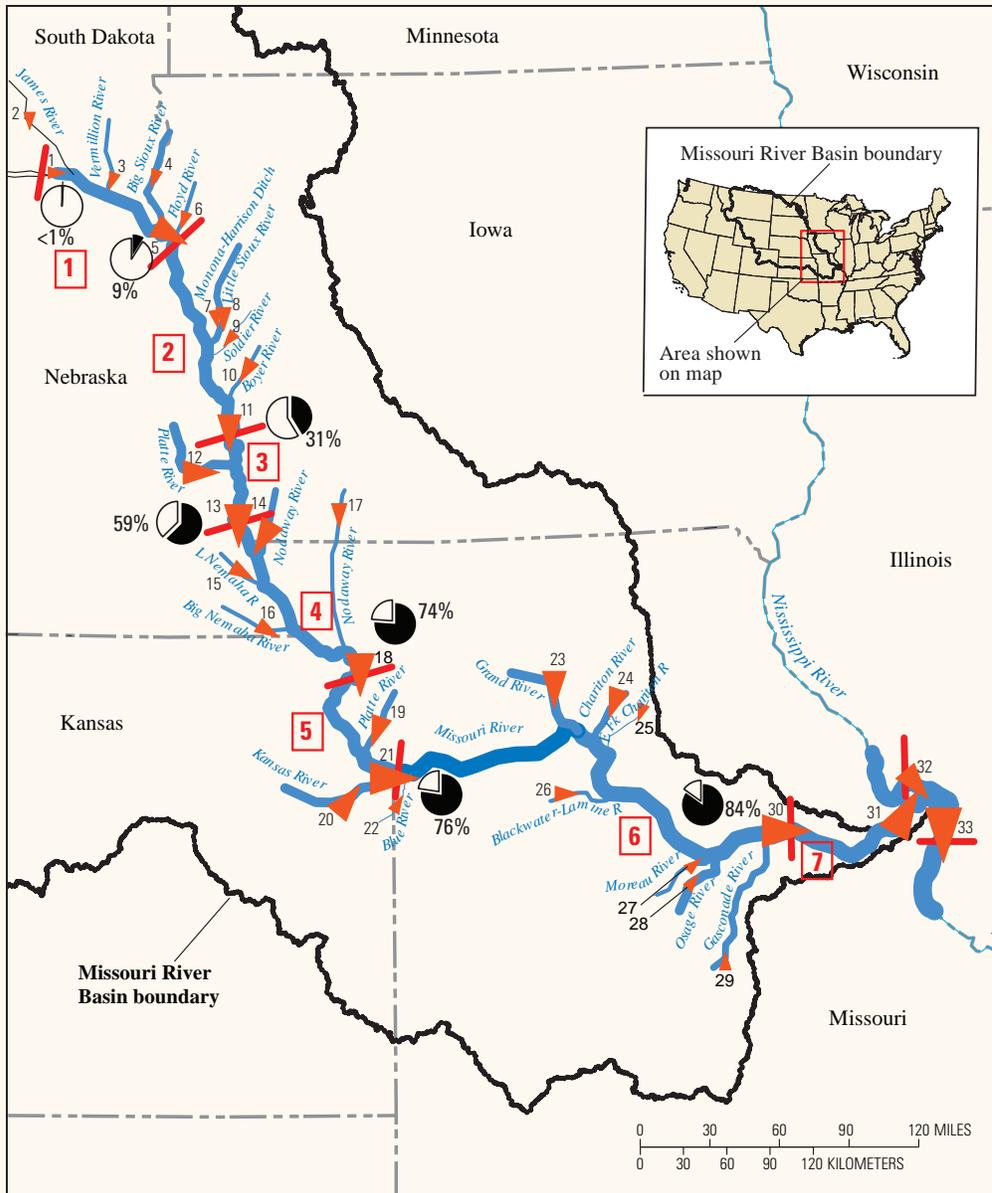


Prepared in cooperation with the U.S. Army Corps of Engineers

# Generalized Sediment Budgets of the Lower Missouri River, 1968–2014



Scientific Investigations Report 2016–5097

**Cover illustration:** Modified version of figure 10 from this report.

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By David C. Heimann

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Scientific Investigations Report 2016–5097

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

**U.S. Department of the Interior**  
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**U.S. Geological Survey**  
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## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<b>Area</b>		
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
<b>Volume</b>		
acre-foot (acre-ft)	1,233	cubic meter (m <sup>3</sup> )
<b>Flow rate</b>		
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)
<b>Mass</b>		
milligram (mg)	0.001	gram (g)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year
<b>Density</b>		
pound per cubic foot (lb/ft <sup>3</sup> )	16.02	kilogram per cubic meter (kg/m <sup>3</sup> )
pound per cubic foot (lb/ft <sup>3</sup> )	0.01602	gram per cubic centimeter (g/cm <sup>3</sup> )

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

## Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) or the National Geodetic Vertical Datum of 1929 (NGVD29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) or the North American Datum of 1927 (NAD27).



# Generalized Sediment Budgets of the Lower Missouri River, 1968–2014

By David C. Heimann

## Abstract

Sediment budgets of the Lower Missouri River were developed in a study led by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers. The scope of the study included the development of a long-term (post-impoundment, 1968–2014) average annual sediment budget and selected annual, monthly, and daily sediment budgets for a reach and period that adequate data were available. Included in the analyses were 31 main-stem and tributary stations of the Lower Missouri River and two Mississippi River stations—the Mississippi River below Grafton, Illinois, and the Mississippi River at St. Louis, Missouri.

Long-term average annual suspended-sediment loads of Missouri River main-stem stations ranged from 0.33 million tons at the Missouri River at Yankton, South Dakota, station to 71.2 million tons at Missouri River at Hermann, Mo., station. Gaged tributary gains accounted for 9–36 percent of the local reach budgets and cumulative gaged tributary contributions accounted for 84 percent of the long-term average suspended-sediment load of the Missouri River at Hermann, Mo., station. Although the sediment budgets for seven defined main-stem reaches generally were incomplete—missing bedload, reach storage, and ungaged tributary contributions—the budget residuals (net result of sediment inputs and outputs) for six of the seven reaches ranged from -7.0 to 1.7 million tons, or from -9.2 to 4.0 percent of the reach output suspended-sediment load, and were within the 10 percent reported measurement error of annual suspended-sediment loads for large rivers. The remaining reach, downstream from Gavin's Point Dam, extended from Yankton, S. Dak., to Sioux City, Iowa, and had a budget residual of -9.8 million tons, which was -88 percent of the suspended-sediment load at Sioux City.

The Lower Missouri River reach from Omaha, Nebraska, to Nebraska City, Nebr., had periods of concurrent sediment data for each primary budget component with which to analyze and determine a suspended-sediment budget for selected annual, monthly, and daily time increments. The temporal changes in the cumulative annual budget residuals were poorly correlated with the comparatively steady 1968–2011 annual stage trends at the Missouri River at Nebraska City, Nebr., station. An accurate total sediment budget is developed by having concurrent data available for all primary suspended and bedload components for a reach of interest throughout a period.

Such a complete budget, with concurrent record for suspended-sediment load and bedload components, is unavailable for any reach and period in the Lower Missouri River. The primary data gaps are in bedload data, and also in suspended-sediment gains and losses including ungaged tributary inputs and sediment storage. Bedload data gaps in the Missouri River Basin are much more prevalent than suspended-sediment data gaps, and the first step in the development of reach bedload budgets is the establishment of a standardized bedload monitoring program at main-stem stations.

The temporal changes in flow-adjusted suspended-sediment concentrations analyzed at main-stem Missouri River stations indicated an overall downward change in concentrations between 1968 and 2014. Temporary declines in flow-adjusted suspended-sediment concentrations during and following large floods were evident but generally returned to near pre-flood values within about 6 months.

Data uncertainties associated with the development of a sediment budget include uncertainties associated with the collection of suspended-sediment and bedload data and the computation of suspended-sediment loads. These uncertainties vary depending on the frequency of data collection, the variability of conditions being represented by the discrete samples, and the statistical approach to suspended-sediment load computations. The coefficients of variation of suspended-sediment loads of Missouri River tributary stations for 1968–2014 were greater, 75.0 percent, than the main-stem stations, 47.1 percent. The lower coefficient of variation at main-stem stations compared to tributaries, primarily is the result of the lower variability in streamflow and sediment discharge identified at main-stem stations. To obtain similar accuracy between suspended-sediment loads at main-stem and tributary stations, a longer period of record is required of the tributary stations. During 1968–2014, however, the Missouri River main-stem station record was much more complete (87 percent) than the tributary station record (28 percent).

## Introduction

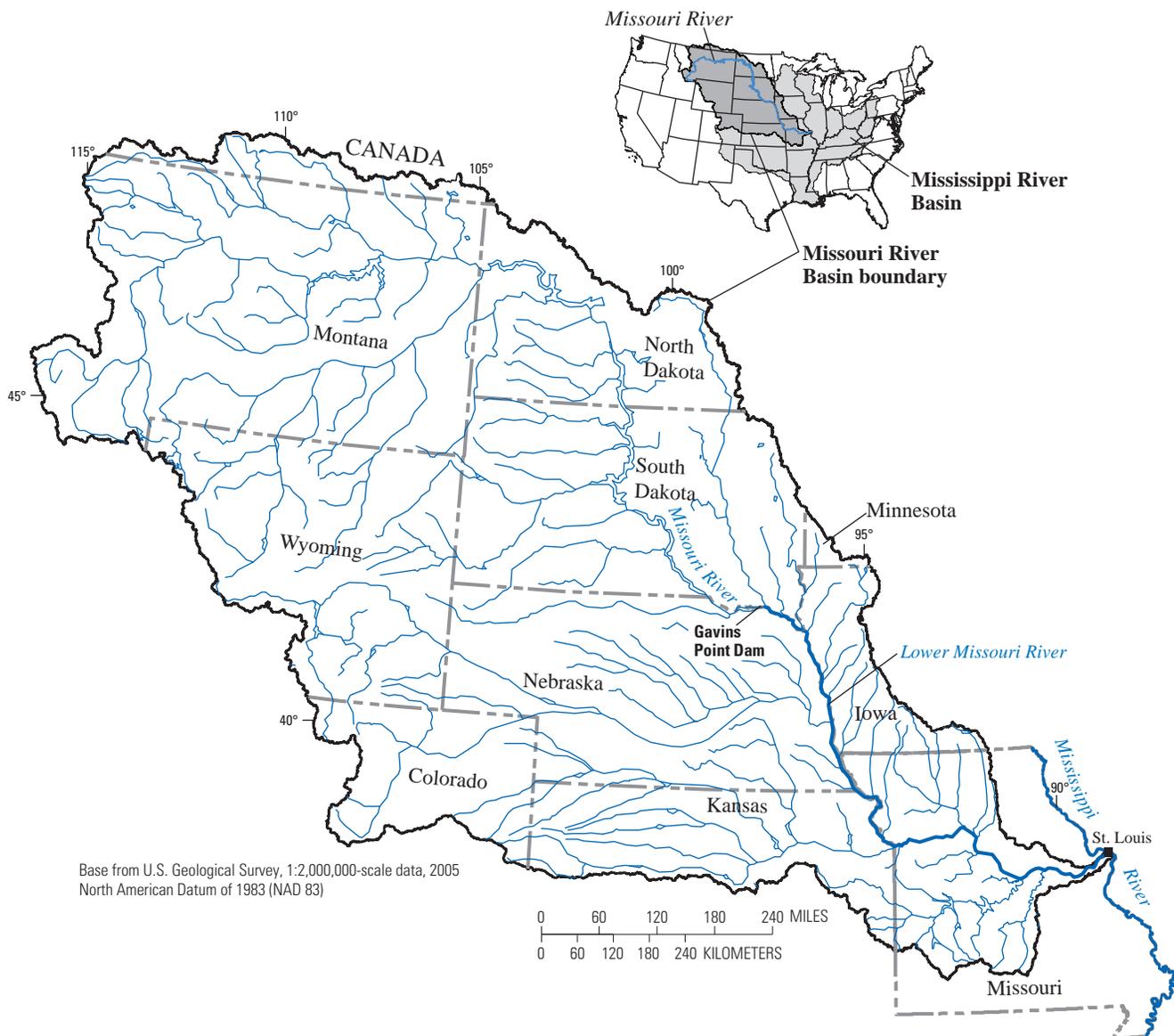
The Missouri River Basin (fig. 1) is the second largest river basin in the United States (the Mississippi River Basin is the largest) draining about one-sixth of the conterminous United States (529,350 square miles). The Missouri River is

## 2 Generalized Sediment Budgets of the Lower Missouri River, 1968–2014

2,341 miles long from its headwaters in western Montana to its mouth at St. Louis, Missouri, making it the longest river in the United States. Bank stabilization and channel modifications to the Missouri River, associated with the Missouri River Bank Stabilization and Navigation Project (BSNP), started in 1912, and modifications began in earnest in the 1930s and continued through the 1980s (U.S. Army Corps of Engineers, 2009). Six major impoundments in the upper Missouri River Basin regulate the flow from 53 percent of the basin area upstream from St. Louis, Mo., following construction that began in 1933 and ended in 1966. These engineered modifications, which include tributary impoundments, and land-use changes, which include changes in agricultural practices, have greatly altered streamflows and, to a greater degree, the supply and transport of sediment in the Lower Missouri River system (Jacobson and others, 2009; Meade and Moody, 2010; National Research Council, 2011). The altered sediment

regime included a substantial decrease in the mass of transported sediment (a reported 70 percent decline in sediment transported by the Missouri River to the Mississippi River since the 1950s), sediment deposition in the main-stem reservoirs, channel bed and bank erosion downstream from dams, and accretion and storage of sediment behind revetments and other river control structures (Meade and Moody, 2010).

Sediment supply, sediment transport, and stream-channel dynamics are physical processes that are interrelated in natural fluvial systems, and an alteration of one component leads to a readjustment of the remaining factors. In a free-flowing, dynamic stream system, these changes occur continuously at a variety of temporal and spatial scales. Monitoring programs by the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers (USACE) and other Federal, State, and local agencies, quantify sediment and streamflow characteristics at stations within the Missouri River Basin. The



**Figure 1.** Missouri River Basin and Lower Missouri River reach (downstream of Gavins Point Dam).

streamflow record is more extensive and complete than the sediment record, but the record of both physical characteristics spans 8 decades at some locations in the basin.

Sediment transport is an integral component of numerous management activities and issues within the Missouri River system. Some of the activities and issues include bed degradation, dredging operations, maintenance of a navigation channel, habitat restoration actions (creation and evolution of emergent-sandbar and shallow-water habitats), nutrient transport, and riparian vegetation dynamics. An informative aid in the management of these and other issues involving sediment in the Missouri River is a sediment budget quantifying the components of sediment transport during a defined time interval. Describing and quantifying sediment transport processes within a defined control volume (channel reach) can be defined in the simplest form by the following equation:

$$\Delta \text{Mass}(t)/\Delta t = \text{SEDin}(t) - \text{SEDout}(t) + \text{Gain}(t) - \text{Loss}(t) \quad (1)$$

where

$\Delta \text{Mass}(t)/\Delta t$  is the budget residual indicating the rate of change in the total mass of unmeasured sediment in the reach with the time interval  $\Delta t$  including storage;

$\text{SEDin}(t)$  is the input sediment mass, integrated with time ( $t$ );

$\text{SEDout}(t)$  is the output mass, integrated with time ( $t$ );

$\text{Gain}(t)$  refers to sediment mass inputs within the reach including those from tributaries, integrated with time ( $t$ ); and

$\text{Loss}(t)$  refers to within-reach sediment mass losses including those from commercial dredging withdrawals, integrated with time ( $t$ ).

The most complete sediment data record for Missouri River Basin stations historically, and currently (2016), exists at

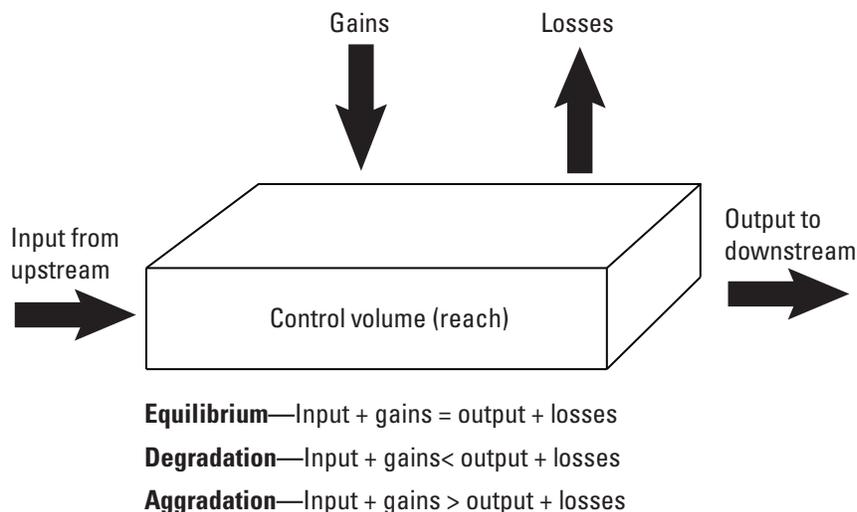
main-stem stations and includes the suspended part of  $\text{SEDin}$  and  $\text{SEDout}$  variables in equation 1, with information more limited for all reach Gain and Loss variables. Depending on the sediment transport characteristics of a particular reach and the time interval, the  $\Delta \text{MASS}/\Delta t$  may represent equilibrium, degradation, or aggradation conditions as defined in figure 2.

## Sediment Sampling and Accounting in the Missouri River Basin

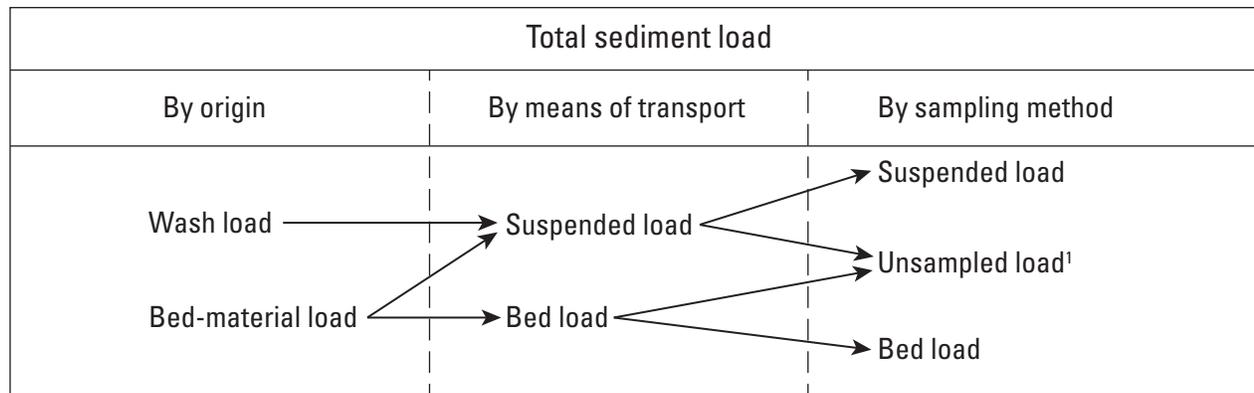
The compilation of the various sediment budget components is complicated by the challenges of measuring sediment that is being transported by multiple mechanisms. The total sediment load of a fluvial system can be categorized in several ways based on origin, means of transport, and sampling method (fig. 3). The sediment sampling programs led by the USACE and then USGS within the Missouri River Basin have focused on defining sediment load based on sampling method and the suspended part of total load.

The routine sediment monitoring program in the basin has included the collection of suspended-sediment concentrations (SSCs), suspended-sediment particle sizes, computed suspended-sediment loads (SSLs), and bed-sediment sizes at selected main-stem and tributary stations. To obtain information on total sediment loads, information on bedload transport has been estimated by theoretical computations or discrete bedload samples at main-stem stations.

The primary form of sediment transport in the Missouri River is the suspended part of total load, and the primary means by which sediment transport has been accounted for in the basin is SSLs. The SSLs primarily have been computed using methods described in Porterfield (1972) and a daily SSC (either measured or estimated) multiplied by the corresponding daily streamflow to obtain a daily SSL. The daily SSLs were then summed to obtain monthly or annual SSLs.



**Figure 2.** Schematic showing components of sediment budget for a river reach. Figure modified from Ohlmacher (1998).



<sup>1</sup>That part of the sediment load that is not collected by the depth-integrated suspended-sediment and pressure-difference bed-load samplers used, depending on the style and size of the sampler(s).

**Figure 3.** Categories of total sediment load (Diplas and others 2008).

A continual trace of SSCs (sedigraph) is developed for the period of interest using discretely sampled SSCs, daily observed SSCs, and estimates of SSCs for intervals between each sample collection. These estimates of SSCs are made using a relation of streamflow to SSC known as a sediment-rating (sediment transport) curve as described by Horowitz (2003).

Sampling of SSC and computation of SSL were led by the USACE at Missouri River Basin stations from the late 1930s through the 1970s, and thereafter were led by the USGS. The SSC sampling interval, timing, and frequency has differed considerably at stations and between stations. The SSC sampling frequency at stations within the Missouri River Basin has differed from daily to about monthly and has differed temporally at a station and among stations. Sampling frequency has tended to be greater at main-stem stations than at tributary stations. Depth-integrated samples (continuous samples obtained from the vertical water column and from multiple sample locations [verticals] along a river transect), and point samples (samples obtained from selected depths or points in the water column at multiple verticals) were used in the collection of SSC and particle-size data. The number of sampled verticals differed by station; but, generally, the number of sample verticals was three to five. All suspended-sediment samples collected after the mid-1950s were obtained isokinetically (stream water entering the sampler nozzle did not differ in velocity from that of the water column). The spacing of the sampled verticals generally was based on equal-discharge increment divisions or equal-width increments (Edwards and Glysson, 1999). Laboratory methods for the analysis of fluvial sediment samples to obtain SSC and particle size are provided in Guy (1969).

Since 2006, SSLs at select stations within the Missouri River Basin have been computed using continuous sampling of optical backscatter (turbidity). Such continuous surrogate methods (see Surrogate Methods for Determination of Sediment Transport<sup>2</sup> section) provide the opportunity to refine SSL

computations to shorter (for example, hourly) estimates, provide a higher correlation with SSC than that between SSC and streamflow, and reduce possible hysteresis effects (referring to the lower SSCs on recession limb of a hydrograph compared to the rising limb for the same flow) common in the SSC-streamflow relation. Additional sediment data collected with less regularity and frequency at Missouri River Basin sediment stations are suspended-sediment particle size samples, bed-sediment particle-size samples, and bedload samples or estimates.

Sediment sampling within the Missouri River Basin has historically focused on active transport of suspended material within the water column of free-flowing reaches; however, sediment storage also can be an important component of sediment budgets. Missouri River main-stem reservoir storage changes have been periodically assessed (U.S. Department of Agriculture, 2009), and Lower Missouri River channel volume changes have been periodically estimated (John Shelley, U.S. Army Corps of Engineers, written commun., 2015). Flood-plain deposition and erosion along the Missouri River is unquantified; however, characteristics of these processes are related to the frequency and magnitude of flooding, channel hydraulics, distance from channel, local relief, and vegetation characteristics. If the reach is in equilibrium, the long-term net change in storage should be near zero, and the elevation of the flood plain remains stable relative to the elevation of the channel bed (Wolman and Leopold, 1957). Equilibrium also can exist when channels actively migrate if deposition equals erosion. Under channel degrading conditions, which is a condition present in much of the Lower Missouri River between 1990 and 2005 (U.S. Army Corps of Engineers, 2009), the opportunity for flooding and flood-plain storage is diminished. Factors that have historically affected the flood-plain storage component of the Lower Missouri River are regulation of flows by the impoundments, levees, and the BSNP. The BSNP increased the flood-plain storage component and resulted in the accretion of Missouri River flood plain between 1912 and

1981 (Ferrell, 1996) at an average rate estimated to be equivalent to 14–33 percent of pre-dam annual SSLs at the Missouri River at Hermann, Mo. (Jacobson and others, 2009).

Indications are that despite modifications in the hydrology and sediment transport characteristics of the Lower Missouri River, substantial amounts of flood-plain sediment storage still takes place in localized areas during flooding (Alexander and others, 2013; Schalk and others, 1998). The post-impoundment Lower Missouri River flows are highly regulated in comparison to the historical flow frequency, magnitude, timing, and duration characteristics (Jacobson and others, 2009). Sedimentation characteristics associated with flooding can vary longitudinally depending on the source of flooding and contributions from tributaries. Average deposition on the Lower Missouri River flood plains has not been assessed and is unknown, and such losses are not subject to offset from gains that result from channel migration as the losses might on a nonchannelized river. Except for upper reaches of the Lower Missouri River (upstream from Sioux City, Iowa) and constructed side channels, bank stabilization is ubiquitous on the Lower Missouri River and generally eliminates bank erosion as a source of suspended sediment.

