In Cooperation with the U.S. Army Corps of Engineers, Omaha District, and the Lower Platte River Corridor Alliance

Sedimentologic and Bed-Material Budget Analyses of Sandbars, Lower Platte River, Eastern Nebraska, 1970 to 2011

By Jason S. Alexander and Nathaniel J. Schaepe

Administrative Report

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

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
yard (yd)	0.9144	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square yard (yd^2)	0.8361	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per day per square mile [$(ton/d)/mi^2$]	0.3503	megagram per day per square kilometer [$(Mg/d)/km^2$]
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)

bar	100	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
pound-force per square inch (lbf/in^2)	6.895	kilopascal (kPa)
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
ton per cubic yard (ton/yd^3)	1,187	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Slope	
mile per mile (mi/mi)	1	meter per meter (m/m)
mile per mile (mi/mi)	1	kilometer per kilometer (km/km)
	Areal erosion rate (land area that has eroded and become part of the river channel)	
acres per mile per year (acre/mi/yr)	0.6513	hectare per kilometer per year (ha/km/yr)

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

°C = (°F-32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)

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

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Abstract

The lower Platte River corridor provides important habitat, including emergent sandbars, for two state- and federally listed bird species: the interior least tern (*Sternula antillarum athallassos)* and the piping plover (*Charadrius melodus)*. In cooperation with the U.S. Army Corps of Engineers and the Lower Platte River Corridor Alliance, the U.S. Geological Survey initiated a study of the sediment sources of sandbars in the lower Platte River. A particular focus of the study was to understand if reductions in sediment inputs from bank erosion would substantially affect mass contributions of sediments important to the composition of sandbars in the lower Platte River.

The study evaluated sediment transport processes in the lower Platte River relative to the potential for sandbar formation with two primary approaches. First, a sedimentologic analysis was used to characterize the longitudinal variation in grain sizes composing the riverbed, riverbanks, and sandbars in 11 reaches of the Platte River, and root-mean-square difference analysis was used to compare grain-size distributions of sandbars in each reach with five

hypothesized sediment sources. Second, a sediment budget analysis was done for the period 1970 to 2011 to investigate the longitudinal balance of sediment supplies, sediment storage, and sediment transport capacity in four segments of the lower Platte River for the range of bed-material grain sizes present. The four segments of the lower Platte River, each bounded by large tributaries, were designated by the tributary at the upstream boundary: Loup River, Shell Creek, Elkhorn River, and Salt Creek. Two different methods were used to construct sediment budgets. The first method used the U.S. Army Corps of Engineers one-dimensional hydraulic model, HEC-RAS, and Sediment Impact Analysis Methods sediment-budget tool. The second method computed the sediment budgets manually, using an at-a-station bed-material transport capacity approach.

Grain-size distributions from samples indicated that grain sizes in sandbars, the riverbed, and the coarse fraction of the riverbanks in the 11 reaches of the central Platte and lower Platte Rivers were composed primarily of very-fine to very-coarse sand, and these sediments generally became finer downstream from the mouth of the Loup River. Median root-mean-square differences from comparisons of sandbar grain-size distributions with those of the five hypothesized sources ranged from 6.0 to 13.5 percent, but were consistently smaller for comparisons with riverbed samples; however, root-mean-square differences between replicate sandbar sample grain-size distributions ranged from 0.8 to 23.6 percent, and averaged 12.7 percent. Median root-mean-square-differences values exceeding 10 percent occurred only for comparisons of samples of sandbars with large tributary riverbeds, indicating that the method generally was not sensitive enough to conclude whether or not streambeds or riverbanks were the primary source of sediment to sandbars.

Composite grain-size distributions indicated that most of the sediments composing sandbars in the lower Platte River were fine to medium sand (between 0.125 and 0.5 millimeters in diameter). The percentage of the total sample mass from sandbars that was fine-to-medium sand ranged from a low of 61 percent in the Elkhorn segment, to a high of 79 percent in the Loup segment. Grain-size specific estimates of bed-material discharges from large tributaries indicated that the Elkhorn and Loup Rivers are the two largest contributors of fine and medium sand to the lower Platte River. The central Platte River also contributes substantial fine and medium sand, but is distinguished by its proportionally larger contributions of coarse and very coarse sand and fine gravel.

Average sediment mass contributions from bank erosion to the lower Platte River were one to two orders of magnitude less than sediment discharges from large tributaries and, in three of the segments, were more than offset or approximately balanced by bank accretion. Mean bank adjustment conditions indicated that the Loup and Salt segments were accreting bank sediments, and the Shell and Elkhorn segments were eroding bank sediments, but when uncertainty of the mean estimates was considered, three of the four study segments had indeterminate bank adjustment conditions.

Large sediment imbalances between lower Platte River segments were indicated by the sediment budget estimated using the HEC-RAS model and the Sediment Impact Analysis Methods sediment budget tool; however, the hydraulic simulations from the HEC-RAS model were considered to be of low quality, and this resulted in irregular sediment budget results from the Sediment Impact Analysis Methods tool. The magnitude of sediment imbalances computed for each segment indicates that channel hydraulics potentially were poorly simulated by the

HEC-RAS model, and improvements to model geometry may be required to refine the model to more accurately simulate channel hydraulics for higher frequency streamflows.

The sediment budget computed using at-a-station estimates of annual bed-material discharge in each lower Platte River segment resulted in more reasonable longitudinal patterns of sediment transport and sediment imbalances that were more proportional with large-tributary discharges of bed sediment, allowing a more coherent picture of the fluvial-sediment system. At-a-station estimates of annual bed-sediment transport capacity increased in the downstream direction, ranging from 3.6 to 7.1 million tons in the Loup segment, to 3.9 to 12.7 million tons in the Salt segment. Compilation of sediment budgets for each segment, for grain sizes larger than 0.0625 millimeters, using the at-a-station estimates of annual bed-material discharge indicated sediment imbalances between adjacent segments, but these imbalances were "too close to call" in most segments when the uncertainty intervals were considered.

Comparison of the proportion of total sediment supplies by source and grain size within each segment indicated that the primary sources of sediments composing sandbars vary by segment, but in all cases, bank erosion, being considered a source before bank accretion occurs, contributes a proportionally small mass of the sediment sizes composing sandbars in the lower Platte River. Across all segments, bank erosion alone was estimated to contribute no more than 9 percent of the total supply of fine or medium sand, and no more than 20 percent of sediment in the sand-size range. By contrast, large tributaries contributed between 0 and 76 percent of fine to medium sands, and upstream segments contributed between 19 and 98 percent. In segments where tributaries contributed little sand, the upstream segment contributed between 90 and 98 percent of the total supply of fine to medium sands.

Introduction

The Lower Platte River (LPR) corridor provides important habitats for two state- and federally listed bird species: the interior least tern (terns; *Sternula antillarum athallassos)* and the piping plover (plovers; *Charadrius melodus)*. The LPR has a braided channel during lower-magnitude streamflows when multiple wetted threads are separated by emergent mid-channel sandbars, islands, or both. Terns and plovers nest annually on sandbars in the river and along shorelines of the active and abandoned open-pit, sand- and gravel-mine lakes on the adjacent valley floor. Sandbars, also referred to as "macroforms," "macroform sandbars," "dunes," and "beaches," are the primary on-river nesting habitat for terns and plovers, and the geometry, abundance, and persistence of these important habitat features is driven by interactions between the hydrology, sediment transport, and channel geomorphology of the LPR (Elliott, 2011; Alexander and others, 2013).

Large main-channel dams, channelization, and streamflow diversions have altered the hydrologic and sediment transport regimes of the Platte River and other sand-bed rivers in the Great Plains region, and these alterations have substantially decreased the area of barren, emergent sandbar habitats available to terns and plovers by causing river-channel narrowing, incision, and vegetation encroachment (Williams, 1978; Eschner and others, 1983; Johnson, 1994; National Research Council, 2005; Ginting and others, 2008). The LPR has been less altered than segments upstream because two large tributaries, the Loup and Elkhorn Rivers, maintain generally natural flood regimes, and contribute substantial base flows to the LPR (Joeckel and Henebry, 2008; Parham, 2007). Nevertheless, the LPR flows near the two largest population centers in Nebraska, the cities of Omaha and Lincoln (fig. 1), and is the locus of substantial ongoing infrastructure and water-resources development pressures.

Figure 1. Map of Platte River Basin in eastern Nebraska, locations of selected U.S. Geological Survey streamgages, and large tributary basin boundaries.

An understanding of the interactions and relative balance between sediment supplies, sediment storage, and the sediment transport capacity of the Platte River is crucial to understanding the interactions between the physical and biological processes in the LPR ecosystem, and thus is important to informed planning and management in the LPR corridor. In cooperation with the U.S. Army Corps of Engineers (USACE) and the Lower Platte River Corridor Alliance (LPRCA), the U.S. Geological Survey (USGS) initiated a study of the sediment sources of sandbars in the LPR to create a framework for understanding how changes in sediment supply from various sources may affect sandbar formation. A particular focus of the study was to understand the relative importance of bank erosion in providing sediments composing sandbars in the LPR, because bank-erosion control is a common management practice used in the LPR corridor to protect bottomlands adjacent to the river. The study used available data and models to examine the sources of sediment important to the composition of sandbars and the longitudinal balance among sediment supplies, sediment storage, and channel sediment transport capacity of sediments composing sandbars in the LPR.

Purpose and Scope

The purpose of this report is to present the methods and results of a study (hereinafter referred to as “the study”) that investigated the sources of sediment important to the composition of sandbars in the LPR. A particular focus of the study was to understand if further reductions in sediment inputs from bank erosion would substantially affect mass contributions of sediments important to the composition of sandbars in the lower Platte River.

The LPR is defined as the 103 miles (mi) of the Platte River that begins downstream from the Loup River confluence (fig. 1). The study focused on the current hydrologic and physical condition of the LPR, a period that began sometime after 1970 (Ginting and others, 2008; Joeckel and Henebry, 2008). The study area lies entirely within Nebraska and includes the LPR and the downstream segments of its large tributaries. The study described in this report was performed at two different spatial scales. The sedimentologic analysis was performed using sediment samples collected within 12 discrete reaches of the Platte River in eastern Nebraska, and thus comparisons were made between samples representing sediments at the reach scale. The sediment-budget analysis was estimated at the segment scale under the assumption that tributary confluences were the locations of major changes in sediment and water contributions to the LPR. The sediment-budget analysis was performed during 1970 to 2011.

As used here (and henceforth herein), the term "reach" is used in this report in reference to lengths of river that are one or more average-channel widths long, and encompass one or more repeated sequences of primary-channel features such as mid-channel sandbars, islands, and/or channel cross-overs (riffles). The term "segment" refers to a length of stream channel that is composed of multiple reaches, and typically bound at the upstream and downstream ends by large tributaries, changes in geologic or physiographic setting, or human infrastructure (dams, diversions, hydropower outfalls, etc.).

