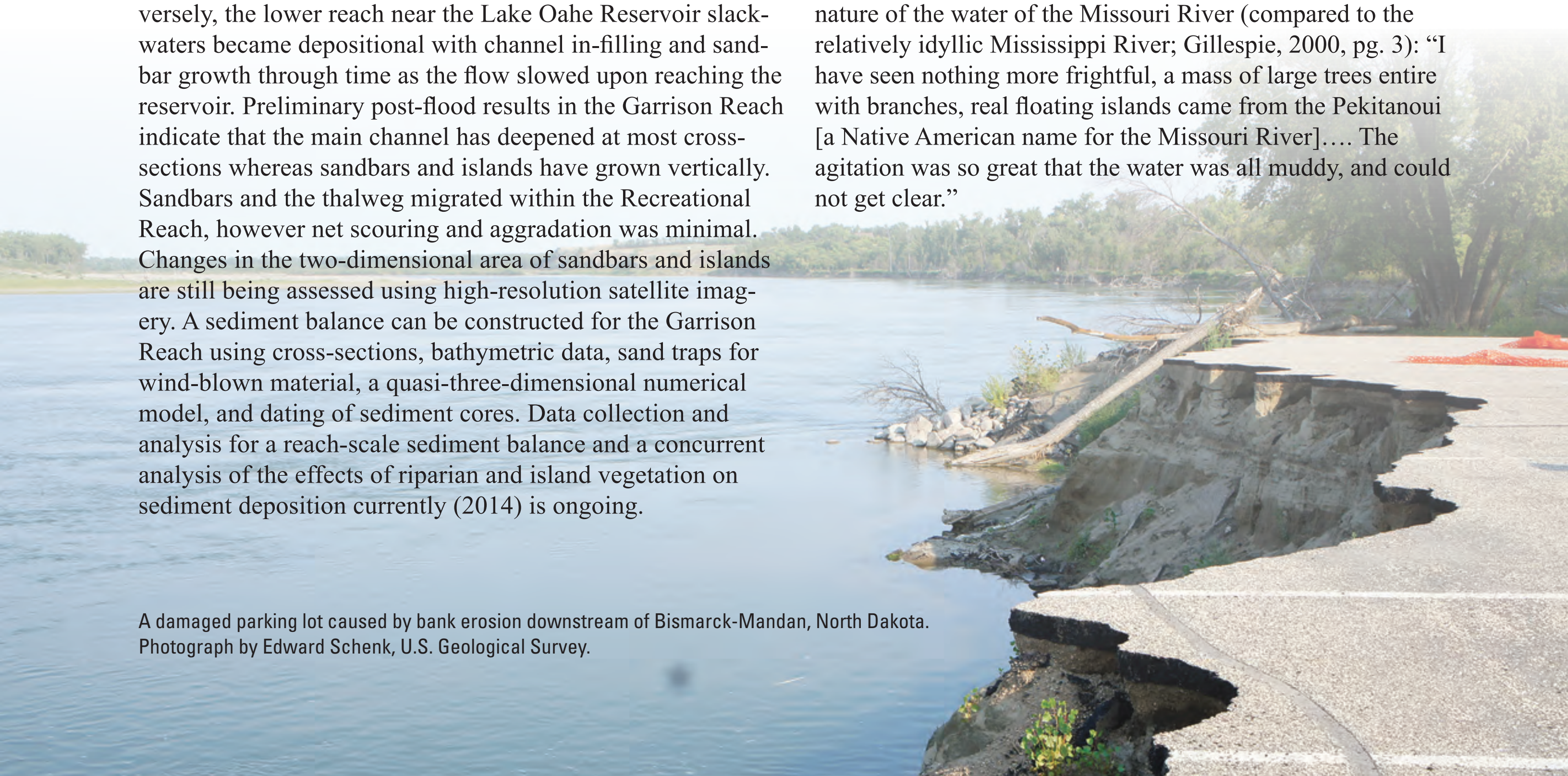
Abstract

The 2011 flood on the Missouri River was one of the largest floods since the river became regulated by a series of high dams in the mid-20th century (greater than 150,000 cubic feet per second during the peak). The flood persisted through most of the summer, eroding river banks, adding sand to sandbars, and moving the thalweg of the channel in many places. The U.S. Geological Survey monitored and assessed the changes in two reaches of the Missouri River: the Garrison Reach in North Dakota, bounded by the Garrison Dam and the Lake Oahe Reservoir, and the Recreational Reach along the boundary of South Dakota and Nebraska bounded upstream by the Gavins Point Dam and extending downstream from Ponca, Nebraska. Historical cross-section data from the Garrison Dam closure until immediately before the flood indicate that the upper reaches of the river near the dam experienced rapid erosion, channel incision, and island/sandbar loss following the dam closure. The erosion, incision, and land loss lessened with time. Conversely, the lower reach near the Lake Oahe Reservoir slackwaters became depositional with channel in-filling and sandbar growth through time as the flow slowed upon reaching the reservoir. Preliminary post-flood results in the Garrison Reach indicate that the main channel has deepened at most cross-sections whereas sandbars and islands have grown vertically. Sandbars and the thalweg migrated within the Recreational Reach, however net scouring and aggradation was minimal. Changes in the two-dimensional area of sandbars and islands are still being assessed using high-resolution satellite imagery. A sediment balance can be constructed for the Garrison Reach using cross-sections, bathymetric data, sand traps for wind-blown material, a quasi-three-dimensional numerical model, and dating of sediment cores. Data collection and analysis for a reach-scale sediment balance and a concurrent analysis of the effects of riparian and island vegetation on sediment deposition currently (2014) is ongoing.

Introduction

The flood of 2011 on the Missouri River was one of the largest floods since the river became regulated by a series of high dams in the mid-20th century. The flood began in the spring and continued well into the summer because of the melt of a large snow accumulation during the winter and a large rain event in the headwaters (Vining and others, 2013). This chapter is a part of a larger series of U.S. Geological Survey (USGS) reports documenting the effects of widespread flooding in 2011 throughout the Mississippi River watershed including the Missouri River. The purpose of this chapter is to describe, in detail, geomorphic studies on two reaches of the Missouri River during and following the flood.

The Missouri River is the longest river in the United States, with a length of more than 2,500 miles (Kammerer, 1990) and drains nearly one-sixth of the continental United States (Elliot and Jacobson, 2006). Father Jacques Marquette recorded the earliest European observations of the river in 1673 when he described the ferocity and sediment laden nature of the water of the Missouri River (compared to the relatively idyllic Mississippi River; Gillespie, 2000, pg. 3): “I have seen nothing more frightful, a mass of large trees entire with branches, real floating islands came from the Pekitanoui [a Native American name for the Missouri River]…. The agitation was so great that the water was all muddy, and could not get clear.”



A damaged parking lot caused by bank erosion downstream of Bismarck-Mandan, North Dakota. Photograph by Edward Schenk, U.S. Geological Survey.

The river quickly gained the nickname “The Big Muddy.” It was hazardous to navigate with frequently shifting sandbars and a high concentration of log jams and submerged snags (fig. 1). Despite these hazards, the river was a vital transportation route first used by the Lewis and Clark expedition to access the Northwest Territories and, for a short time, to transport by river paddleboat freight and passenger transport as far upstream as Fort Benton, Montana (Gillespie, 2000). As stated by “Steamboat Bill” Heckmann, “We separated the men from the boys at the mouth of the Missouri. The boys went up the Mississippi and the men went up the Big Muddy [Gillespie, 2000, back cover].”

Freight and passenger traffic on the upper reaches of the river slowed with the rise of the railroad and eventually ended with the damming of the river (Gillespie, 2000). The unpredictable nature of the river, in terms of flow, sandbar locations, and snags, mostly was tamed in the mid-20th century with the creation of a series of large dams to provide water for the Great Plains states, improve navigation, and provide flood control (table 1).

The series of large dams sustain high low flows during droughts by releasing a consistent discharge and reduce the severity of flood peak flows by retaining floodwaters. Despite their function for flood protection, among other uses, dam releases during excessively wet periods must exceed routine discharge because the reservoir behind the dam will reach full capacity. Heavy rainstorms and abnormally large snow pack in the spring of 2011 led to releases that produced the largest flood of the dam-regulated era on the upper Missouri River (Holmes and others, 2013; Vining and others, 2013). The discharge below the Garrison Dam in North Dakota exceeded 155,000 cubic feet per second (ft^3/s) for more than 2 weeks with high discharges continuing through the summer (Galloway and others, 2013). The flow through the Garrison Reach did not recede to normal levels until September and October, nearly 6 months after the rainstorms in the headwaters. For comparison, the next largest flood (1975) was approximately one-half the discharge of the flood of 2011.

Figure 1. The historical (1832) Missouri River channel including large wood snags, bank erosion, and vegetated islands and banks. “View on the Missouri, Alluvial Banks Falling in, 600 Miles above St. Louis” (George Catlin, 1832, oil on canvas, Smithsonian American Art Museum 1985.66.363.)

Table 1. List of dams on the Missouri River from upstream to downstream.

[N/A; not applicable]

Dam name	Reservoir name	Year completed	Dam length (feet)	Hydraulic height (feet)	Max storage (acre-feet)	Normal storage (acre-feet)	State
Toston		1940	705	47	6,460	4,100	Montana
Canyon Ferry	Canyon Ferry Lake	1953	1,000	165	2,051,000	1,947,000	Montana
Hauser	Hauser Lake	1911	732	120	139,890	64,253	Montana
Holter	Holter Lake	1918	1,364	120	306,000	245,000	Montana
Black Eagle	Long Pool	1891	1,670	36	0	1,710	Montana
Rainbow	N/A	1910	1,405	42	1,237	1,237	Montana
Cochrane	N/A	1957	856	100	0	8,464	Montana
Ryan	N/A	1915	1,465	76	3,613	3,653	Montana
Morony	N/A	1929	842	93	13,889	13,598	Montana
Fort Peck	Fort Peck Lake	1940	21,026	220	19,100,000	15,400,000	Montana
Garrison	Lake Sakakawea	1953	11,300	180	24,500,000	18,500,000	North Dakota
Oahe	Lake Oahe	1966	9,300	200	23,600,000	19,300,000	South Dakota
Big Bend	Lake Sharpe	1963	10,570	78	1,900,000	1,725,000	South Dakota
Fort Randall	Lake Francis Case	1954	10,700	160	6,300,000	3,800,000	South Dakota
Gavins Point	Lewis and Clark	1958	8,700	50	540,000	375,000	South Dakota/Nebraska

Flood debris, mostly large woody debris, at the entrance of a flood plain sand splay approximately 10 river miles downstream from Bismarck-Mandan, North Dakota. Photograph by Edward Schenk, U.S. Geological Survey.

Purpose and Scope

The purpose of this report is to detail preliminary USGS efforts to document geomorphological effects of the 2011 flood on the channel and flood plain of the Missouri River. Understanding channel change, including islands and sandbars within the channel, is important for habitat, navigation, recreation, and property protection and enhancement. Flood plain dynamics also are important for habitat and for providing a sediment source and sink for channel processes. The report presents methods, data, and results from two reaches of the Missouri River, the Garrison Reach in North Dakota and the Recreational Reach along the borders of South Dakota and Nebraska. Readers of this report can use the material to determine appropriate methods for determining channel and flood plain change along large rivers following other floods or to determine what data gaps exist in current USGS flood assessment studies.

The goals of the USGS geomorphic efforts following the flood include determining modifications of channel and flood plain geometry (changes in channel cross-sectional area, depth, and width), sediment dynamics in the channel and on the flood plain, trends in channel erosion and deposition, and the spatial extent and quality of wildlife habitat.