## Need for Study

The sediment budget of a river reach, and the associated equilibrium status, will vary longitudinally and temporally; therefore, to have an understanding not only of the predominant transport conditions in a reach of interest but also to have the ability to detect change within a time frame and reach of interest is important. As impetus for this study, the National Research Council (2011) documented that

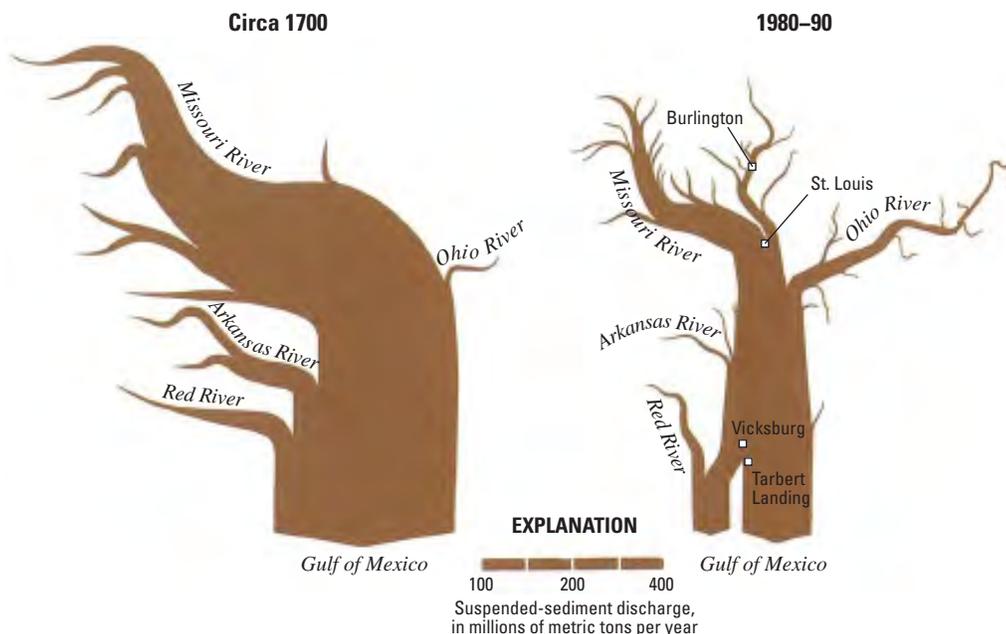
“Corps of Engineers and the U.S. Geological Survey scientists have been conducting valuable collaborative investigations of Missouri River sedimentary processes that should be used as the foundations for a more detailed and extensive sediment budget. Over time, continued collaboration may lead to a more formal program for data collection and evaluation. The Corps and the USGS should extend their collaborative efforts and develop a detailed Missouri River sediment budget for the headwaters to the river’s mouth, with provisions for continuing revisions and updates as new data become available.”

Jacobson and others (2009), when referring to the need for sediment information in restoration activities on the Missouri River, documented that

“Sediment budgets—an accounting of sediment transport, erosion, and deposition—are fundamental to understanding geomorphic evolution of altered river systems.”

A sediment budget, developed from the extensive existing sediment data collected at Missouri River main-stem and primary tributary stations, is a first step toward addressing these stated information needs. Such generalized suspended-sediment budgets of the Missouri and Mississippi Rivers have been determined for selected periods in previous studies (figs. 4–5). The process of developing such a sediment budget and the likely applications of such a tool also provide a means of assessing temporal and spatial data gaps and limitations.

As an initial step toward the attainment of a detailed Missouri River sediment budget, the USGS, in cooperation with the USACE Kansas City and Omaha Districts, developed



**Figure 4.** Suspended-sediment budget of the Mississippi River Basin (Meade, 1995).

6 Generalized Sediment Budgets of the Lower Missouri River, 1968–2014

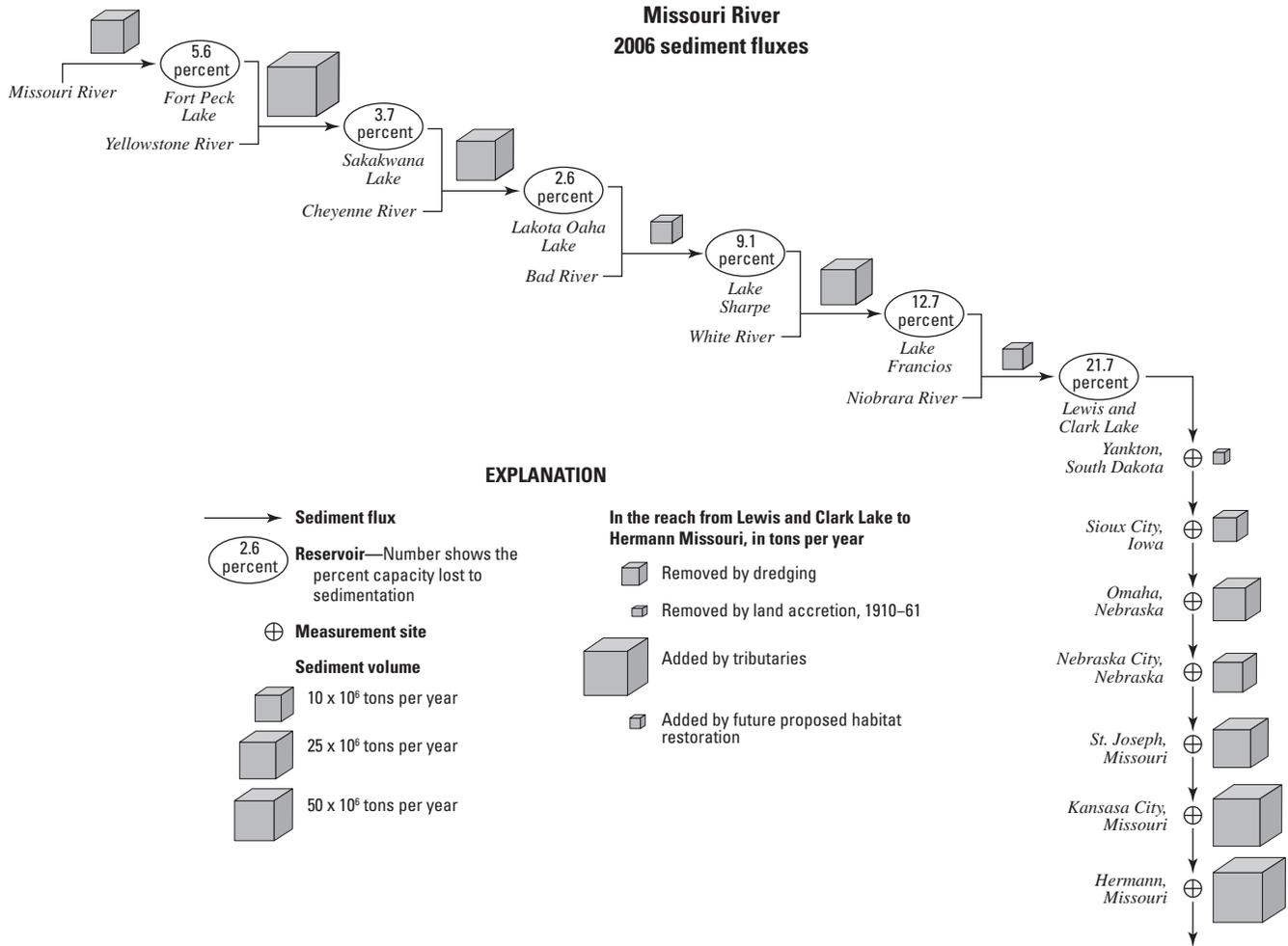


Figure 5. Generalized framework for a Missouri River sediment budget (National Research Council, 2011).

a generalized sediment budget for the Lower Missouri River using existing sediment data. The primary objectives of this effort are indicated in the following list.

1. Use the best available information to establish the initial framework for a sediment budget with which to update the National Research Council (2011) conceptual sediment budget.
2. The quantification of bedload transport is of importance in understanding Missouri River channel bed dynamics. When and where possible, incorporate the bedload part of total sediment load into a generalized sediment budget.

**Purpose and Scope**

The purpose of this report is to summarize the results of a study that was completed to determine sediment budgets of the Lower Missouri River. The sediment budgets include

suspended-sediment data and, when and where available, bedload data. The scope of the study includes the development of a long-term (1968–2014) post-impoundment budget for main-stem reaches within the Lower Missouri River—from Yankton, S. Dak., to St. Louis, Mo. Included in the analysis are 31 Missouri River main-stem and tributary stations and 2 Mississippi River stations—the Mississippi River below Grafton, Ill., station and the Mississippi River at St. Louis, Mo., station. Example sediment budgets for annual, monthly, and daily periods are presented for a selected Lower Missouri River reach. The available sediment data at the study sites were compiled; annual loads were computed as needed and data supported it. Temporal changes in SSCs and SSLs were assessed for 1930–2014 to put the post-impoundment period in temporal context, and reach-by-reach sediment budgets were developed. Data gaps and uncertainties in the development of an annual, monthly, and daily suspended-sediment and bedload budgets are presented, and surrogate sediment data collection methods also are discussed.

## Study Methods

The main-stem reservoirs on the Missouri River effectively trap sediment and have greatly altered the sediment transport regime of the river. The Lower Missouri River, the section of river downstream from Gavins Point Dam, the downstream-most main-stem dam was, therefore, selected for the determination of a sediment budget in this study (fig. 1). Stations selected for the study, data availability, and methods used in determining budget components and sediment budgets for long-term, annual, monthly, and daily periods are described in the following sections of this report.

### Station Selection

Sediment monitoring stations within the Lower Missouri River Basin and beyond used in the development of a sediment budget were selected from main-stem and tributary stations based on available record. Lower Missouri main-stem stations used in the study included the following stations: Yankton, S. Dak. (USGS station identification 06467500); Sioux City, Iowa (USGS station identification 06486000); Omaha, Nebr., (USGS station identification 06610000); Nebraska City, Nebr. (USGS station identification 06807000); St. Joseph, Mo. (USGS station identification 06818000); Kansas City, Mo. (USGS station identification 06893000); Hermann, Mo. (USGS station identification 06934500). These stations are hereafter referred to as “Yankton”, “Sioux City”, “Omaha”, “Nebraska City”, “St. Joseph”, “Kansas City”, and “Hermann” stations. In the case of tributary stations, selection criteria also included the size of drainage area (greater than 250 square miles) and station location (most downstream sediment station on a tributary). The two stations on the Mississippi River, the Mississippi River below Grafton, Ill. (USGS station identification 05587455) and Mississippi River at St. Louis, Mo. (USGS station identification 07010000), also were selected to determine the contributions of the Missouri River and upper Mississippi Rivers to the sediment loads of the Mississippi River at St. Louis, Mo., station. These stations are hereafter referred to as “Grafton” and “St. Louis”. Measured or estimated sediment data from 33 selected USGS stations (8 Missouri River main-stem, 23 tributaries, and 2 Mississippi River stations) were used in the study analyses (fig. 6). Characteristics, sediment data availability, and corresponding annual average flows for the 33 stations are listed in [table 1](#).

### Sources of Sediment Data

The primary sediment data used in the development of sediment budgets are SSLs computed and published by the USACE and USGS. Bedload data are limited to discrete measurements or theoretical estimates made for main-stem stations. Other miscellaneous sediment data, including commercial dredging data and reintroduced sediment data associated

with Missouri River Recovery Program (MRRP; U.S. Army Corps of Engineers, 2015) activities are incorporated in the sediment budgets where available. The sources and availability of sediment data used in this study are described in the following sections.

### Annual, Daily Suspended-Sediment Loads

The primary sediment data used in the determination of sediment budgets for the Lower Missouri River are historical SSLs from main-stem and tributary stations. The earliest SSL record used in this study was from 1930 to 1931 and published by the Chief of Engineers (1935). The USACE calculated and published daily sediment loads for Missouri River Basin sediment stations from 1937 to 1974 (U.S. Army Corps of Engineers, 1951; 1957; 1965; 1970; 1972; 1976). Annual SSLs were calculated for this study at stations where SSLs were not published but SSC and streamflow data were available. Post-1974 sediment loads calculated by the USGS generally were determined by the subdivision (Porterfield, 1972) method using SEDCALC (Koltun and others, 1994) or GCLAS software (Koltun and others, 2006). Since 2006, daily loads for select stations (the number of selected stations differs by year; generally about 5 stations) also have been computed by USGS using the turbidity surrogate method (Rasmussen and others, 2009). Another method used for the determination of annual SSLs was LOADEST software (Runkel and others, 2004). For this study, the method was used at stations for which SSC and streamflow data were collected but loads were not previously computed. The S-LOADEST version of the program, written for the commercial statistical package TIBCO Spotfire S+ (TIBCO Software Inc., version 8.1), was used to compute SSL estimates as described by Heimann and others (2010). The LOADEST incorporates explanatory variables of streamflow (a linear or quadratic relation), time (a linear or quadratic relation), and seasonality into one of nine predefined regression models. The LOADEST estimates include a measure of predictive uncertainty, and the 95-percent confidence levels and associated coefficient of variation of annual SSLs for selected stations in the Missouri River Basin are provided in Heimann and others (2010) and Heimann and others (2011). Annual SSLs primarily were used in the determination of the sediment budgets used in this study. These data are summarized by station in [table 2](#) along with the 1968–2014 computed or estimated average SSL and an overall coefficient of variation (ratio of standard deviation to mean). Available daily SSLs for the selected stations are provided in [table 3](#).

During the post-impoundment budget period, 6 of the 33 selected stations had complete annual SSL record, including 5 of the 8 main-stem stations (Sioux City, Omaha, Nebraska City, St. Joseph, and Hermann) and 1 of the 23 tributary stations (Platte River at Louisville, Nebr.). For this study, the post-impoundment budget period is water years 1968–2014 (a water year is the 12-month period from October 1, for any given year, through September 30, of the following

8 Generalized Sediment Budgets of the Lower Missouri River, 1968–2014

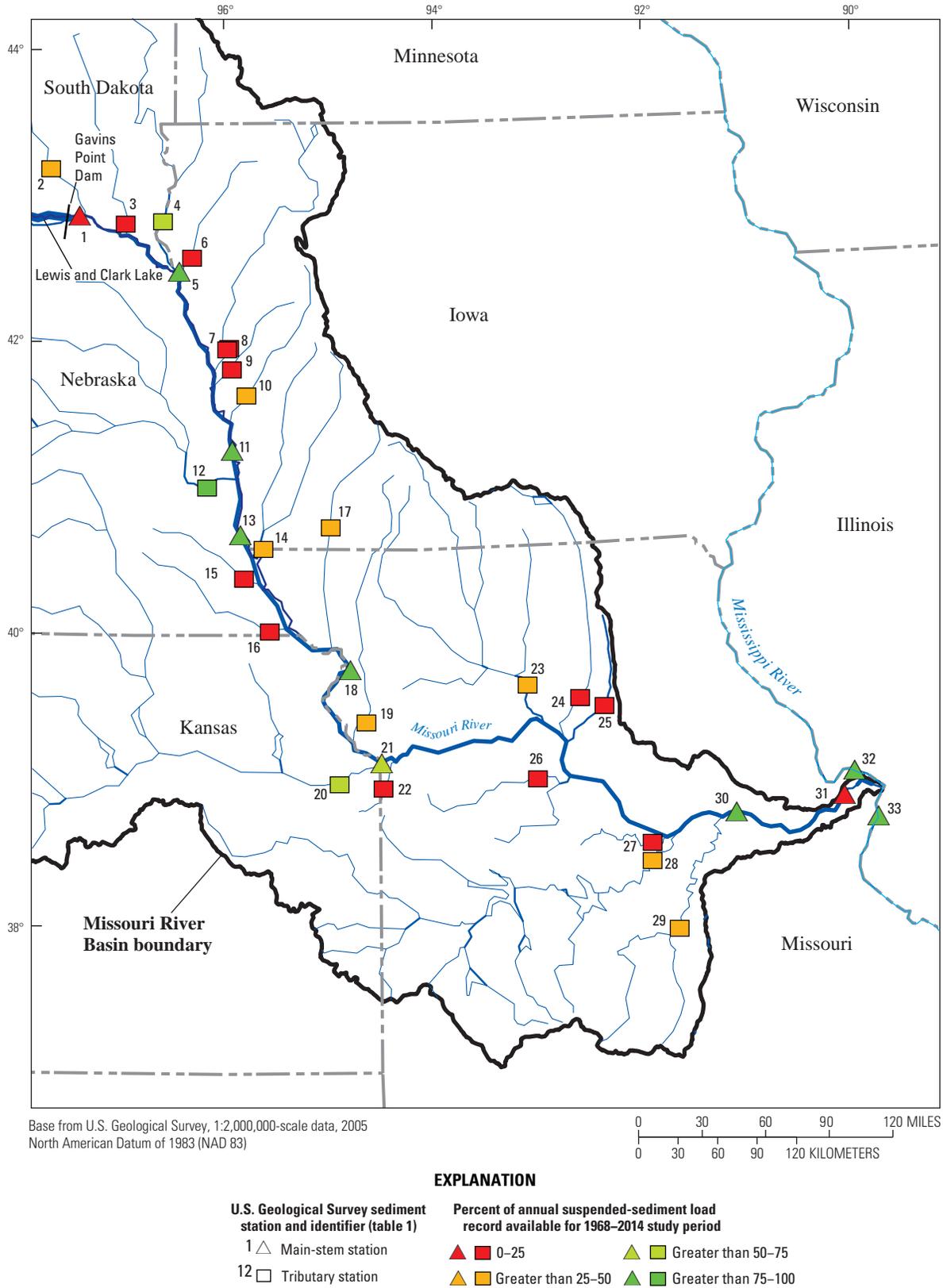


Figure 6. Sediment monitoring stations used in sediment budget analyses and annual sediment load availability, Lower Missouri River Basin, 1968–2014.

year; the water year is designated by the calendar year in which it ends). During 1968–2014, 22 of the 33 stations used in the analysis had less than 50 percent annual SSL record available, and the average annual station SSL availability was 45 percent. The longest period of concurrent availability of annual SSL data among the selected stations was during 1966–92 water years (table 1). Despite SSC data being used in the computation of historical published sediment loads, the SSCs generally were not published or retained, and, therefore, the availability of SSC data is more limited than SSL data (table 1). Average station availability of daily SSLs during the post-impoundment analysis period was 22 percent. Most daily SSL record was pre-1980, and the maximum availability was during the 1948–51 water years (table 1). Of the 33 selected stations, 14 stations (all but one station are tributary stations) did not have daily SSL data available during the post-impoundment analysis period.

A long-term average annual SSL was estimated for four major Missouri River tributaries (Vermillion River, Soldier River, Big Nemaha River, and Little Nemaha River; table 2) because stations on these tributaries lacked SSC and SSL data during 1968–2014. An estimated average annual SSL for 1968–2014 at the Vermillion River near Vermillion, S. Dak., station was determined by taking the ratio of concurrent streamflow at this station and at the Big Sioux River at Akron, Iowa, station times the long-term SSL at the Big Sioux River at Akron, Iowa station. The long-term SSL at the Big Nemaha River at Falls City, Nebr., station was determined by taking the ratio of concurrent SSL record with the Platte River at Louisville, Nebr., station outside of the 1968–2014 computation times the long-term SSL for the Platte River at Louisville, Nebr., station. The SSL at the Little Nemaha River at Auburn, Nebr., station was determined by taking the ratio of 1968–2014 streamflows for the Little Nemaha at Auburn, Nebr., and Big Nemaha River at Falls City, Nebr., stations times the long-term SSL estimate for the Big Nemaha River at Falls City, Nebr., station. Similarly, an estimated long-term SSL for the Soldier River at Pisgah, Iowa, station was determined by taking the ratio of concurrent SSL record with the Boyer River at Logan, Iowa, station times the long-term SSL for the Boyer River at Logan, Iowa, station. The associated uncertainty of these estimates is substantial and may approach 100 percent.

## Bedload data

The counterpart to SSL in the determination of total sediment load by the sampling method is bedload (fig. 3). Bedload is defined as “the sediment that slides, rolls, or skips along in almost continuous contact with the streambed” (Hubbell, 1964). A consistent bedload sampling program does not exist on the lower Missouri River, and available data are sparse, sporadic, and limited only to Missouri River main-stem stations (tables 1 and 4). Some bedload measurements (BL–84

sampler) have been made in the upper sections of the Lower Missouri River (Galloway and others, 2013; Rus and others, 2015), and recent (2010–14) longitudinal surveys of bedload transport have been led by the USACE using time-sequenced bathymetric techniques (Abraham and Pratt, 2010; Abraham and others, 2010; John Shelley, U.S. Army Corps of Engineers, written commun., 2015) and the Integrated Section Surface Difference over Time version 2 (ISSDOTv2) method (Abraham, 2009). Much of the available Lower Missouri River bedload data, however, are theoretical estimates calculated by means of a variety of formulae and the modified Einstein procedure (Einstein, 1950; Colby and Hembree, 1955) is used most consistently. Such theoretical values include estimates of bedload and the unmeasured load (fig. 3) as the values were determined by subtracting the measured SSL from the theoretical total load. Available bedload data, including measured and theoretical values, cover a substantial range of flows at each station that the data were obtained and, collectively, cover a temporal range from 1950 to 2014 (table 4).

Bedload in large, low gradient rivers has been estimated to range from less than 5 percent (Holmes, 1996; Nittrouer and others, 2008) to 8 percent (Gaeuman and Jacobson, 2007) of the total sediment load. In studies of sediment transport during the 2011 flood and post-flood periods, bedload measured at Lower Missouri River sites using a BL–84 sampler generally was less than 13 percent of total load and differed greatly with flow and by site (Galloway and others, 2013; Rus and others, 2015).

## Miscellaneous Sediment Data

The removal of sediment from the Lower Missouri River by commercial dredging activities has been well documented; however, quantities of other possible sediment gains and losses are estimated (side-channel chute development, channel storage) or unknown (flood-plain storage). Commercial dredging information was available by reach (from Nebraska City, Nebr., to the mouth) and by water year for 1974 through 2014 (table 5); John Shelley, U.S. Army Corps of Engineers, written commun., 2015). Annual calendar-year totals by reach were available for 1974–97, and monthly totals by reach were available for 1998–2014. The average monthly distribution of the annual dredging totals for 1998–2014 were used to discretize the annual 1974–97 totals into estimated monthly values. These monthly estimates then were used to compute commercial dredging totals by water year for 1974–97. The average of 1974–80 water year dredging totals, by reach, was used as an estimate for 1968–73 values. Channel-bed dredging involves the removal and disruption of bed material in storage within the control volume (consisting of a river reach defined upstream and downstream by main-stem stations and laterally by the extent of the active flood plain). In terms of the effect of dredging on the Missouri River sediment budget, the direct

loss of material from the reach control volume is obvious, but the possible secondary effects of dredging on the suspended-sediment and bedload components presented in this study are unquantified. The disturbances and losses to the volume of channel-bed material may result in increases, decreases, or no net effects on SSLs and bedload transport at the downstream station nearest to the activity.

In response to riverine and flood-plain habitat losses resulting from the BSNP (Ferrell, 1996), the USACE began restoring shallow-water habitat in the Lower Missouri River in the mid-1990s through the MRRP. The MRRP projects may reintroduce sediments that were accreted from the BSNP (1912–81), which overlapped the budget analysis period (1968–2014). Some transported sediments, therefore, could potentially have been deposited and later reintroduced within the long-term budget analysis period and be considered a no-net change in storage within the control volume. The MRRP efforts include a variety of channel modifications including side-channel chutes, dike notches, and revetment chutes. Reintroduced material is primarily associated with side-channel chute construction, and contributions from the chute projects were based on documented direct inputs during chute construction and an estimated erosion rate of side-cast materials. Chute development and erosion was estimated based on time-lagged bathymetric surveys or on the chute target dimensions and an estimated rate of erosion as described in Heimann and others (2015). The temporal range of side-channel chute data is from 1993 through 2014, and the spatial extent is within reaches downstream from Sioux City, Iowa (table 6).

Missouri River channels and flood plains can serve as reach budget storage or sediment sink (loss) or sediment source (gains), and this budget component is highly variable temporally and spatially. The quantity of flood-plain storage and the retention period of sequestered sediments in the post-impoundment Lower Missouri River are poorly quantified and are inferred from the reach budget residuals, as are other unmeasured budget components and errors. Missouri River bed volume and mass change have been quantified through periodic longitudinal channel surveys. Based on Missouri River channel-bed surveys led by the USACE in 1994, 2007, 2008, 2009, 2012, 2013, and 2014 (John Shelley, U.S. Army Corps of Engineers, written commun., 2015), and by using an estimated bed density of 97 pounds per cubic foot, the annual channel storage change of selected reaches accounted for -8.6–14.8 percent of annual SSLs at reach input stations (table 7).

## Temporal Variations in Suspended-Sediment Loads and Concentrations

Qualitative temporal variations in SSLs and SSCs were assessed, where available, to put the 1968–2014 budget period in historical context. Annual SSLs and annual flow-weighted concentrations (computed by dividing annual SSL by annual

flow) were plotted with time during 1930–2014 to indicate changes in loads and concentrations, including changes resulting from impoundments. The flow-adjusted SSCs (the residuals from a simple linear regression model of observed SSCs using streamflow as the explanatory variable, expressed in milligrams per liter) at main-stem stations for 1968–2014 also were determined. The observed SSC and streamflow values used in the analyses were obtained from the USGS National Water Information System (NWIS) database at <http://dx.doi.org/10.5066/F7P55KJN>. Qualitative temporal relations in flow-adjusted SSCs (depicted using a second-order polynomial curve fitted to the residuals) can be used to evaluate the magnitude and duration of changes in observed SSCs resulting from effects other than changes in flow.

## Determination of Sediment Budgets

A sediment budget residual was computed for budgets of multiple time intervals by applying equation 1 to a defined control volume. The control volume consisted of a river reach defined upstream and downstream by main-stem stations and laterally by the extent of the active flood plain.

The sediment budget residuals, representing the  $\Delta\text{Mass}/\Delta t$  variable in equation 1 and expressed in tons per budget time interval, were determined by taking the input station SSL; adding the corresponding bedload (if known) and the known gains from tributaries and MRRP activities; and then subtracting known losses from commercial dredging, the output bedload (if known), and the output station SSL. Although the sediment budget residual is determined from simple addition and subtraction of the components in equation 1, the various components represent a variety of particle-size classes and transport mechanisms. Meade and Moody (2010) also indicated that a shortcoming of depictions of sediment transport is the spatial presumption of hydraulic connectivity from source to sink; however, in reality, sediment travels in episodic pulses of varying time scales.

The sediment budget residuals included the change in sediment storage in the reach during the specified time interval, included the unmeasured gains and losses, and included the errors in the measurement and calculation of the measured components. Developed sediment budgets, all using equation 1 but with varying values for  $\Delta t$ , included an average annual post-impoundment sediment budget (1968–2014 water years) for all reaches between the Yankton and St. Louis stations and included example annual (1968–2014 water years), monthly (1968–76 water years), and daily (1968–76 water years) budgets for the Omaha, Nebr., to Nebraska City, Nebr., reach. For the long-term and annual budgets, the net budget residuals are compared to the stage trend (U.S. Army Corps of Engineers, 2012) for average flows at the corresponding main-stem Missouri River stations within the analysis reach, to determine if the sign of the two indicators are in agreement. Details of the development of each budget period presented in this study are discussed in the following sections.