Description of the Lower Platte River and Previous Work

The Platte River begins at the confluence of the North Platte and South Platte Rivers near North Platte, Nebr., and flows through a broad alluvial valley that narrows toward its mouth at the Missouri River (Elliott and others, 2009). Hereinafter, unless otherwise indicated, all cities and towns are within the state of Nebraska. At its mouth, the Platte River drains approximately

86,000 square miles (mi^2). The Platte River gains approximately 26,500 mi^2 of drainage area downstream from its confluence with the Loup River, of which more than 90 percent (approximately 24,200 mi^2) can be accounted for by the collective drainage areas of the Loup River, Shell Creek, Elkhorn River, and Salt Creek. The remaining drainage area of the Platte River, approximately 2 percent of the total basin area, is the bottomlands of the LPR and small, mostly ungaged tributaries draining the dissected loess plains and glacial tills of eastern Nebraska (Missouri River Basin Commission, 1975). From the confluence with the Loup River to the confluence with the Elkhorn River, the slope of the LPR is approximately 0.091 percent (Bentall, 1991), the valley averages 7.3 miles in width, channel width ranges from 650 to 4,540 feet (ft), and average channel sinuosity is 1.08 mile per mile (mi/mi) (Elliott and others, 2009). Just downstream from the mouth of the Elkhorn River, the LPR flows into the eastern Platte River gorge (Joeckel and Henebry, 2008), and the valley width narrows to an average of 3 miles (Joeckel and Henebry, 2008). In the eastern Platte River gorge, channel width ranges from 600 to 2,780 ft, channel slope averages 0.075 percent (Bentall, 1991), and average channel sinuosity is 1.14 mi/mi (Elliott and others, 2009).

The hydrologic and sediment transport regimes of the LPR are dependent on the hydrologic and sediment transport regimes of the central Platte River (collectively refers to the segments of the Platte River extending from the confluence of the North and South Platte Rivers to the confluence with the Loup River), the Loup and Elkhorn Rivers, Salt Creek and, to a lesser extent, on flows in smaller tributaries draining the lower Platte River valley, including Shell Creek (Missouri River Basin Commission, 1975; Bentall and Shaffer, 1979). Along the central Platte River are numerous streamflow diversions to irrigation, municipal, and hydroelectric supply canals, and these diversions have fragmented and reduced the supplies of water and sediment delivered to the LPR (Murphy and others, 2004). Estimates of Platte River mean annual sediment discharges near Grand Island for pre- and post-development periods indicate that reductions in streamflow associated with water developments on the North Platte, South Platte, and central Platte Rivers have decreased sediment discharges by as much as one-half since the beginning of the 20th century (Randle and Samad, 2003).

Streamflows in the Loup and Elkhorn Rivers are affected by groundwater seepage, which provides a steady base flow to the LPR even during dry periods (Bentall and Shaffer, 1979). Neither the Loup nor the Elkhorn River has a large main-stem flood-control dam or major transbasin diversion. Consequently, the hydrologic and sediment-transport regimes of the LPR are more natural than those in the central Platte River (Eschner and others, 1983; Ginting and Zelt, 2008; Dietsch and others, 2009). The Missouri River Basin Commission (1975) estimated that the central Platte, Loup, and Elkhorn Rivers contributed more than 80 percent of the sediment transported by the LPR to the Missouri River, or 11, 44, and 28 percent, respectively.

The LPR channel narrowed after upstream water developments in the 20th century reduced the magnitude of low-frequency streamflows (Ginting and others, 2008), but most of the changes to channel morphology occurred before 1970. Joeckel and Henebry (2008) evaluated changes in overall channel area, island area, and channel width between 1938 and 2005 in two discrete segments along the lower Platte River: an approximately 10-mi segment just downstream from the mouth of the Loup River (upstream segment); and an approximately 11-mi segment in the vicinity of Louisville, within the eastern Platte River gorge (downstream segment). Between 1938 and 2005, active channel area decreased by 20 percent and island area decreased by 50 percent in the upstream segment. In the downstream segment between 1941 and 2005, active channel area decreased by 10 percent and island area decreased by 80 percent. In the upstream segment, most of the net change in channel area occurred from 1938 to the mid-1950s. In the downstream segment, channel area initially increased after 1941, but then decreased between the early 1970s and early 1990s. Decreases in channel area in both segments were caused by the abandonment of channel anabranches, and the attachment of islands to the channel banks (Joeckel and Henebry, 2008). A study by the USACE (2011) along a segment centered between the two studied by Joeckel and Henebry (2008) indicated that river-channel width and area decreased by 10 to 30 percent between 1938 and 2003, but most of the decrease occurred before 1970.

Previous studies of bank erosion indicate that the LPR has spatially variable rates of bank erosion. In these studies, bank erosion was expressed as a two-dimensional quantity, derived from areas of land-use change, whereby terrestrial land adjacent to the river observed in an aerial photo or map was observed as part of the river channel in a subsequent aerial photo or map. A rate of land area lost was calculated as the land area that changed to river channel (in units of acres), divided by the number of years between observations, and divided by the length of each study area to produce a rate of land area lost to the river per year per river mile ("areal bank erosion rate"). The Missouri River Basin Commission (1975) evaluated bank erosion rates along three adjacent segments in the LPR and concluded that bank erosion rates varied from 0.47 to 0.78 acres of land area lost per river mile per year and were highest in the most upstream segment. Similarly, Joeckel and Henebry (2008) indicated that bank erosion rates were 0.29 acres per mile per year near Columbus and 0.13 acres per mile per year (acre/mi/yr) near Louisville. A study by Rodekohr and Engelbrecht (1988), however, indicated that shorter-term bank erosion rates tended to be higher (0.03 to 3.46 acre/mi/yr) than longer-term bank erosion rates (0.02 to 0.43 acre/mi/yr), and that no clear, spatially variable pattern in bank erosion rates was evident in the LPR. The U.S. Army Corps of Engineers (1990) study indicated that bank erosion of unprotected banks accounted for less than 5 percent of the total bed-material discharge in the LPR; however, the USACE (1990) study also indicated that the LPR has a greater density of bank protection structures than other reaches of the Platte River in Nebraska, and the effect of these bank protections on natural bank erosion rates has not been investigated.

Riverbed stability in the LPR has been evaluated previously, but these studies have been limited to the areas near streamgages. Chen and others (1999) evaluated riverbed stability in several tributaries and the main stem of the LPR and indicated that the riverbed in the tributaries and main stem upstream from the mouth of the Elkhorn River was stable (not degrading or aggrading), but the Elkhorn River near its confluence with the LPR, and the LPR and tributaries flowing into the LPR downstream from the mouth of the Elkhorn were all degrading over the last one-half of the 20th century. The Platte River near Louisville, for example, was estimated to have a degradation rate of approximately 0.35 feet per decade (Chen and others, 1999). A similar analysis of bed stability by the USACE (2011) at several sites along the LPR concluded that no clear or consistent spatial or temporal pattern of bed-elevation change was apparent in the LPR, although the study did not employ statistical procedures to detect trends in river stage with time. The authors of this study visually inspected the trend plots in USACE (2011) and would argue they appear to show evidence of degradation near North Bend and aggradation near Ashland for streamflows larger than 10,000 cubic feet per second (ft^3/s).

Approach and Methods

The study evaluated sediment transport processes in the LPR relative to the potential for sandbar formation with two primary approaches. First, a sedimentologic analysis was used to characterize the longitudinal, reach-to-reach variation in grain sizes composing the riverbed, banks, and sandbars along the LPR, and a simple, quantitative analysis was used to compare respective grain-size distributions (GSD) of hypothesized sediment sources with those from sandbars. Second, a sediment budget analysis was done at the segment scale from 1970 to 2011 to investigate the longitudinal balance of sediment supplies, sediment storage, and sediment transport capacity in the LPR for a range of sediment grain sizes, including those grain sizes most commonly composing sandbars. Results from both approaches were interpreted to make conclusions, where possible, regarding the relative importance of bank-erosion-derived sediments to the composition of sandbars.

Sedimentologic Analysis of Sandbars and Sediment Sources

Sandbars are constructed when macro-scale bedforms migrating along the riverbed stall and become emergent above the water surface, often as river stage recedes to expose the top of the bedform (Smith, 1971). Thus, by the nature of their origin as bedforms, sandbars are constructed of bed material. The bed material composing the sandbar must originate upstream from where it is deposited, and is likely to be composed of a mixture of three primary sources: bed material from the immediate locality or adjacent upstream reach; bank material from bank erosion; and bed material from a nearby large tributary (Colby, 1963). For some rivers that drain basins formed in sandy soils, upland erosion would be a fourth primary source of bed material. But for the LPR, upland erosion, particularly in the small watersheds flowing into the LPR valley, is likely to contribute mainly to the washload component of sediment transport (Missouri River Basin Commission, 1975). Thus, one approach to isolating the sources of sediment in sandbars is to compare grain-size distributions of various sediment sources with those from sandbars.

Schaepe and Alexander (2011) sampled the riverbed and bank material of large tributaries (Loup and Elkhorn Rivers, and Salt and Shell Creeks), and the riverbed, banks, and sandbars of nine reaches in the LPR and two reaches of the central Platte River (table 1). The sediment samples obtained by Schaepe and Alexander (2011) were analyzed for grain-size distribution (GSD) by an independent contractor retained by the USACE, Omaha District, and the results of the analysis were provided to the USGS for use in the study (Dan Pridal, USACE, written commun., January 2012). The sample results delivered to the USGS included calculations of GSD percentiles and characteristic grain-size and sorting descriptions obtained using the GRADISTAT software (Blott and Pye, 2001).

Table 1. Lower Platte River, Nebraska, sediment sampling reaches of Schaepe and Alexander (2011).

For each of the 10 most-downstream reaches of Schaepe and Alexander (2011) (hereinafter referred to as “sampling reaches”), five sources of sediment were hypothesized to be the primary contributors of sediment to sandbars: bed material from the sampling reach immediately upstream; bed material from within the sampling reach; coarse-fraction bank material from the upstream sampling reach; coarse-fraction bank material from within the sampling reach; and bed material from the nearest upstream large tributary flowing into the sampling reach (if applicable). The fundamental premise of the hypothesis was, neglecting the effects of sediment mixing, the smallest difference in GSD would be observed between a sandbar and its primary source of sediment.