The purpose and scope of the studies, to meet these goals, are as follows:

Garrison Reach, North Dakota

- Historical geomorphic analysis—Determine trajectory of channel change following the completion of the Garrison Dam and subsequent dam operation to provide a baseline for flood studies.
- Flood geomorphic analysis—Determine flood effects on islands, sandbars, and channel banks and compare to results for objective 1.
- Sediment balance—Determine the sources, sinks, and loads of sediment throughout the reach. This objective includes data from the historical and flood geomorphic analyses.
- Vegetation analysis—Determine flood effects on in-channel and flood plain large woody debris and standing trees for island maintenance, sediment balance, fisheries, and navigation interests.

Recreational Reach, Nebraska

- Flood geomorphic analysis—Determine flood effects on islands and sandbars within the Missouri River National Recreational River reach.

Study Sites

The Missouri River is a predominately sandbed river that rises in the western part of Montana and Wyoming and southern sections of the Canadian Provinces of Saskatchewan and Alberta. The river meanders through a wide alluvial valley, at times coming into contact with Tertiary sandstone and glacial deposits along the bluffs and slopes adjacent to the valley bottom (Kume and Hanson, 1965). The course of the river is controlled largely in the upper reaches by the late-Wisconsinan glacial margin (Kume and Hanson, 1965) and maintains a meandering channel characterized by extensive mid-channel and lateral sandbars that also may grade into islands when stabilized by vegetation (Angradi and others, 2004).

The Missouri River has been altered substantially by a number of main-stem dams in the upper and middle reaches, and by channelization and bank stabilization downstream from Sioux City, Iowa (Elliott and others, 2009). The Missouri River Basin contains the Nation's largest reservoir system with more than 73 million acre-feet [91 cubic kilometers (km^3)] of storage for irrigation, urban use, and flood abatement (Galat and others, 2005; Jacobson and others, 2009). Both study reaches for the flood of 2011 are affected by dam regulation and are relatively unchannelized compared to the downstream Missouri River (fig. 2).

Garrison Reach, North Dakota

The Garrison Reach of the Missouri River is a free-flowing section of the river bounded upstream by the Garrison Dam (river mile 1,390) and downstream by the Lake Oahe Reservoir. There are two primary tributaries to the reach: the Knife River that enters the river near Stanton, North Dakota, and the Heart River that joins the river immediately downstream from Mandan, N. Dak. The reach is approximately 80 river miles long with 20 miles of variability in the downstream extent because of changing reservoir levels at Lake Oahe. At low reservoir levels, the free flowing reach of river can exceed 100 miles, whereas at high levels the river may end near Bismarck-Mandan (approximately river mile 1,315). The Bismarck-Mandan metropolitan area is the only sizeable urban area along the reach (fig. 2).

The hydrologic regime of the reach is controlled largely by the Garrison Dam. Mean monthly discharge is approximately 22,000 ft^3/s at the USGS streamgage in Bismarck, N. Dak. (USGS streamgage 06342500). Discharge data for streamgages on the Missouri River are available from the USGS National Water Information System, *http://waterdata.usgs.gov/nwis*. Flow inputs by the Knife and Heart Rivers tend to peak in the spring with snow melt, occasionally exceeding 30,000 ft^3/s, but can decrease to nearly no flow during the late summer and fall. The mean discharges are 516 and 269 ft^3/s for the Knife and Heart Rivers respectively (USGS streamgage

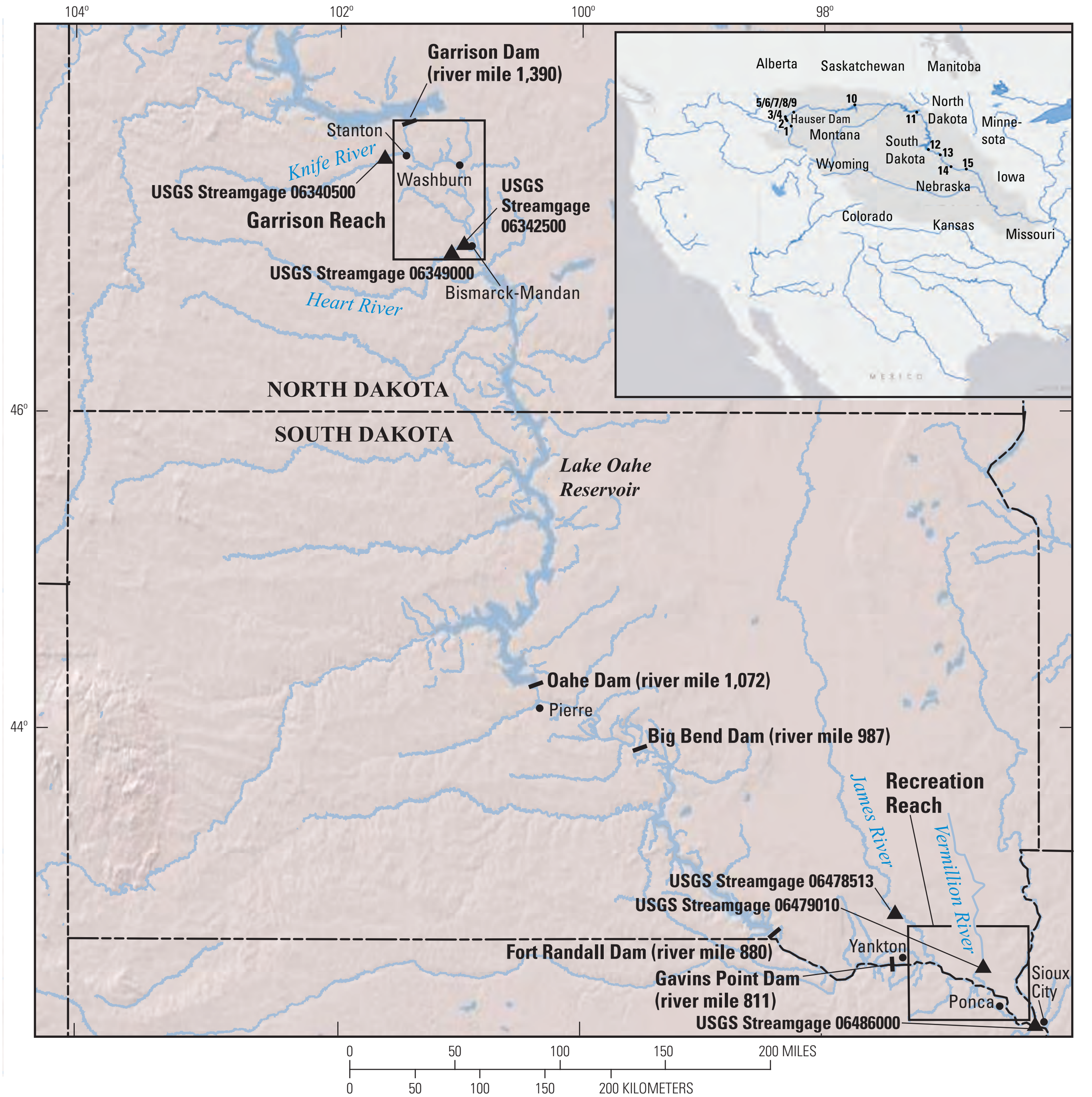


Figure 2. The Garrison Reach and Recreational Reach study sites along the Missouri River. River miles are provided and dam locations (from table 1) are shown on the inset map. U.S. Geological Survey (USGS) streamgages are presented with their unique identifier. The list of dams includes: 1) Toston, 2) Canyon Ferry, 3) Hauser, 4) Holter, 5) Black Eagle, 6) Rainbow, 7) Cochrane, 8) Ryan, 9) Morony, 10) Fort Peck, 11) Garrison, 12) Oahe, 13) Big Bend, 14) Fort Randall, and 15) Gavins Point.

06340500 and 06349000 for information on the Knife and Heart Rivers, respectively). The largest flood on the Garrison Reach during dam regulation, before 2011, was the 1975 flood, which nearly reached 68,900 ft^3/s, whereas the flood in 2011 was approximately 155,000 ft^3/s at Bismarck, N. Dak. (USGS streamgage 06342500, fig. 3). Details on the cause of the flood of 2011 and flood discharges have already been discussed in the "Introduction" section as well as in related USGS reports (Galloway and others, 2013; Holmes and others, 2013; Vining and others, 2013).

The 2011 flood was a long-duration, dam-attenuated runoff flood; however, short-duration, ice-jam floods are common on the upper Missouri River. Localized flooding is a concern throughout the reach because of ice jams in the early spring. Although ice jamming was not a factor in the flood of 2011, it is still a substantial component of the geomorphic, hydrologic, and perhaps biological aspects of the Garrison Reach. Predicting channel change following the flood will require a greater understanding of the effects of ice jams in the reach. Ice jams can cause considerable channel scouring, avulsion, remove vegetation in the riparian zone, and affect the morphology of sandbars upstream from the jam, within the jam, and downstream from the jam when it breaks up and releases a pulse of water (Ettema and Daly, 2004). This topic has received comparatively little study, but is currently being explored in the Garrison Reach to determine future flood risks following the 2011 flood event.

Recreational Reach, Nebraska

The Recreational Reach of the Missouri River is a 59-mile free-flowing section that is bounded upstream by the Gavins Point Dam (river mile 811) and downstream by Ponca, Nebraska (river mile 752). The name of the river reach is derived from the Missouri National Recreational River, a national park unit that encompasses most of the reach. Unlike the Garrison Reach, which follows the maximal extent of the Wisconsin glaciation, the Recreational Reach of the river does not coincide with a glacial limit and likely evolved through the modification of a subglacial drainage system (Waite Osterkamp, U.S. Geological Survey, written commun., 2013). This section of the Missouri River is the most downstream reach that lacks substantial contemporary modifications and channelization. The hydrologic regime primarily is controlled by releases from the Gavins Point Dam. Mean discharge is approximately 30,000 ft^3/s at the USGS streamgage at Sioux City, Iowa (USGS streamgage 06486000). Major tributaries to the Recreational Reach include the James and Vermillion Rivers. The James River, which has a total drainage area of 21,116 square miles, enters the Missouri River near Yankton, South Dakota. The Vermillion River, which has a total drainage area of about 2,300 square miles, enters the Missouri River near river mile 772. The mean discharges are 1,650 ft^3/s and 400 ft^3/s for the James and Vermillion Rivers, respectively (USGS streamgage 06478513 and 06479010 for information

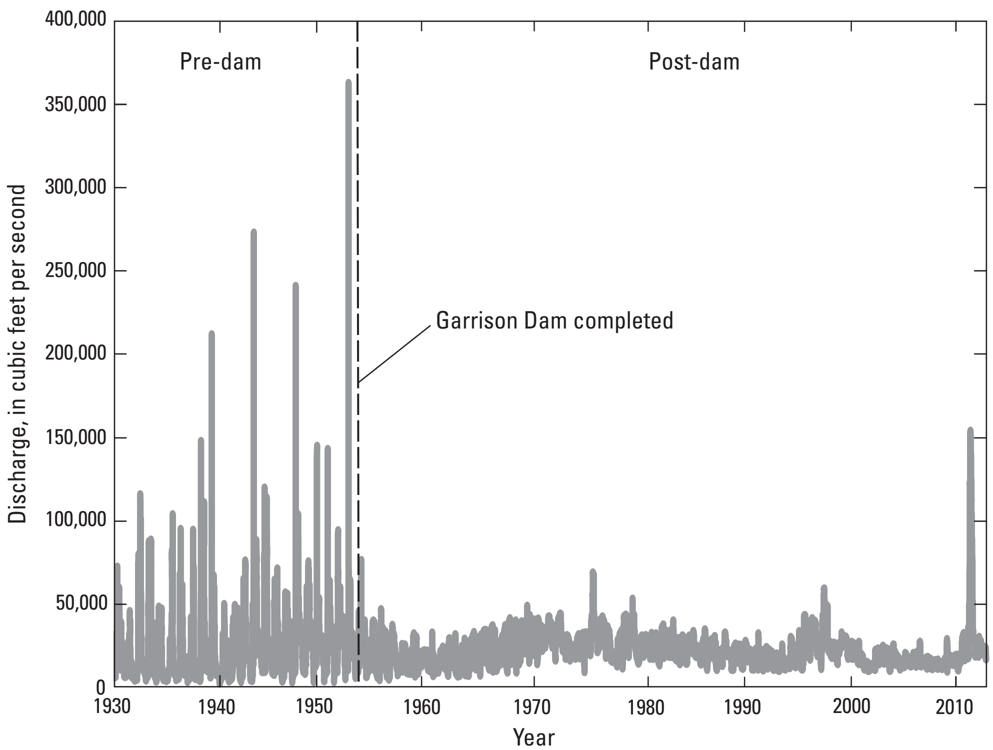


Figure 3. Hydrograph for U.S. Geological Survey streamgage 06342500 at Bismarck, North Dakota demonstrating the change in flood flows following the completion of the Garrison Dam.

on the James and Vermillion Rivers respectively). The largest flood on the Recreational Reach during dam regulation, before 2011, was the 1984 flood, which reached 104,000 ft^3/s, whereas the flood in 2011 was approximately 192,000 ft^3/s (as measured at Gavin's Point Dam). A large flood also was recorded in 1952 of indeterminate size because of ice-jamming that may have caused more channel and flood plain change than the 1984 flood (Waite Osterkamp, U.S. Geological Survey, written commun., 2013).