## Average Annual Post-Impoundment Sediment Budget

A single sediment budget residual (in tons) was calculated using available data for the primary budget components in equation 1 for each of seven main-stem reaches in the average annual post-impoundment (1968–2014) sediment budget. An average annual SSL for the 47 years was determined for each station (table 2). The Lower Missouri River and Mississippi River main-stem station values represented the “SEDin” and “SEDout” components in equation 1 and the average annual tributary value, the “Gains”. Availability of annual record at main-stem stations used in the budgets averaged 87 percent. Availability of annual record at tributary stations during 1968–2014 used in the study averaged 28 percent. Sediment contributions from about 2 to 65 percent (average 20 percent) of the local drainage areas of the main-stem reaches was unaccounted for in the sediment budgets resulting in an underestimation of the actual reach “Gain” component. Additional quantified “Gains” included estimated reintroduced material from the MRRP, and “Losses” included commercial dredging removals by reach.

Averaged post-impoundment bedload transport was included in three reach budgets using published bedload-streamflow data sets computed with the modified Einstein procedure. The post-impoundment bedload (plus unmeasured part of total load) estimates for the Nebraska City, St. Joseph, Kansas City, and Hermann stations were computed using bedload values developed for a range of flow conditions (ENTRIX, Inc., 2011) using 1994–2009 averaged sediment data. These data allowed for the inclusion of a bedload estimate in three post-impoundment reach budgets (Nebraska City to St. Joseph stations, St. Joseph to Kansas City stations, and Kansas City to Hermann stations) and also provided consistency in computation methods and resulting bedload estimates among reaches.

## Annual, Monthly, Daily Sediment Budgets

The computation of budget residuals at shorter time scales (annual, monthly, and daily) could better capture the episodic nature of sediment transport not seen in long-term averaged data. Annual, monthly, and daily sediment data were limited to main-stem station inputs and outputs for most reaches in the Lower Missouri River. The reach between the Omaha and Nebraska City stations was selected to provide an example of an annual budget because a single primary Gain (tributary)—the Platte River—is within the reach, and because annual SSL data were available for the Platte River at Louisville, Nebr. station. Information regarding annual sediment storage was unavailable in the reach and the reach was not commercially dredged. The annual reintroduction of sediments as a result of chute construction was estimated to have been between 2000 and 2009 in the reach and was included in the annual budget. Annual bedload estimates were unavailable for the Missouri River at Omaha, Nebr., station during the analysis period, so this component was not quantified. The

47 annual budget residuals for 1968–2014, therefore, include unquantified net changes in storage, in bedload, and in errors in the measurement and computation of SSLs.

Similar to the determination of annual sediment budgets, examples of monthly and daily sediment budgets also were determined for the reach between the Omaha and Nebraska City stations using equation 1. Monthly and daily data for SSL components in this reach budget were available for 1968–76. Storage and bedload values were unknown, commercial dredging did not take place in this reach, and MRRP activities also did not take place in this reach during 1968–76.

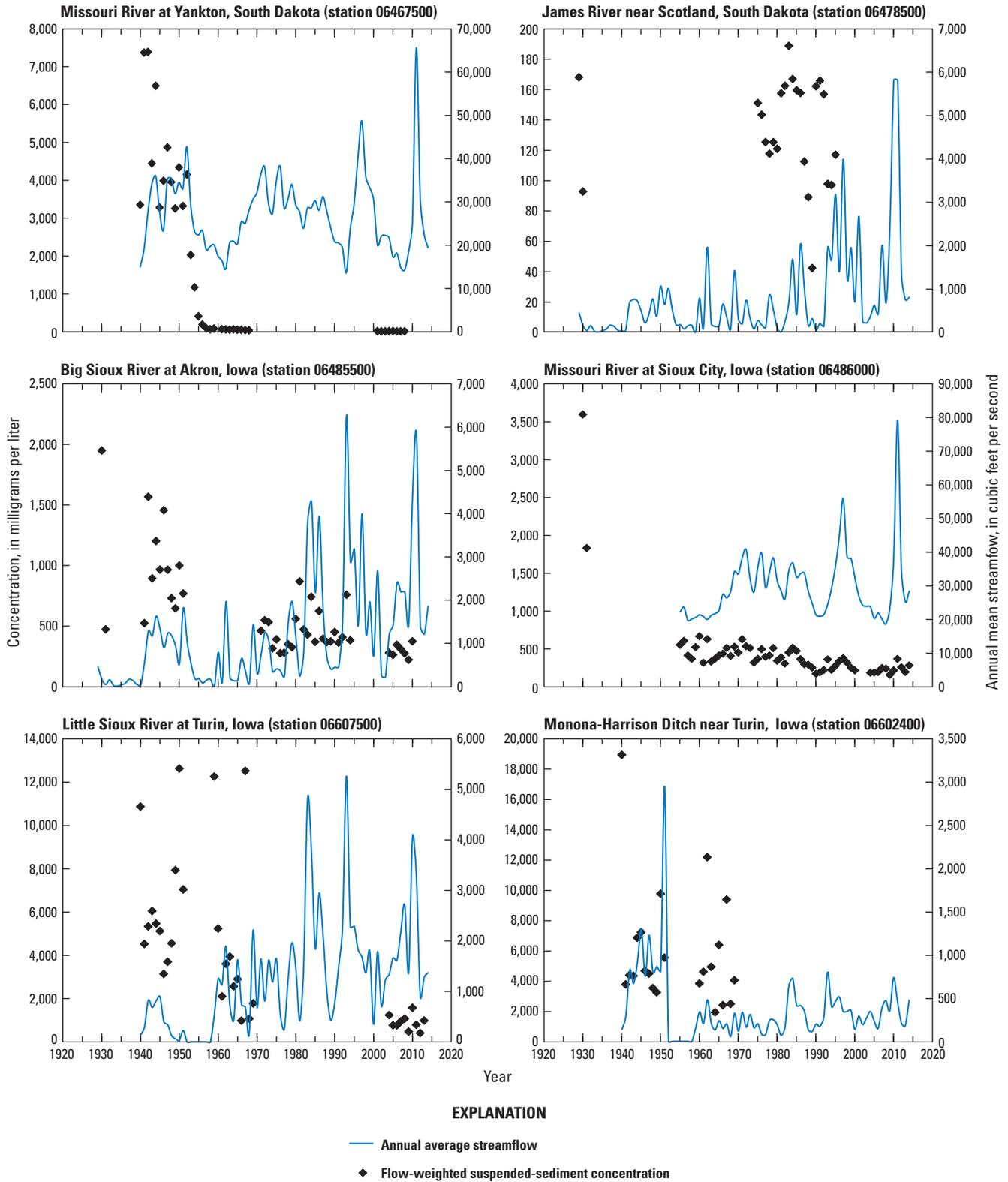
## Sediment Budgets of the Lower Missouri River

Sediment budgets for the Lower Missouri River that include long-term (1968–2014), annual, monthly, and daily budgets are presented. Numerous data gaps exist in the sediment record (table 1) used in the development of the budgets, and the temporal changes in SSCs and SSLs were determined at selected stations during 1930–2014 to put the available data in historical context.

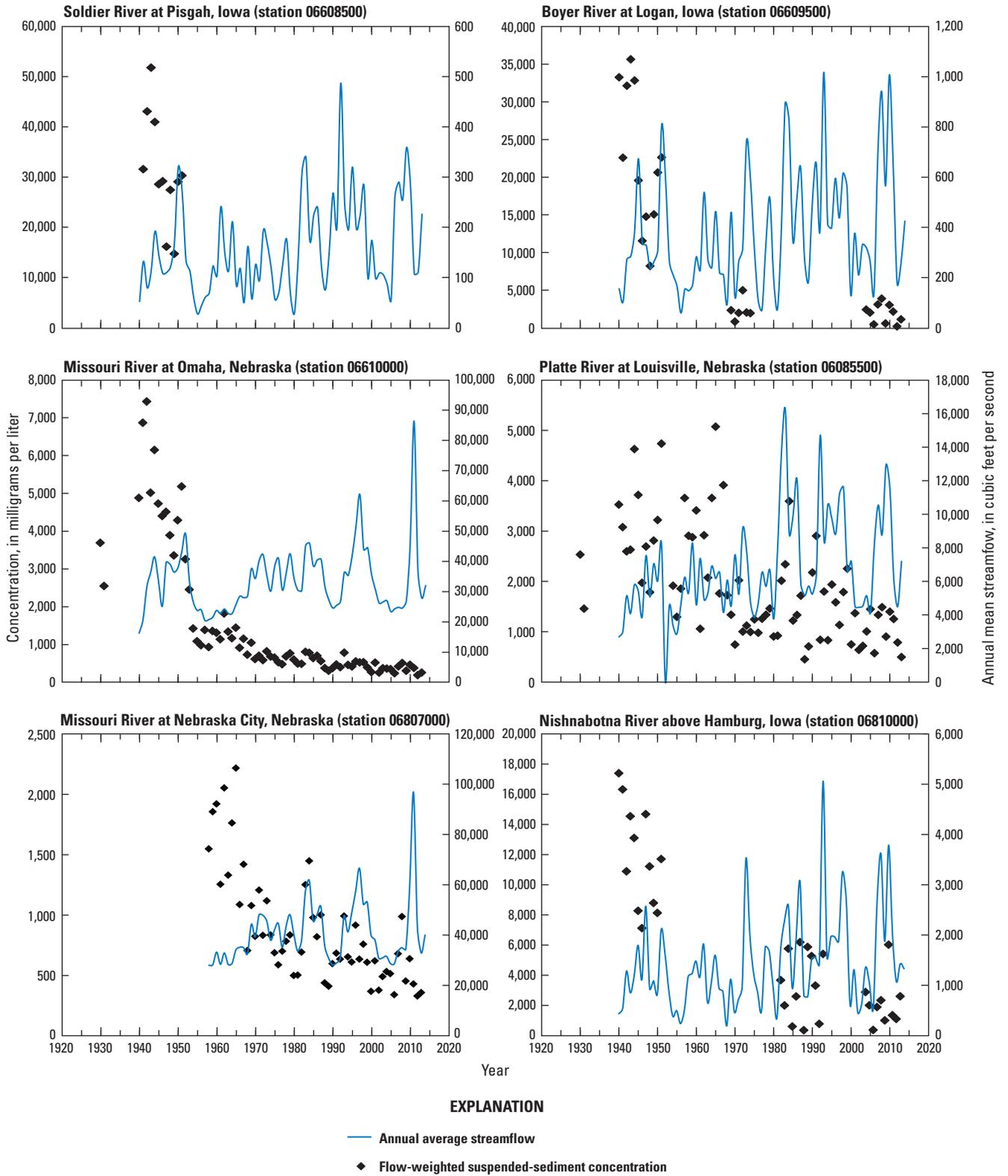
## Temporal Changes in Suspended-Sediment Concentrations and Loads

The sediment record for the post-impoundment budget period is far from complete for most stations; therefore, to view the temporal changes in the partial available record, it is useful to infer a longer term temporal context. The decline in SSC and SSL at Missouri River main-stem stations with time has been well documented (Keown and others, 1986; Meade and Moody, 2010). Causes for the declines have been attributed to main-stem impoundments, tributary impoundments, and erosion control measures. Post-impoundment (1968–2009) declines in SSCs at selected Missouri River stations were from 54.9 to 99.7 percent, and declines in SSLs at selected stations were from 50.5 to 99.8 percent compared to pre-impoundment values (Heimann and others, 2011). Similarly, declines in SSCs were from -54.9 to -93.2 percent and SSLs were from -50.5 to -89.2 percent at selected tributaries during the same period (Heimann and others, 2011).

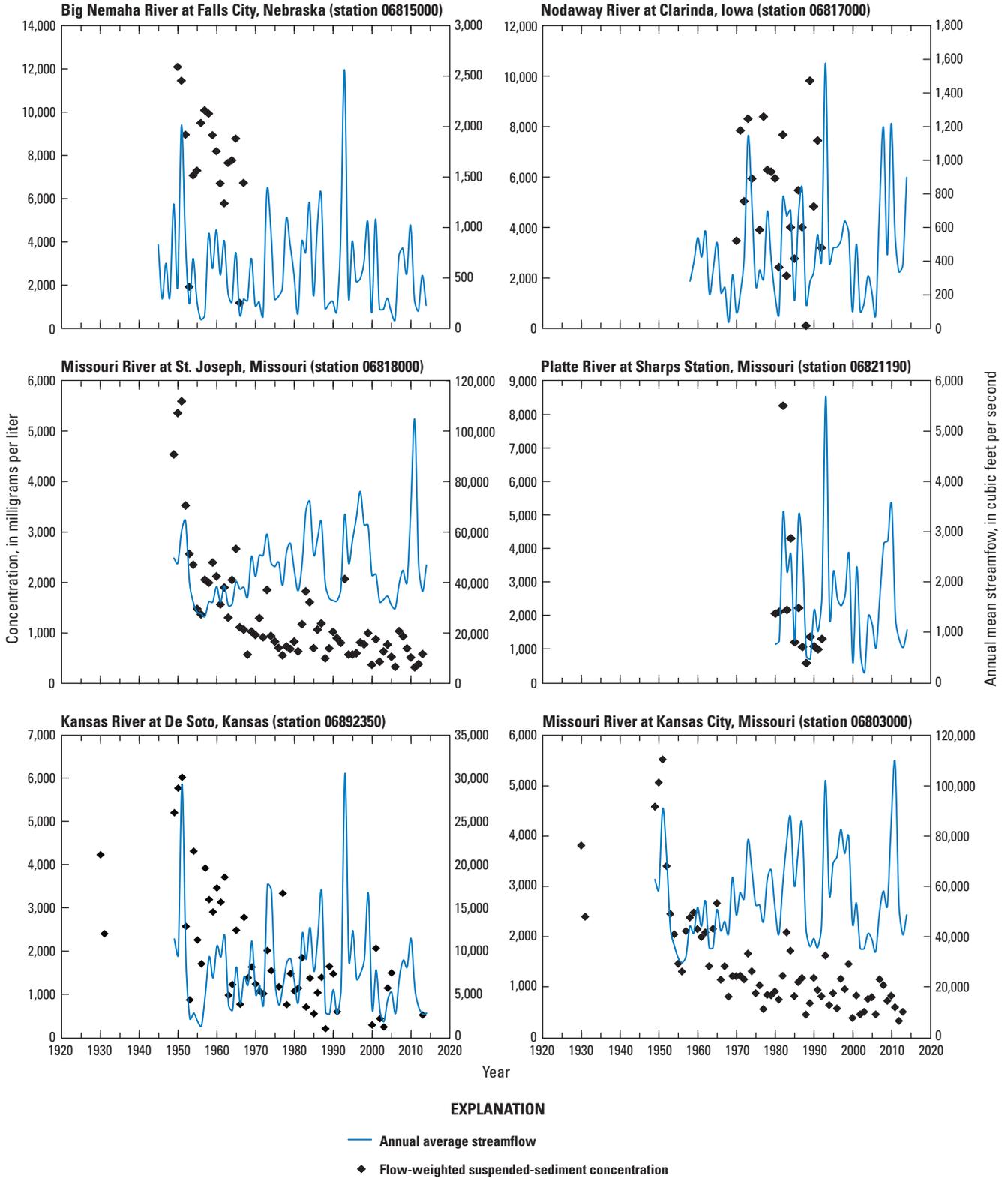
Temporal changes in annual, flow-weighted SSC and annual SSL values for the study sites indicate declining SSC and SSL values at most stations during 1930–2014 (figs. 7–8). Because most temporal changes in sediment loads and flow-weighted concentrations were downward (figs. 7–8) and because most missing record was in the latter part of the analysis period (table 1), the use of partial record at some tributary stations as an average long-term estimate could possibly overestimate the actual long-term average SSL values. Exceptions to this apparent systemic decline in sediment



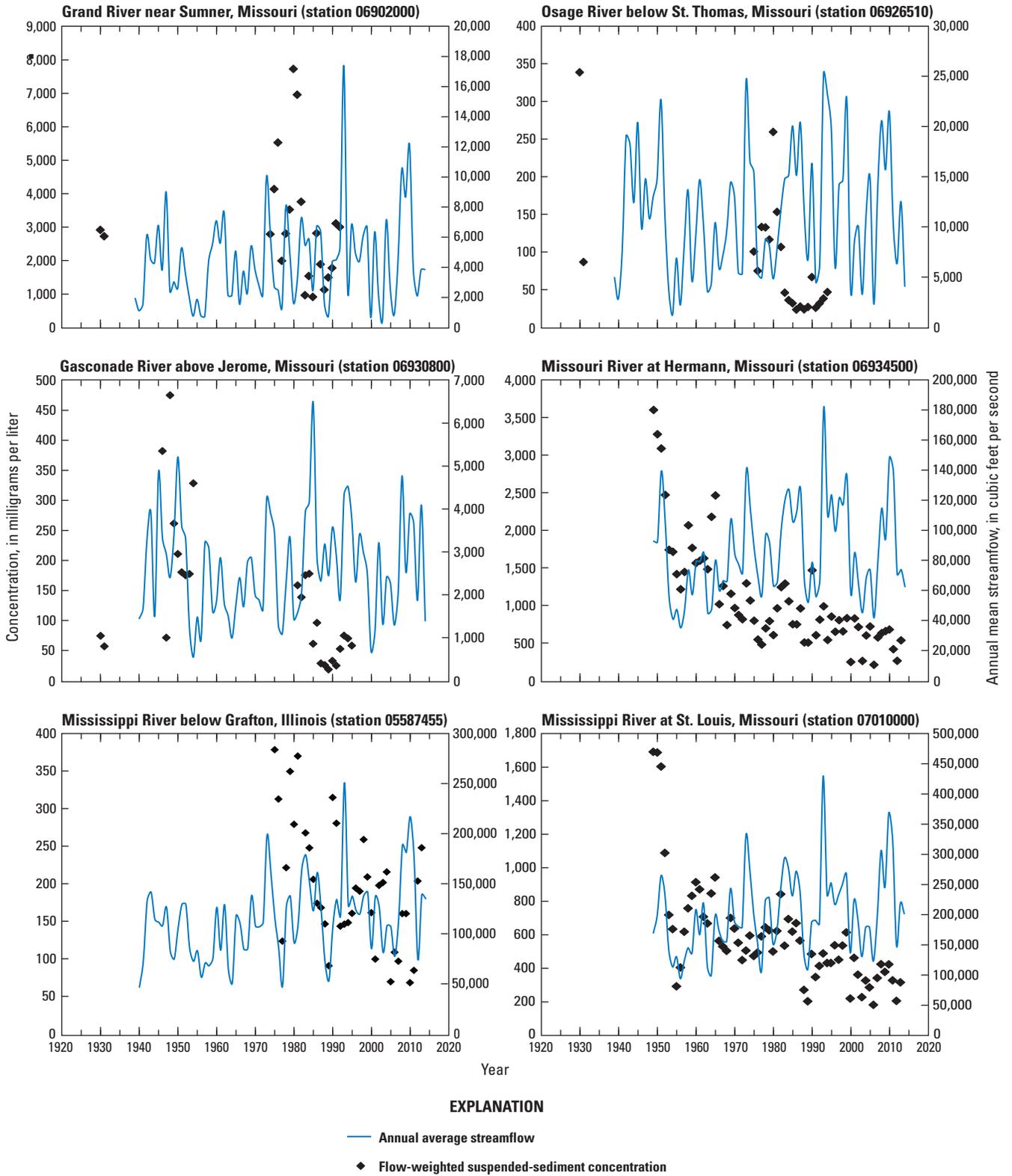
**Figure 7.** Temporal changes in flow-weighted suspended-sediment concentrations at selected stations in the Missouri and Mississippi River Basins, 1930–2014.



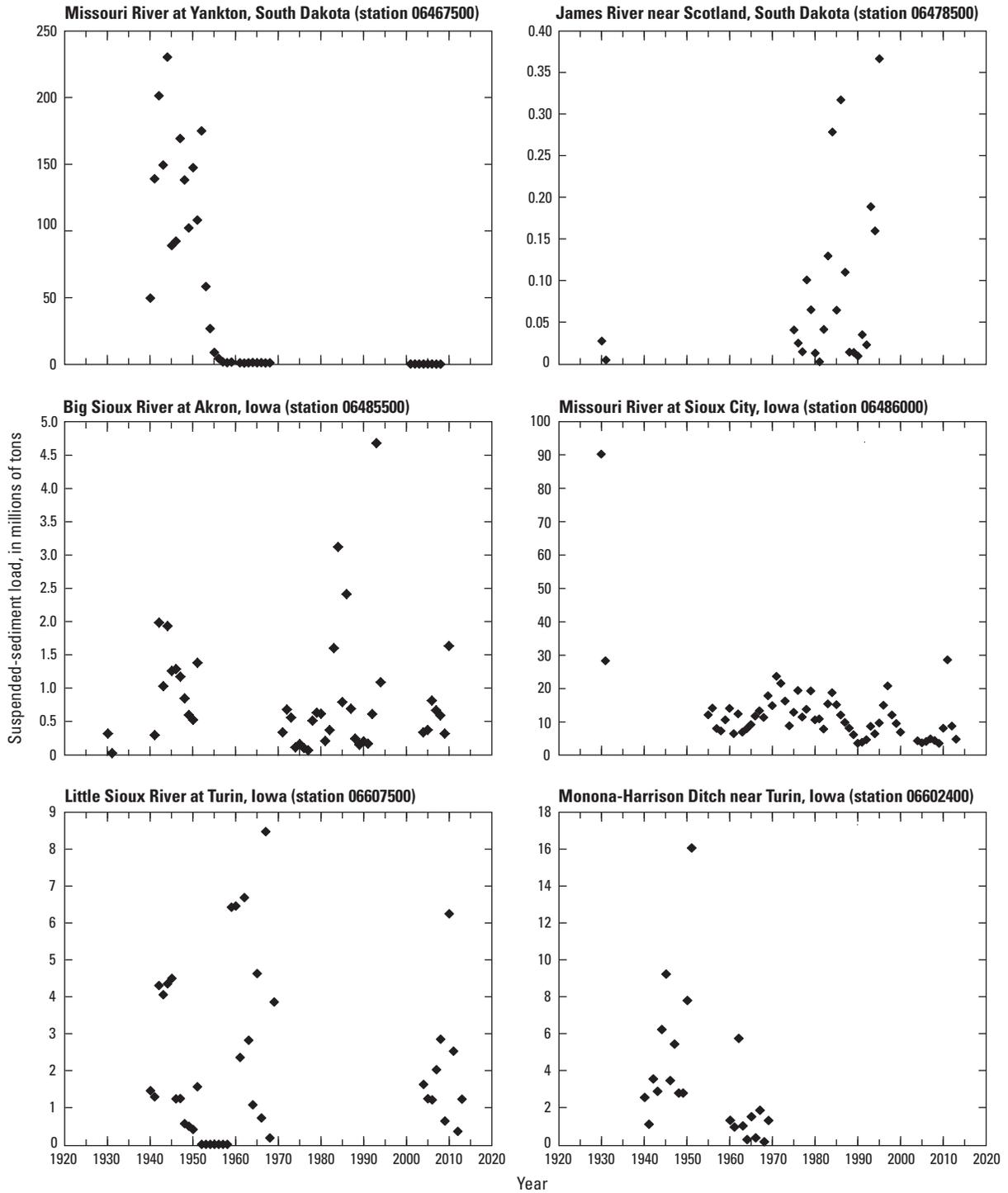
**Figure 7.** Temporal changes in flow-weighted suspended-sediment concentrations at selected stations in the Missouri and Mississippi River Basins, 1930–2014.—Continued



**Figure 7.** Temporal changes in flow-weighted suspended-sediment concentrations at selected stations in the Missouri and Mississippi River Basins, 1930–2014.—Continued



**Figure 7.** Temporal changes in flow-weighted suspended-sediment concentrations at selected stations in the Missouri and Mississippi River Basins, 1930–2014.—Continued

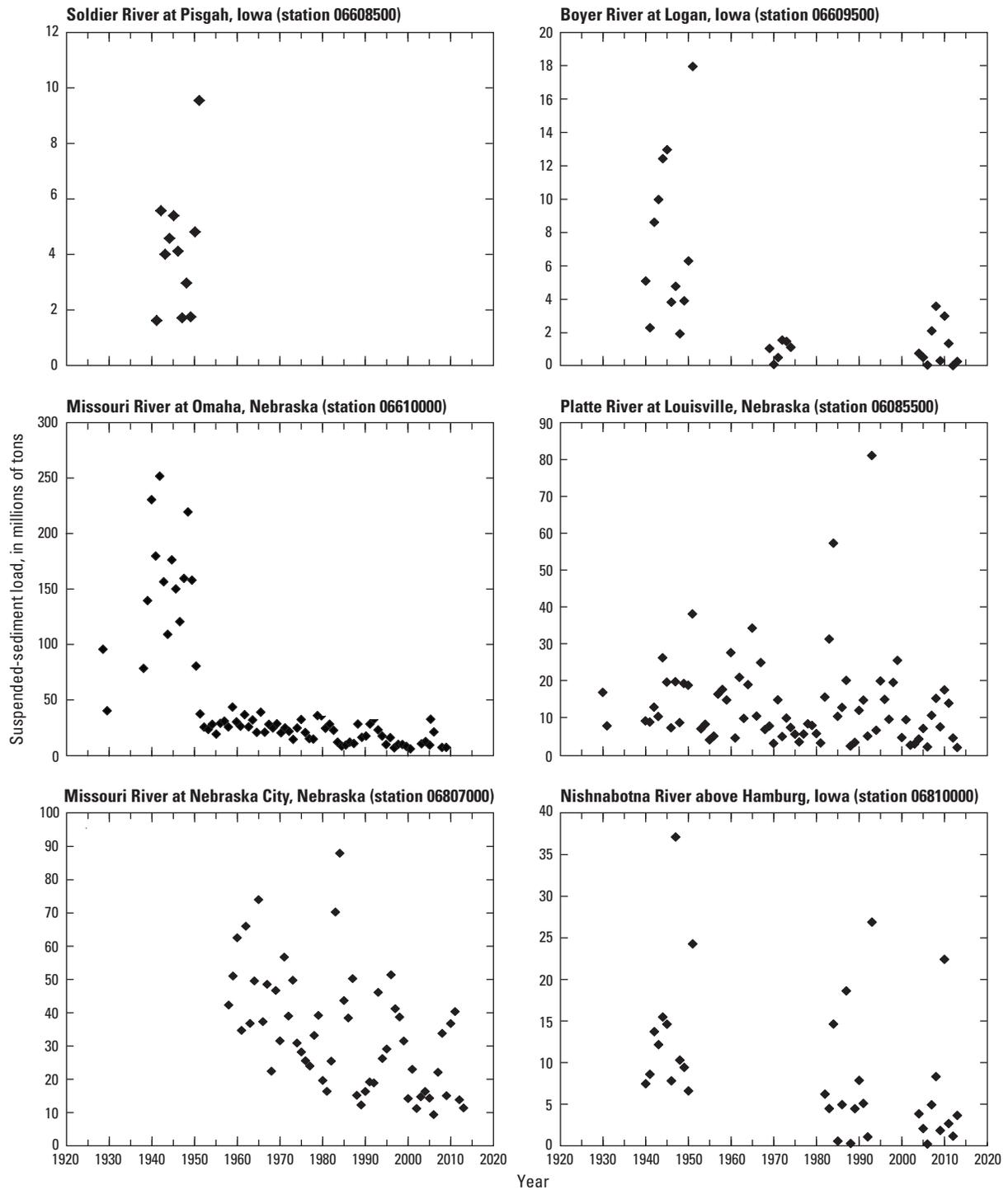


**Figure 8.** Temporal changes in suspended-sediment loads at selected stations in the Missouri and Mississippi River Basins, 1930–2014.

transport were at stations with insufficient record with which to make a determination and included stations on the James River, Soldier River, Big Nemaha River, Little Nemaha River, Nodaway River, and Platte River (Mo.).