Two steps were used to evaluate the similarity of GSD of sandbars relative to each of the hypothesized sources. First, composite GSD were calculated for each hypothesized source within the 10 most-downstream sampling reaches. Next, the GSD of each hypothesized source was compared to the GSD of sandbars within each sampling reach using a root-mean-square-difference equation.

Schaepe and Alexander (2011) collected multiple samples of the river bed and sandbars within each of the sampling reaches. A representative GSD was created for the riverbed and sandbars within each sampling reach by mathematically compositing the associated grain-size frequency distributions using the following generalized normalization formula:

$$Pc_a = \frac{\sum_i^n (m_{i_a} + m_{(i+1)_a} + \cdots + m_{(n-1)_a} + m_{n_a})}{\sum_i^n (M_i + \cdots + M_n)} \qquad (1)$$

Where Pc_a is the composite-mean fraction by mass of samples within grain-size bin *a*;

m_{i_a} is the mass of sediment from sample *i* within grain-size bin *a*;

M_i is the total mass of sediment from sample *i*; and

n is the total number of samples associated with a particular feature (river bed or sandbar) within a tributary or sampling reach of interest.

This simple mass-weighted average composite of multiple samples was used only for sandbar and bed-material samples.

In the case of the river banks along the main channel of sampling reaches, Schaepe and Alexander (2011) typically collected two samples at each bank sample site, a sample of the coarse fraction, and another of the fine fraction. These two fractions varied in exposed thickness. For comparison with the GSD of sandbars, the calculated composite GSD for the riverbank source used only the coarse-fraction samples of the exposed river bank because this fraction was assumed to have been formed by deposition of bed material. Because of sampling instrument imprecision and variable sampling effort, the sample weights of each bank-material sample varied, but did not correlate with thickness of the sampled sedimentary unit; thus, for each sampling reach with multiple bank-material samples, the coarse-fraction sample GSDs were composited using a formula that weighted each sample relative to its respective bank exposure thickness:

$$Pc_a = \sum_i^n (p_a \frac{t}{T})_i \quad (2)$$

Where Pc_a is the fraction of the composited sample mass within grain-size bin *a*;

p_a is the fraction of sediment mass from sample *i* within grain-size bin *a*;

t is the exposed thickness of the deposit that sample *i* was obtained from, in units of length; and

T is the total exposed thickness of *n* deposits, in units of length.

To evaluate similarity between the GSD of sandbars within the sampling reaches and each of the five hypothesized sources, a root-mean-square difference formulation (RMSD) (Davis, 1986) was used, whereby the GSD of each hypothesized source was treated as an estimator of the GSD of sandbars using the following equation:

$$RMSD = \sqrt{\frac{\sum_a^n (pc_a - Pc_a)^2}{n}} \quad (3)$$

Where $RMSD$ is the root-mean-square difference between grain-size distributions in percent;

pc_a is the percent of sediment mass in grain-size bin *a* for the sandbar sample;

Pc_a is the percent of sediment mass in grain-size bin *a* for a hypothesized source; and

n is the total number of grain-size bins compared.

Because the units of RMSD are the same as the units of the samples (percent of sample mass in a particular grain-size bin), a smaller RMSD indicates smaller overall percent difference between sample GSDs. Thus, for sandbars in each sampling reach, the primary source of sediment was assumed to be the hypothesized source with the lowest RMSD.

Quality Assurance

Twelve replicate sediment samples were collected by Schaepe and Alexander (2011), 6 sandbar-material replicates, 3 riverbed-material replicates, and 3 bank-material replicates. These field replicates represented variation in sample grain-size distribution arising from slight spatial variation in sampling location. Differences between primary and replicate samples were characterized using two main approaches: summary statistics of absolute differences in percent of sample within individual grain-size class bins, and root-mean-square difference between grain-size distributions of the primary and replicate samples, in percent.

Sediment Budget Analysis Methods

A sediment budget uses the principle of continuity of mass, applied over a discrete spatial scale, to estimate the relative balance of sediment supply, sediment storage, and sediment transporting capacity of a river. The sediment budget, applied over a specified length of river, can be summarized with the following general equation:

$$Qs_{in} + \Delta S = Qs_{out} \quad (4),$$

where Qs_{in} is the input of sediment, Qs_{out} is the sediment exported out, and ΔS is the change in sediment storage. Sediment inputs included those from the channel upstream and tributary contributions. Sediment output was presumed to be equivalent to the sediment-transport capacity of the length of river, where such a presumption is consistent with a system that has unlimited supplies of sediment. Changes in storage result from the depositional and erosional processes that manifest as channel migration or an imbalance in the sediment transport capacity of the river relative to its inputs of sediment. A river that has a hydrologic regime in relative equilibrium with its associated supplies of sediment will have no net evacuation or accumulation of sediment in the bed or banks (Lane, 1954; Reid and Dunne, 1996).

Sediment budgets were developed for four discrete segments of the LPR, each bounded by large tributaries and designated by the name of the tributary at the upstream boundary: Loup River, Shell Creek, Elkhorn River, and Salt Creek, hereinafter referred to as Loup, Shell, Elkhorn, and Salt segments, respectively. For example, the "Loup" segment is the length of the LPR that begins at the confluence with the Loup River and extends for approximately 21 mi downstream to the confluence with the next large tributary, Shell Creek (fig. 1). Sediment inputs to each segment were quantified using at-a-station sediment-transport capacity estimates for the large tributaries and the central Platte River. Changes in sediment storage within each LPR segment were estimated using a geographical information system (GIS) analysis of bank erosion and deposition, and a specific-gage analysis of bed elevation. Sediment output from each segment was determined using two methods. The first method estimated bed-material transport capacity of the study segments using the USACE 1-dimensional hydraulic model HEC-RAS (hereinafter referred to as the "HEC model") (U.S. Army Corps of Engineers, 2010b). The second method estimated bed-material transport capacity of the segments using an at-a-station sediment-transport capacity approach. This second sediment-transport capacity estimate for each segment was made because analysis of the HEC model indicated it was not adequately simulating the hydraulics of streamflows with magnitudes less than the 1-percent exceedance (the streamflow exceeded 1 percent of the time for the study period).

Methods Used to Estimate Sediment Inputs to Segments of the Lower Platte River

Two primary sources of sediment were assumed for each segment of the LPR: bed-material deliveries from adjacent upstream segments, and within-reach large tributary sediment deliveries. For the three most-downstream segments, inputs of sediment from upstream bed-material transport were considered the sediment outputs from each adjacent upstream segment (described in the *Methods used to Estimate Bed-Material Discharge and Construct Sediment Budgets in Segments of the Lower Platte River* section in this report). For the Loup segment, inputs of bed-material sediments were the Loup River, and the central Platte River, both of which were treated as "tributary" to the LPR.

Methods Used to Estimate Sediment Inputs from Large Tributaries and the Central Platte River

Estimation of bed-material contributions from large tributaries and the central Platte River to the LPR used an "at-a-station" approach, whereby estimates of sediment transport capacity were made using available hydraulic data from representative streamgages. At-a-station estimation of bed-material transport capacity consisted of five primary steps: selection of sediment-transport equations; selection of representative streamgages to apply equations; generation of hydraulic geometry relations for representative streamgages; generation of streamflow frequencies for representative streamgages; and calculation of annual bed-material discharge.

For the analyses described in this report, the lands within the Platte River Basin downstream from the Loup River confluence, and not accounted for by large tributaries, were assumed to contribute negligible masses of sediment, or sediments finer in diameter than 0.0625 millimeter (mm), making them unlikely to contribute substantially to bed-material transport processes in the LPR.

The Loup segment is distinguished from other segments in the LPR because a large hydroelectric facility near Columbus has a tailrace that delivers water to the Platte River approximately 2 mi downstream from the Loup River confluence. The water exiting the tailrace originates from a diversion on the Loup River approximately 34 mi upstream from its mouth, and exits the hydroelectric generation plant into the tailrace as “clear water” (water with little or no sediment discharge). With the exception of a small tributary draining dissected loess plains, no primary drainages flow into the tailrace channel (Missouri River Basin Commission, 1975). Thus, for the purposes of the study described in this report, the tailrace from the hydroelectric facility was assumed to contribute negligible masses of bed-material to the LPR.

Selection of Sediment Transport Equations

Two predictive equations were selected to estimate annual bed-material discharge from large tributaries to lower Platte River segments: Engelund and Hansen (1967), and Yang (1973). These equations were selected because they are widely considered to be the most accurate total bed-material fraction formulations for large sand-bed rivers like the LPR (Molinas and Wu, 2000; Reid and Dunne, 1996; Stevens and Yang, 1989), and generally are practical to apply with available hydraulic geometry data from streamflow-gaging stations and samples of bed-material grain sizes. Potentially most important to the bed-material budget analysis, the Engelund and Hansen (1967) and Yang (1973) formulations are available as sediment-transport routines within HEC-RAS, which allowed for method continuity with estimations of bed-material transport in main-stem segments using the HEC model. These equations often are referred to as “total load equations;” however, the equations only consider sediments available on the riverbed, and thus do not include washload (sediments not observed on the bed at the time of sampling) (Reid and Dunne, 1996). A complete review of the predictive equations is beyond the scope of this report;

however, brief descriptions of each equation are provided for method documentation. The reader is referred to Garcia (2008) for detailed descriptions of the physical theory and experimental basis of the equations.

The Engelund and Hansen (1967) equation is a dimensionless equation for sediment concentration by weight based on the concept of excess stream power (Bagnold, 1966):

$$C(d) = 0.05 \left[\frac{G_s}{G_s-1}\right] \left[\frac{U*S_o}{([G_s-1]*g*d)^{0.5}}\right] \left[\frac{R*S_o}{(G_s-1)*d}\right] \quad (6)$$

where:

$C(d)$ is dimensionless concentration for sediment of grain-size diameter d;

G_s is sediment specific gravity, dimensionless;

U is mean flow velocity, in units of length per unit time;

S_o is slope, dimensionless;

g is gravitational acceleration, in units of length per time squared;

d is particle diameter, in units of length; and

R is hydraulic radius in units of length (average flow depth [D] is substituted in rivers that are much wider than deep).

The Yang (1973) sediment-transport formula also is based on the concept of unit stream power, and was developed as a statistical regression analysis using sediment transport data from a laboratory flume:

$$\log C(d) = a_1 + a_2 \log\left[\frac{US_o}{\omega_d} - \frac{U_c S_o}{\omega_d}\right] \quad (7)$$

where:

$C(d)$ is concentration in parts per million for sediment of grain-size diameter d;

a_1 is a regression parameter based on particle settling velocity and the shear velocity of the flow;

a_2 is a regression parameter based on particle settling velocity and the shear velocity of the flow;

ω_d is particle settling velocity based on particle diameter d, in units of length per time; and

U_c is the critical velocity at incipient motion of particle of diameter d, in units of length per time; and other symbols are as defined above.