Study Methodology and Results

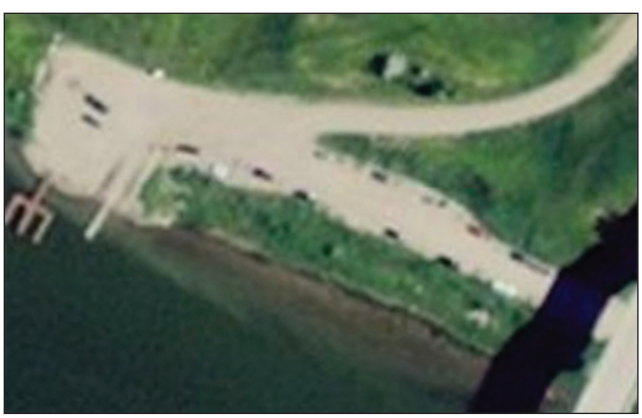
The two studies have been broken down into the components described in the "Purpose and Scope" section, which include the historical geomorphic analysis of the trajectory of channel change following dam closure (Garrison only), the geomorphic assessment of the flood of 2011 (both the Garrison and Recreational Reach), the sediment balance for the reach (Garrison Reach only), and the effect of vegetation on flow and sedimentation (Garrison Reach only). The purpose of the historical geomorphic assessment is to understand how the river had been adjusting to dam regulation before the flood of 2011, thus providing baseline information for understanding the changes associated with the flood (Skalak and others, 2013). The four sections in this report following the "Historical Geomorphology—Patterns and Processes of the Missouri River Before the Flood of 2011" section are related to studies of the effects of the flood on the channel, prominent landform features in the channel (islands and sandbars), and the interaction of sediment and vegetation with hydrology.

Historical Geomorphology—Patterns and Processes of the Missouri River Before the Flood of 2011

Quantifying historical channel patterns and processes is important for understanding the magnitude of effects caused by the flood of 2011. Trends in channel, island, and sandbar dynamics also affect endangered species habitat along the Missouri River including the Least Tern (*Sternula antillarum*), Piping Plover (*Charadrius melodus*), and Pallid Sturgeon (*Scaphirhynchus albus*). Landform trends also are important for evaluating the long-term (decadal to centennial scale) sediment balance of the river which, in turn, is important for understanding channel scour and fill, flood risk, fishery habitat, and water quality. Islands are defined by perennial vegetation (trees, shrubs, perennial grasses) whereas sandbars lack persistent vegetation.

Trends in island and sandbar dynamics were determined by analyzing repeat aerial photography collected between 1950 and 2002 along the Garrison Reach. High-resolution satellite imagery obtained with GeoEye™, RapidEye™, and Quickbird™ platforms was used for the period 2002 to 2012 because of the high quality of this imagery (fig. 4). The satellite imagery is being provided by a partnership with the USGS Northern Prairie Wildlife Research Center in Jamestown, N. Dak. (Larry Strong, U.S. Geological Survey, unpub. data, 2012).

Islands and sandbars in the upper section of the Garrison Reach (fig. 5) have degraded since dam closure, likely due to the lack of upstream sediment source, and through incision and the development of a single-threaded channel that



Standard aerial imagery

GeoEye™ imagery from 2012

Figure 4. Comparison of traditional aerial photography and high-resolution satellite imagery provided by the U.S. Geological Survey Northern Prairie Wildlife Research Center and produced by the GeoEye™ satellite platform.

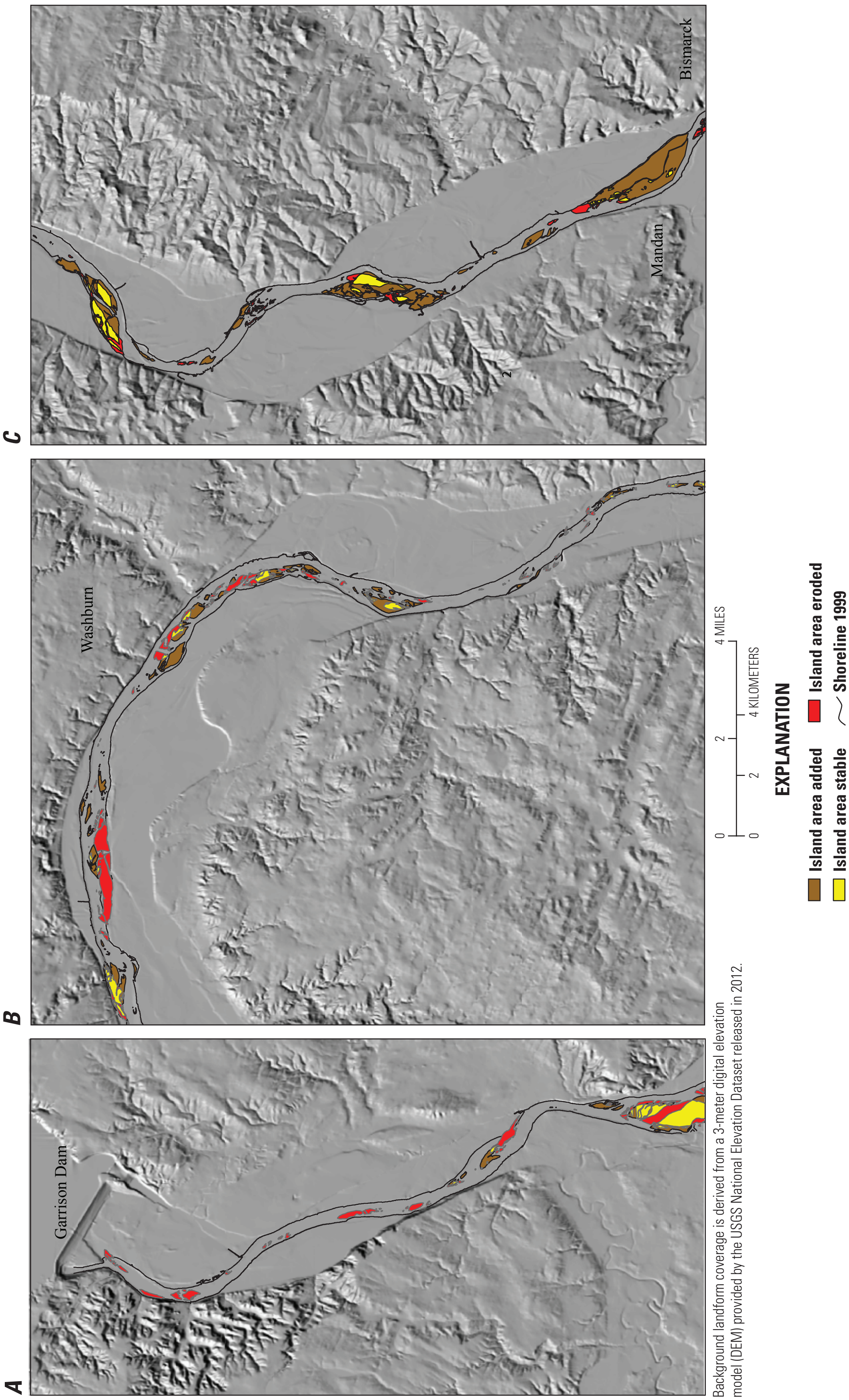


Figure 5. Island delineations from 1950 to 1999 on the Garrison Reach divided into *A*, an upper zone; *B*, a middle zone; and *C*, a lower zone. Island delineations were normalized by river stage to ensure that photography was comparable between dates.

typically develops downstream from dams (Williams and Wolman, 1984; Grant and others, 2003; Skalak and others, 2013). The sediment-free water leaving the Garrison Dam apparently has scoured the pre-existing islands and sandbars along the upper segment nearest the dam. The middle segment of the Garrison Reach is meta-stable with little observable change in the areal extent of islands or sandbars. The lower segment of the river, near Bismarck-Mandan, has an increase in sandbar area—a change likely due to decreased velocity as flow enters the backwater from Lake Oahe. The channel transition from eroding downstream from a dam to aggrading as the river approaches a downstream reservoir is common on most large rivers where dams and reservoirs are ubiquitous (Skalak and others, 2013).

Further information about recent sandbar dynamics on the Garrison Reach is available through the USGS Northern Prairie Wildlife Research Center (*http://www.npwrc.usgs.gov/*).

Most of the historical geomorphic analysis on the Garrison Reach used repeat cross-sectional surveys contracted by the U.S. Army Corps of Engineers between 1954 and 2007 (U.S. Army Corps of Engineers, 2000). Sixteen of the cross-sections were re-surveyed in the summer of 2012 to determine channel change following the flood. Surveys used a Real Time Kinetic (RTK) Global Positioning System (GPS) unit for precision surveying over land surfaces (fig. 6). The aqueous (underwater) part of the cross-section was surveyed using an Acoustic Doppler Current Profiler (ADCP).

Classification of the geomorphological characteristics using aerial photography indicate that the channel morphology of about 5 percent of the 59-mile reach of the Recreational Reach downstream from Gavins Point Dam is controlled by bedrock and about 32 percent is controlled by bank stabilization structures (Elliott and Jacobson, 2006). Repeat cross-sectional surveys administered by the U.S. Army Corps of Engineers for the Recreational Reach between 1965 and 2002 indicate a widening and deepening of the channel near Gavin's Point Dam with channel aggradation of more than 3 feet beginning approximately 100 miles downstream from the dam (Waite Osterkamp, U.S. Geological Survey, written commun., 2013; Elliott and Jacobson, 2006). The evacuation of bed and bank sediment near the dam has led to the exposure of logs and woody debris that had been buried by a mix of fluvial and wind (aeolian) processes. Channel narrowing and decreases in sandbar size have occurred along the Recreational Reach since dam closure (Elliott and Jacobson, 2006). Estimates of bank erosion along the reach suggest that erosion rates decreased from 1975 until high flows of 1995–97 contributed to increased bank-erosion rates on the Recreational Reach (Elliott and Jacobson, 2006).