The temporal changes in flow-adjusted SSCs at main-stem Missouri River stations indicated an overall downward

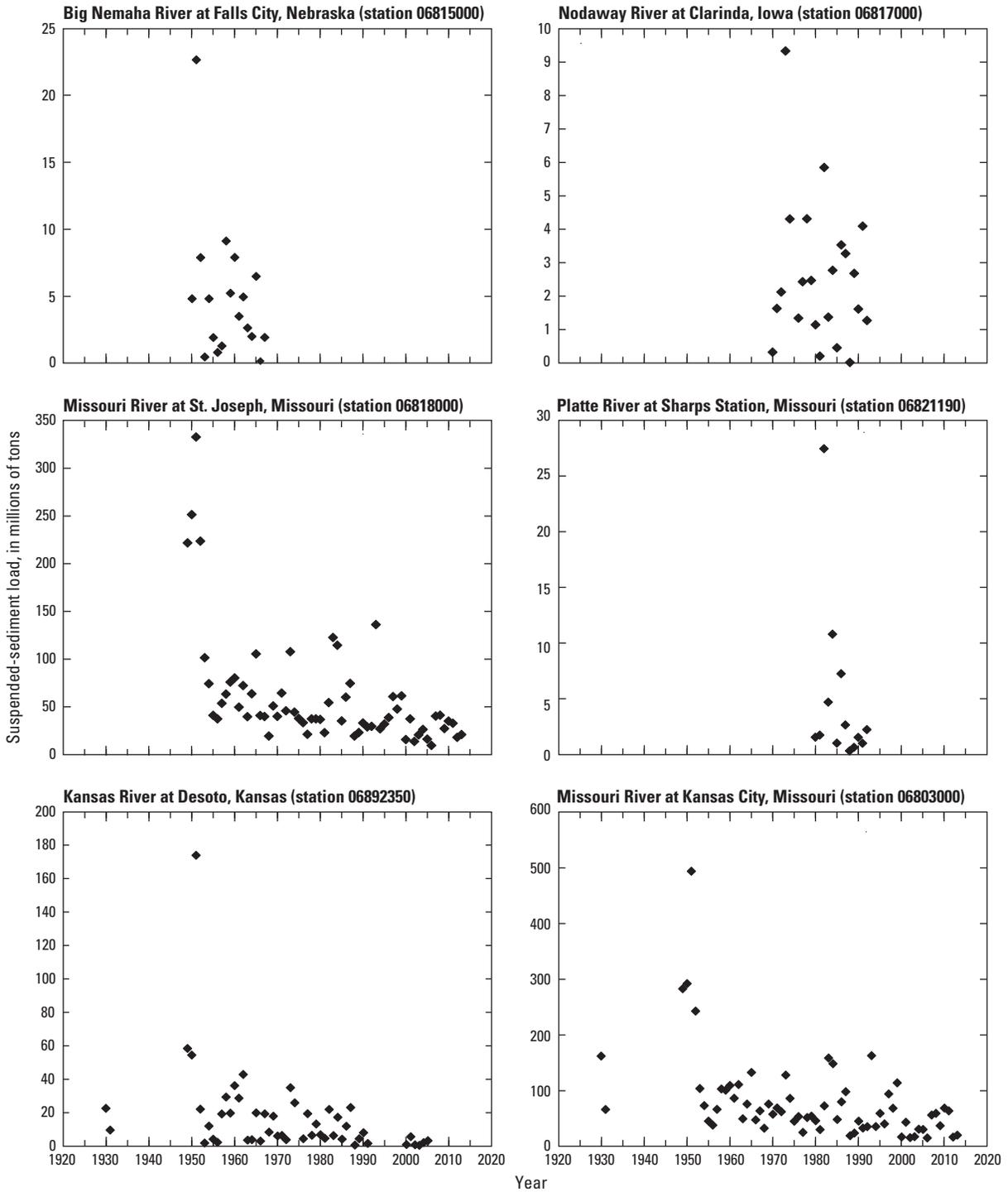
change in concentrations between 1968 and 2014 (fig. 9). The decline in flow-adjusted concentrations at upper Lower Missouri River stations (Sioux City, Omaha, and Nebraska City) were greater between 1968 and about 1990 than between 1990 and 2014, and changes in flow-adjusted SSCs for the St. Joseph, Kansas City, and Hermann stations were greater



**Figure 8.** Temporal changes in suspended-sediment loads at selected stations in the Missouri and Mississippi River Basins, 1930–2014.—Continued

between 1990 and 2014 than before 1990. This difference could be an indication of longitudinal differences in the temporal adjustment of the Lower Missouri River to post-impoundment (and other factors affecting sediment supply) conditions in sediment transport. Temporary declines in flow-adjusted SSC during and following large floods were evident

(most notably during 2010–11 at all stations and during 1993 at the Hermann station) but appeared to be short-lived. The SSC residuals in the sediment transport relation generally returned to near pre-flood values within about 6 months.

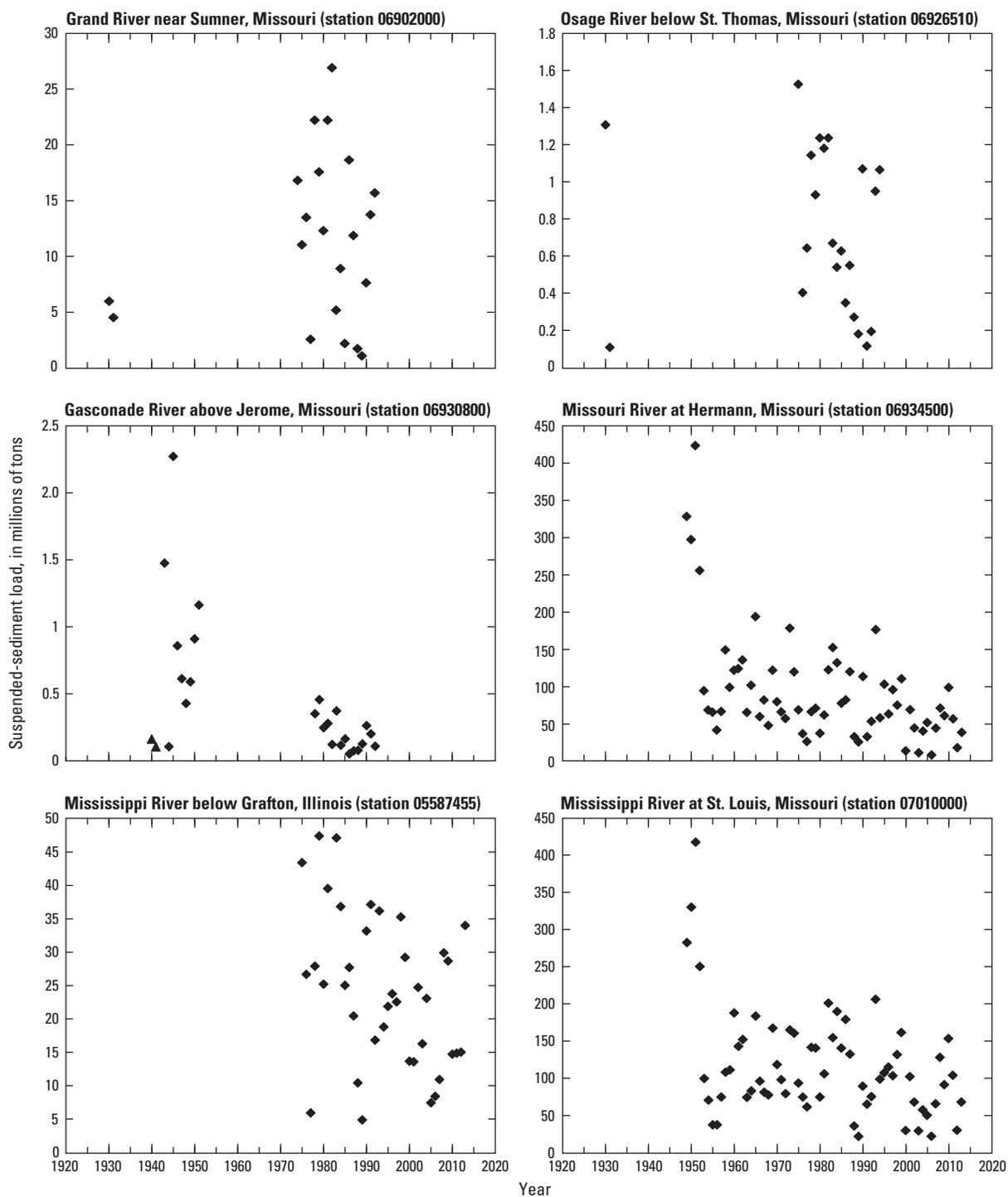


**Figure 8.** Temporal changes in suspended-sediment loads at selected stations in the Missouri and Mississippi River Basins, 1930–2014.—Continued

### Long-Term, 1968–2014 Sediment Budget

A generalized long-term sediment budget was determined for the post-impoundment period (1968–2014) using the available record as a best estimate of the long-term average suspended-sediment transport (table 8; fig. 10). Long-term average annual SSLs among the Missouri River main-stem

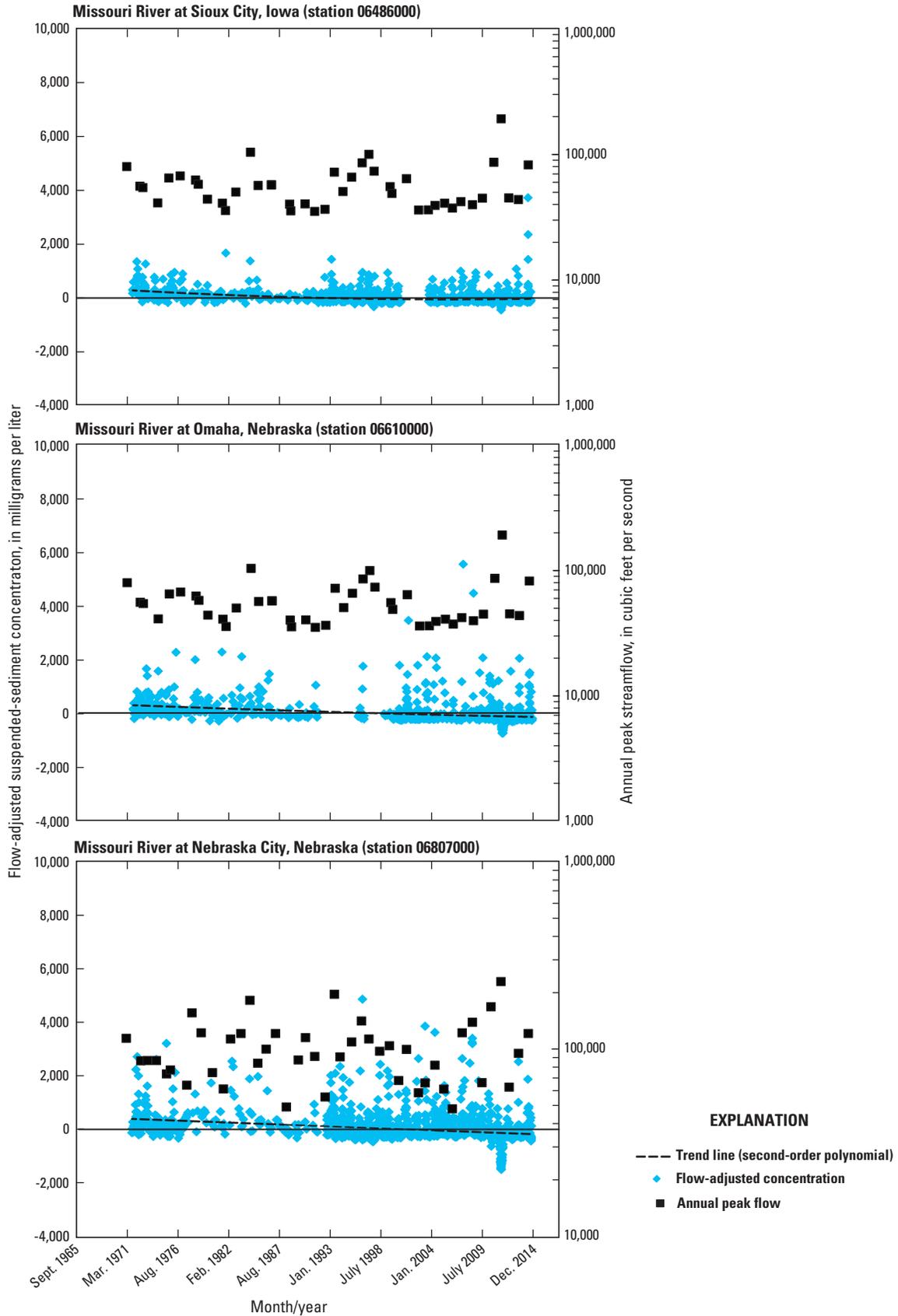
stations ranged from 0.33 million tons at the Yankton station to 71.2 million tons at the Hermann station. Gaged tributary gains accounted for 9–36 percent of the local reach budgets, and cumulative gaged tributary contributions accounted for 84 percent of the long-term average SSL at the Hermann station. Although the budgets generally were incomplete and missing bedload, channel and flood-plain storage, and ungaged



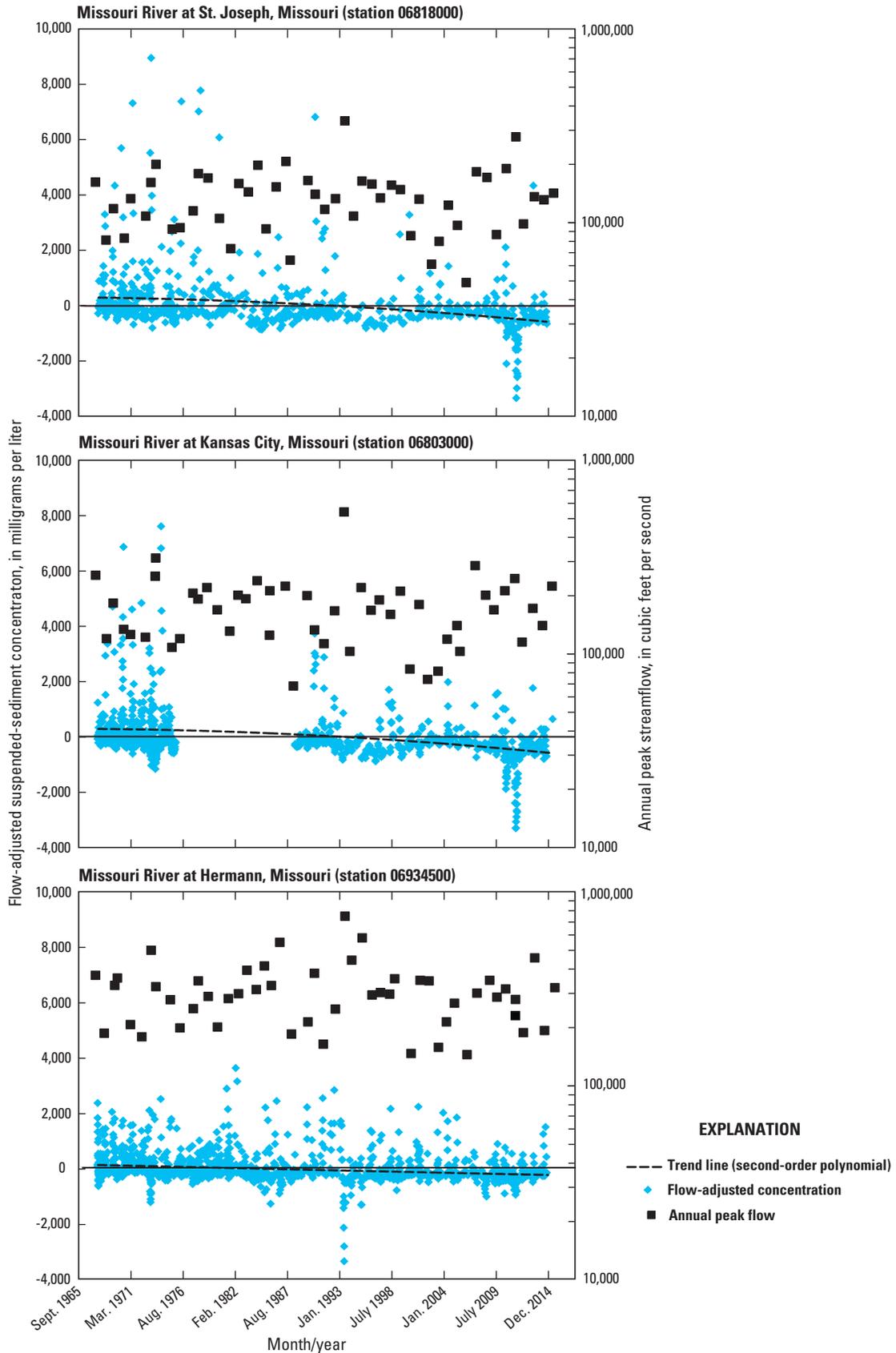
**Figure 8.** Temporal changes in suspended-sediment loads at selected stations in the Missouri and Mississippi River Basins, 1930–2014.—Continued

tributary contributions, the budget residuals for six of the seven reaches ranged from -7.0 to 1.7 million tons, or from -9.2 to 4.0 percent of the reach output SSL, and were within the 10 percent reported measurement error of annual SSLs for large rivers (Colby, 1956; Holmes, 1996). The remaining reach, Yankton, S. Dak., to Sioux City, Iowa, had an average

budget residual of -9.8 million tons per year, (-88 percent of the reach output SSL), indicating the input SSL and reach gains from gaged tributaries accounted for a small part of output SSL. A reach-by-reach description of the long-term sediment budget is provided in the following sections.



**Figure 9.** Temporal changes in flow-adjusted suspended-sediment concentrations at main-stem Lower Missouri River stations, 1968–2014.



**Figure 9.** Temporal changes in flow-adjusted suspended-sediment concentrations at main-stem Lower Missouri River stations, 1968–2014.—Continued

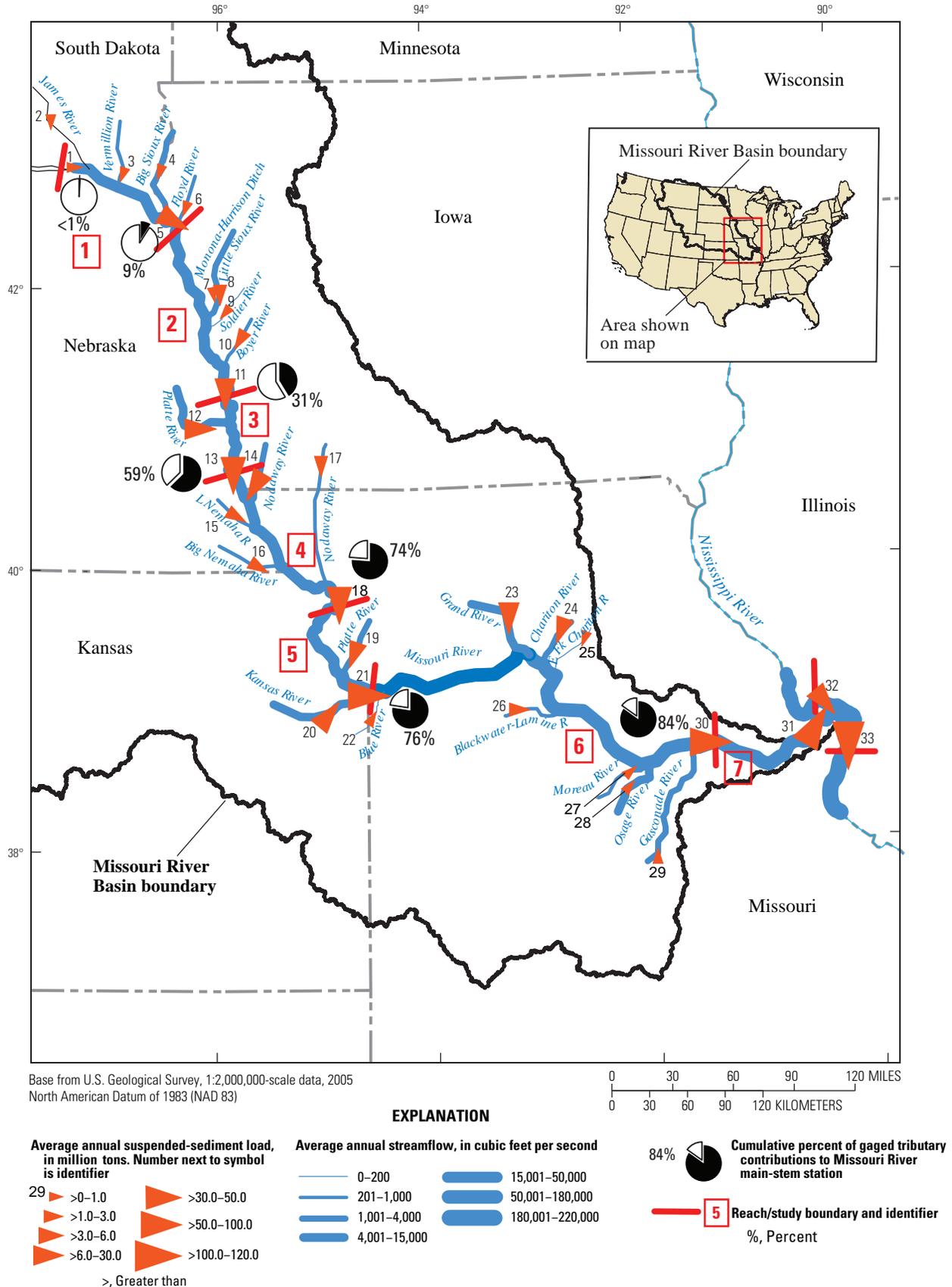


Figure 10. Generalized suspended-sediment budget of the Lower Missouri River, 1968–2014.

## Reach 1—Missouri River at Yankton, S. Dak., to Sioux City, Iowa

The 79-mile reach from Yankton to Sioux City had the largest average budget residual of any of the seven reaches at -9.8 million tons per year, accounting for 88.0 percent of the 1968–2014 average annual SSL at the Sioux City station (11.2 million tons; [table 8](#)). The measured tributary SSL inputs in this reach in total averaged about 1.0 million tons per year, and the 9.8 million tons per year residual generally could be accounted for by storage losses from bank and channel-bed scour. The largest measured gain in this reach was from the Big Sioux River at Akron, Iowa, station with an average SSL of about 0.80 million tons per year ([fig. 11](#)). Cumulative measured tributary inputs upstream from the Sioux City station account for 9.3 percent of the average annual SSL at the Sioux City station. The ungagged local contributing drainage accounts for about 15 percent of the local reach drainage area. No annual bedload data were available for this reach nor were any quantified changes in storage from commercial dredging or MRRP activities.

The Missouri River within the Yankton to Sioux City reach has degraded in response to the sediment-free discharge from Gavins Point Dam (U.S. Army Corps of Engineers, 2012). Streambed degradation downstream from dams is a widely documented fluvial adjustment of the coarse sediment supply to the carrying capacity of the river. The 1968–2011 stage trends downstream from Gavins Point Dam and at the Sioux City station were downward and directly correlated with the substantial suspended-sediment budget deficit determined for this reach. During the budget period, the stage trend at the tailwaters of Gavins Point Dam indicated a decline of about 12 feet (ft; U.S. Army Corps of Engineers, 2012) for a flow of 20,000 cubic feet per second (ft<sup>3</sup>/s); however, the average flow at the Yankton station was 26,000 ft<sup>3</sup>/s. Between 1968 and 2011, the stage at the Sioux City station declined 12 ft for a flow of 30,000 ft<sup>3</sup>/s (U.S. Army Corps of Engineers, 2012); a flow comparable to the average 1968–2014 flow at the Sioux City station of 32,000 ft<sup>3</sup>/s. The declining stage trend was consistent among the range of flows at the Sioux City station. A substantial part of the stage declines at the Yankton and Sioux City stations was during high-flow (1995–1998 and 2011). Geomorphological analyses of the approximately 60 miles of the Missouri River downstream from Gavins Point Dam (Pokrefke and others, 1998; Biedenbarn and others, 2001; Elliot and Jacobson, 2006) indicated that channel-bank erosion is a substantial source of transported sediment and perhaps a larger source of transported material than bed scour, at least in some reaches and measurement periods.