Particle settling velocity was estimated using the following equation presented by Julien (1998):

$$\omega_d = \frac{8\nu_m}{d}([1 + 0.0139d_*^3]^{0.5} - 1) \quad (8)$$

where:

ω_d and d are as before;

ν_m is the kinematic viscosity of the mixture, in units of length squared per time; and

$$d_* = d\left[\frac{(G_s - 1)g}{\nu_m^2}\right]^{1/3} \quad (9)$$

where:

d_* is the dimensionless particle diameter; and

$d, G_s, g,$ and ν_m are as before.

All bed-material transport capacity calculations assumed a water temperature of 68°F (20°C) for constant kinematic viscosity of water.

Selection of Representative Streamgages in Large Tributaries

Five streamgages were chosen to represent the hydraulic geometry and streamflows of the central Platte River and four large tributaries to the LPR (table 2). Ideally, streamgages would be located at the mouth of the respective river or stream and have daily streamflow records spanning the entire study period; however, only two streamgages met these conditions. The streamgages on the central Platte River and Elkhorn River were located near the mouths of their respective drainages (table 2), and had daily streamflow periods of record that spanned all of the study period. The streamgage on the Loup River near Columbus was located near the mouth of the Loup River, but deactivated shortly after water year 1978. The streamgages chosen for Shell Creek and Salt Creek were located further upstream within their respective drainage basins, but each had daily streamflow periods of record spanning the period of study. At streamgages with incomplete periods of record between 1970 and 2011, or which did not represent the total drainage area of their respective basin, adjustments were made to either scale the flow frequency between streamgages with more complete periods of record (see *Streamflow Frequencies of Large Tributaries* section in this report) or scale the annual bed-material sediment discharges by basin area.

Table 2. Streamgages used to represent channel hydraulic geometry and streamflow for at-a-station estimations of annual bed-material sediment discharge of large tributaries to the lower Platte River, Nebraska, by river segment.

At-a-Station Hydraulic Geometry Relations of Large Tributaries

Equations 6 and 7 require estimations of hydraulic radius (R), flow depth (D), flow velocity (U), and friction slope (S_o) for each increment of streamflow within the annualized flow frequency distribution. Channel width (W) was substituted for hydraulic radius, R, a common practice for rivers that are much wider than deep during most hydraulic conditions (Garcia, 2008). At-a-station hydraulic geometry statistical relations were used to generate estimations of *W*, *D*, and *U*. Channel bed slope (S_b) was used as a reasonable approximation of friction slope (S_o) (Dingman, 2009), and was obtained either from Bentall (1991) or by calculating the water-surface slope using measurements made on a USGS 7.5-minute topographic quadrangle map. The hydraulic geometry relations used the series of empirical models in the form of power laws presented by Leopold and Maddock (1953):

$$W = aQ^b \tag{10}$$

$$D = cQ^f \tag{11}$$

$$U = kQ^m \tag{12}$$

The coefficients *a, c,* and *k* and exponents *b, f,* and *m* are numerical constants and *Q* is streamflow.

Hydraulic geometry relations were generated for each of the five tributary streamgages using measurement data available on the USGS National Water Information System (NWIS) (USGS, 2013a) (table 3). Measurement data were filtered before generation of the hydraulic geometry relations to remove measurements made during the winter months (December, January, and February) when ice effects can produce anomalous hydraulics, to account for changes in the location of a streamgage or bridge, and to remove extreme data outliers that were unresolvable. For the Platte River near Duncan, a two-stage hydraulic geometry relation was constructed because scatterplots of the relations indicated substantial curvature at approximately 500 ft^3/s, above which channel width increased at a much slower rate, depth increased at a much faster rate, and current velocity increased at a slightly faster rate (table 3).

Table 3. At-a-station hydraulic geometry relations for selected streamgages on large tributaries to the lower Platte River, Nebraska.

Streamflow Frequencies of Large Tributaries

Annual bed-material discharge for each large tributary was evaluated across the range of daily average streamflows during 1970 through 2011. For each tributary streamgage, the daily streamflow record from the 1970–2011 study period (USGS, 2012) was used to construct streamflow cumulative-exceedance frequency curves (also called "flow-duration curves"), which represent the percentage of time, during the 1970–2011 study period, a particular streamflow was equaled or exceeded (fig. 2). Fifteen frequency intervals were generated, one each for the 0, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, and 100th daily exceedance percentiles, using the methods described in Searcy (1959). In the case of the Loup River, the period of record at the most downstream streamgage, the Loup River at Columbus (USGS streamgage 06794500, fig. 1) ended in 1978 (table 2), but a streamgage located approximately 20 miles upstream, the Loup River near Genoa (USGS streamgage 06793000, fig. 1), had a longer period of record. In this case, a synthetic cumulative-exceedance curve was generated using the following equation:

$$\hat{Q}_{y_i} = Q_{x_i}\left(\frac{q_{y_i}}{q_{x_i}}\right) \tag{16}$$

where $\hat{Q}_{y_i}$ is the synthetic streamflow, in units of length cubed per time, at flow exceedance percentage *i* for the gage, *y*, with the incomplete period of record;

Q_{x_i} is the streamflow, in units of length cubed per time, at flow exceedance percentage *i* for the gage, *x*, with a complete period of record;

q_{y_i} is the streamflow, in units of length cubed per time, at flow exceedance percentage *i* for the gage, *y*, for the overlapping period of record with gage *x*; and

q_{x_i} is the streamflow, in units of length cubed per time, at flow exceedance percentage *i* for the gage, *x*, for the overlapping period of record with gage *y*.

Figure 2. Streamflow cumulative-exceedance frequency curves of daily average streamflows at selected U.S. Geological Survey streamgages on large tributaries of the lower Platte River, 1970 to 2011.

Calculation of Annual Bed-Material Discharge from Large Tributaries

The bed-material sediment transport equations (6) and (7) were applied using a bed-material fraction approach (Molinas and Wu, 2000), whereby predictive sediment transport equations are applied at a discrete streamflow to estimate the sediment-transport capacity for a discrete grain size regardless of grain-size availability. Tributary riverbed samples collected by Schaepe and Alexander (2011) were composited using equation (1), and the composite GSD (table 4) was used to approximate grain-size availability in the riverbed.

Table 4. Summary of sediment-sample sources and composite grain-size distributions for the riverbed, riverbanks, and large tributaries of segments of the lower Platte River, Nebraska.

The estimates of annual bed-material sediment discharge used the complete range of streamflows recorded during the 1970–2011 study period, but the time intervals over which each flow magnitude was applied were scaled to its flow duration for a single year. For a discrete streamflow, Q_x, the sediment-transport-capacity estimation was based on the following general formulation (Molinas and Wu, 2000):

$$C_{tQ_x} = \sum_i^n C_{ti} \tag{17}$$

where:

C_{tQ_x} is the total bed-material discharge for streamflow Q_x, in units of mass per time;

n is the total number of grain-size fractions; and

$$C_{ti} = P_{bi} \times C_{pi} \quad (18)$$

where:

C_{ti} is the total mass of bed-material discharge for grain-size fraction i, in units of mass per time;

P_{bi} is the fraction of the bed sediment mixture composed by size fraction i; and

C_{pi} is the potential total bed-material discharge for size fraction *i* assuming uniform sediment size, in units of mass per time.

The sediment transport routines embedded in HEC-RAS use the geometric mean of the limits bounding particle-size bins (nominal sizes of bounding sieves) to represent individual grain-size fractions denoted by subscript, *i* (U.S. Army Corps of Engineers, 2010a). Thus, the geometric mean also was used for the annual bed-material discharge calculations for large tributaries.

To estimate the annual bed-material discharge from each tributary during 1970 to 2011, the flow exceedance frequency intervals were normalized to annualized frequencies (number of days within a year that a flow is equaled or exceeded) by multiplying the percentage of time in each frequency interval by 365 days:

$$t_{Q_x} = f_{Q_x} \times 365 \quad (19)$$

where t_{Q_x} is the number of days per year that streamflow Q_x is equaled or exceeded in a theoretical year;

f_{Q_x} is the fraction of time that streamflow Q_x was equaled or exceeded during 1970 to 2011 ; and

365 is the number of days in common calendar year.

Estimates of total annual bed-material discharge from each tributary were then calculated as:

$$C_T = \sum_x^n C_{tQ_x} \times t_{Q_x} \quad (20)$$

where C_T is the estimated total annual bed-material discharge for a tributary, in units of mass per year; and

n is the total number of streamflow-frequency intervals.

Estimation of Changes in Sediment Storage in the Banks and Riverbed of Segments of the Lower Platte River

Sediment storage within each segment was assumed to occur in the banks of the river, and on the riverbed. Changes in storage associated with bank erosion and accretion were estimated using a GIS analysis of temporal changes in channel area and forested floodplain area, and were the only storage component included in the sediment budget calculations. Changes in bed storage with time were estimated using specific-gage analysis at representative streamgages, and were used as a validation check of the results from the sediment budget calculations.

To identify potential large temporal differences in bank erosion or accretion rates, rates of bank erosion and accretion within each segment were estimated for two time periods, 1970 to 1993, and 1993 to 2003. Estimations of erosion and accretion were calculated using land-use GIS datasets for 1970, 1993, and 2003 created by the USACE for Phase 2 of the lower Platte River Cumulative Impact Study (U.S. Army Corps of Engineers, 2008). Digital orthophoto quarter-quadrangles (DOQQ) from 1970, 1993, and 2003 were paired with the land-use datasets in the GIS, and were visually inspected for consistency.

Alterations to each land-use dataset were made for several reasons. In most cases, changes to land-use polygons were needed to differentiate between islands and floodplain areas with mature vegetation, and islands and floodplains considered to be in an incipient state. Incipient floodplain and islands were defined as areas with immature, low-standing vegetation including grasses, shrubs, and sapling trees. In the original land-use datasets provided by the USACE, vegetated areas were grouped into single polygon areas regardless of the maturity of vegetation. In some cases, alteration of the landuse datasets required reclassification of the individual feature polygons; however, in other instances alteration required dividing the existing polygons into smaller polygons consisting of incipient and maturely vegetated areas. The 1970 and 1993 DOQQs were developed from black-and-white photography, which made differentiation between mature and incipient areas more difficult. In these cases the vegetation was compared to vegetation outside of the channel to help assess the vegetation's maturity. Other changes were made to the individual land-use datasets when additional detail was required to delineate the channel boundary between a channel bank or in-channel island boundary. All edits made to the land- use dataset within GIS were performed while viewing the data on screen at 1:5,000 scale.