The thalweg, the deepest part of the channel, between the 1950s and 2007 was identified in the Garrison Reach to determine changes in channel incision and fill. The result of the repeat cross-sectional surveys (fig. 7) indicate that channel adjustment to the new hydrologic regime occurred during the few decades following the Garrison Dam completion in 1953. The upstream segment of the Garrison Reach adjusted to dam closure faster than the downstream segment—a typical pattern below dams (fig. 7). Channel disturbance because of upstream dams has been determined to attenuate downstream in time and intensity (Williams and Wolman, 1984; Schmidt and Wilcock, 2008; Hupp and others, 2009). Note also the effect of the 1975 flood (68,900 ft^3/s in Bismarck, N. Dak.) on rates of adjustment in the downstream segment—an effect that persisted for several years.

The repeat cross-sectional surveys also were used to determine the change in channel cross-sectional area (an indicator of channel conveyance or capacity). Channel cross-sectional area was calculated using the elevation of the highest recorded discharge during the survey period (68,900 ft^3/s, 1975). This elevation was used as a bankfull indicator to calculate the cross-sectional area for each transect at each date surveyed. The results (fig. 8) indicate the trend of scour and fill that was noted using repeat aerial photography. The river has increased channel capacity near the dam where net scour developed in response to the sediment deficit produced by dam closure. As sediment is introduced to the reach through bank erosion and bed degradation the amount of scour decreases until the channel begins to aggrade toward the downstream end of the reach because of the backwater effects of Lake Oahe. This trend is significant for future flood risk assessment near Bismarck-Mandan and is of interest for the flood of 2011 assessment. More information about the historical channel change in the Garrison Reach is available in a related peer-reviewed journal article (Skalak and others, 2013).

Effects of the Flood of 2011 on the Channel, Islands, and Sandbars

The historical geomorphic assessment provides an understanding of how the river has adjusted following dam regulation. With this knowledge, the effects of the flood of 2011 may be put into comparative perspective. The flood was not only the highest discharge since the dam era on the Missouri River but also one of the longest duration floods. The length and peak of the flood entrained, transported, and deposited considerable amounts of sediment, in-channel and on the flood plain.

Changes in island and sandbar areal extent throughout the Garrison Reach following the flood were assessed by repeat high-resolution satellite imagery and before-and-after cross-sectional surveys. The results, compiled by USGS offices in Bismarck, N. Dak., Reston, Virginia, and Jamestown, N. Dak., will help not only with the geomorphic study of the river but also with determining the change in piping plover and least tern habitat.

U.S. Army Corps of Engineers cross-sectional surveys before (2007) and after (2012) the flood indicate that the channel has changed dramatically in some locations (U.S. Army Corps of Engineers, unpub. data, 2012). Areas near the Garrison Dam that had been identified as historically erosional

Figure 6. Cross-sectional survey methods *A*, at a real time kinetic (RTK) Global Positioning System (GPS) base station; *B*, walking a sandbar using an RTK mobile unit; and *C*, collecting bathymetry using an Acoustic Doppler Current Profiler (ADCP). Photographs by Edward Schenk, summer of 2012.

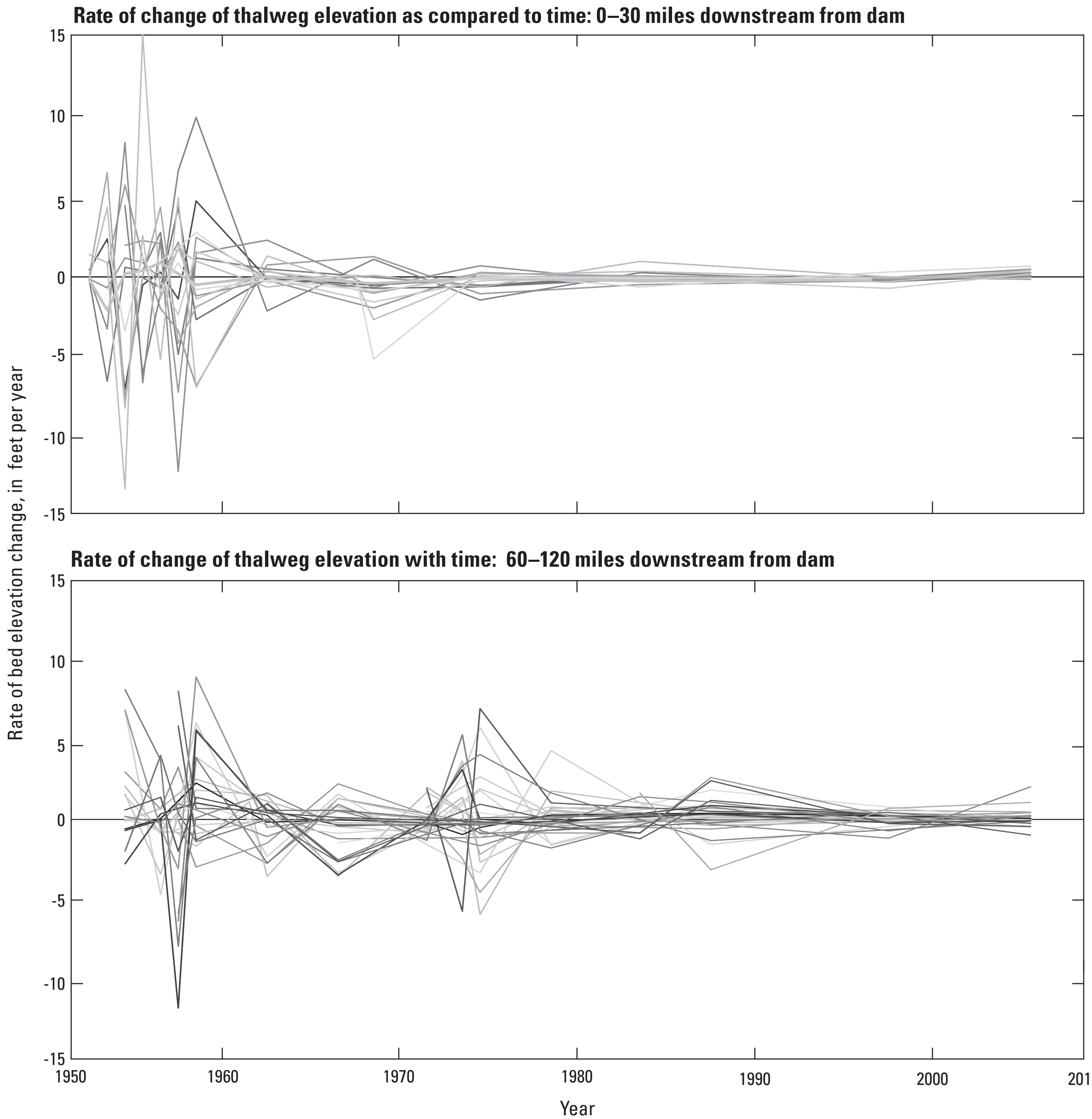


Figure 7. Rates of change in thalweg elevation for individual repeat-survey cross-sections from the time of the Garrison Dam closure until 2009 separated into an upper and lower river segment (0 to 30 miles downstream from the dam and 60 to 120 miles downstream from the dam).

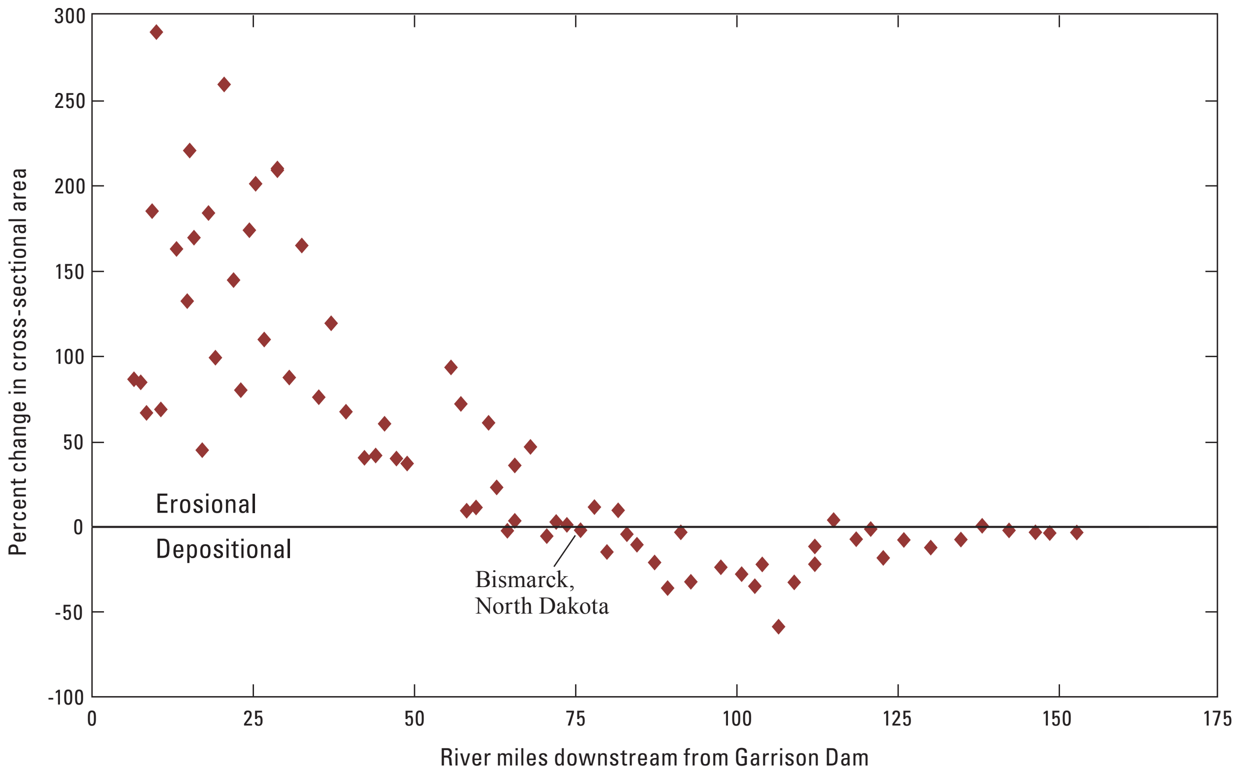


Figure 8. Percent change in cross-sectional area from the 1954 to 2007 repeat cross-sectional surveys compared to distance downstream from the Garrison Dam. The location of Bismarck, North Dakota, is noted for reference as the approximate location of the backwater effects of Lake Oahe.

(fig. 8) were characterized by incision in the main channel (channel containing the thalweg) and considerable local deposition on adjacent horizontal surfaces (including the flood plain, islands, and sandbars). The amount of main channel incision decreased, as indicated by the 2007 and 2012 difference in bed elevation, in the downstream segment of the reach (fig. 9).

Before-and-after flood geomorphic analysis on the Recreational Reach was applied on two 5,000-foot reaches, extending longitudinally along the river channel and approximately centered at river mile 776 and 770, using repeat cross-sectional surveys developed by the USGS Nebraska Water Science Center. The Nebraska Water Science Center surveyed numerous cross-sections in 2010, approximately equally spaced along each 5,000-foot reach, and these same cross-sections were re-occupied in 2011 and 2012 to determine the channel change following the flood. Surveys were developed using the same methods as the Garrison Reach.

On the Recreational Reach, repeat cross-sectional surveys reveal the formation and migration of sandbars and shifts in the thalweg, but no substantial net scour or aggradation across the channel. The elevation of the re-occupied points along the 5,000-foot transect at river mile 776 decreased, on average, by approximately 0.7 feet between August 2010 and November 2011, and the variability of elevations increased between the two surveys. The elevation of the thalweg at river mile 776 did not change substantially from August 2010 to March 2012. Representative repeat cross-sections (similar to the average change seen along each 5,000 foot transect) are provided in figure 10. A large sandbar migrated into the reach at river mile 776 (approximately 600 to 2,000 feet on the horizontal axis; fig. 10*A*). At river mile 770, no net change in elevation of re-occupied points across the channel was observed between August 2010 and November 2011, but the variability of elevations increased (fig. 10*B*). The depth of the thalweg at river mile 770 did not change substantially from August 2010 to March 2012; however, the thalweg shifted across the channel during the flood.