## Reach 2—Missouri River at Sioux City, Iowa, to Omaha, Nebr.

The residual of the sediment budget for the 116-mile reach from Sioux City to Omaha is a long-term average deficit

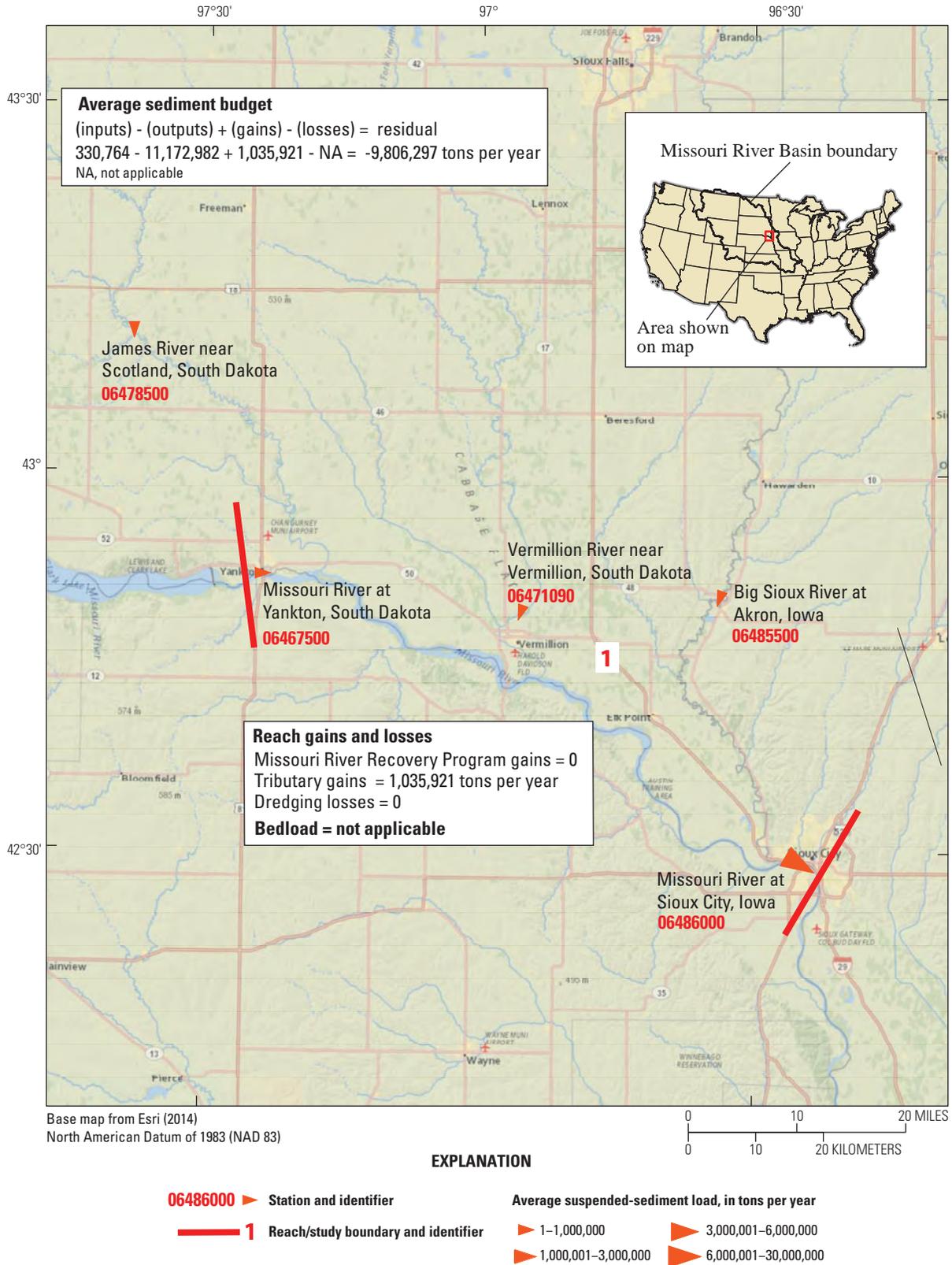
of about 1.7 million tons per year ([table 8](#)). The residual of -1.7 million tons is -9.2 percent of the average annual SSL of 18.9 million tons at the Omaha station and within the reported 10 percent accuracy of annual SSLs (Holmes, 1996). Cumulative tributary inputs in the Sioux City to Omaha reach account for 30.6 percent of the long-term average annual SSL of the main stem at the Omaha station, although sediment contributions from about 20 percent of the local drainage area were unmeasured. The largest sediment gain in the reach was from the Little Sioux River at Turin, Iowa, station with an estimated SSL of 1.9 million tons per year ([fig. 12](#)).

No corresponding long-term information on bedload transport was available for the Sioux City to Omaha reach. The average annual MRRP-associated gain for this reach was about 0.20 million tons ([table 8](#)). The corresponding stage trends for the main stem at the Omaha station for 1968–2014 indicated a change of -1 ft for a flow of 10,000 ft<sup>3</sup>/s to -4 ft for a flow of 40,000 ft<sup>3</sup>/s (U.S. Army Corps of Engineers, 2012), and the average 1968–2014 flow was 36,000 ft<sup>3</sup>/s. A substantial part of the stage decline at the Omaha station at average and lower flows can be attributed to flooding in 2011; and, since 2011 stages have rebounded in this reach (Dan Pridal, U.S. Army Corps of Engineers, written commun., 2016). Increasing stages of about 2 ft at constant higher flows (100,000 ft<sup>3</sup>/s) possibly indicate aggrading conditions from bank and flood-plain storage during the same period; however, the increases in stages also could be an indication of levee construction or modifications.

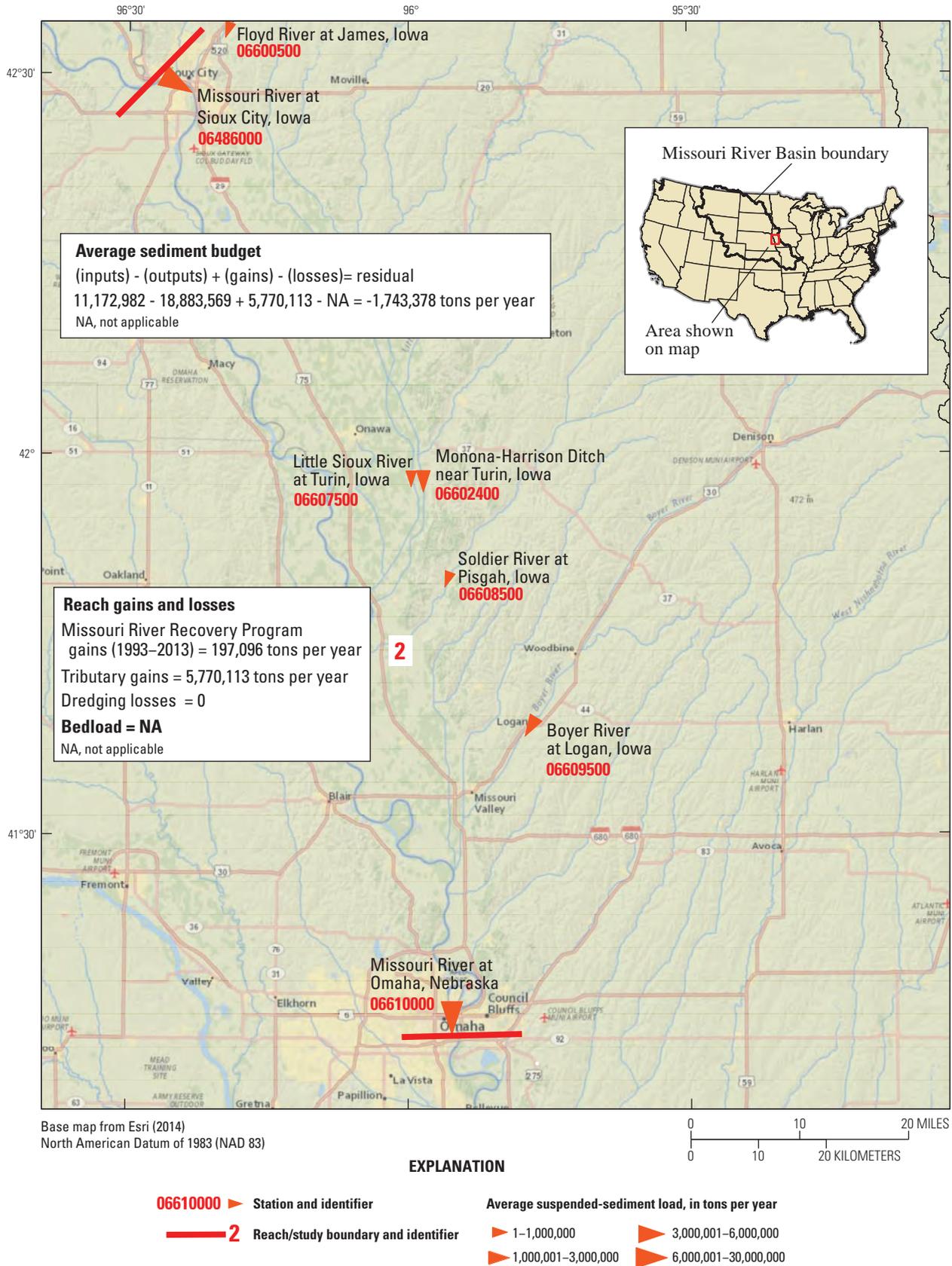
## Reach 3—Missouri River at Omaha, Nebr., to Nebraska City, Nebr.

The reach from Omaha to Nebraska City is the shortest (53 miles) and “simplest” main-stem reach; the reach only has one primary tributary (Platte River). The long-term sediment budget residual was -0.5 million tons or -1.7 percent of the SSL at the Nebraska City station ([table 8](#)). Tributary contributions were 11.1 million tons per year or 36.8 percent of SSLs at the Nebraska City station. Downstream from the confluence with the Platte River and beyond, the cumulative tributary inputs to the Missouri River account for most (in this reach 59.4 percent of the SSL at the Nebraska City station) of the sediment sources in the Lower Missouri River. Although the Platte River is the only major tributary in this reach, it generally was the largest tributary supplier of sediment to the Lower Missouri River. The average annual load at the Platte River at Louisville, Nebr., station was about 11.1 million tons ([table 8](#); [fig. 13](#)). The Platte River drainage area also accounts for about 98 percent of the local reach drainage area.

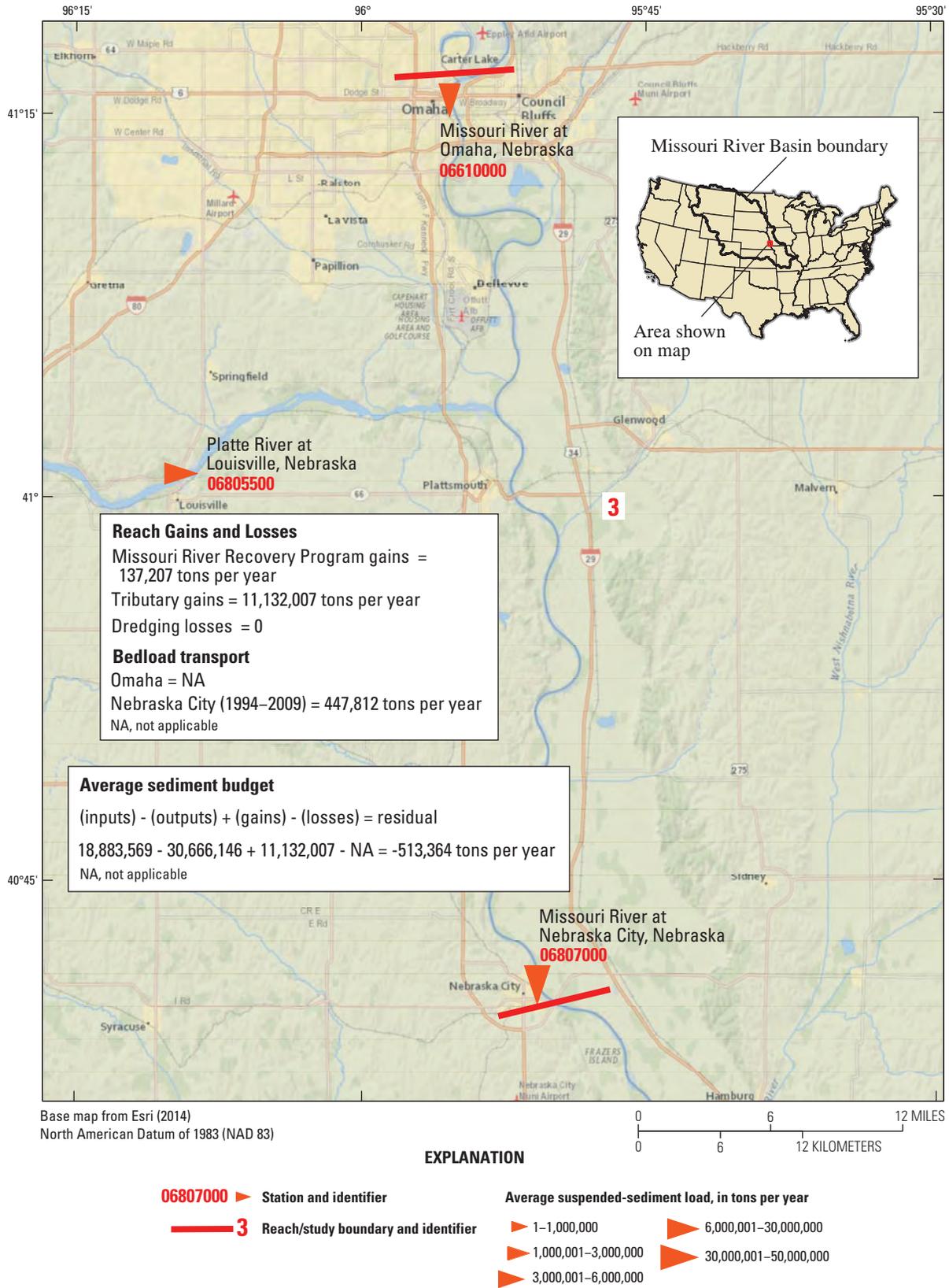
The average annual bedload input in the reach was unknown, but the estimated average output was 0.45 million tons. The average MRRP additions were about 0.14 million tons per year, and commercial dredging did not take place



**Figure 11.** Long-term average sediment budget, Lower Missouri River reach 1, Yankton, South Dakota, to Sioux City, Iowa, 1968–2014.



**Figure 12.** Long-term average sediment budget, Lower Missouri River reach 2, Sioux City, Iowa, to Omaha, Nebraska, 1968–2014.



**Figure 13.** Long-term average sediment budget, Lower Missouri River reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–2014.

in the reach. The net stage change during 1968–2011 for the reach was small and near 1 ft for a flow of 40,000 ft<sup>3</sup>/s (U.S. Army Corps of Engineers, 2012), and the average streamflow of the main stem at the Nebraska City station was 42,600 ft<sup>3</sup>/s for the post-impoundment period. Stages for higher streamflows (70,000–180,000 ft<sup>3</sup>/s) indicated possible bank and flood-plain aggradation because stages increased about 2 ft during the same period.

#### Reach 4—Missouri River at Nebraska City, Nebr., to St. Joseph, Mo.

During 1968–2014, the net average suspended-sediment budget residual in the 114-mile reach from Nebraska City to St. Joseph was 1.7 million tons per year or 4.0 percent of the average annual load for the St. Joseph station (42.3 million tons; table 8). The local contribution from tributaries in this reach was 13.5 million tons per year or 31.7 percent of the SSL at the St. Joseph station, and cumulative contributions from tributaries accounted for 74.3 percent of the SSL at the St. Joseph station. The largest contributing tributary in this reach was the Nishnabotna River. The average SSL was 6.4 million tons per year for the Nishnabotna River above Hamburg, Iowa, station (fig. 14). The SSLs at the Little Nemaha River at Auburn Nebr., station (1.6 million tons per year; fig. 14) and Big Nemaha River at Falls City, Nebr., station (2.9 million tons per year; fig. 14) have greater uncertainty (possibly 100 percent) compared to other tributary gains in the reach because these tributary SSLs were estimated. The gaged tributaries account for only 35 percent of the local reach drainage area and, therefore, the additional 65 percent of unmeasured sediment contributions could be substantial and add to the already positive budget residual.

The 1994–2009 average annual theoretical bedload transport at the Nebraska City station was 0.45 million tons per year and at the St. Joseph station was 0.34 million tons per year, based on theoretical ratings developed using data from ENTRIX, Inc. (2011). The difference in the 1994–2009 average annual theoretical bedload estimates for the Nebraska City to St. Joseph reach was +0.10 million tons per year and was used as the estimated net bedload transport in the 1968–2014 budget for this reach (table 8). During 1968–2014, the average total dredging loss was 0.09 million tons per year, and the estimated average annual total MRRP gain was 0.30 million tons. The stage trend for the St. Joseph station indicated net degrading conditions for 1968–2011 that ranged from -3.5 ft for a flow of 40,000 ft<sup>3</sup>/s to -1.5 ft for a flow of 70,000 ft<sup>3</sup>/s (U.S. Army Corps of Engineers, 2012). During the analysis period, the average annual flow for the St. Joseph station was 49,000 ft<sup>3</sup>/s. Stages for constant flows greater than 100,000 ft<sup>3</sup>/s indicated increasing stage trends and possible aggrading conditions of about 2–3 ft. The sediment budget for this reach was more complete than that of most Missouri River reaches, and the difference between the positive total budget residual

and the negative stage trend indicated that data gaps and uncertainties limit the determination of aggrading or degrading conditions based on budget residuals alone.

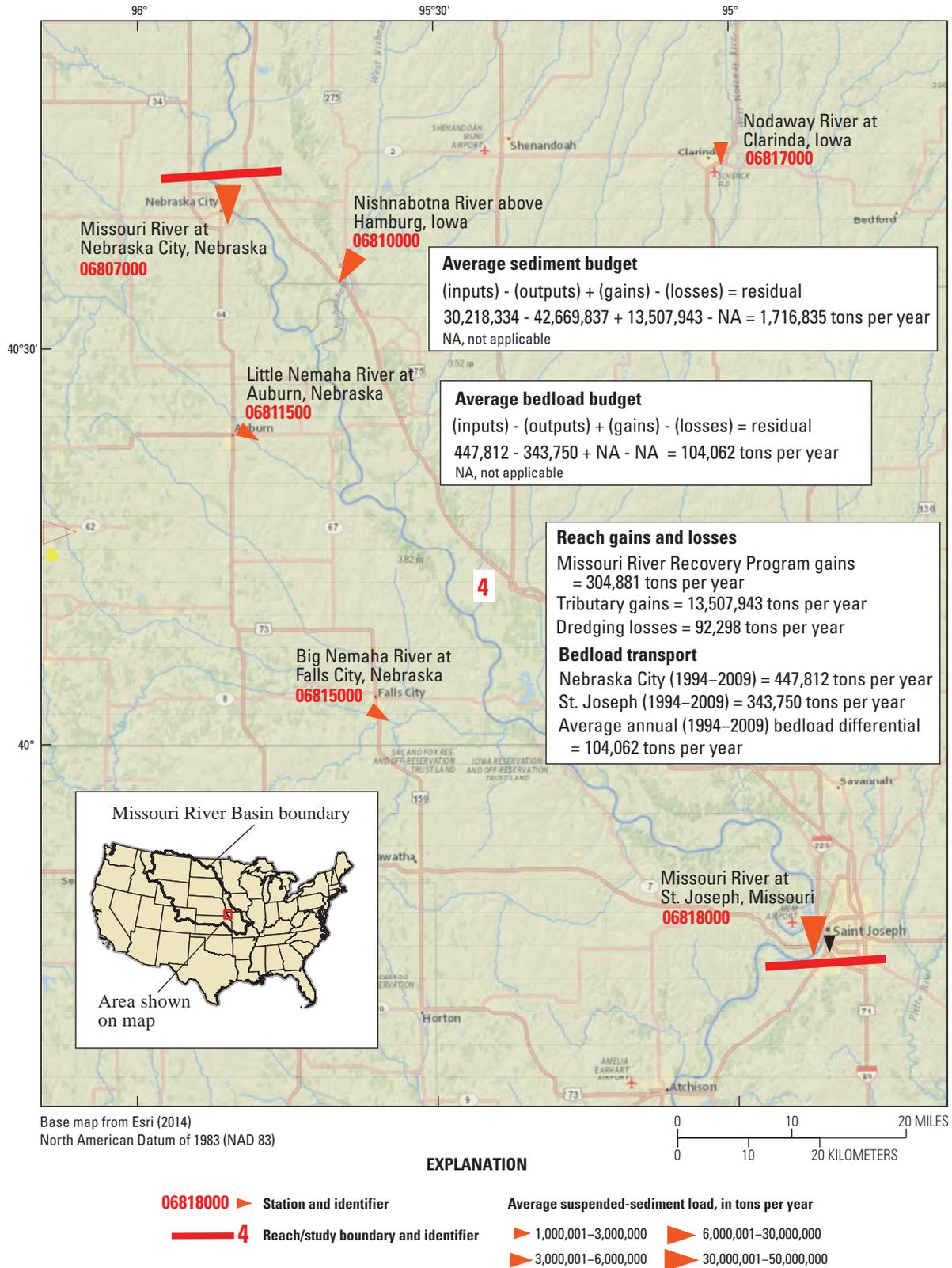
#### Reach 5—Missouri River at St. Joseph, Mo., to Kansas City, Mo.

The net suspended-sediment budget residual in the 82-mile reach from St. Joseph to Kansas City was -2.8 million tons or -4.9 percent of the average 57.2 million tons per year total sediment load at the Kansas City station (table 8). Tributaries accounted for 11.7 million tons or 20.6 percent of average reach outputs, and cumulative gaged tributary contributions accounted for 76.1 percent of the long-term average annual SSL at the Kansas City station. The largest tributary in this reach was the Kansas River. The average annual SSL at the Kansas River at De Soto, Kans., station was 8.8 million tons (fig. 15). Sediment contributions from the ungaged local reach drainage area should not be a substantial gain because the local ungaged drainage area was within the error of the basin area determination.

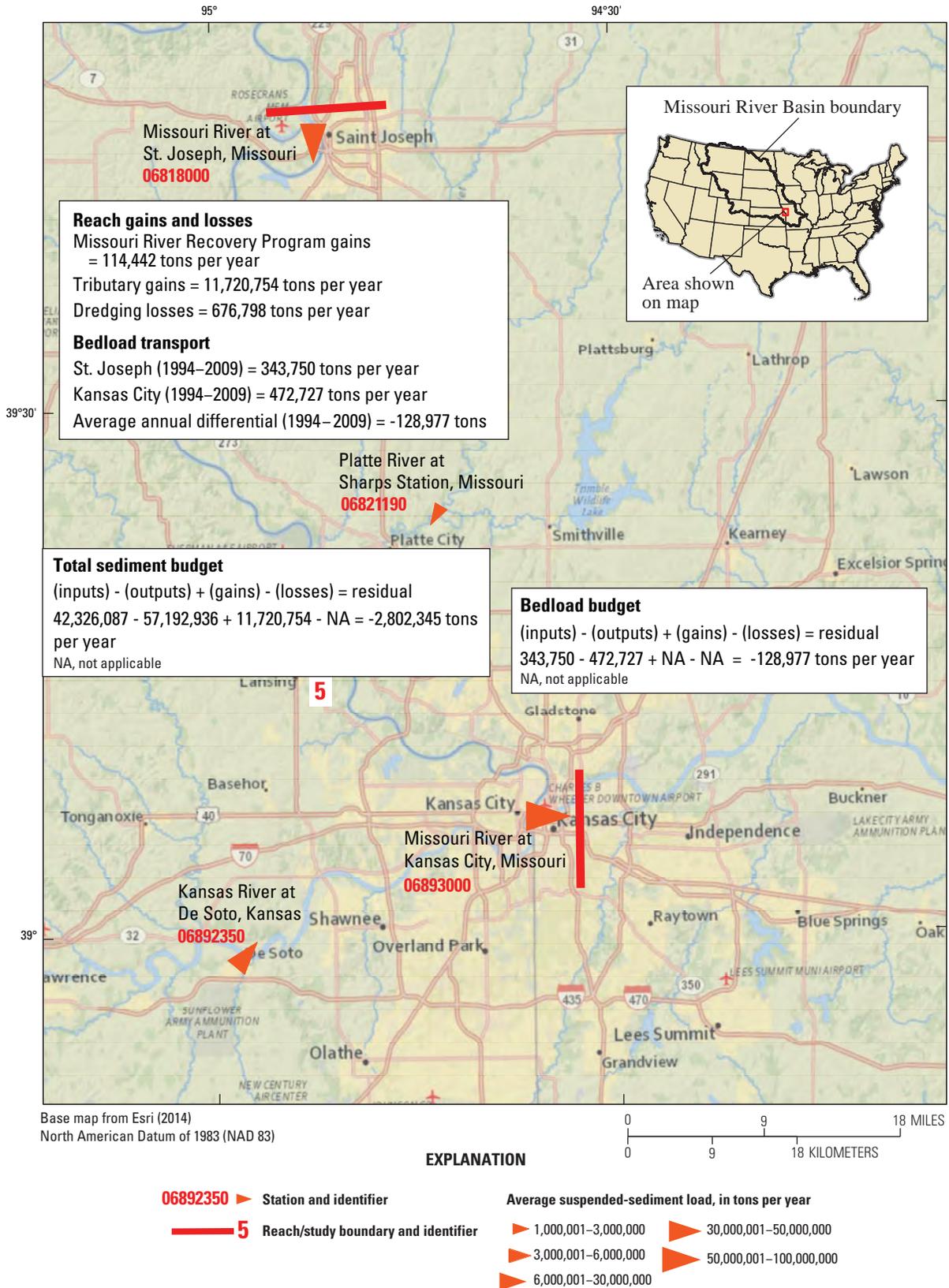
For 1994–2009, the average annual theoretical bedload transport at the St. Joseph station was 0.34 million tons and at the Kansas City station was 0.47 million tons using data from ENTRIX, Inc. (2011). The difference in the 1994–2009 theoretical bedload estimates for the St. Joseph to Kansas City reach was -0.13 million tons per year and was used as the bedload estimate in the 1968–2014 budget (table 8). The average annual total dredging loss in the reach for 1968–2014 was about 0.7 million tons per year, and the average annual total MRRP contribution was about 0.68 million tons per year. Stage trends during 1968–2011 for the Kansas City station also indicated degrading conditions that were -7 ft for a flow of 40,000 ft<sup>3</sup>/s and -6 ft for a flow of 70,000 ft<sup>3</sup>/s (U.S. Army Corps of Engineers, 2012), and the average 1968–2014 annual flow at the Kansas City station was 58,500 ft<sup>3</sup>/s. The decline in stage trends was consistent for all reported flows.