Erosion and accretion rates were calculated by utilizing the "Erase" functionality in the analysis toolbox within ArcGIS™ (Environmental Systems Research Institute, variously dated). All polygon features within the active channel were selected for each year and separated into their respective segments (Loup to Shell, Shell to Elkhorn, Elkhorn to Salt, and Salt to mouth). The Erase tool was then used to create polygon features that captured areas of individual polygons that were altered during the times specified. The final products were polygon features of gains and losses in channel area for each segment for the periods selected during 1970–93 and

1993–2003, which were derived from bank-line differencing of polygon features from the beginning and end of each time interval (fig. 3).

Figure 3. Map showing example of bank-line differencing of polygon features used to estimate bank erosion and accretion rates for segments of the lower Platte River, Nebraska, 1970 to 1993.

Average bank heights used to calculate sediment mass contributions from bank or island erosion, or deposition from bank or island accretion, were estimated for each segment using a combination of the bank height measurements made by Schaepe and Alexander (2011) and Alexander and others (2013) (table 5). Each bank height measurement made by Schaepe and Alexander (2011) was adjusted to the stage of 90-percent-exceedance streamflow (the streamflow that is exceeded 90 percent of the time from 1970 to 2011) at the nearest streamgage using the stage-interpolation method for the lower Platte River presented in Alexander and others (2013). Schaepe and Alexander (2011) measured between 3 and 7 bank heights within each segment. Alexander and others (2013) measured bank heights at 86 locations along the Salt segment. The ratio of average bank heights in the Salt segment calculated using the larger dataset of Alexander and others (2013) relative to the average bank heights from the more sparse measurements of Schaepe and Alexander (2011) was 0.86, indicating that the smaller sample size of Schaepe and Alexander (2011) yielded results that tended to overestimate the average bank height. Thus, the estimates of average bank heights in the other segments, based on the Schaepe and Alexander (2011) data were assumed to have been biased high, and were adjusted using the 0.86 factor obtained for the Salt segment (table 5).

Table 5. Average bank heights in segments of the lower Platte River, Nebraska.

The assumed bank height for calculations of accretion of bank or islands was lower than that used for erosion calculations because field observations by the authors indicated that accreted bank height for young floodplains or islands was not the same as those of mature floodplains and islands ("mature" and "young" were judged by relative diameter and height of floodplain forest communities). Calculations of bank accretion within each segment assumed the accreted thickness was 60 percent of the average bank height for each segment. This assumption is based on the fact that the coarse fraction of bank exposures sampled by Schaepe and Alexander (2011) constituted approximately 60 percent of the total bank height on average. For the purposes of this study, the coarse fraction of the riverbank was assumed to be the fraction that corresponded to the initial accretion of the riverbanks or islands (incipient) by stabilization of bank-attached sandbars.

Polygon areas of erosion and deposition were summed for each segment and the totals reflected total erosion and accretion of channel area during each respective period. Total mass of bank material from erosion or accretion was estimated for each grain-size fraction, and summed for *n* fractions to compute total mass storage changes:

$$M_b = \sum_i^n A \times Z_B \times 1.35 \times P_{ib} \quad (21)$$

where

M_b is the total mass of bank material eroded or accreted, in tons;

A is the total area of floodplain or island eroded, or accreted, in square yards;

Z_b is the segment average bank height at the 90-percent exceedance streamflow, in yards

1.35 is a constant used to convert volume in cubic yards to sediment mass in tons (Marron, 1992); and

P_{ib} is the fraction of the total mass that is composed of grain size i.

For each segment, grain-size distributions from riverbank samples within each of the sampling reaches of Schaepe and Alexander (2011) were composited using equation (2) (table 4). For the purposes of constructing the sediment budgets in each segment, the average rate of bank erosion from 1970 to 2003 was used.

Changes in sediment storage in the riverbed within each segment were evaluated using a specific-gage analysis following methods similar to those used by Chen and others (1999), and Jacobson (1995). These methods use paired stage and discharge measurements taken at streamgages to evaluate temporal trends in stage for a given discharge (Chen and others, 1999) and in mean riverbed altitude (Jacobson, 1995). Three streamgages were chosen to represent the four segments of the LPR based on location and length of their respective periods of record. The Platte River at North Bend (USGS streamgage 06796000; fig. 1) was chosen to represent the Loup and Shell segments. The Platte River near Ashland (USGS streamgage 06801000; fig. 1) was chosen to represent the Elkhorn segment. The Platte River at Louisville (USGS streamgage 06805500; fig. 1) was chosen to represent the Salt segment.

Measurement data from each streamgage were extracted from the USGS National Water Information System (USGS, 2013a). Measurement data collected during winter months (December, January, and February), any streamflow measurements made in the presence of ice, and measurements with stage or channel geometry values deemed obvious “outliers” that could not be resolved were removed. “Outliers” were defined as data points that were an order-of-magnitude different than other data points for the same discharge, and an explanation for the difference could not be inferred from accompanying information. Three subsets of measurement data at each streamgage were then extracted; one set each for streamflows within 10 percent of the flow rates having 90-, 50-, and 10-percent exceedance frequencies (see *Streamflow Frequencies of Segments of the Lower Platte River* section of this report). For each of the three subsets of measurement data, two primary measures of streambed elevation were examined for temporal trends: river stage and mean riverbed altitude (MRA). River-stage values were adjusted for a datum shift at the North Bend streamgage that occurred in water year 1971 (USGS, 2013b). Mean riverbed altitude was defined as:

$$\bar{Z} = S_w + Z_l - D \tag{22}$$

where:

$\bar{Z}$ is mean riverbed altitude, in feet, within vertical coordinate system of streamgage (NGVD 29 or NAVD 88);

S_w stage of water surface, in feet;

Z_l datum of streamgage, within vertical coordinate system of streamgage; and

D average water depth, computed as streamflow cross-sectional area divided by water-surface top width.

For each streamflow-exceedance frequency, at each streamgage, the non-parametric Kendall (1938) rank-correlation analysis was used to test for the presence of temporal trends (for period since first available measurement point) in stage, and in MRA. A trend was considered statistically significant if the probability value (*p*-value) for the Kendall tau statistic (*tau*) was 0.05 or less. If a significant trend was detected, the robust regression procedure of Theil (1950) was used to compute the slope of the trend.

Methods Used to Estimate Bed-Material Discharge and Construct Sediment Budgets for Segments of the Lower Platte River

The remaining element in the sediment budget equation (equation 4) is sediment outputs. For this study, estimates of annual bed-material discharge in each segment were used as the measure of sediment output. Two approaches were used to estimate annual bed-material discharge for sediment budgets for segments of the LPR. The first method used an available 1-dimensional hydraulic model to estimate annual bed-material discharge within each segment, and an automated sediment budgeting tool available within the model to generate the sediment budgets. The second method used the at-a-station approach (see *Methods used to estimate sediment inputs from large tributaries and the central Platte River* section of this report) to estimate annual bed-material discharge within each segment, and the sediment budgets were computed manually. For each segment, a streamflow frequency distribution and a composite grain-size distribution were required as primary inputs to estimate annual bed-material discharge.

The two different approaches to estimate annual bed-material discharge and compute sediment budgets were used because the hydraulic simulations from the 1-dimensional HEC model were later deemed to be of inadequate quality for streamflows less than the 90-percent-exceedance magnitude, and model-based estimates of sediment transport in each segment were considered unreliable. A second method was deemed necessary to provide a more reliable estimate of annual bed-material discharge from study segments, and to allow for estimation of uncertainty and sensitivity in sediment budget components.

Streamflow Frequencies of Segments of the Lower Platte River

The LPR has five active streamgages at which river stage is monitored and where statistical relations between observed stages and streamflow existed. Of these five streamgages, two have periods of record that span the 1970–2011 study period: the Platte River at North Bend (USGS streamgage 06796000; fig. 1) and the Platte River at Louisville (USGS streamgage 06805500; fig. 1). The streamgage at the Platte River near Ashland (USGS streamgage 06801000; fig. 1), has a gap in the period of record from 1953 to 1988. The three streamgages are located within three separate segments: Shell, Salt, and Elkhorn, respectively (fig. 1). The daily streamflow records for each streamgage for water years within the 1970–2011 study period (USGS, 2012) were used to generate streamflow frequency distributions for calculating the daily average flows corresponding to standard exceedance frequencies (0, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, and 100th exceedance percentiles) for the Shell, Elkhorn, and Salt segments, using methods described in Searcy (1959) (fig. 4).

Figure 4. Streamflow cumulative-exceedance frequency curves of daily average streamflows at selected U.S. Geological Survey streamgages in the lower Platte River Basin, Nebraska.

For the Loup segment, no streamgage was present to represent the flow regime; therefore, it was assumed that the primary difference in streamflow between the Shell segment and the Loup segment was the streamflow discharged by Shell Creek, the largest tributary (by drainage area) flowing into the segment. Thus, a synthetic streamflow frequency distribution was generated for the Loup segment by subtracting the flow-exceedance frequency percentiles of the synthetic frequency distribution for Shell Creek from the equivalent percentiles of the streamflow frequency distribution for the Platte River at North Bend. A synthetic streamflow frequency distribution was used for Shell Creek because approximately 40 percent of the basin is downstream from the only active streamgage in that drainage, Shell Creek near Columbus (USGS streamgage 06795500; fig. 1) (table 2) . The synthetic streamflow frequency distribution for Shell Creek was generated using an equation that scaled the frequency distribution to differences in basin area:

$$Q_{S_i} = Q_{x_i}\left(1 + \left(1 - \frac{A_g}{A_t}\right)\right) \tag{23}$$

where Q_{S_i} is the synthetic streamflow, in cubic feet per second, at flow-exceedance percentage *i*;

Q_{x_i} is the streamflow, in cubic feet per second, at flow-exceedance percentage *i*;

A_g is the drainage area, in units of square length, at the streamgage where streamflow exceedance frequencies were generated from monitoring data; and

A_t is the total drainage area of the basin of interest, in units of square length.

Composite Bed-Material Samples for Segments of the Lower Platte River

Sediment samples collected by Schaepe and Alexander (2011) were used to define the bed-material GSD for the four segments. Representative bed-material GSDs were generated for each segment by compositing bed-sediment sampling data from each of the sampling reaches of Schaepe and Alexander (2011) using equation 1 (table 4).

Bed-Material Budget Using a One-Dimensional Hydraulic Model and Automated Sediment Budgeting Tool

The geometry of the LPR channel varies from reach to reach (Elliott and others, 2009), and more substantially across broader segments associated with longitudinal changes in geologic controls (Bentall, 1991; Joeckel and Henebry, 2008; Elliott and others, 2009). Estimation of the bed-material transport capacity in segments of the LPR would, ideally, incorporate the range of hydraulic conditions associated with the range of channel hydraulic geometries present in the LPR.