Bathymetric surveys and stage-discharge relations at USGS streamgages during and following the flood support the trends determined in the cross-sectional surveys. Measurements of stage-discharge relations for the streamgage at Bismarck, N. Dak., (USGS streamgage 06342500) indicated channel in-filling on the rising limb of the flood and scour at the peak and falling limb of the flood (fig. 11). Bathymetry near Bismarck-Mandan, collected using multibeam integrated sonar, verified scour with areas of intense erosion near bridge piers and pilings and migrating dune structures in the straight sections of the reach.

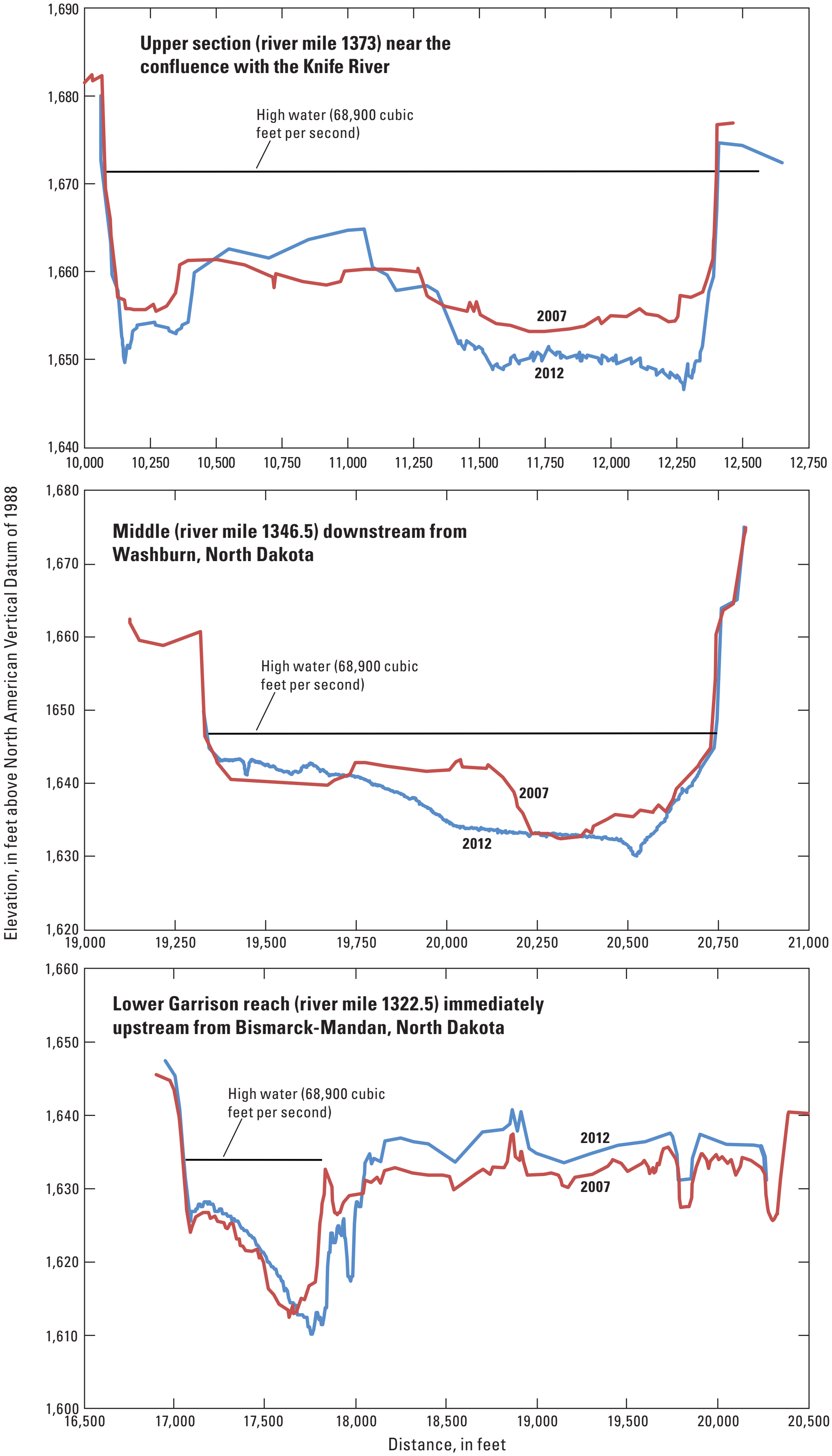


Figure 9. Representative cross-sections from the upper, middle, and lower river segments of the Garrison Reach with pre- and post-flood surveys depicted. The high water stage from the previous flood of record post-dam completion is provided to illustrate the height of water for medium frequency floods (68,900 cubic feet per second). Surveys extend from the edge of the terrace across the active flood plain on one side of the Missouri River to the edge of the terrace on the opposite side of the river. Surveys include the entire flood plain and channel of the Missouri River.

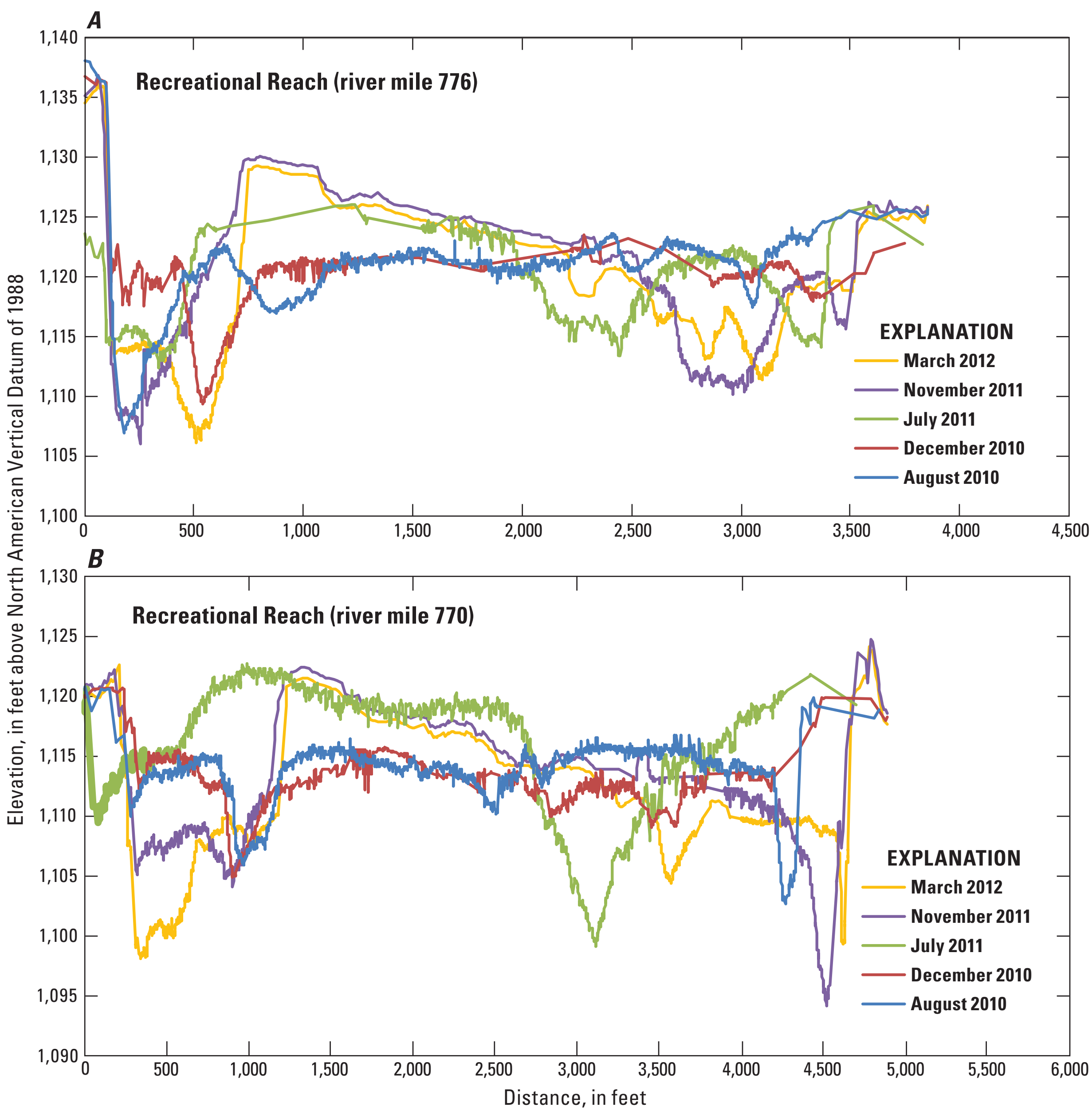


Figure 10. Representative repeat cross-sectional surveys from the two 5,000-foot reaches in the Recreational Reach between August 2010 and March 2012 for *A*, river mile 776 and *B*, river mile 770.

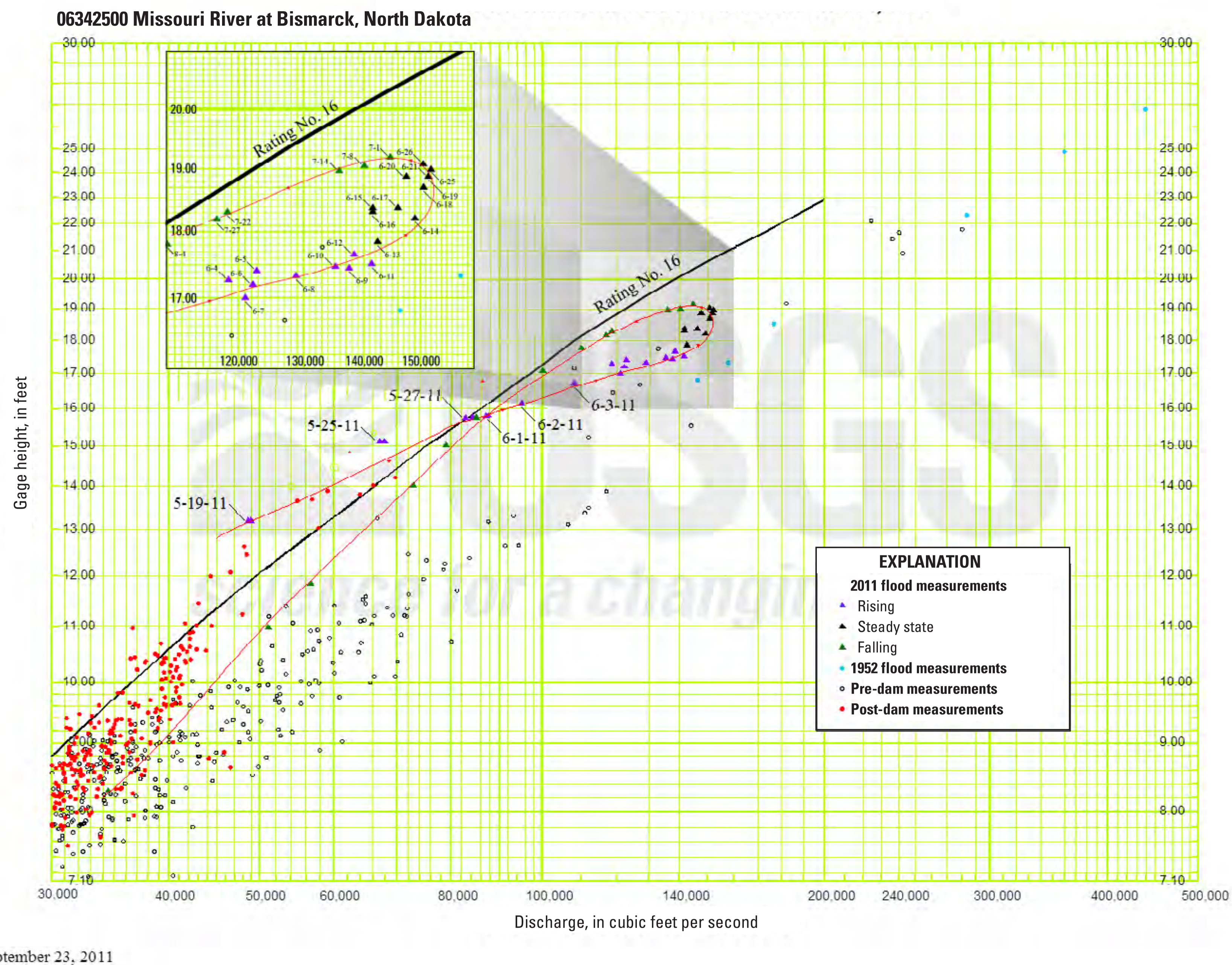


Figure 11. The stage-discharge relation at Bismarck, North Dakota, (USGS streamgage 06342500) before dam regulation, after dam regulation, and during the flood of 2011.