#### Reach 6—Missouri River at Kansas City, Mo., to Hermann, Mo.

The reach from Kansas City to Hermann is the longest main-stem study reach (268 miles) and included eight major gaged tributaries in the reach budget. The average suspended-sediment budget residual for 1968–2014 was 0.07 million tons per year or 0.1 percent of the total sediment load of 71.7 million tons at the Hermann station (table 8). The largest sediment gain in the reach was at the Grand River near Sumner, Mo., station with an average SSL of 9.8 million tons, and the second largest sediment gain in the reach was at the Chariton River near Prairie Hill, Mo., station with an average annual SSL of about 3.6 million tons per year (fig. 16).



**Figure 14.** Long-term average sediment budget, Lower Missouri River reach 4, Nebraska City, Nebraska, to St. Joseph, Missouri, 1968–2014.



**Figure 15.** Long-term, average sediment budget, Lower Missouri River reach 5, St. Joseph, Missouri, to Kansas City, Missouri, 1968–2014.

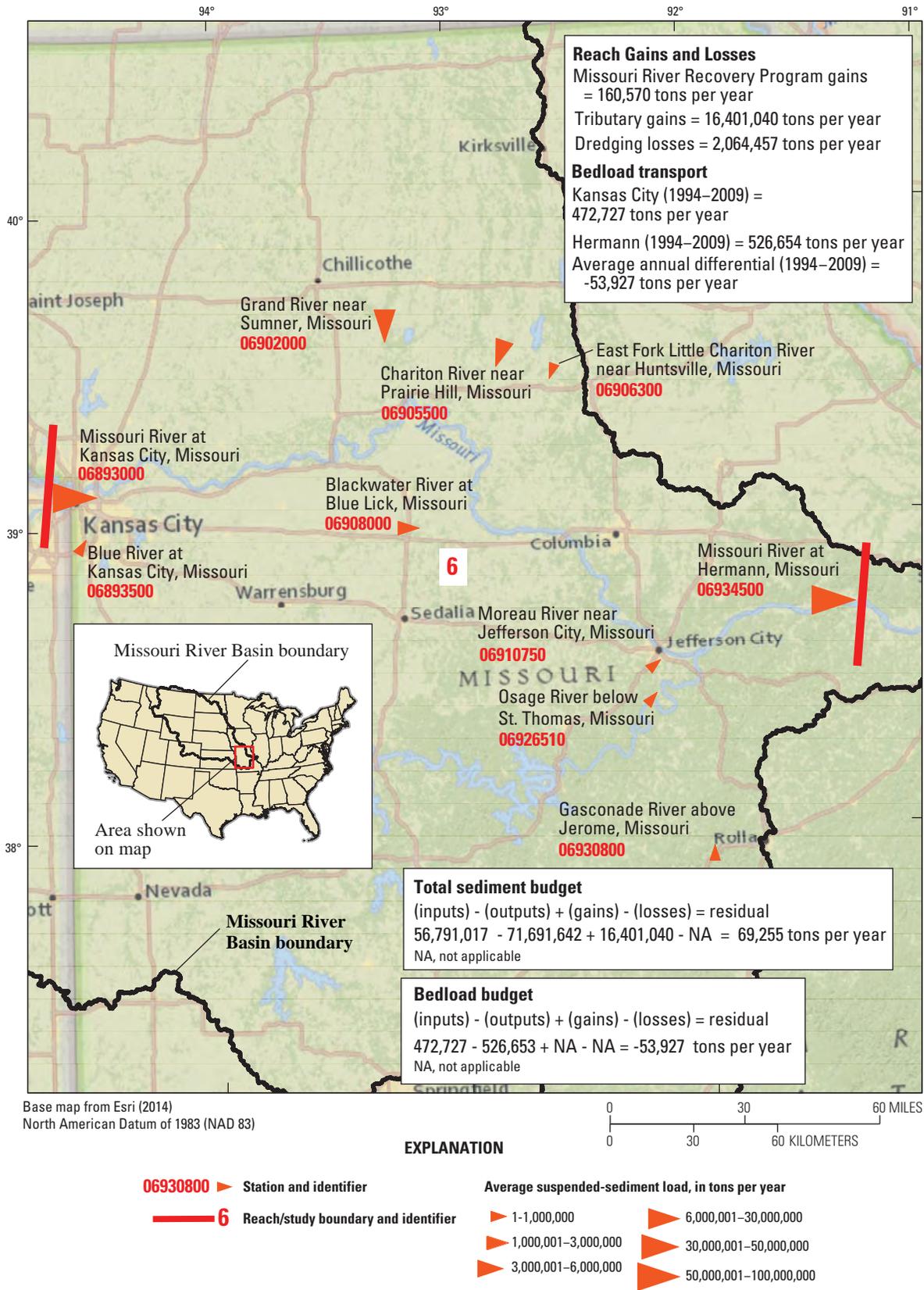


Figure 16. Long-term, average sediment budget, Missouri River reach 6, Kansas City, Missouri, to Hermann, Missouri, 1968–2014.

For the reach from Kansas City to Hermann, the total SSL was 16.4 million tons per year, and 82 percent was contributed from the Grand River near Sumner, Mo., and Chariton River near Prairie Hill, Mo., stations. Sediment data, however, were unavailable since the early 1990s. The cumulative, gaged Lower Missouri River tributary SSL inputs, which are derived from about 86 percent of the interim drainage area between Gavins Point Dam and Hermann station, accounted for about 84 percent of the long-term average annual SSL at the Hermann station.

The average annual bedload transport at the Kansas City station was 0.47 million tons and at the Hermann station was 0.53 million tons using 1994–2009 data from ENTRIX, Inc. (2011), and the bedload residual for the Kansas City to Hermann reach used in the 1968–2014 budget was -0.05 million tons (table 8). The average annual total MRRP gain in the reach was 0.16 million tons, and average annual total commercial dredging loss was 2.0 million tons. The corresponding stage trend for 1968–2011 in the reach indicated a change in stage from -2 ft (for flow of 70,000 ft<sup>3</sup>/s) to -1 ft (for a flow of 100,000 ft<sup>3</sup>/s; U.S. Army Corps of Engineers, 2012), with a corresponding average annual flow of 87,000 ft<sup>3</sup>/s. Stage trends for flows of 200,000 and 300,000 ft<sup>3</sup>/s indicated little change with time and stages for flows of 400,000 and 500,000 ft<sup>3</sup>/s indicated small increases of 1–2 ft. Whether the increases are the result of possible bank and flood-plain storage or if the increases are the result of levee modifications is unclear, which also is the case for stations with increasing stage trends at higher flows.

## Reach 7—Missouri River at Hermann, Mo., to the Mississippi River at St. Louis, Mo.

The net suspended-sediment budget residual for the reach from the Missouri River at Hermann to the Mississippi River at St. Louis (including the upper Mississippi River gains as measured at the Grafton station) was -7.0 million tons or -6.9 percent of the average annual SSL at the St. Louis station (102.8 million tons; table 8; fig. 17). No major tributaries contribute sediment between the Hermann station and the mouth of the Missouri River. The 1968–2011 SSL at the Hermann station was 69 percent of the SSL at the St. Louis station, and the average SSL at the Grafton station was 23 percent of the post-impoundment SSL for the St. Louis station. The 1994–2009 bedload estimate for the Hermann station was 0.53 million tons using data from ENTRIX, Inc. (2011); however, no long-term or annual bedload estimates were available for the Grafton or St. Louis stations. The average annual total MRRP additions in the reach were zero and the average annual commercial dredging amount in the Missouri River part of the budget reach was 1.3 million tons per year. Corresponding stage trends for 1968–2009 at the St. Louis station indicated a 0 to -1 ft change in stage for a constant flow of 200,000 ft<sup>3</sup>/s (Watson and Biedenbarn, 2009), which closely corresponds to the 1968–2009 average annual flow of 218,000 ft<sup>3</sup>/s at the

St. Louis station. Stages at higher flows (300,000–700,000 ft<sup>3</sup>/s) also indicated little net change with time. Despite the 0.3 percent increase in drainage area between the Hermann station and the Missouri River at St. Charles, Mo., station, the estimated long-term loads between the two stations had an average 17 percent increase. The SSL estimate at the Missouri River at St. Charles, Mo., station, however, is based on only three available years (2006–8) of concurrent record with the Hermann station and the uncertainty in this estimate is substantial.

## Annual, Monthly, and Daily SSL Budgets

The Lower Missouri River reach from Omaha, Nebr., to Nebraska City, Nebr., had periods of concurrent record for each of the primary suspended-sediment components with which to analyze and determine a SSL budget for selected annual, monthly, and daily time increments (table 9). The determination of annual, monthly, and daily sediment budget examples are limited to this reach because data gaps, even in the SSL record for most tributary stations, generally prevent the determination of annual, monthly, and particularly daily sediment budgets in most Lower Missouri River reaches.

### Annual Budget

Other than 5 consecutive years of negative annual sediment budget residuals in the early 1970s, the residuals for the Omaha, Nebr., to Nebraska City, Nebr., reach were marked by substantial oscillations between years (table 9; fig. 18). The annual SSL budget residuals for the Omaha to Nebraska City reach ranged from about -14 to 12 million tons (fig. 18). For the Nebraska City station, the budget residuals represented a range from -24 to 40 percent of the annual SSL and generally were between -20 and 20 percent. The temporal changes in the cumulative partial budget residuals (fig. 19) were poorly correlated with the comparatively steady 1968–2011 annual stage trends at the Nebraska City station for a flow of 30,000 ft<sup>3</sup>/s (fig. 20). The steady stages provide an indication that the annual budget residuals during this period should be minimal. The comparison displays the net variability in the annual SSL budget components and provides an indication of the net magnitude of missing budget components (bedload, sediment storage, and sampling and computation errors). The example also indicates that even in this “simple” and data rich reach, the development of an accurate detailed sediment budget is limited by data gaps.

### Monthly Budget

A monthly SSL budget was estimated for the Omaha, Nebr., to Nebraska City, Nebr., reach using concurrent record for 1968–76. A monthly SSL budget could account for sediment transport differences on the time scale of large

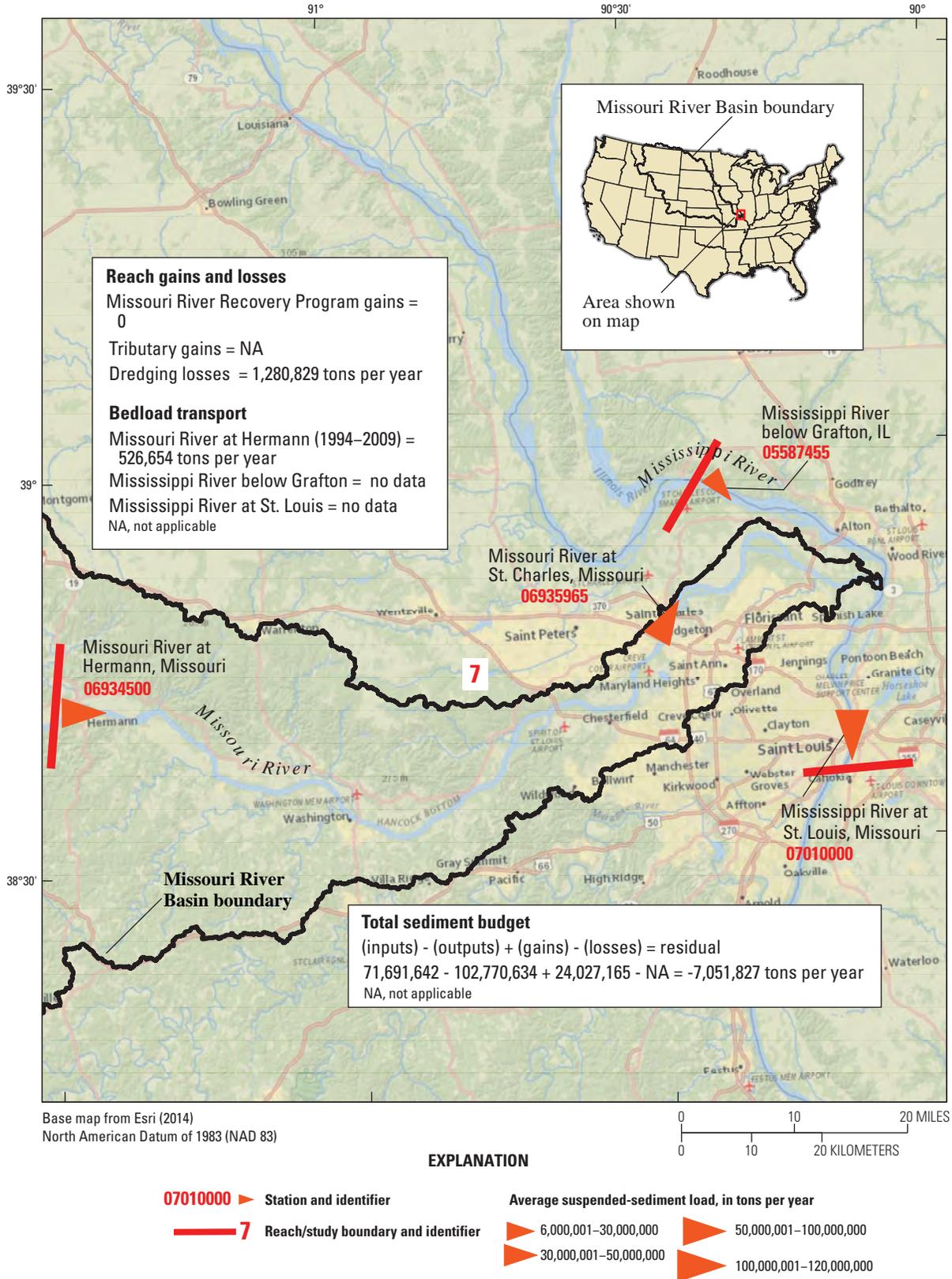
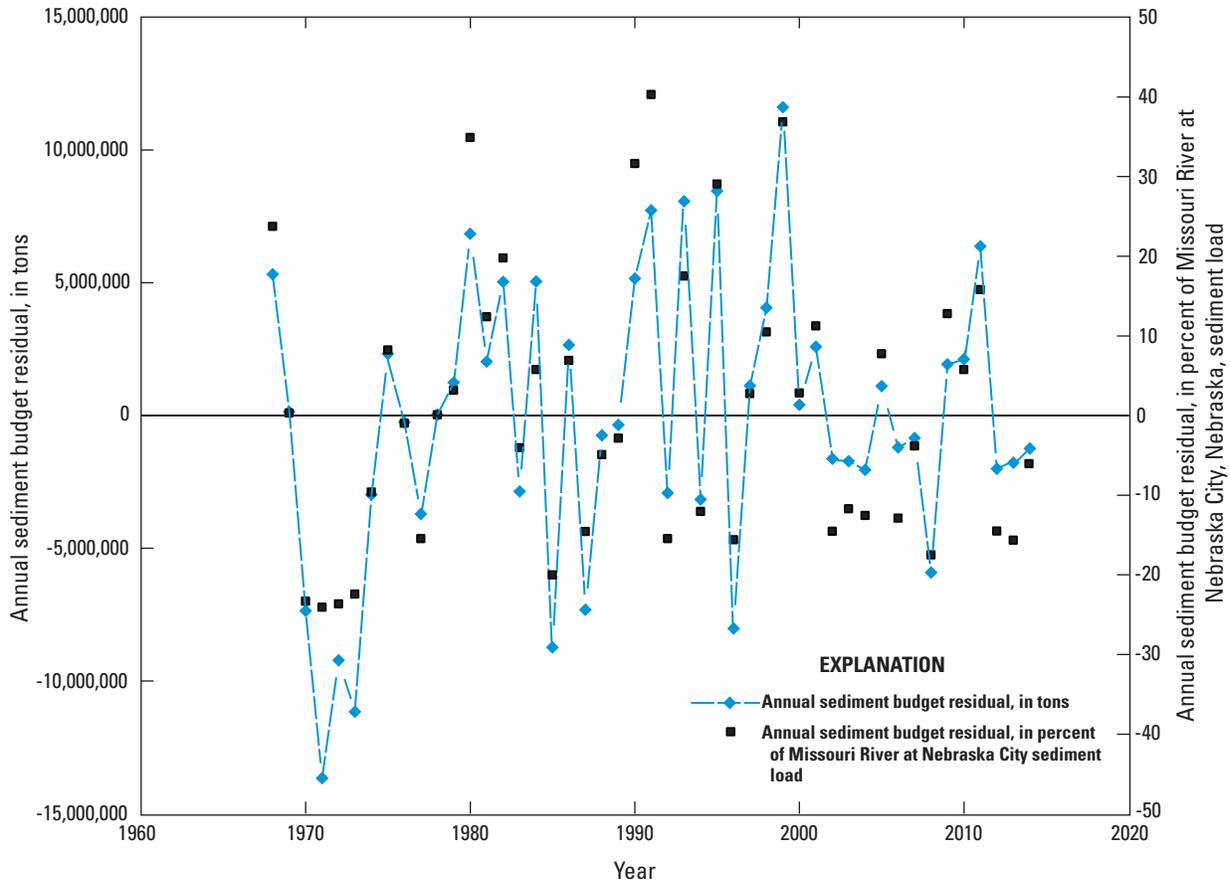


Figure 17. Long-term average sediment budget, Lower Missouri River reach 7, Hermann, Missouri, to St. Louis, Missouri, 1968–2014.



**Figure 18.** Annual, monthly, and daily sediment budget for the Lower Missouri River, reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–2014.

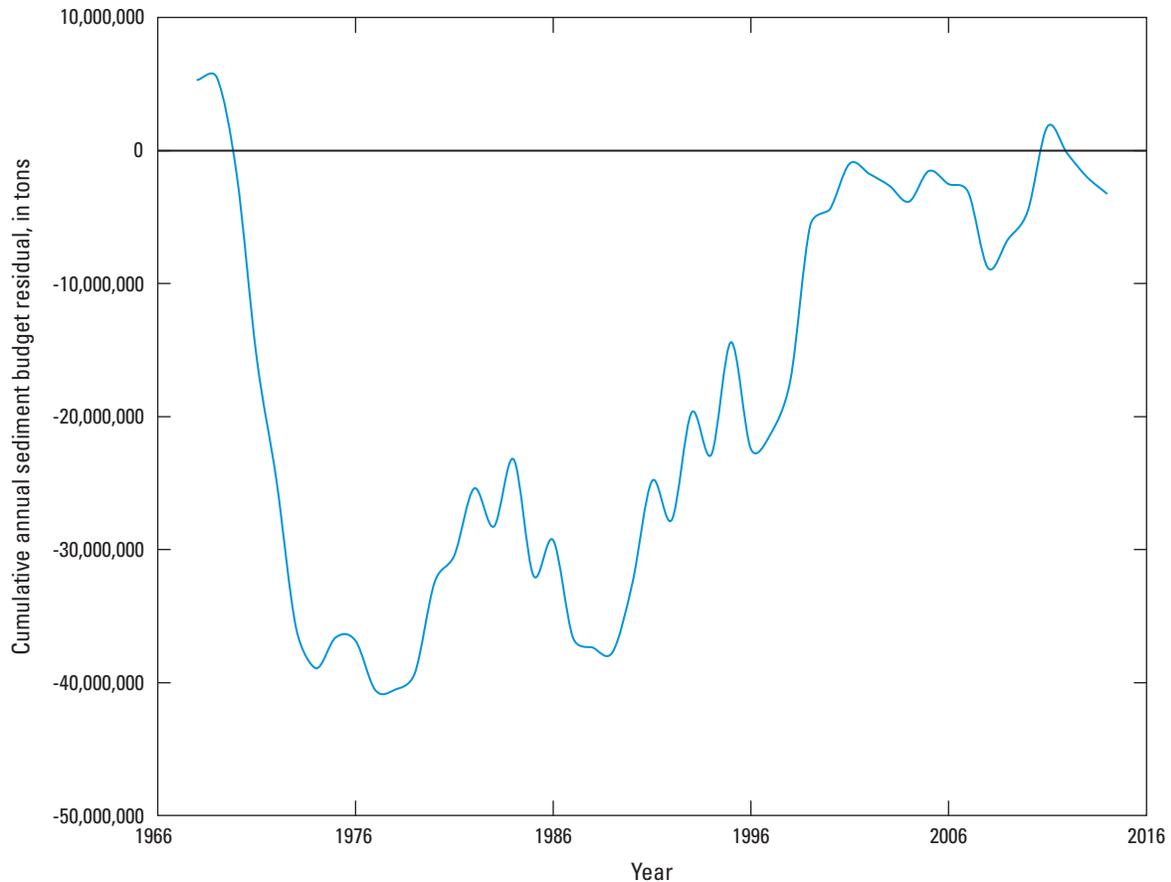
hydrologic events that include regional flooding or seasonal changes in sediment transport. The SSL monthly budget residuals for the Omaha to Nebraska City reach ranged from about -7 to 2 million tons (table 9; fig. 21). For the Nebraska City station, the budget residuals represented a range from about -60 to 50 percent of the monthly SSLs and generally were between -40 and 40 percent. The monthly residual plot indicates that negative annual budget residuals; for example, those in 1970–73, primarily can be attributed to a few months of large negative residuals in each year.

## Daily Budget

Similar to the computation of the monthly SSL budget, concurrent daily SSLs also were available for the Omaha, Nebr., to Nebraska City, Nebr., reach for 1968–76. A complicating factor in estimating a sediment budget residual at the daily time scale is accounting for the travel time, or lag, between stations in the reach. The sediment travel time can substantially differ from the daily SSL computation interval; therefore, sediment travel times may not correspond to an even daily computation increment. Lag times used in analyses

differed between stations; however, for simplicity, lag times were uniform between station data pairs. The lag time combination that minimized the overall average budget residual for each reach was determined and used for all conditions. In reality, the lag or travel times between stations will differ with streamflows and water velocities. To minimize the net daily budget residuals, a 1-day lag time was applied in the budget calculations to the Missouri River at Omaha, Nebr., station and Platte River at Louisville, Nebr., station records.

The magnitude of daily sediment budget residuals in the Omaha to Nebraska City reach ranged from about -1.6 to 0.60 million tons (table 9; fig. 22). For the Nebraska City station, the residuals represented a range from -90 to 260 percent of the daily SSLs and generally were between -75 and 75 percent. The skew in positive residuals expressed as a percent of output load (fig. 22) generally coincided with periods of high SSLs at the Omaha station. The skew in positive residuals may be the result of sediment storage within the main stem or may be from inadequately accounting for changes in travel times between the Omaha and Nebraska City stations in the daily budget computations. The increase in the value of the ratio of budget residual to output SSL in the annual (20 percent), monthly (40 percent), and daily (75 percent)



**Figure 19.** Cumulative annual sediment budget residuals for Lower Missouri River reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–2014.

budget determinations demonstrates the greater variability and uncertainty associated with smaller incremental estimates of the budget residual and station SSLs.

The daily incremental SSL data allow for the determination of budget residuals during specific hydrological or short-term periods of interest not represented in monthly or annual budgets and help to further discern the episodic nature of sediment transport. For example, the daily budget residuals during floods in the Omaha to Nebraska City reach indicated a consistent shift in sediment transport dynamics from a negative residual condition to a positive residual condition near the flood peak or on the recession side of the peaks of three floods during 1968–78 (fig. 23). The days of large positive budget residuals on the flood recession may correspond to periods of sediment storage on the flood plain or in the channel.

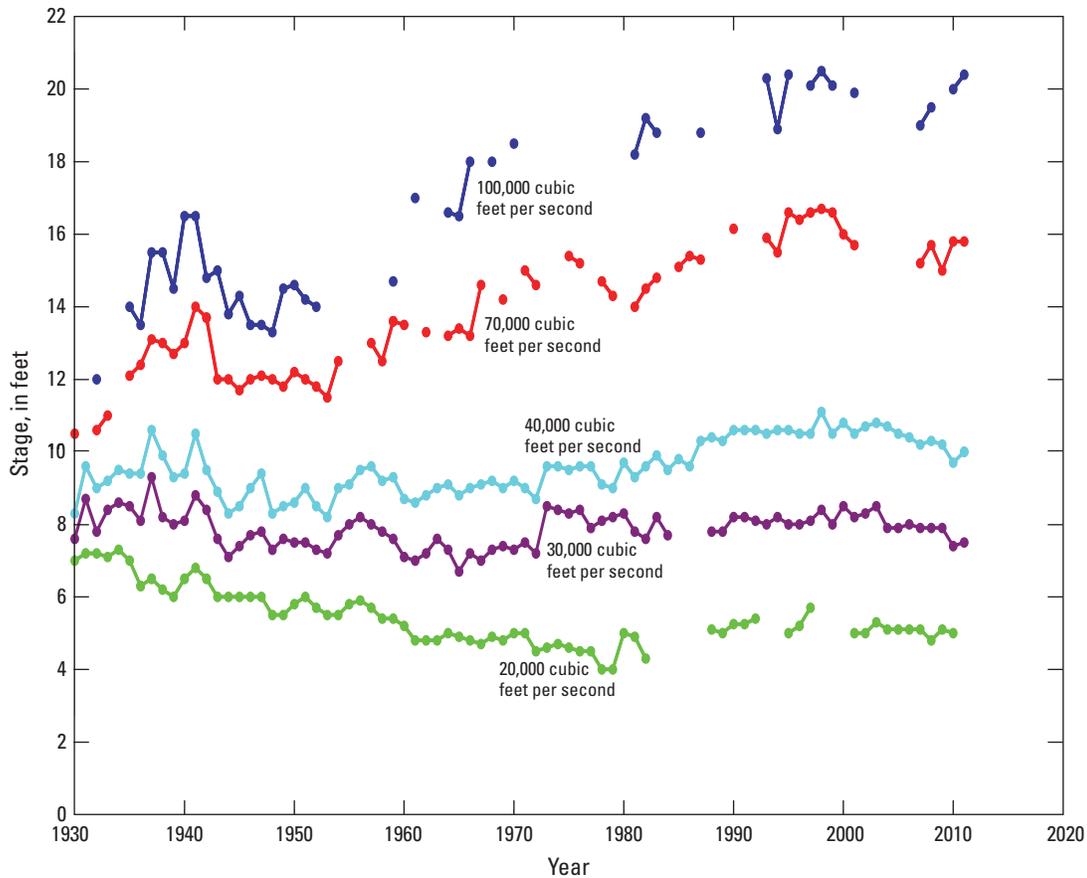
### Bedload Component of Sediment Budgets

For the Missouri River, substantially less bedload transport data are available than suspended-sediment data, and the data that do exist represent sporadic and discrete measurements or theoretical estimates at main-stem stations

(table 6), limiting the potential for incorporating bedload into sediment budgets. Available bedload data were incorporated into long-term reach budgets for the Nebraska City to St. Joseph stations, St. Joseph to Kansas City stations, and Kansas City to Hermann stations. Bedload data were limited for these selected main-stem stations to stations using theoretical bedload-streamflow ratings. Available measured and computed bedload transport data for the Lower Missouri and Mississippi River stations used in this study for 1950–2014 are summarized in figure 24.