The Sediment Impact Analysis Methods (SIAM) is a sediment budget tool, which uses the one-dimensional hydraulic modeling software HEC-RAS (U.S. Army Corps of Engineers, 2010b) to simulate channel hydraulic conditions within river segments, and account for changes in bed-material transport associated with changes in channel morphologic, hydrologic, and hydraulic conditions between adjacent river segments (Gibson and Little, 2006). The HEC-RAS model (HEC model) used for the analysis described herein was constructed by aggregating channel geometries and associated hydraulic characteristics from three different available hydraulic models, all originally constructed for flood-inundation studies along the LPR. The aggregated model was provided to the USGS by the USACE, Omaha District, and a summary of the three component models, their associated input geometries, hydraulic assumptions, and calibration procedures can be found in Appendix 1 of this report.

Sediment budgets generated using the SIAM tool identify the relative balance between sediment supplies and transport capacity in discrete river segments, and these data can be used to make comparisons with sediment imbalances and morphodynamic data generated from specific-gage analysis or other indicators of channel stability (U.S. Army Corps of Engineers, 2010b). For this study, the four segments of the LPR (Loup, Shell, Elkhorn, and Salt) also were the designated sediment budget segments (called “sediment reaches” in SIAM) for the SIAM analysis. For each river segment, the SIAM tool requires several inputs to generate a sediment budget: a “hydrologic frequency” distribution whereby streamflow intervals are appropriated to fractions of a year; a HEC-RAS “plan” file that includes channel water-surface profiles generated for each of the intervals of the streamflow-frequency distribution and spanning all river segments; a composite grain-size distribution for the riverbed in each segment; estimated inputs of sediment by grain-size bin from tributaries or other designated sources; and changes in storage by grain-size bin. The changes in storage used in the SIAM tool were the changes in bank storage estimated from the GIS analysis. Changes in storage in the riverbed, computed from the specific-gage analysis of temporal trends in riverbed elevation, were used only as validation checks of the segment sediment-balance results generated by the SIAM tool.

HEC-model simulations were made for each segment to generate 15 water-surface profiles representing the 15 streamflow frequency intervals (see *Streamflow Frequencies of Segments of the Lower Platte River* section of this report). Several iterations of the simulations were made before the final hydraulic simulations to identify and modify problem areas for the final SIAM sediment-budget analysis. First, trial simulations were made to test whether or not the HEC model would successfully generate profiles for each interval of streamflow magnitude, and to identify potential areas for improvement of the model. After the trial simulations, modifications to the model geometry and a set of test simulations were made to generate the hydraulics inputs for initial testing of the SIAM tool. Final model simulations were made to generate hydraulics for the SIAM analysis of the segments. All model simulations were made assuming that flows remained in the sub-critical flow range. All SIAM analyses utilized the dimensionless Engelund-Hansen (1967) and Yang (1973) equations (equations 6 and 7, respectively) as implemented within HEC-RAS, the composite grain-size distributions of the riverbed generated for each segment, and the changes in bank storage estimated from the GIS analysis. Trial simulations and initial HEC model troubleshooting, model modifications for initial and final hydraulic simulations, and test SIAM outputs are summarized in appendix 2; appendix 3 summarizes an evaluation of the HEC-model hydraulic simulations.

At-a-Station Bed-Material Budget

After an evaluation of the HEC model concluded that the channel geometry used by the model was not adequate to simulate hydraulics for streamflows at or below the magnitude of the 10-percent-exceedance discharge (see appendixes 2 and 3), a second set of bed-material sediment-transport calculations was deemed necessary to estimate bed-material transport capacity in the segments of the LPR. A second set of sediment budgets was constructed by estimating the bed-material transport capacity in each segment. The second set of sediment budgets used the same at-a-station methods as those employed for estimation of annual bed-material discharge from large tributaries (see *Methods Used to Estimate Sediment Inputs from Large Tributaries and the Central Platte River* section of this report). As before, use of equations 6 and 7 required generation of at-a-station hydraulic geometry relations at representative streamgages, as well as streamflow frequencies, estimates of friction slope, and bed-material GSD. For each segment of the LPR, data for streamflow frequencies and bed-material GSD were the same as those used as inputs to the HEC model and SIAM tool. Channel bed slope, as before, was used to approximate hydraulic friction slope for each segment, and was obtained from values published in Bentall (1991). Hydraulic geometry relations for three streamgages in the LPR were used to represent the hydrology of the LPR (as they were for the SIAM tool): the Platte River at North Bend (USGS streamgage 06796000; fig. 1), the Platte River near Ashland (USGS streamgage 06801000; fig. 1), and the Platte River at Louisville (USGS streamgage 06805500; fig. 1). These three streamgages were used to represent the streamflows of the Shell, Elkhorn, and Salt segments, respectively (table 6). The Platte River at North Bend streamgage also was used to represent the hydraulic geometry of the Loup segment, which is broadly morphologically similar to the Shell segment (Elliott and others, 2009).

Table 6. At-a-station hydraulic geometry relations for selected streamgages in the lower Platte River, Nebraska.

The estimation of bed-material-transport capacity and subsequent calculation of a sediment budget involves many uncertainties and simplifying assumptions associated with channel hydraulics, bed-material grain-size distributions, riverbank material grain-size distributions, and bank heights (Reid and Dunne, 1996). The uncertainties associated with estimation of sediment transport and sediment yields can be large enough to overshadow the ability of a sediment-budget analysis to detect longitudinal imbalances in the sediment system (Grams and Schmidt, 2005). Although addressing all sources of uncertainty associated with a sediment budget for segments of the LPR was beyond the scope of this study, some estimation of uncertainties was deemed useful for understanding the relative magnitudes of longitudinal sediment imbalances.

Estimations of uncertainty intervals for individual components of the at-a-station sediment budget focused on grain sizes larger than 0.0625 millimeters (mm) because composite samples indicated that 4 percent or less of sediments in sandbars were finer than 0.0625 mm (table 4). Uncertainty intervals were estimated in two primary ways. First, uncertainty of annual bed-material discharge from tributaries and outputs from study segments was estimated with a sensitivity analysis of equations 6 and 7 by variation of the bed-material GSD. The sensitivity analysis computed an interval of the estimated bed-material discharge for each equation using the finest and coarsest bed-material GSD among samples from each tributary and LPR segment. The finest and coarsest samples were identified as having the finest and coarsest median-grain diameters, respectively. Second, uncertainty intervals for bank sediment storage assumed bank-height was the largest source of uncertainty in the storage component in each LPR segment, and the intervals were created by estimating confidence intervals of bank mass erosion and accretion. For bank mass erosion, the 95-percent confidence interval was generated using the standard-error of the mean bank height for the large bank height sample collected by Alexander and others (2013) in the Salt segment. For bank mass accretion, the 95-percent confidence interval was generated using the standard error of the mean thickness of the coarse fraction of bank heights sampled by Schaepe and Alexander (2011).

The uncertainty intervals for sediment-budget components were used to evaluate whether or not imbalances between the segment-mean values in the sediment budgets were large enough to conclude a dominant segment "condition." For example, if the mean for the annual masses from bank erosion was contained by the uncertainty interval for mass bank accretion, or the reverse, the dominant bank storage condition was assumed to be too close to call or "indeterminate" (Grams and Schmidt, 2005). However, if the mean masses of both storage processes (erosion and accretion) were not contained by the other's uncertainty interval, the dominant condition for the segment was concluded to be the one with the highest mean value. Likewise, for segment sediment balance, if the mean inputs or outputs were contained by the other's uncertainty (sensitivity) interval, then a condition of "indeterminate" was concluded. However, if neither the mean inputs nor outputs were contained by the other's uncertainty interval, a predicted channel adjustment condition of "degradation" nor "aggradation" was concluded, depending upon which component (inputs or outputs) had the larger mean value. Bank storage was factored into the segment sediment balance calculations only if a dominant condition could be concluded for that process; otherwise, bank erosion and accretion were concluded to be in balance, within the uncertainty.

Sedimentologic and Bed-Material Sediment Budget Analysis of Sandbars in the Lower Platte River

Identification of sandbar sediment sources using sedimentologic analysis indicated that sediment grain-size distributions from sandbars generally were most similar to grain-size distributions from bed-material samples from within the respective sampling reaches; however, the sedimentologic analysis was inconclusive because the range of differences between grain-size distributions from sandbars and those from bed material and coarse-fraction bank material were within the range of uncertainty estimated from replicate samples.

The sediment budget analysis indicated that sediment derived from riverbank storage commonly was balanced by bank accretion within respective LPR segments. In the segment where bank erosion was greater than bank accretion, the mass of sediment derived from bank erosion was as much as one to two orders of magnitude smaller than other sediment budget components, depending on the sediment transport equation used. Despite concluding that the sediment budget indicated that bank erosion yields a relatively small proportion of sediment in sandbars, the study was not designed to determine if the process of bank erosion, by altering channel bank morphology and reach-scale hydraulics, is important to formation of sandbars.

Sedimentologic Analysis of Sandbars and Sediment Sources

Grain-size distributions from samples collected by Schaepe and Alexander (2011) indicate that grain sizes in sandbars, the riverbed, and the coarse fraction of the riverbanks from the central Platte and lower Platte Rivers were composed primarily of very-fine to very-coarse sand, and these sediments generally became finer downstream from the mouth of the Loup River. The median, 10^{th}, and 90^{th} percentiles of sampled sandbar grain diameters indicate that sandbars mostly were composed of medium to coarse sand in the most downstream reaches of the Platte River upstream from the Loup River confluence, very-fine to coarse sand in the reaches between the Loup and Elkhorn Rivers, and fine to coarse sands downstream from the Elkhorn River (fig. 5).

Figure 5. Longitudinal distribution of composite grain-size distributions of sediment samples from sandbars, the riverbed, and riverbanks, and root-mean-square difference between sediment grain-size distributions of sandbars and five hypothesized sediment sources, lower Platte River, Nebraska.

The spatial pattern of the coarsest grain sizes upstream and just downstream from the mouth of the Loup River, the finest sediments mid-way between the Loup and Elkhorn Rivers, and intermediate grain sizes downstream from the Elkhorn River was repeated in the longitudinal distributions of grain sizes for the riverbed and coarse fraction of the riverbanks along the LPR. Median grain diameters indicated that the riverbed generally was coarser and the coarse fraction of the riverbanks generally was finer than the median diameters of sediment in sandbars along the length of the LPR. Median, 10^{th}, and 90^{th} percentiles of sampled grain diameters indicated that the riverbed was composed of fine to very coarse sand downstream from the mouth of the Loup River, and the coarse fraction of the riverbanks generally was composed of silts to medium sands.