Numerical Modeling Using the Flood of 2011 Data, Bismarck-Mandan Reach

A multidimensional model (a two-dimensional model with vertical structuring, often referred to as a 2.5-dimensional model) is being developed for an 18-mile reach of river in the vicinity of the Bismarck-Mandan metropolitan area. The purpose of the Bismarck-Mandan model is to complement other results from the study and to use the data produced by the bathymetric, hydrological, and sediment efforts to simulate streamflow and channel changes within the 18-mile reach. Model results, in the future, can be extended to other reaches of the river with additional elevation and water profile data.

Currently (2014), the FaSTMECH (Flow and Sediment Transport Morphological Evolution of Channels; McDonald and others, 2005) model is being used to simulate the flow and channel changes near Bismarck-Mandan. The FaSTMECH model is one of several numerical models included in the International River Interface Consortium (iRIC) software package. A public domain software package, iRIC was developed by USGS researchers in Golden, Colorado, in collaboration with the Foundation of Hokkaido River Disaster Prevention Research Center in Japan (*http://i-ric.org/en/index.html*).

The Missouri River multidimensional model is based on a curvilinear orthogonal grid developed in FaSTMECH using bathymetric data collected in the summer of 2011, and light detection and ranging (lidar) data obtained in 2012 and provided by the North Dakota State Water Commission (unpub. data, 2012; fig. 12). The model is calibrated to 10 streamflow conditions (water level and discharge) during the summer of 2011 that range from 80,500 to 151,000 ft^3/s as observed during data cruises developed by the North Dakota State Water Commission (unpublished data). Once model calibration is complete, simulations will be completed at a range of streamflows to predict where the most change (erosion or deposition) should happen within the reach. Future goals for the numerical modeling include refining the scale in the Bismarck-Mandan reach to predict channel changes in detail and extending the model grid into the Lake Oahe delta front to determine rates of infilling and how that may affect the risk of ice jamming (This may be a long-term problem for the Bismarck-Mandan area because channel infilling, as indicated in figure 8, will increase flood stage for an individual flood volume and can also increase channel complexity leading to a greater frequency of ice jams).

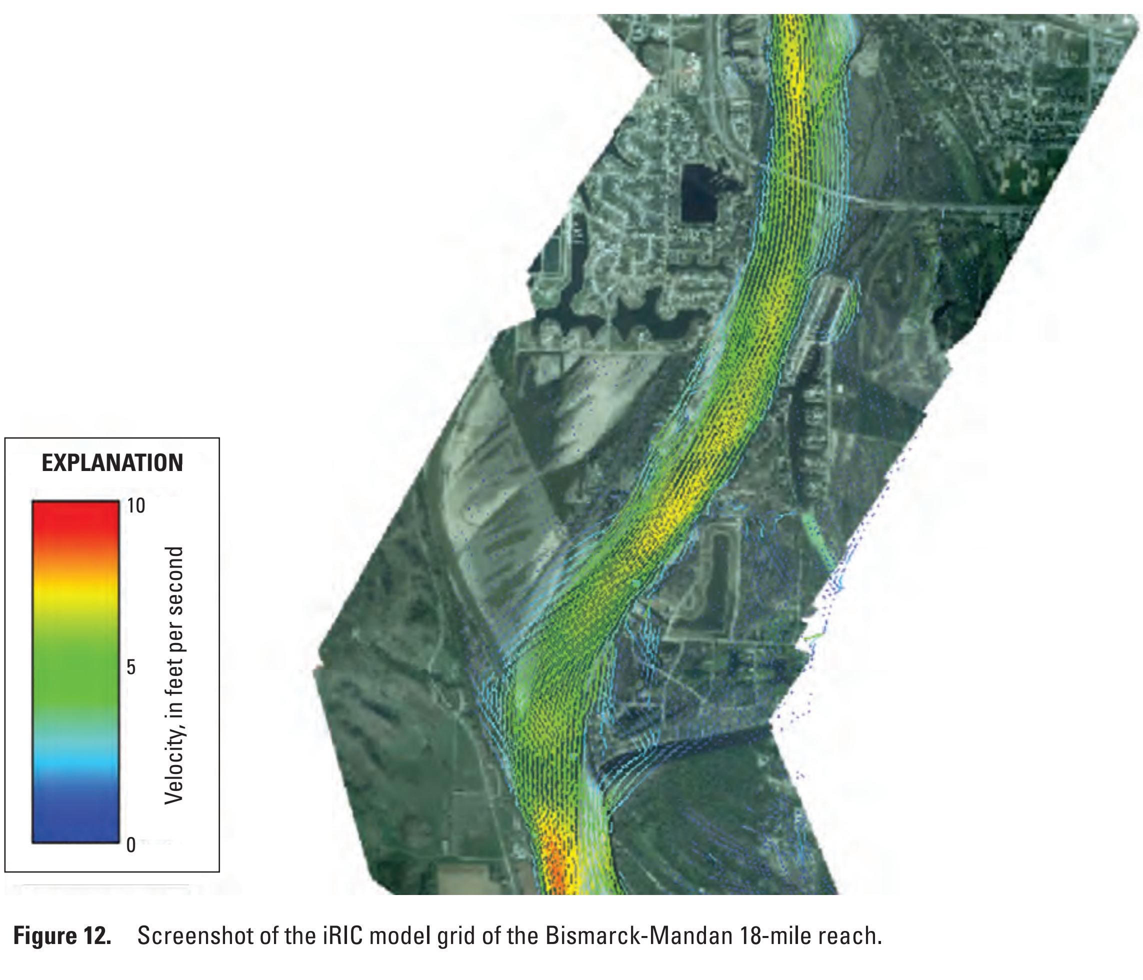


Figure 12. Screenshot of the iRIC model grid of the Bismarck-Mandan 18-mile reach.

Sediment Balance

Determining the source, storage, and fate of sediment is important for understanding and interpreting present channel form as well as the drivers of channel change. The upstream source of sediment has been blocked by dams; thus, sediment must come from the channel banks (erosion), the channel bed (channel incision), pre-existing sandbars and islands, tributary inputs, and aeolian (wind) processes.

Sources of sediment from bank erosion were identified from repeat aerial photography and cross-sectional surveys, from channel incision through cross-sectional surveys and bathymetric information, and from aeolian (wind) processes through sand traps.

Sediment storage was determined through repeat lidar Digital Elevation Models (DEMs) created in 2009 and 2012. A difference model was used to estimate the spatial extent of deposition and erosion on sandbars and islands. Differences in elevation between 2009 and 2012 provided estimates of flood deposition and erosion on flood plain landforms as well (fig. 13). The horizontal pixel resolution for the lidar coverage is approximately 4 feet and the vertical resolution is less than 1 foot.

Riparian deposition also was determined using 323 sediment samples collected between May and October, 2012 at 35 sandbar, island, and flood plain sites in the Garrison Reach. Samples included depth of deposition from the flood of 2011 and were analyzed for sediment size and mineral/organic content at the USGS National Research Program in Reston, Virginia. Sediment size was analyzed using standard sediment sieves and organic content was determined using a standard 16 hour loss on ignition (LOI) burn conducted at 752 degrees Fahrenheit (Nelson and Sommers, 1996). Samples were taken from sediment cores and small trenches depending on the site and the best method for determining pre-flood surfaces. Sediment particle size from before the flood was compared to flood and post-flood samples. Results indicate that the sediment (primarily fine sand) deposited during the flood was finer than the sand surface before the flood (table 2). The finer sand grains deposited by the flood have implication for piping plover and least tern habitat. Both species of birds require coarse sand for habitat, a change to a finer grained substrate indicates a potential loss of habitat (Faanes, 1983; Anteau and others, 2012). Further monitoring is needed to determine if the mean particle size on the flood plain, sandbars, and islands will return to

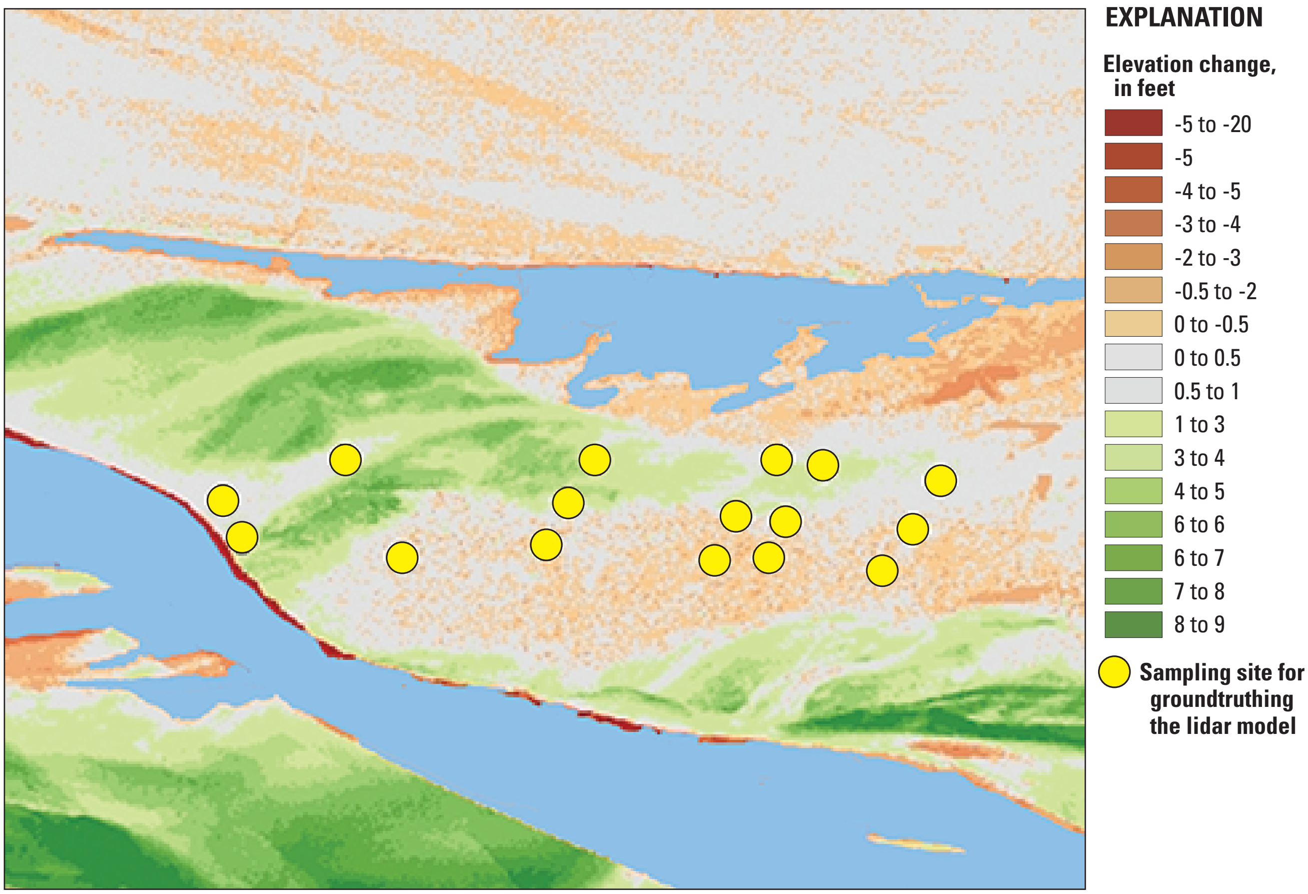


Figure 13. An example of the lidar difference model—the brighter the green, the higher the deposition and the brighter the red, the higher the vertical erosion. Blue indicates open water at normal river stage. The figure is of the left flood plain of the Missouri River downstream from Bismarck-Mandan, North Dakota. The 16 dots on the figure represent sampling points for groundtruthing the light detection and ranging (lidar) model.