### Sediment Data Gaps and Uncertainties

Sediment data gaps and uncertainties, as related to the development of a sediment budget for the Lower Missouri River, include factors that affect the availability, location, and accuracy of the primary budget components. Data gaps and uncertainties differ for each budget component, for each reach, and with time. Ultimately, identification of data gaps and limitations of sediment-budget components are determined by the desired applications and the corresponding time increment and spatial requirements of those applications.



**Figure 20.** Temporal trend in the stage of the Missouri River at Nebraska City, Nebraska, station for selected constant streamflows, 1930–2011 (U.S. Army Corps of Engineers, 2012).

## Data Gaps

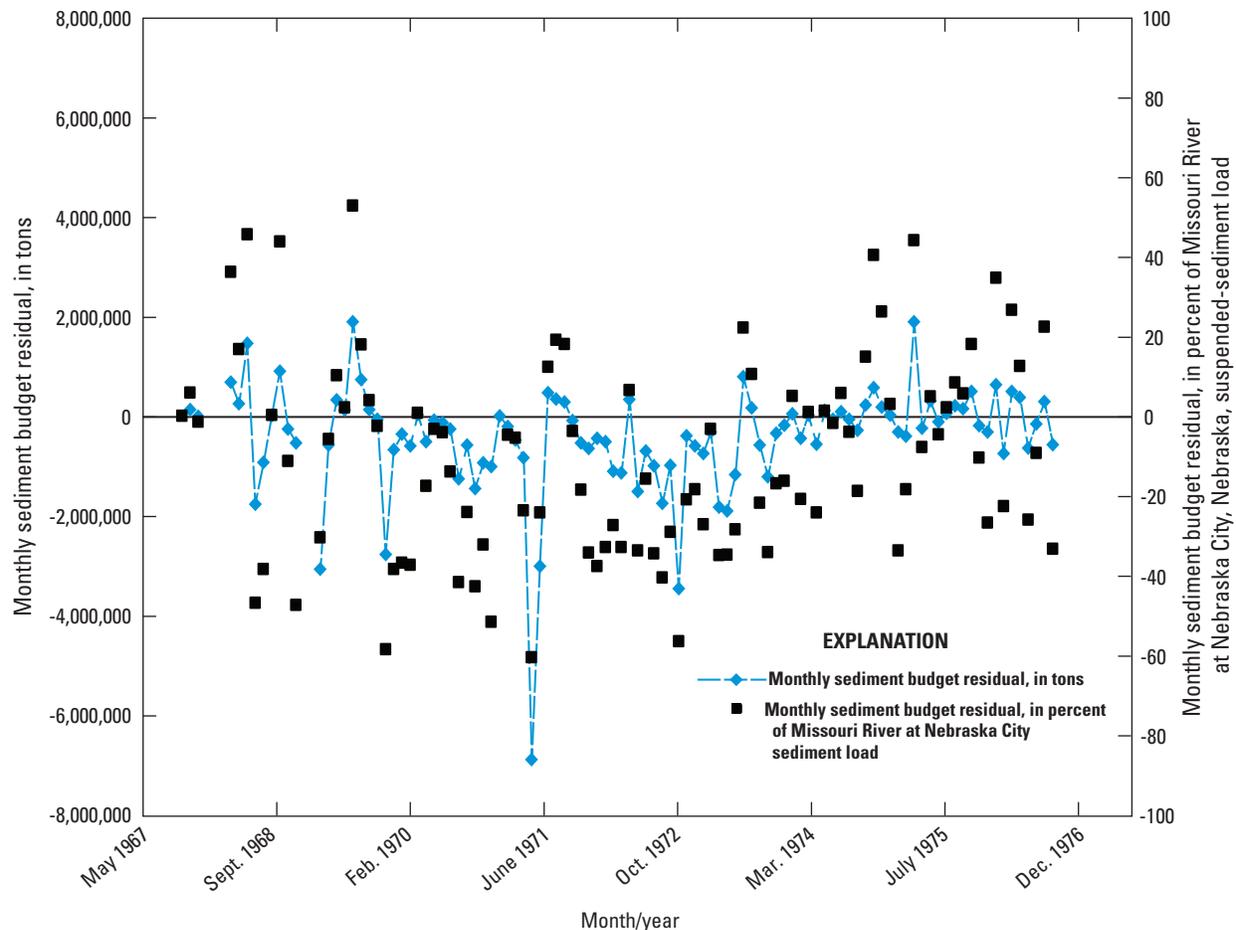
An accurate total sediment budget is developed by having concurrent data for all suspended-sediment and bedload components in equation 1 for a reach of interest throughout a time period. A complete sediment budget, with concurrent record for suspended-sediment and bedload components, is unavailable for any reach and period in the Lower Missouri River; therefore, a generalized sediment budget was the remaining alternative. A generalized sediment budget uses the best estimates based on some stations with complete measured record and some stations with partially or fully estimated record.

Uncertainty in the long-term, annual, monthly, and daily budgets was introduced because SSL budgets were estimated based on the available partial record. The uncertainty increased with an increase in the period of missing record. More sediment record is missing in the latter part of the study period at most tributary stations, and considering the declines in SSC and SSL with time (figs. 7–8), the use of partial record for a long-term average may overestimate the actual averages.

Data gaps prevented the determination of reliable annual, monthly, and daily SSL budgets for most Lower Missouri

River reaches and shortened the analysis period for the reach where example budgets were developed. Currently (2016), sediment budgets are restricted to reaches defined by main-stem stations. To measure storage components, subreach budgets would require additional resources and targeted data-collection efforts, which include additional SSC monitoring, bedload measurements, and hydrographic surveys (Krahulik and others, 2015). Because a primary data gap in main-stem reach budgets corresponds to the paucity of tributary SSL and bedload data, the greater the local reach tributary contributions, the greater the resources that will be required to obtain finer spatial resolution or to enable sediment budgeting at short temporal increments.

Bedload data gaps in the Missouri River Basin are much more prevalent than suspended-sediment data gaps, and the first step in the development of reach bedload budgets would be the establishment of a standardized bedload monitoring program at main-stem and tributary stations. Bedload transport is highly variable in space and time, and theoretical calculations and measurements have large uncertainties that will require careful consideration to design optimized bedload-streamflow ratings. Because transport capacity varies with



**Figure 21.** Monthly suspended-sediment budget residuals for Lower Missouri River reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–76.

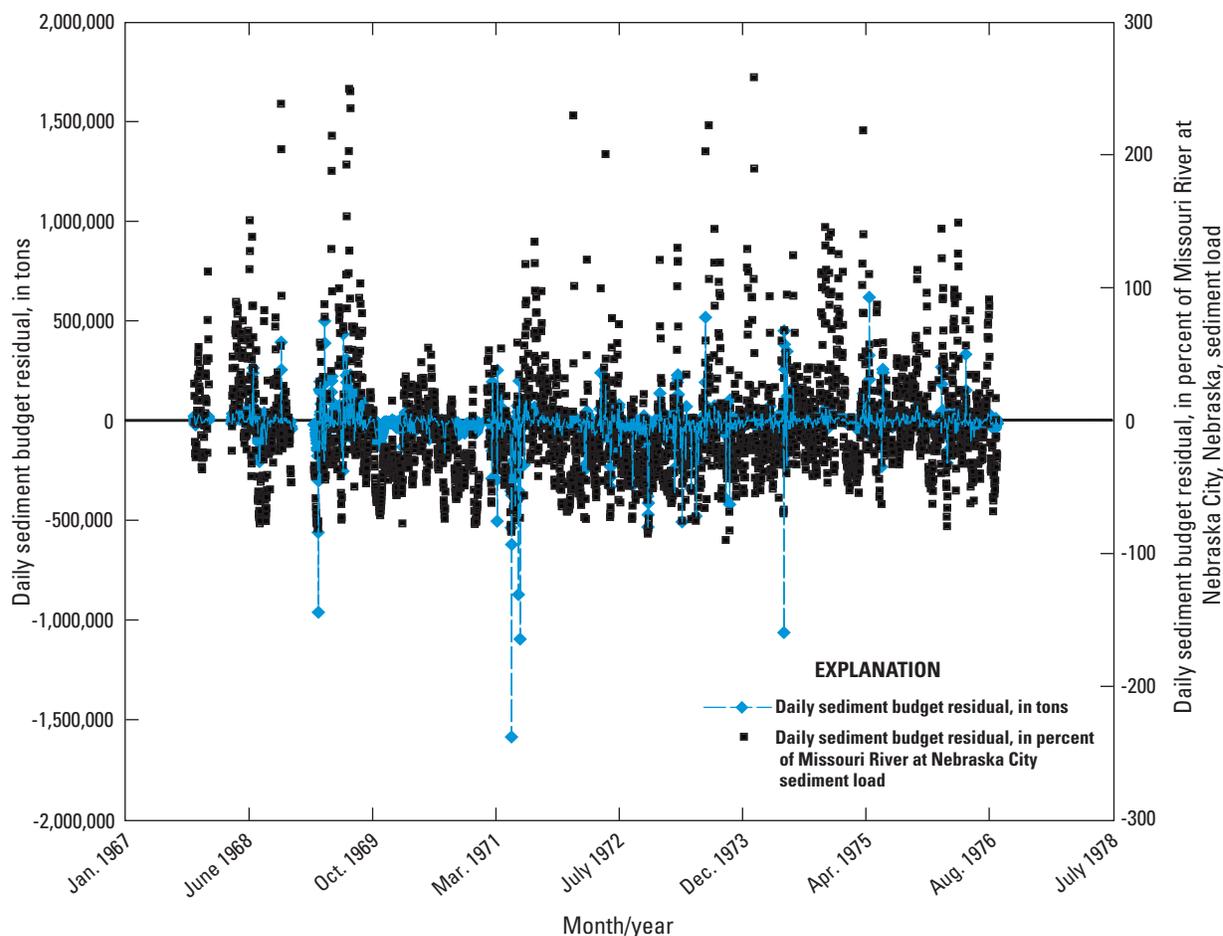
time and space, transitions between bedload and suspended-load transport need to be considered at stations designed to monitor total load; thus, a complementary deployment of suspended and bedload instrumentations and sampling designs will be required.

Sediment data gaps in the Lower Missouri River sediment budgets, in addition to bedload, include ungaged tributaries and local sediment contributions and flood-plain storage. The part of ungaged local drainage area ranged from about 0 to 65 percent in sediment budget reaches. Overall, about 15 percent of the Lower Missouri River drainage area upstream from the Hermann station was unmonitored. Many tributary stations are not located at, or in proximity to, the mouth of the gaged tributary and, therefore, the total tributary sediment loads probably are underestimated. For example, the Hermann station is nearly 100 miles upstream from the mouth of the Missouri River; and, despite the lack of major interim tributaries, for the periods of concurrent SSL data at the Hermann station and the Missouri River at St. Charles, Mo., station, the SSLs differed by an average of 17 percent. Although the spatial extent of flood-plain deposition along the Lower Missouri

River has been studied after the 2011 flood (Alexander and others, 2013), such analyses or further determinations of the volume of deposits have not routinely been attempted. Such budget components are not insignificant but are difficult to quantify and, therefore, are lumped together and quantified based on the net budget residual of the quantified components. Currently (2016), the quantification of missing budget component values, therefore, cannot be differentiated from sampling and load computation errors in known budget variables.

## Data Uncertainties

Data uncertainties associated with the development of a sediment budget include uncertainties associated with the collection of suspended-sediment and bedload data and the computation of SSLs. These uncertainties vary depending on the frequency of data collection, variability of conditions being represented by the discrete samples, and statistical approach to SSL computations.



**Figure 22.** Daily suspended-sediment budget residuals for Lower Missouri River reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–76.

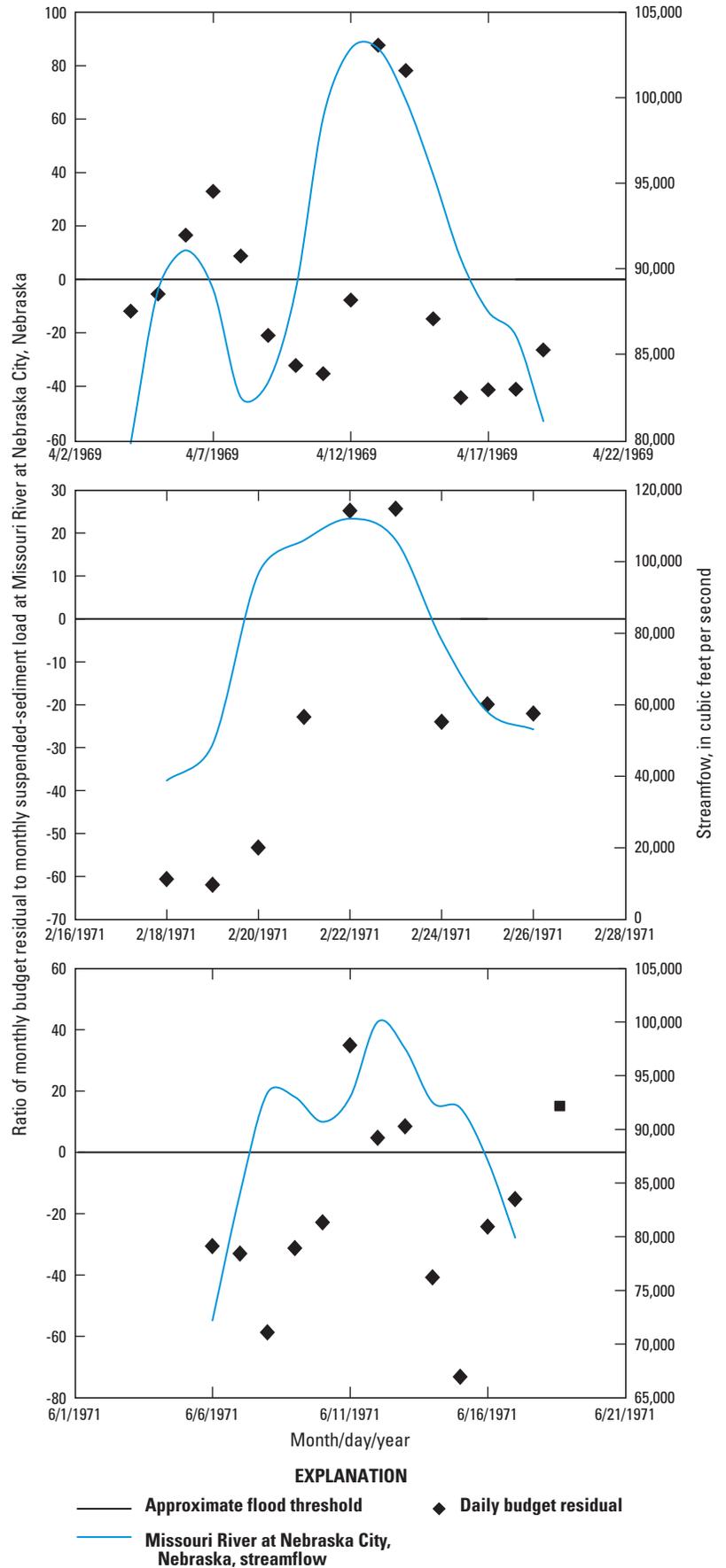
## Suspended-Sediment Concentrations and Streamflow

A primary issue in sampling for determination of SSCs is the uncertainty as to how well the sample is representative of the population (fig. 25). Factors contributing to this uncertainty are sampling error (for example, the nonisokinetic sampling methods or sampling an inadequate number of verticals across the channel); sampling timing and frequency (for example, sampling when the highest concentrations generally are collected, which is during the rising limb of the hydrograph, and sampling the full range of flow conditions); and uncertainties associated with laboratory analysis.

During the post-impoundment analysis period, isokinetic samplers were in use at all Missouri River Basin stations used in this study. The transition from nonisokinetic to isokinetic samplers potentially only affects the presented long-term (1930–2014) SSC and SSL changes in this study (figs. 7–8). The implementation and use of isokinetic (D–43, P–43, P–46; Benedict and Nelson, 1944; Dardeau and Causey, 1990) sediment samplers on the Missouri River and its tributaries began at downstream—Missouri, Kansas, and most

Nebraska—stations when observations began in 1948, but the use of the samplers was not fully implemented until 1955 at upstream—Yankton and Omaha—main-stem stations (the sediment record at the Sioux City station began in 1955). The Omaha sampler (Federal Interagency Sedimentation Project, 1940) was used in sediment sampling at the Yankton and Omaha stations and at large tributary stations upstream from the Omaha station prior to the use of isokinetic samplers. A comparison study of field samples that were collected using nonisokinetic and isokinetic samplers indicated the nonisokinetic samplers tended to overestimate SSCs compared to the isokinetic samplers. Reported average sampled SSC ratios between the Omaha sampler and the D–43 sampler from multiple field observations ranged from 1.06 to 1.32, and the reported average sampled SSC ratio between the Omaha and P–43 samplers was 1.13 (Benedict and Nelson, 1944).

The determination of accurate SSLs is dependent upon thorough and consistent sampling, analysis, and computation methods. The number of verticals used in the collection of SSC samples at Missouri River main-stem stations has differed between stations and with time; the number of vertical samples determines if the composite sample is statistically



**Figure 23.** Daily suspended-sediment budget residuals during selected floods for Lower Missouri River reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–76.

representative of the spatial variability in SSC across the channel. Generally, three verticals have been used in SSC sample collection at stations upstream from the St. Joseph station, and five verticals have been used in SSC sample collection at the St. Joseph station and at downstream Missouri River stations. For added consistency in sediment sampling methods, the number of verticals for all Missouri River main-stem stations was modified to four verticals during the 2009 water year (U.S. Geological Survey National Water Information System, <http://dx.doi.org/10.5066/F7P55KJN>). Historically, sample collection has primarily followed a regular schedule interval and, with time, such a sampling method should capture the full range of flow conditions, particularly if efforts are made to capture conditions during extreme flows. Replicate sediment samples are not routinely collected with the current (2016) sediment monitoring programs at Missouri River main-stem stations, but analysis of replicate sediment samples collected during extreme flows during the 1993 flood on the Missouri River indicated the percent difference between samples to be within 8 percent (Holmes, 1996).

Daily streamflow values are used with SSC data to determine SSLs; therefore, uncertainties in streamflow data add to uncertainties in SSLs. Uncertainties in streamflows include measurement errors that generally are within about 5 percent (Turnipseed and Sauer, 2010), but the errors can be greater during periods of ice, during rapidly changing stage, and with compounding of errors in the development and application of a stage-discharge rating. Stage-discharge rating errors may be caused by stage measurement errors or rating instability resulting from changing morphology of channel bed, channel banks, or levees.

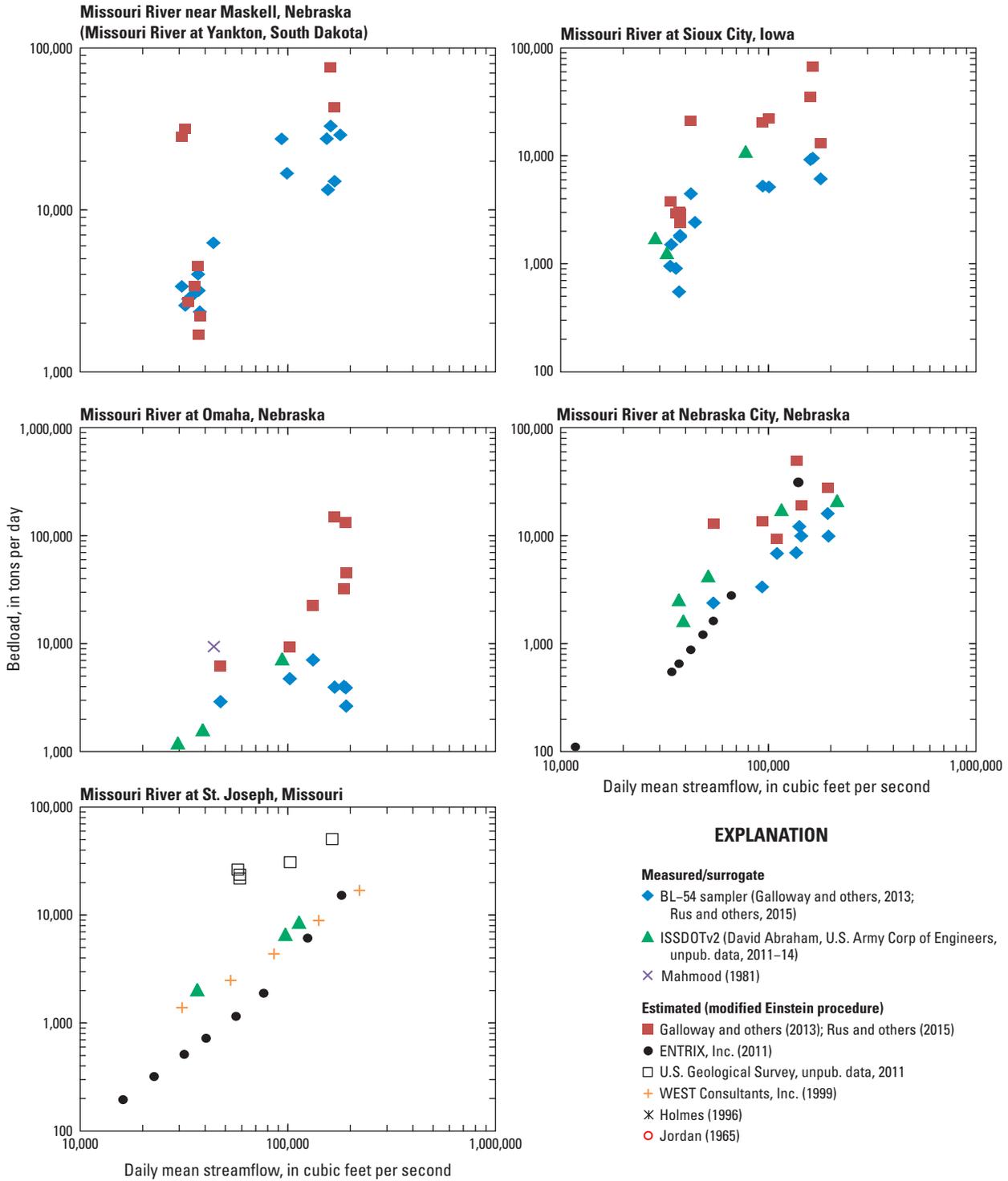
## Suspended-Sediment Loads

Uncertainties in SSLs include the uncertainties associated with SSC and streamflow in addition to uncertainties specific to the SSL computations. The uncertainties in SSLs are greatest for short-interval (daily) load estimates because this time interval commonly is finer than the SSC data collection interval (near weekly to monthly but variable with time and among stations), and as a result, SSC and SSL values are determined by interpolation. Annual loads would be expected to have less uncertainty than loads for shorter time intervals because sampling and computation errors (periods of overestimation and underestimation of SSC and SSL) would tend to “cancel out” during longer periods (Walling, 1977). Colby (1956) indicated the accuracy of sediment loads computed for a large river, such as the Mississippi River in which flow is comparatively constant, sediments are fine, and concentrations are high enough to sample accurately, to be about 10 percent. Holmes (1996) states that the annual SSLs for the Hermann, Grafton, and St. Louis stations generally have been thought to be within 10 percent of the true value. The accuracy of annual loads could be much greater in smaller streams that have greater

variability in the temporal and spatial distribution of sediment concentrations and streamflow. The USACE assigned adjective appraisals and corresponding possible outside error percentages to published historical sediment loads for Missouri River Basin sediment records. Assigned error categories included excellent (0–10 percent), good (11–20 percent), fair (21–30 percent), and poor (greater than 30 percent error). Published records for multiple stations used in this study generally were rated “good” overall, placing them in the 11–20 percent error range.

In general, the intensity and longevity of sediment record is greater at the Missouri River main-stem stations compared to tributary stations, resulting in greater uncertainty (as determined by the 1968–2014 coefficient of variation by station [table 2]) in sediment transport at most tributary stations compared to main-stem stations. The average (geometric mean) coefficients of variation of annual SSLs of Missouri River tributary stations for 1968–2014 were greater, 75.0 percent, compared to the main-stem stations, 47.1 percent. Similarly, Parker (1988) determined that the standard error of the average of annual SSLs for Lower Missouri River tributary stations was substantially larger than those of for main-stem Missouri River stations even at tributary stations of comparable record length. The greater variability of flow and sediment transport at the tributary stations may be the determining factor in the greater coefficient of variation for tributaries because even the Platte River at Louisville, Nebr., station (a tributary station with full annual record during 1968–2014) had a coefficient of variation that was high (88 percent). The lower coefficient of variation at main-stem stations compared to tributaries, therefore, primarily is the result of the lower variability in streamflow and sediment discharge identified at main-stem stations. To obtain similar accuracy between SSLs at main-stem and tributary stations, a longer period of record is required of the tributary stations (Nordin and Meade, 1981). During 1968–2014, however, the average Missouri River main-stem station record was much more complete (average 87 percent) than the tributary station record (average 28 percent). The SSLs of tributaries upstream from the Hermann station account for 84 percent of the 1968–2014 average SSL for the Hermann station; however, only about 20 percent of SSC samples collected in 2014 at the Missouri River Basin stations used in this study were collected at tributary stations.

An example of how the frequency of SSC sampling could affect the determination of SSLs at a particular station is available for the Hermann station during 1949–2009. The total number of annual SSC samples available for analysis at the Hermann station ranged from 12 to 191 samples (fig. 26). The coefficient of variation of the annual SSL computed using annual LOADEST regression models generally changed inversely with the number of annual sediment samples and ranged from 5 to about 20 percent.