Longitudinal patterns of the root-mean-square difference (RMSD) between GSDs of sandbars and those of hypothesized sources do not show clear indications of a source with consistently lower RMSD values, or indicate one of the five hypothesized sources with GSD consistently most similar to sandbars. Just upstream from the Loup River downstream to the Elkhorn River, RMSD between sandbars and sources varied from approximately 0.2 to 1.0 percent for most hypothesized sources, and was lowest for upstream riverbanks and within-reach riverbed samples. Downstream from the Elkhorn River, RMSD of the within-reach riverbed was consistently lower than other sources, and indicates the grain-size distribution of sandbars was most similar to the within-reach riverbed in the eastern Platte River gorge. RMSD values for tributary riverbed GSDs compared with sandbars, although not the largest differences within the individual reaches where these sources were evaluated, were consistently more dissimilar from sandbars than were the riverbed and banks.

Comparison of the distributions of RMSD values across hypothesized sources indicated that sandbars in the LPR had GSDs that were least different from the riverbed of the upstream reach and the within-reach riverbed (fig. 6). Median RMSD values for sandbar grain-size distributions compared with the hypothesized sources ranged from 6.0 to 13.5 percent, but were consistently smaller for within-reach and upstream-riverbed comparisons, indicating that overall grain-size distributions of sandbars were most similar to grain sizes sampled from the riverbed. Median RMSD values for comparisons of sandbars GSD with the GSD of within-reach riverbed and upstream riverbed were 6.0 percent. Median RMSD values for comparison of sandbar GSD with the GSD of within-reach riverbanks and upstream riverbanks were 8.0 and 9.0 percent, respectively. Median RMSD values for comparisons of sandbar GSD with the GSD of tributary riverbed was 13.5 percent.

Figure 6. Boxplot diagrams showing frequency distributions of root-mean-square differences between sampled grain-size distributions from sandbars and those from five hypothesized sediment sources, lower Platte River, Nebraska.

Quality Assurance

Comparison of measured primary and replicate grain-size distributions for sediment samples produced an average absolute difference among individual grain-size bins of approximately 1 percent, a median difference of 0 percent, and a total range of -48 to 38 percent (fig. 7). Absolute differences between grain-size bins were greatest in the sand-sized grain diameters, where the majority of sample mass for each sample was observed (fig. 7). Sandbars tended to have the greatest absolute differences in percent of sample within each size bin, averaging a -2.2 percent difference, median difference of 0.1 percent, and standard deviation of 15.4. Replicate samples from the riverbed and riverbanks had mean differences between individual grain-size bins near zero, median differences of -0.2, and standard deviations of approximately 7.8 and 9.5, respectively.

Figure 7. Graphical summaries of measured primary and replicate grain-size distributions of sediment samples from sandbars, the riverbed, and riverbanks of the lower Platte River, Nebraska: (*A*) absolute differences between percent of sample within individual grain-size intervals and; (*B*) root-mean-square difference between primary and replicate grain-size distributions for sandbar, riverbed, and riverbanks.

Root-mean-square differences between primary and replicate sample GSDs averaged approximately 10 percent, and ranged from 0.8 to 23.6 percent. Sandbars had the widest range of RMSD between primary and replicate samples' grain-size distributions, and had average and median RMSD of approximately 12.7 percent. Mean values of RMSD between primary and replicate riverbed and riverbank samples' GSDs were 7.5 and 7.0, respectively. Given the small sample size, the reader is cautioned concerning the representativeness of the quality-assurance values; however, for this study area, mean RMSD of 10 percent or less would be expected between GSD from replicate samples collected in slightly different locations. Mean RMSD values from comparisons between sandbar grain-size distributions and hypothesized sediment sources (presented above in *Sedimentologic Analysis of Sandbars and Sediment Sources* section) ranged from 6.3 to 13.5, and median RMSD values ranged from 6.0 to 13.5. Median RMSD values exceeding 10 percent occurred only for the comparison of sandbars with tributary riverbed samples. Thus, the median RMSD values calculated for comparisons with other hypothesized sources' GSDs generally are within the range shown for natural spatial variation in grain-size distributions from sandbars, indicating the sedimentologic analysis likely was not sensitive enough to detect whether or not the primary source of sediment in sandbars was the riverbed or riverbanks.

Bed-Material Sediment Budget for Segments of the Lower Platte River

Grain-Size Specific Sediment Supplies to the Lower Platte River

Composite GSDs of samples from sandbars indicated that most of the sediment composing sandbars in the LPR was fine to medium sand (between 0.125 and 0.5 mm in diameter) (fig. 8). The percentage of the total sample mass from sandbars that was fine to medium sand ranged from a low of 61 percent in the Elkhorn segment, to a high of 79 percent in the Loup segment. Coarse sand (0.5 to 1.0 mm in diameter) was the next most abundant grain-size interval, followed by very fine sand, very coarse sand, very fine gravel, fine gravel, and muds.

Figure 8. Grain-size-frequency distributions of composite samples from sandbars in segments of the lower Platte River, Nebraska.

Estimates of annual bed-material discharge from large tributaries to the LPR varied within each tributary by the predictive equation used to make the estimate (table 7). In general, estimates of tributary annual bed-material discharge made using the Engelund-Hansen equation (1967) tended to be larger than those made using the Yang (1973) equation. Estimates of annual total bed-material discharge from individual large tributaries using the Engelund-Hansen (1967) equation ranged from a low of 2.1 million tons per year (million tons/yr) to 7.1 million tons/yr for all bed-material grain sizes (table 7), and from 0.29 million tons/yr to 6.4 million tons/yr for sediments coarser than mud. The combined total of annual bed-material contributions from large tributaries estimated using the Engelund-Hansen (1967) equation was approximately 17 million tons/yr for all bed-material grain sizes and 11 million tons/yr for sediments coarser than mud. Estimates of annual total bed-material discharges from individual large tributaries using the Yang (1973) equation ranged from approximately 0.97 million tons/yr to 2.1 million tons/yr for all grain sizes, and 0.055 million tons/yr to 1.8 million tons/yr for sediments coarser than mud. The combined total of annual bed-material discharges from large tributaries to the LPR using the Yang (1973) equation was 7.2 million tons/yr for all bed-material grain sizes and 4.6 million tons/yr for sediments coarser than mud.

Table 7. Summary of estimates of annual bed-material discharge from large tributaries to segments of the lower Platte River, Nebraska, 1970-2011.

Assessment of the accuracy of the estimates of annual bed-material discharges from the large tributaries is difficult because few previous estimates have been made, and previous estimations of bed-material sediment discharge to the LPR generally also incorporated measured suspended-sediment data that included washload (for example Missouri River Basin Commission [1975] and Randle and Samad [2003]). Nevertheless, previous published estimates of large tributary sediment discharges provide some context for the relative order-of-magnitude of the estimates made for this study. Previous published estimates of annual sediment discharges from the four largest tributaries (table 8), central Platte, Loup, and Elkhorn Rivers, and Salt Creek, are in reasonable agreement with estimates made for the study (table 7). Previous published estimates of average annual sediment discharges for the central Platte River, which are the most abundant, range from approximately 0.4 million tons/yr to 1.9 million tons/yr, and include three values ranging from 0.71 to 0.84 million tons/yr (table 8), similar to the estimates reported herein using the Yang (1973) equation (table 7). Estimates of average annual sediment discharges calculated previously for the Loup River Basin had a wide range, but the most recent estimate of 1.8 million tons/yr made by the Loup Power District (2011) using the Yang (1973) method (table 8), is in close agreement with those estimated for this study (table 7). Similarly, estimates of sediment discharges made by the Missouri River Basin Commission (1975) for the Elkhorn River and Salt Creek (table 8) fall within the ranges of estimated values from this study (table 7). Estimates of sediment discharges from Shell Creek made for the study are substantially larger than those published by the Missouri River Basin Commission (1971), but are reasonably close if the mud particles are excluded. The large difference between estimates at Shell Creek likely is related to the muddy composition of bed material, for which equations 6 and 7 are known to perform poorly (Julien, 1998).

Table 8. Selected previously published estimates of annual sediment discharge from large tributaries to the lower Platte River, Nebraska.

Grain-size-specific estimates of annual bed-material discharges from large tributaries, as a percentage of total mass, indicated that the Elkhorn and Loup Rivers are the two largest contributors of fine and medium sand to the LPR (fig. 9). The central Platte River also contributes substantial fine and medium sand, but is distinguished by its proportionally larger contributions of coarse and very coarse sand and fine gravel. The Loup River also contributes a substantial proportion of particles between 4 and 16 mm, but the magnitude of the predicted discharges of sediments of these diameters is very small relative to finer particles (table 7). Nonetheless, the coarser particles may play an important role in emergent sandbar formation because these would be the first particles on the bed to stall when streamflow wanes (Leopold and Wolman, 1957). Estimates of bed-sediment discharges from Shell and Salt Creeks indicated that these two basins probably do not contribute substantially to sediments composing sandbars in the LPR (fig. 9).

Figure 9. Distribution of total annual tributary bed-material sediment discharge to the lower Platte River, Nebraska, by grain-size class and large tributary, 1970-2011.

Changes in Sediment Storage in the Banks and Bed of the Lower Platte River

Estimates of bank erosion and accretion rates in the LPR varied by the time over which they were calculated and by river segment. Bank erosion rates, shown as both incremental eroded area and rate of erosion by mass in table 9, varied between 0.3 and 1.0 acre/mi/yr and, with the exception of the Loup segment, were between 17 and 100 percent greater from 1993 to 2003 than from 1970 to 1993 (table 9). Between 1970 and 1993, the rate of bank erosion varied from 1.0 ac/mi/yr in the Loup segment, to 0.3 acre/mi/yr in the Elkhorn segment (table 9). During the same time, bank accretion rates were greater than erosion rates, varying from 0.6 to 1.8 ac/mi/yr, and were greatest in the Loup segment. Between 1993 and 2003, average bank erosion rate in the Loup segment (0.5 ac/mi/yr) was one-half the rate of the previous period, but the rate was slightly greater in the Shell and Salt segments (0.7 acre/mi/yr), and at 0.6 acre/mi/yr in the Elkhorn segment was double the rate of the previous period.

Table 9. Estimates of riverbank erosion and accretion in segments of the lower Platte River, Nebraska, 1970–2011.