Table 2. Sediment particle size pre- and post-flood of 2011 as delineated using flood horizon (debris) in sediment cores or trenches.

[The difference in particle size between dates is statistically significant using a paired two tailed Student's T-test and the assumption that a p-value less than 0.05 is significant. Particle size is presented in inverse phi scale units—the higher the number, the coarser the sediment grains. For more information on inverse phi scale units see Schenk and others (2009). The flood plain landscape designation is largely vegetated by grasses, whereas a forested flood plain designation indicates that it was generally vegetated by dense stands of cottonwood trees.]

River miles	Landscape type	Pre-flood phi index	Post-flood phi index
1,380	High bank	2.7	2.9
1,380	Sandbar	3.0	3.0
1,380	Island	3.4	3.1
1,376	Flood plain	6.5	1.9
1,376	Forested flood plain	2.4	2.6
1,376	Forested flood plain	2.3	1.6
1,376	Forested flood plain	2.4	2.5
1,376	Sandbar flats	2.8	1.0
1,376	Levee	2.3	2.0
1,362	Flood plain	3.5	3.6
1,360	Bank	3.1	2.8
1,360	Bank	3.0	2.6
1,350	Flood plain	2.3	1.8
1,303	Flood plain	3.5	2.2
1,283	Flood plain	2.3	1.8
1,283	Flood plain	2.6	1.9
1,283	Flood plain	3.0	2.5
	Mean	**3.0**	**2.3**
	Median	**2.8**	**2.5**
T-test 0.03		*p*-value (2 tailed, paired)	

pre-flood distributions through winnowing of fine sediment by wind transport.

Long-term sediment storage (multiple floods) is being analyzed using six sediment cores collected on flood plain surfaces downstream from Bismarck-Mandan using a vibracore (fig. 14*A*). Samples were collected from each core at clear stratigraphic breaks (fig. 14*B*) and analyzed for particle size and sediment age using radioisotopes, including Lead-210 (^{210}Pb) and the atomic-bomb isotope Cesium 137 (^{137}Cs). Sediment analysis occurred at USGS National Research Program laboratories in Reston, Virginia. Radioisotope activities were measured by gamma-ray spectroscopy using a broad energy germanium detector (Appleby, 2001). Particle size was determined using standard sediment sieves. Determining the age of previous flood deposits, through sediment dating, will determine the relative magnitude of sedimentation from the flood of 2011 compared to past events.

Sediment transport was measured using suspended sediment and bedload samplers before, during, and after the flood (Galloway and others, 2013) and by sand traps measuring overland aeolian transport (Leatherman, 1978). An individual sand trap consists of a polyvinyl chloride (PVC) pipe 3.9 inches in diameter (the design was in metric: 10 cm diameter) with a 2 inch wide horizontal slot that allows blowing sand to enter the interior. The opposite face of the pipe has a slot for venting air but is screened with a fine mesh (63 microns) to prevent sediment from escaping the pipe. A smaller PVC pipe is fitted inside the large pipe and is used to collect the sediment (fig. 15). Sediment is removed every 2 weeks and is dried and weighed. Four collectors are placed at each site with the primary collector positioned to collect sediment from the dominant wind direction (northwest) and the other three collectors positioned to collect sediment from the northeast, southeast, and southwest. Four steel pins are placed nearby to measure dune deflation or growth (fig. 15). Each study area consists of three sites (12 sand collectors and pins per study area): a site in a nonvegetated zone, another in a partially vegetated zone, and another in a heavily vegetated zone. This design is used to determine the effect of vegetation on wind transport of sediment.

Results from the first year of the study (2012) indicate that there is substantial transport of sand by aeolian processes. Almost all of the transport occurs in the nonvegetated regions of sandbars and islands. Dune stability, measured by the steel pins, is highest in the vegetated area and the most variable in the non-vegetated areas (fig. 16*A*). Similar observations of high aeolian rates of sand deposition have been made in the Recreational Reach despite the lack of monitoring using sand traps. Stratigraphic analysis of deposition patterns on islands within the Recreational Reach has indicated deposition of more than 6 feet of aeolian sediment since dam regulation (Waite Osterkamp, U.S. Geological Survey, written commun., 2013).

Vegetation Analysis

The interaction between vegetation, hydrology, and geomorphology is complex but important for understanding causes and effects of channel and flood plain change on the Missouri River. The Missouri River riparian zone has a legacy of large well-developed cottonwood forests (Johnson and others, 1976). The trees provide resistance to flow during floods, bank anchoring, and increase the channel complexity when they fall into the channel. Early explorers and boat captains on the Missouri River often noted the dangers of snags in the channel and observed the eddies and currents that could develop around large log jams or sandbars created by one or several large snags (Gillespie, 2000).

The purpose of studying vegetation on the Missouri River is to determine how the vegetation has changed following the flood and how vegetation during the flood created sedimentation and scour patterns on the flood plain, islands, and sandbars (fig. 17).

Figure 14. *A*, a vibracore unit taking a sample near the Lake Oahe delta (photograph by Katherine Skalak, August 2012); and *B*, an example of a vibracore sample with the pre-flood sediment on the right-hand side of the picture and flood sediment (sand) on the left-hand side. The break between pre-flood and flood sediment is marked by the yellow tag with a red dot (1.07 meters on the tape).

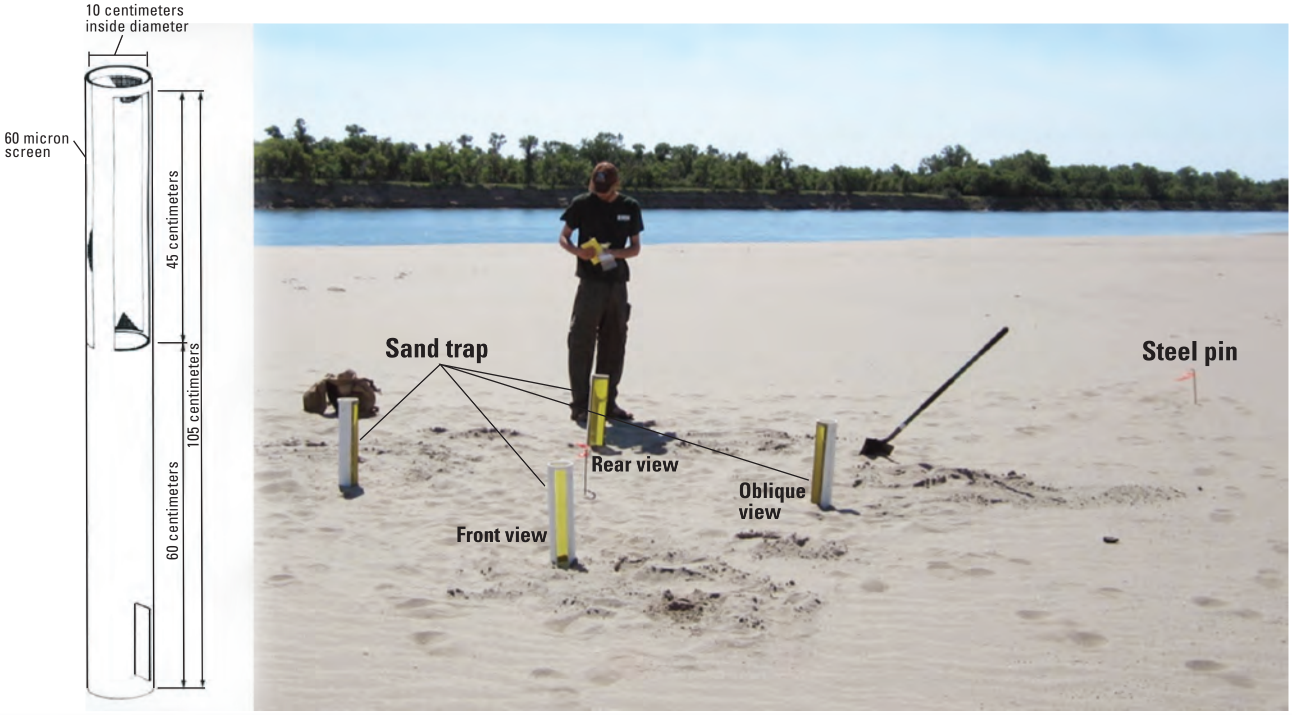


Figure 15. A typical sand trap setup with a schematic of an individual sand trap on the left [schematic from Rosen (1978)]. Photograph by Rochelle Nustad, July 2012.

Flood discharge and sediment plume entering the Missouri River channel from the Garrison Dam flood spillway. Photograph by Joel Galloway, U.S. Geological Survey.