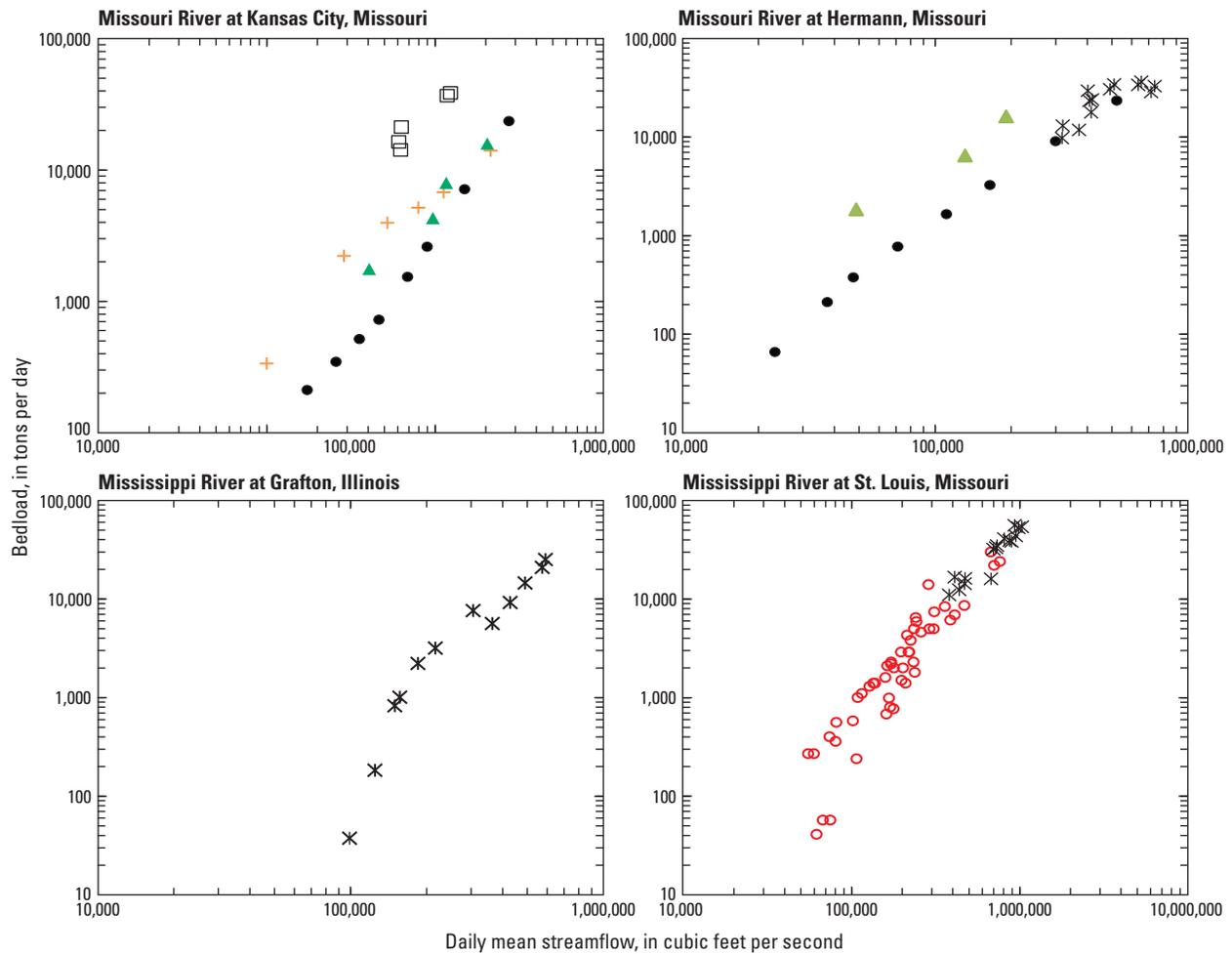


**Figure 24.** Bedload and daily average streamflow for Lower Missouri River and Mississippi River main-stem stations, 1950–2014.

### Bedload

The large documented temporal and spatial variability in bedload transport (Hubbell, 1964; Edwards and Glysson, 1999) limits the capability to capture a truly representative sample. Gaeuman and Jacobson (2007) state that physical

samples of bedload are subject to substantial errors in field conditions. Additionally, despite the availability and use of numerous theoretical equations for the prediction of bedload and total-sediment transport, Gomez (2006) states that “it is not yet possible to make reliable predictions of bedload-transport rates”. Subsequent research into bedload estimates



#### EXPLANATION

##### Measured/surrogate

- ◆ BL-54 sampler (Galloway and others, 2013; Rus and others, 2015)
- ▲ ISSDOTv2 (David Abraham, U.S. Army Corp of Engineers, unpub. data, 2011–14)
- × Mahmood (1981)

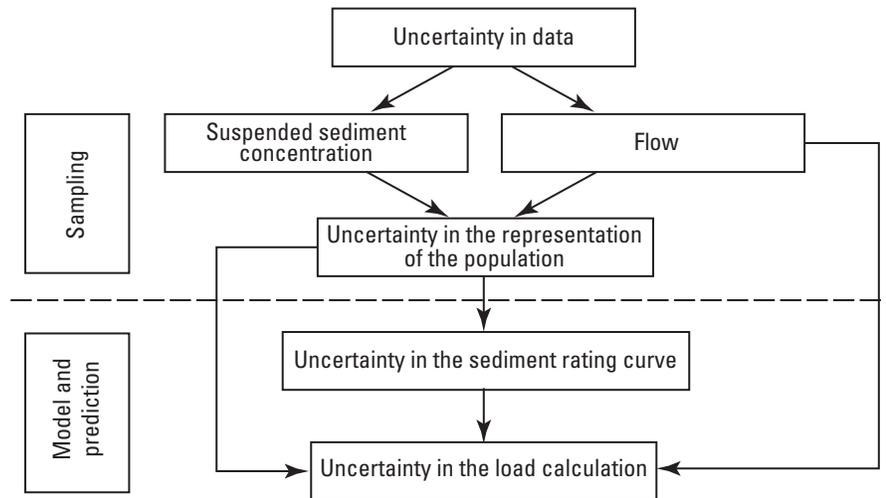
##### Estimated (modified Einstein procedure)

- Galloway and others (2013); Rus and others (2015)
- ENTRIX, Inc. (2011)
- U.S. Geological Survey, unpub. data, 2011
- + WEST Consultants, Inc. (1999)
- × Holmes (1996)
- Jordan (1965)

**Figure 24.** Bedload and daily average streamflow for Lower Missouri River and Mississippi River main-stem stations, 1950–2014.—Continued

utilizing time-lagged channel surveys, including the ISSDOTv2 method (Abraham, 2009) and that of McElroy and Mohrig (2009), are under evaluation. Although the absolute accuracy of bedload measurements from the ISSDOTv2 method has yet to be determined, the methodology has been validated in flume studies (Abraham and others, 2011; Abraham and others, 2015), and the variations of data about the

average for Missouri River bedload estimates were generally between 20 and 30 percent (Abraham and Pratt, 2010) with maximum errors between 55 and 80 percent. Additional modifications to the method have since been introduced to limit measurement bias (Shelley and others, 2013).



**Figure 25.** Primary sources of uncertainty in the computation of suspended-sediment loads (Smith and Croke, 2005).

## Surrogate Methods for Determination of Sediment Transport

Surrogate methods for the characterization of sediments, including concentrations and fluxes of suspended sediments and bedload, are continually being developed to provide real-time continuous measurements, lower monitoring costs, provide greater safety in sampling, and provide a more accurate (reduce uncertainty) means of determining sediment transport in rivers and streams (Gray and Gartner, 2009). Application of such methods for the determination of SSC and bedload data within the Missouri River Basin can assist in the determination of sediment budgets at a variety of temporal and spatial scales. A summary of the primary surrogate techniques used to determine sediment characteristics on the Missouri River including technologies in development is provided in the following sections.

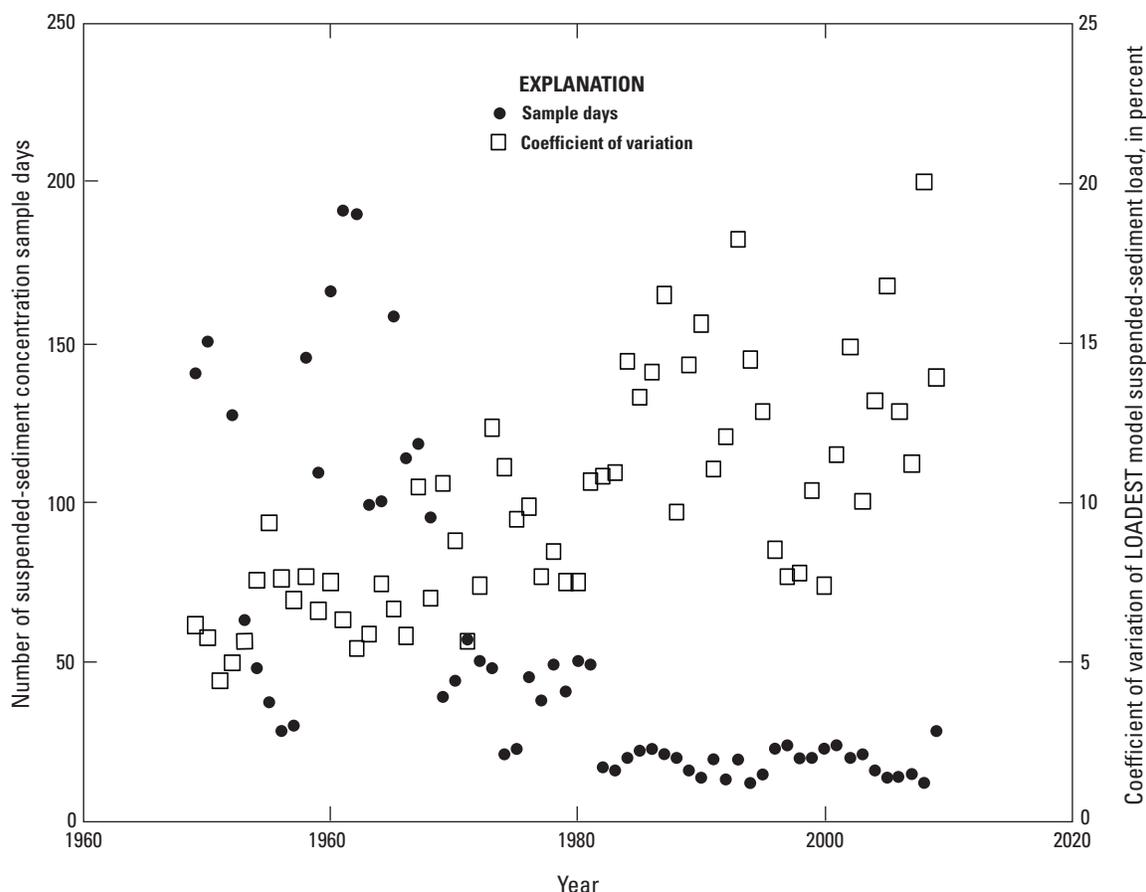
### Suspended-Sediment Concentrations

The use of continuous bulk optical properties of water (turbidity) is the most commonly used surrogate for SSCs and is currently (2016) collected at three main-stem Missouri River stations (Nebraska City, St. Joseph, and Hermann), and partial annual record is available at one primary tributary station (Platte River at Louisville, Nebr.). The use of turbidity record and regression models between turbidity and SSC previously have been used in the computation of published annual SSLs at several Missouri River main-stem stations (Heimann and others, 2010) and are currently (2016) used in the computation of daily SSLs at the St. Joseph and Hermann stations (the models and supporting documentation are available on the National Real-Time Water-Quality Web site <http://nrtwq.usgs.gov/>).

Regression models for SSC using turbidity as the explanatory variable have been demonstrated to have a higher coefficient of determination ( $r^2$ ) than models using streamflow (Rasmussen and others, 2009). Lewis (1996) indicated that regression models using turbidity instead of streamflow improved the root-mean-squared errors of sediment rating curve estimates of SSC by 7–15 percent.

Once an initial regression model is developed relating turbidity and SSC, SSC samples can be collected less frequently, the long-term operation costs for a sediment monitoring station can be reduced, and predictive uncertainty of estimates can be quantified. A continuous sediment surrogate also can allow for the availability of data during episodic events that may be difficult to obtain otherwise (Rasmussen and others, 2009). An established regression model between SSC and turbidity also can be used to quantify SSC and SSL at shorter time increments (for example, hourly) and at specific subreach locations of interest. According to Rasmussen and others (2009), the use of linear regression models between SSC and turbidity can provide a more reliable SSC than either the Porterfield (1972) method or traditional transport-curve (sediment rating curve) method (Walling, 1977; Horowitz, 2003; Putnam and Pope, 2003). The turbidity surrogate method also provides the added benefit of being able to quantify uncertainty in SSC estimates by means of prediction intervals (Rasmussen and others, 2009) and could possibly be used to close the accuracy gap between tributary and main-stem sediment record.

The use of other surrogate techniques (such as backscatter and laser diffraction techniques alone or in combination with turbidity data) to determine suspended sediment is increasing. These techniques can be used as stand-alone systems or in combination to augment or extend turbidity data and to provide continuous SSC and particle-size class information (Voichick and Topping, 2014). The SSC is determined



**Figure 26.** Graph showing inverse trends with time of the number of suspended-sediment concentration samples per year and the corresponding coefficient of variation of annual suspended-sediment load estimates, Missouri River at Hermann, Missouri, 1949–2009. (Loads computed using annual LOADEST regression models: Heimann and others, 2010).

by a site-specific relation between SSC determined for discrete samples and acoustic backscatter from suspended-sediment particles crossing the beam emitted by hydroacoustic instruments. The instrumentation includes acoustic velocity meters and acoustic Doppler velocity meters, and favorable results have been provided in applications throughout the United States, including Idaho and Washington (Wood, 2010; Wood and Teasdale, 2013); Vermont (Medalie and others, 2014); the Mississippi River delta in Louisiana (Perkey and others, 2010; Heath and others, 2015); Hudson River in New York, (Wall and others, 2006); and the Colorado River in Colorado (Topping and others, 2004; Topping and others, 2006; Voichick and Topping, 2014). A multifrequency acoustic Doppler velocity meter array currently (2016) is being tested at an installation at the Nebraska City station (Nania, 2015). Multifrequency arrays have the potential to provide information on sediment size fractions (Wood, 2014) in addition to SSC. According to Gray and Gartner (2009) “Multifrequency hydroacoustics shows the most promise for revolutionizing collection of continuous suspended-sediment data by instruments that require only periodic calibration for correlation to average concentrations in river cross sections”.

The use of laser diffraction is another means of providing continuous real-time SSC and sediment particle-size data. Laser diffraction instruments measure optical scattering of light with a wide range of angles, providing a multiparameter measurement of 32 particle-size classes (Agrawal and others, 2008; Gray and Gartner, 2009; Gray and others, 2010). A complicating factor in the use of laser diffraction instruments to determine SSC is that laser diffraction instruments estimate a volumetric concentration of sediment as opposed to a mass concentration (Agrawal and others, 2008). To determine SSC, therefore, particle density estimates are required to make the conversion to mass concentrations or the development of a site-specific regression model that relates SSC to volumetric concentration is required. The site-specific regression model would be similar to the models used with turbidity as the surrogate. The applicability of this technique to determine SSC and size fractions has been demonstrated on a small Missouri River tributary (Hubbart, 2012) and currently (2016) is being tested at the Nebraska City station (Nania, 2015).

## Bedload

Surrogate methods for the determination of bedload, including active and passive-type samplers, are an alternative to traditional measurements and theoretical computations. The traditional bedload samplers (Helley Smith, BL–84 sampler; Davis, 2005) and theoretical computations of bedload by total sediment transport equations (for example, modified Einstein procedure) used at Missouri River main-stem stations have limitations in representing true bedload transport as described in the “Bedload” subsection of the “Data Uncertainties” section. Traditional bedload samplers include box or basket samplers, pan or tray samplers, pressure-difference samplers, and trough or pit samplers (Gray and others, 2010). In theory, the traditional method could be used to calibrate the surrogate method and provide information on accuracy and spatial and temporal differences compared to this standard method. A difficulty in applying surrogate bedload methods to the Lower Missouri River is the inability to calibrate the surrogate technologies to “true” measurements because of the limitations in the traditional measurements and theoretical techniques (Gaeuman and Jacobson, 2007).

Surrogate bedload technologies, operating with active- and passive-type sensors, have the advantage in many cases to be applied continuously and automatically at a river site (Gray and others, 2010). Active or direct sensors include acoustic Doppler current profilers, sonar (including estimation of bedload transport rates from bathymetric differencing), radar, and smart sensors. Passive sensors include geophones (pipes or plates) that are in direct contact with the streambed, hydrophones that are deployed in the water column (Marineau and others, 2012), impact sensors (Hilldale and others, 2014), and magnetic detection. A sonar (bathymetric differencing) technique has been the surrogate technique most applied to date (2016) in the Lower Missouri River. McElroy and Mohrig (2009), Abraham (2009), and Abraham and others (2010) present methodologies for relating time-lapsed bed-form data to bedload transport. The USACE (Abraham and Pratt, 2010; 2014, unpub. data) and USGS (2011, unpub. data) have collected time-lapsed, bed-form data using a multibeam echo sounder at multiple Missouri River locations. The purpose of the time-lapsed, bed-form data are to develop standardized methodology for collecting and processing bed-form data that will be used as a surrogate for determining bedload transport.

## Summary

Sediment budgets of the Lower Missouri River were developed in a study led by the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers. The sediment budgets included suspended-sediment data and, when and where available, bedload data. The scope of the study included the development of sediment budgets for the post-impoundment period (1968–2014) for main-stem reaches of

the Lower Missouri River—from Yankton, South Dakota, to St. Louis, Missouri. Included in the analysis were 31 Missouri River main-stem and tributary stations and two Mississippi River stations—the Mississippi River below Grafton, Illinois, and the Mississippi River at St. Louis, Mo.

Annual flow-weighted suspended-sediment concentration and annual suspended-sediment loads for the study sites indicated declining suspended-sediment concentrations and loads at most stations during 1930–2014. The temporal changes in flow-adjusted suspended-sediment concentrations analyzed at main-stem Missouri River stations indicated an overall downward change in concentrations between 1968 and 2014. The declines in flow-adjusted concentrations at the Missouri River at Sioux City, Iowa; Missouri River at Omaha, Nebraska; and Missouri River at Nebraska City, Nebr., stations were greater between 1968 and about 1990 than between 1990 and 2014, and changes in flow-adjusted suspended-sediment concentrations for the Missouri River at St. Joseph, Mo.; Missouri River at Kansas City, Mo.; and Missouri River at Hermann, Mo., stations were greater between 1990 and 2014 than before 1990. This difference could be an indication of longitudinal differences in the temporal adjustment of the Lower Missouri River to post-impoundment (and other factors affecting sediment supply) conditions in sediment transport. Temporary declines in flow-adjusted suspended-sediment concentrations during and following large floods were evident but generally returned to near pre-flood values within about 6 months.

A generalized long-term (1968–2014) sediment budget for seven reaches, defined by main-stem stations, was determined for the post-impoundment period (1968–2014). Long-term average annual suspended-sediment loads among the Missouri River main-stem stations ranged from 0.33 million tons at the Missouri River at Yankton, S. Dak., station to 71.2 million tons at the Missouri River at Hermann, Mo., station. Gaged tributary gains accounted for 9–36 percent of the local reach budgets, and cumulative gaged tributary contributions accounted for 84 percent of the long-term average suspended-sediment load at the Missouri River at Hermann, Mo., station. Although the budgets generally were incomplete and missing bedload, storage, and ungaged tributary contributions (accounting for 20 percent of local reach drainage area, on average), the budget residuals for six of the seven reaches ranged from -7.0 to 1.7 million tons, or from -9.2 to 4.0 percent of the reach output suspended-sediment load, and were within the 10 percent reported measurement error of annual suspended-sediment loads for large rivers. The remaining reach, Yankton, S. Dak., to Sioux City, Iowa, had an average budget residual of -9.8 million tons per year (-88 percent of the reach output suspended-sediment load), indicating the input suspended-sediment load and reach gains from gaged tributaries accounted for a small part of output suspended-sediment load.

The Lower Missouri River reach from Omaha, Nebr., to Nebraska City, Nebr., had periods of concurrent sediment data for budget components with which to analyze and determine a suspended-sediment budget for selected annual, monthly, and

daily time increments. The temporal changes in the cumulative annual budget residuals were poorly correlated with the comparatively-steady 1968–2011 annual stage trends at the Nebraska City, Nebr., station. The comparison provides an indication of the net variability in the annual budget residuals and the net magnitude of missing budget components (bedload, sediment storage, and sampling and computation errors). The example also indicates that even in this “simple” and data rich reach, the development of an accurate detailed sediment budget is limited by data gaps.

A monthly suspended-sediment load budget could account for sediment transport differences on the time scale of large hydrologic events that include regional flooding or seasonal changes in sediment transport. The monthly budget residual plot indicates that negative annual budget residuals primarily can be attributed to a few months of large negative residuals in each year. The daily incremental data allow for the determination of budget residuals during specific hydrological or short-term periods of interest not captured in monthly or annual budgets. The increase in the value of the ratio of budget residual to reach output suspended-sediment load in the annual (20 percent), monthly (40 percent), and daily (75 percent) budget determinations demonstrates the greater variability and uncertainty associated with smaller incremental estimates of the budget residual and station suspended-sediment loads. The daily budget residuals during selected floods in the Omaha, Nebr., to Nebraska City, Nebr., reach during 1968–76, indicate a consistent shift in sediment transport dynamics from a negative residual condition to a positive residual condition near the flood peak or on the recession side of the peaks. The periods of large positive budget residuals on the flood recession may correspond to periods of sediment storage on the floodplain or in the channel.

The Missouri River has substantially less bedload transport data available than suspended-sediment data, and the data that do exist represent sporadic and discrete measurements or theoretical estimates at main-stem stations, limiting the potential for incorporating bedload into sediment budgets. Available bedload data were incorporated into long-term reach budgets for the Nebraska City, Nebr., to St. Joseph, Mo.; St. Joseph, Mo., to Kansas City, Mo.; and Kansas City, Mo., to Hermann, Mo., reaches. Bedload data were limited for these selected main-stem stations to those using theoretical bedload-streamflow ratings.

An accurate total sediment budget is developed by having concurrent data available for all primary suspended-sediment load and bedload components for a reach of interest throughout a period. Such a complete budget, with concurrent record for suspended-sediment load and bedload components, is unavailable for any reach and period in the Lower Missouri River. The primary data gaps are in bedload data and also in suspended-sediment gains and losses that include unaged tributary inputs and sediment storage. Bedload data gaps in the Missouri River Basin are much more prevalent than suspended-sediment data gaps, and the first step in the development of reach bedload budgets would be the establishment

of a standardized bedload monitoring program at main-stem stations.

Data uncertainties associated with the development of a sediment budget include uncertainties associated with the collection of suspended-sediment and bedload data and the computation of suspended-sediment loads. These uncertainties vary depending on the frequency of data collection, variability of conditions being represented by the discrete samples, and statistical approach to SSL computations. The intensity and longevity of sediment sampling at the Missouri River main-stem stations are greater than at tributary stations, resulting in greater uncertainty in sediment transport at most tributary stations. The average (geometric mean) coefficients of variation of annual SSLs of Missouri River tributary stations for 1968–2014 were greater, 75.0 percent, compared to the main-stem stations, 47.1 percent. The lower coefficient of variation at main-stem stations compared to tributaries, primarily is the result of the lower variability in streamflow and sediment discharge identified at main-stem stations. To obtain similar accuracy between suspended-sediment loads at main-stem and tributary stations, a longer period of record is required of the tributary stations. During, 1968–2014, however, the average Missouri River main-stem station record was much more complete (average 87 percent) than the tributary station record (average 28 percent). Suspended-sediment loads in tributaries upstream from the Missouri River at Hermann, Mo., station, account for 84 percent of the 1968–2014 average suspended-sediment load for the Missouri River at Hermann, Mo., station; however, only about 20 percent of suspended-sediment concentration samples collected in 2014 at the Missouri River Basin stations used in this study were collected at tributary stations.

Surrogate methods for the characterization of sediments, including suspended sediments and bedload, can be used to provide real-time continuous measurements, lower monitoring costs, provide greater safety in sampling, and provide a more accurate means of determining sediment transport in rivers and streams. The use of continuous bulk optical properties of water (turbidity) is the most commonly used surrogate for suspended-sediment concentrations. A difficulty in applying surrogate bedload methods for the Lower Missouri River is the inability to calibrate the surrogate technologies to “true” measurements because of the limitations in the traditional and theoretical techniques. A sonar (bathymetric differencing) technique has been the surrogate technique most applied to date (2016) in the Lower Missouri River. The U.S. Army Corps of Engineers and U.S. Geological Survey have collected time-lapsed, bed-form data using a multibeam echo sounder at multiple Missouri River locations for the purposes of developing surrogate methods for determining bedload transport in the Missouri River.

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## Tables 1–9

Tables 1–9 are available for download as Excel files at <http://dx.doi.org/10.3133/sir20165097>.

**Table 1.** Summary of sediment data availability and station characteristics of sediment monitoring stations used in study.

**Table 2.** Annual suspended-sediment loads and flow-weighted concentrations for selected stations in the Lower Missouri and Mississippi River Basins, 1930–2014.

**Table 3.** Daily suspended-sediment loads for selected stations in the Lower Missouri and Mississippi River Basins, 1939–2014.

**Table 4.** Summary of bedload measurements and computations available for selected stations on the Lower Missouri and Mississippi Rivers, 1950–2014.

**Table 5.** Missouri River commercial dredging mass by year and river reach, 1968–2014.

**Table 6.** Estimated Missouri River Recovery Program sediment additions by year and by reach, 1993–2014

**Table 7.** Selected annual bed mass changes by reach, Lower Missouri River, 2007–14.

**Table 8.** Long-term, average sediment budget for the Lower Missouri River, by reach, post-impoundment period, 1968–2014.

**Table 9.** Annual, monthly, and daily sediment budget for the Lower Missouri River, reach 3, Omaha, Nebraska, to Nebraska City, Nebraska, 1968–2014.

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