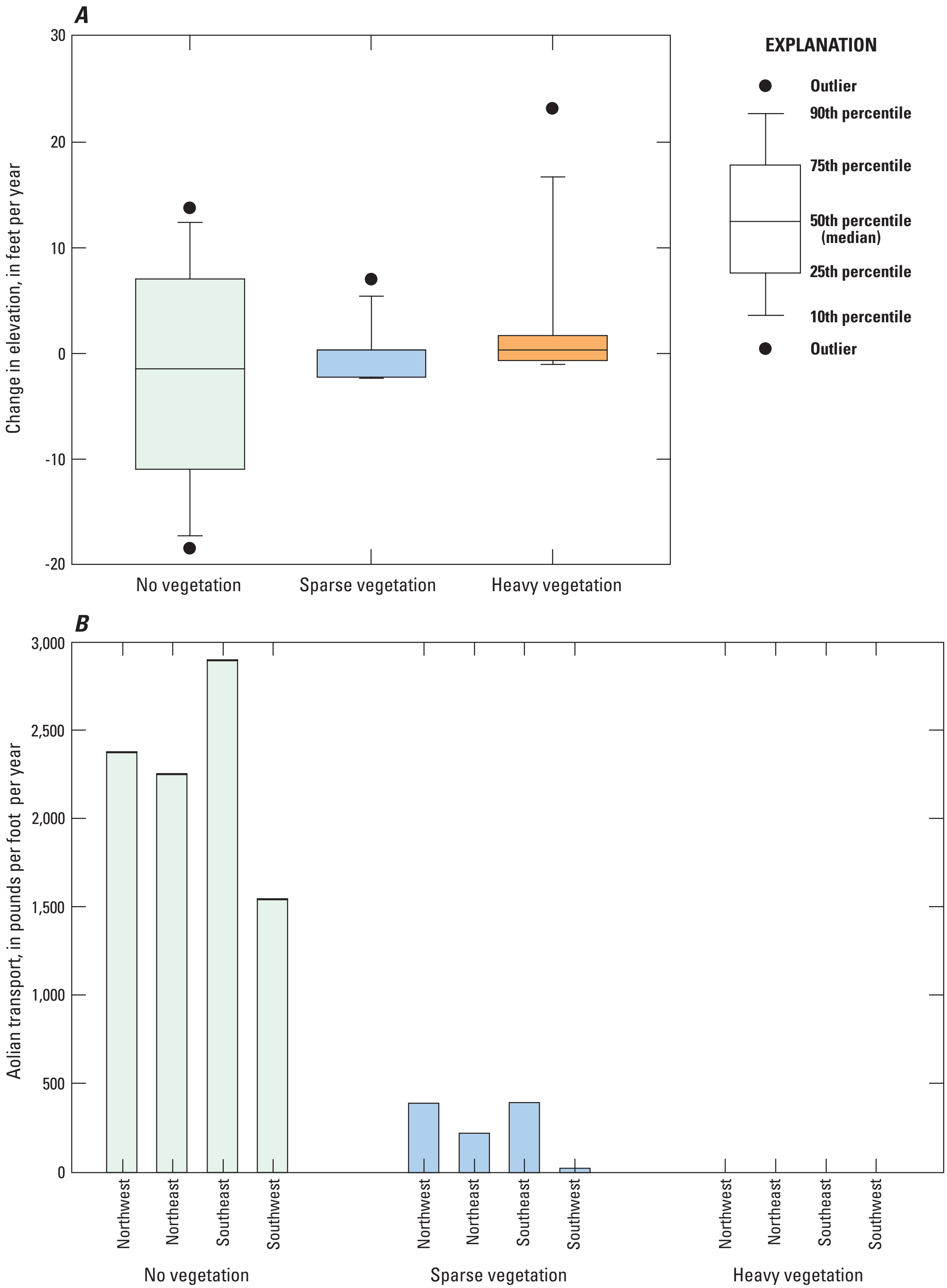


Figure 16. Sand trap results in the Garrison Reach of the Missouri River. *A*, The amount of deflation or aggradation near the sand traps as measured by steel pins; and *B*, the amount of sand collected at the four sand traps located at each site.

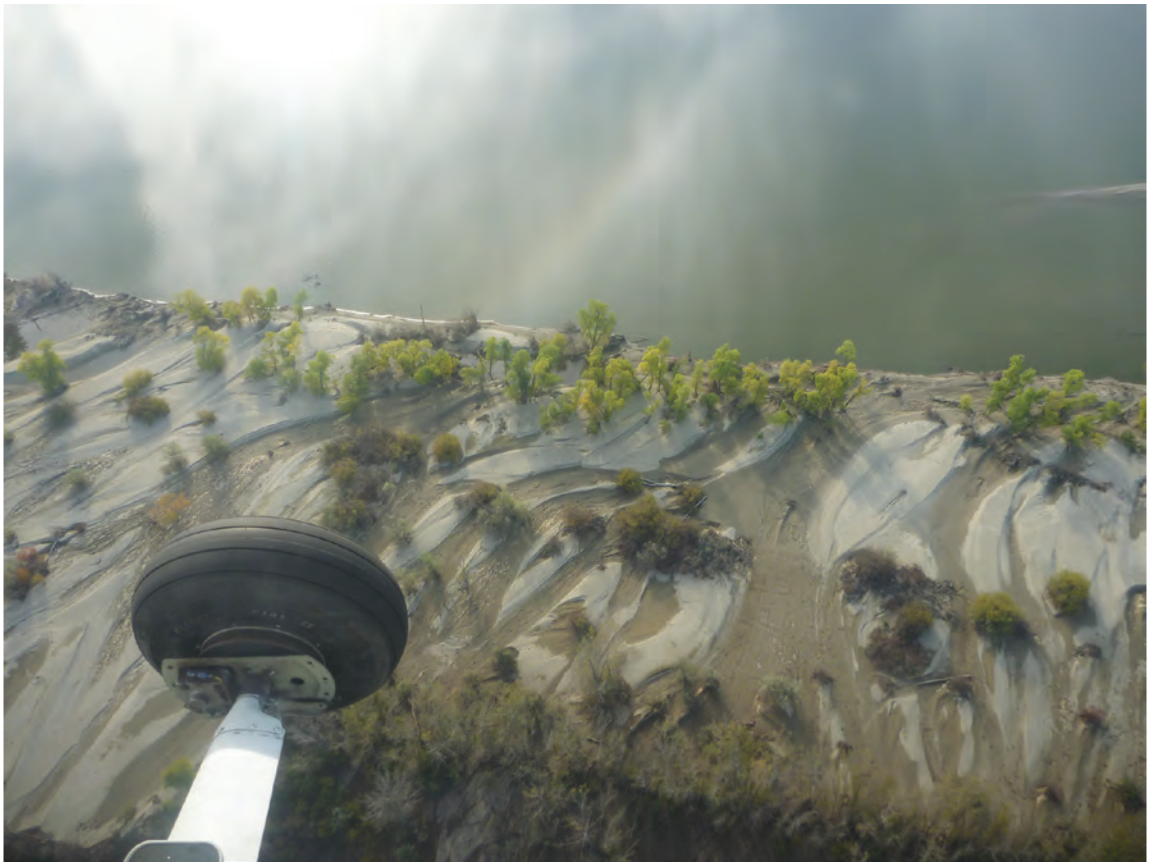


Figure 17. Sand splays downstream from Bismarck-Mandan, North Dakota. The light green trees along the bank are cottonwoods (*Populus deltoides*)—notice the patterns of deposition and scour relative to the vegetation. Photograph by Edward Schenk, October 2011.

Vegetation surveys consisted of analysis of Quickbird™ and GeoEye™ high-resolution satellite imagery for different dates, tree cores to determine time of tree root crown burial (see recent articles on dendrogeomorphology; for example, Hupp and Bornette, 2003), and an intensive survey of deposition and forest density at a site downstream from Bismarck-Mandan (fig. 18). Preliminary results indicate that dense riparian forests alter sediment deposition patterns by slowing water velocity, creating sand deposits at the upstream forest edge. In-channel large woody debris also seems to increase as the channel nears the Lake Oahe backwater. The amount of large woody debris, in-channel and on the flood plain, seems to be much greater than pre-flood, likely due to upstream island erosion during the flood. In-channel large wood prior to the flood followed no clear trend, as noted by a previous survey of the Garrison Reach (Angradi and others, 2004). A satellite imagery survey of in-channel large wood after the flood (2012) showed that post-flood distribution of in-channel wood peaked near the town of Washburn (fig. 2) then dropped to ambient levels before increasing dramatically (nearly exponentially) a few miles downstream from the cities of Bismarck and Mandan (fig. 2) as the channel approaches the backwaters of the Oahe Reservoir. Results are preliminary but may improve the understanding of flood effects on the flood plain and the amount of new large woody debris pieces introduced to the channel following the flood (largely through mass wasting). Continued analysis may also help with forecasting the risk of seasonal ice jams that threaten infrastructure, resources, and lives.

Summary

The 2011 flood on the Missouri River was the largest flood since the river became regulated by a series of high dams in the mid-20th century. Flow in the Missouri River, other than during exceptional floods like the flood of 2011, is highly regulated by dams and reservoirs that sustain relatively high low flows during droughts and reduce the severity of peak flows during moderate flows. Despite their function for flood protection, dam releases occasionally must exceed routine discharge because of reservoirs reaching capacity from upstream precipitation and snowmelt. Heavy rainstorms and abnormally large snow pack in the spring of 2011 led to releases that produced the largest flood of the dam-regulated era on the upper

Figure 18. Sand splay depositional patterns related to vegetation. *A*, U.S. Geological Survey employee walking along the top of what was once a fence row, where the top of corn stalks are apparent and *B*, U.S. Geological Survey employee walking along dune structures immediately inside a cottonwood (*Populus deltoides*) forest. The field pictured in the top photo is behind the position of the photographer during the second picture. Note the transition between dunes and the low deposition area in the background as the sand splay enters the forest. Both photographs are in the location noted in the light detection and ranging (lidar) difference model figure (fig. 13). Photographs by Edward Schenk, May 2012.

Missouri River. The flood persisted through most of the summer eroding river banks, adding sand to sandbars, and moving the thalweg of the channel in many places.

The U.S. Geological Survey (USGS) monitored and assessed the geomorphic changes following the flood of 2011 in two reaches of the Missouri River: the Garrison Reach in North Dakota bounded by the Garrison Dam and the Lake Oahe Reservoir, and the Recreational Reach along the boundary of South Dakota and Nebraska, which is bounded by the Gavins Point Dam and extends downstream from Ponca, Nebraska. Historical cross-section data indicate that the upper reaches of river near the dam experienced rapid erosion, channel incision, and island/sandbar loss following completion of the dam in 1953. The erosion, incision, and land loss lessened over time as the channel adjusted to a new flow regime. The lower reach near the Lake Oahe Reservoir backwater became depositional as velocities decreased in this part of the river.

Preliminary post-flood results in the Garrison Reach indicate that the thalweg has deepened at most cross-sections, whereas sandbars and islands have increased in elevation through vertical sediment accretion. Bank erosion is evident but in terms of sediment volume, the erosion seems to be minor compared to channel bed degradation and sandbar deposition. Stage-discharge relations at the Bismarck streamgage (Garrison Reach) indicate that during the flood the thalweg and channel filled with sediment that later was scoured during the flood recession. Sandbar and thalweg migration was observed in the Recreational Reach but no net scouring or aggradation was evident in this section of the river. Changes in two-dimensional area of sandbars and islands are still being assessed using high-resolution satellite imagery.

A sediment balance is being constructed for the Garrison Reach using survey data, bathymetric information, sand traps for wind-blown material, a quasi-three-dimensional (two dimensions and time) numerical model, and dating of sediment cores. Sand traps were installed at three study sites on sandbars. Each site consisted of three sampling locations with various amounts of vegetation (unvegetated to highly vegetated). Preliminary results indicate that wind derived sand transport is substantial and possibly greater following the flood because of the increase in areal extent of exposed unvegetated sandbars and islands. Quantification of the amount of sand moved by wind processes is still being determined.

A quasi-three-dimensional model is being constructed to evaluate potential channel changes in the Bismarck-Mandan metropolitan area (North Dakota). The model selected for this exercise is the FaSTMECH two-dimensional vertically structured numerical model, one tool in the greater International River Interface Cooperative (iRIC) software suite provided by the USGS and the Foundation of Hokkaido River Disaster Prevention Research Center. The model, when complete, can predict sediment transport, water velocity, and channel erosion/aggradation for different flow scenarios for the targeted river reach around.

A concurrent analysis of the effects of riparian and island vegetation on sediment trapping is underway and will complement the understanding of the effects of the flood on the river landscape. The analysis is based on relations between a difference model of flood plain elevations and mappings of riparian forest cover. Sediment accumulation and erosion near various vegetative communities and in-channel large woody debris are also being assessed.

This report summarizes two geomorphic studies along the Missouri River during and following the historic flood of 2011. Much of what has been presented is preliminary. For the most up-to-date information, contact the USGS Water Science Center in the appropriate state.

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Flood damage upstream from Bismarck-Mandan, North Dakota during the flood of 2011.
Photograph by Joel Galloway

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