Mean sediment mass contributions from bank erosion to the LPR for the 1970–1993 and 1993–2003 periods were one to two orders of magnitude less than sediment discharges from large tributaries and, in three of the study segments, were more than offset or approximately balanced by bank accretion (table 9). Dominant bank-adjustment conditions from 1970 to 2003 indicated that the Loup and Salt segments were accreting sediments at rates of 34,000 and 45,000 tons per year (tons/yr), respectively, and the Shell and Elkhorn segments were eroding bank sediments at rates of 27,000 and 1,000 tons/yr, respectively. When the uncertainty of the mean estimates was considered, three of the four study segments had “indeterminate” bank-adjustment conditions, indicating that the balance between bank erosion and accretion was “too close to call” if uncertainty was considered. If mud-sized sediments were excluded from the mean adjustment estimates, and uncertainty considered, the Loup and Shell segments were predicted to have net bank accretion and erosion, respectively (table 9).

If bank erosion was considered a source of sediment, an analysis of total mass of sediment from bank erosion in each segment indicates that most of the sediment delivered by bank erosion (neglecting accretion) ranged in size from fine to coarse sand (0.125 to 1.0 mm), but the banks also yield a substantial mass of muds (fig. 10). Bank erosion within each segment yielded between 16,000 and 182,000 tons of fine-to-medium sand per year from 1970 to 2003, producing a total of approximately 420,000 tons/yr of fine and medium sand for the entire LPR. Despite bank erosion yielding a substantial mass of sediment in the size range important to the composition of sandbars, in most segments the mass of predicted bank erosion was more than offset or roughly balanced by the mass accreted in new bank deposits.

Figure 10. Distribution of estimated sediment delivery from bank erosion in the lower Platte River, Nebraska, by grain-size class and river segment, 1970–2011.

Results from the specific-gage analysis at three streamgages in three segments of the LPR indicated that the riverbed has been either degrading (net evacuation of sediment from the riverbed) or stable during the study period (table 10). For the streamgage at North Bend, negative trends in river stage ranging from -0.05 to -0.01 feet per year (ft/yr) were detected for streamflows at the 90-, 50-, and 10-percent-exceedance frequencies, but a trend in riverbed altitude (-0.01 ft/yr) was detected only for the streamflow with 50-percent exceedance. For the streamgage near Ashland, the period of record limited stage and riverbed altitude trend analyses to no earlier than 1989, and no trend in river stage or bed altitude was detected for any of the streamflow-exceedance frequencies, indicating general riverbed stability since 1989. For the streamgage at Louisville, negative trends in river stage and riverbed altitude were detected for streamflow with 50-percent exceedance frequency, indicating degradation rates between -0.03 and -0.02 ft/yr, but no trends were detected for either stage or bed altitude at other streamflow exceedance frequencies (table 10).

Table 10. Results from specific gage analysis for selected streamgages in the lower Platte River, Nebraska.

Some of the results of the specific gage analysis indicate net evacuation of riverbed sediments at North Bend and Louisville, but the fact that trends were detected at some sites for river stage with no trends detected for riverbed altitude, or no trends for other streamflow frequencies, precludes a conclusion of overall riverbed instability. At the North Bend streamgage, negative values of Kendall’s *tau* were calculated for all trend analyses, but trends were not significant for riverbed altitude for streamflows at the 10- and 90-percent exceedance frequencies. Likewise, four of six calculated *tau* values for the Platte River at Louisville indicate negative trends in river stage and riverbed altitude, but only two were statistically significant. River stage was expected to be more sensitive to changes in the riverbed altitude across the adjacent river reach because, under sub-critical flow conditions, downstream river stage is the primary elevation control on upstream river stage; however, if the assumption of extrapolating specific-gage analysis across a reach or segment is valid, the trend indicated by river stage also would be expected to be apparent in trends of riverbed altitude at the streamgage. It is possible that the substantial width of the Platte River, which is the denominator to channel hydraulic (cross-sectional) area in the calculation of average water depth, and is three orders of magnitude larger than average depth for most streamflows, suppresses the sensitivity of trend analyses to detect changes in riverbed altitude. Another factor contributing to indeterminacy is uncertainty in mean water depth caused by dynamic migration of bedforms (dunes). Additional analyses, such as examination of trends in official USGS rating relations at each streamgage, or repeat surveys of older channel cross sections (such as those used for the HEC model), could provide additional lines of evidence regarding bed stability in the LPR.

Bed-Material Budgets in Segments of the Lower Platte River

Sediment Budgets Using a One-Dimensional Hydraulic Model and Automated Sediment Budget Tool

Results of the final SIAM sediment budget computations for the four segments did not change substantively relative to the computations made prior to refinement of the original HEC-model geometry (see appendix 2 in this report for summary of initial model run). Final sediment budgets estimated by the SIAM tool were not improved by model refinements indicated after a review of model hydraulics and geometry provided by the U.S. Army Corps of Engineers (Dan Pridal, USACE, written commun., May 2013). As with estimates of sediment-transport capacity made for the large tributaries, the Engelund-Hansen (1967) equation consistently produced estimates greater than those made using the Yang (1973) equation, but both equations, as implemented in the SIAM analysis, produced irregular sediment budgets assessed to be of poor quality. Of particular concern were two longitudinal patterns in the estimates of sediment-transport capacity computed using the SIAM tool: decreasing or equal sediment transport capacity in the downstream direction, and within-segment sediment imbalances equal to or greater than published values of median annual suspended-sediment transport in the LPR. Because of these concerns, only a summary of the gross, segment-scale bed-material sediment balance is presented herein to document the results of the final SIAM analysis.

Segment-scale sediment transport capacity computed using the Engelund-Hansen (1967) equation within SIAM decreased substantially in the downstream direction, from 26.7 million tons/yr in the Loup segment, to 22.3 million tons/yr in the Salt segment, and had a low of 12.4 million tons/yr in the Elkhorn segment (table 11). Similarly, estimates of sediment transport capacity made using the Yang (1973) equation were approximately balanced between the Loup segment (13.3 million tons/yr) and the Salt segment (13.9 million tons/yr), but had a computed minimum of 7.2 million tons/yr in the Elkhorn segment. The pattern of downstream decreasing or equal sediment transport capacities is compounded by large disparities between the computed magnitudes of sediment-transport capacities and sediment supplies in each segment, resulting in large sediment imbalances, both positive (aggradation) and negative (degradation) (table 11). In the Loup segment, the computed sediment-transport capacity substantially exceeded the estimated sediment supplies from upstream, tributaries, and bank erosion, resulting in a computed negative sediment imbalance between -10.6 and -22.6 million tons/yr. Likewise, the large decrease in sediment-transport capacity in the Elkhorn segment relative to estimated sediment supplies resulted in a large positive sediment imbalance between 8.3 and 21.9 million tons/yr .

Table 11. Summary of bed-material balance computed for segments of the lower Platte River, Nebraska, 1970-2011, using the U.S. Army Corps of Engineers' SIAM tool.

Despite the large sediment imbalances estimated for segments by the SIAM tool, the patterns of imbalance are not necessarily out-of-sync with the geomorphic system of the LPR (fig. 11). For example, a substantial amount of the water in the Loup segment is derived from a clear-water return from a hydropower plant (Bentall and Schaffer, 1979), and diversions of river water to the power plant were expected to result in reduced sediment transport capacity of the Loup River below the diversion, and reduced supplies of bed material delivered as inputs to the LPR. Thus, a deficit of sediment inputs in the Loup segment potentially results from reduced sediment supplies and clear-water return, but that deficit was not expected to be greater than the annual mass of sediment removed at the diversion point. Recent analysis by the Loup Power District (2011) indicated that less than 2.0 million tons/yr of sediment are removed from the river at the diversion annually, which indicates that the SIAM-simulated deficit of more than 10.6 million tons/yr is inconsistent with the fluvial-sediment system. In the Elkhorn segment, the average bed slope of the LPR decreases relative to upstream segments (Bentall, 1991); thus, a sediment supply surplus is a reasonable outcome for decreased sediment transport capacity relative to the large supply incoming from the Elkhorn River.

Figure 11. Bed-material imbalances in segments of the lower Platte River, Nebraska, 1970–2011, by sediment-transport equation, as estimated using U.S. Army Corps of Engineers' Sediment Impact Analysis Methods tool.

The magnitude of sediment imbalances computed for each segment indicates that channel hydraulics potentially were simulated poorly by the HEC model, and improvements to model geometry may be required to refine the HEC model to more accurately simulate channel hydraulics for greater frequency streamflows (see appendix 2 for further explanation of model performance during higher frequency streamflows). For example, estimates of annual suspended-sediment transport published by Heimann and others (2011), computed using measured suspended-sediment data, indicate that the lower Platte River at Louisville had a median annual suspended-sediment discharge of 9.8 million tons/yr from 1976 to 2009. These data indicate that the measured median annual suspended-sediment discharge at Louisville is approximately the magnitude of the supply deficit computed with SIAM for the Salt segment using the Engelund-Hansen equation (fig. 11), and the sediment deficit computed for the Loup segment and the sediment surplus computed for the Elkhorn segment are as much as double that magnitude. Such large sediment imbalances would result in substantial channel degradation and aggradation in the Loup and Elkhorn segments, respectively; however, such large changes in riverbed elevation have not been detected in specific gage analyses performed for this study or others (Chen and others, 1999; USACE, 2011).

At-a-Station Bed-Material Budgets

The sediment budgets computed using at-a-station estimates of annual bed-material transport capacity resulted in some agreement with sediment imbalances at the segment scale identified with the SIAM tool but, in general, produced a longitudinal pattern of bed-material discharge estimates more aligned with observations of bed-material storage conditions in the LPR and in proportion more consistently with sediment loads estimated for large tributaries. As before, estimates of annual bed-material transport capacity using the Engelund-Hansen (1967) equation were consistently greater, in some cases three times as much, as estimates made using the Yang (1973) equation (table 12); however, the estimates of annual bed-material discharge produced with the at-a-station method were substantially lower overall relative to those from the HEC model and SIAM tool. At-a-station estimates of annual bed-sediment transport capacity increased in the downstream direction, but the relative increase varied between the two equations: using the Engelund-Hansen (1967) equation, the increase was 81 percent, from approximately 7.1 million tons/yr in the Loup segment to 12.7 million tons/yr in the Salt segment; whereas, the Yang (1973) equation indicated an increase of 8.5 percent, from 3.6 million tons/yr in the Loup segment to 3.9 million tons/yr in the Salt segment (table 12).

Table 12. Summary of at-a-station estimates of annual bed-material discharge for segments of the lower Platte River, 1970-2011.

Compilation of sediment budgets for each segment for grain sizes larger than 0.0625 mm and using the at-a-station estimates of annual bed-material transport capacity indicated sediment imbalances between adjacent segments, but these imbalances were too close to call in most segments if the uncertainty intervals were considered (table 13). Channel conditions (degradation or aggradation) were predicted using mean values for sediment-budget components in equation 4. These sediment budgets indicated degradation was the dominant condition for the Loup, Shell, and Salt segments, and that aggradation conditions dominated for the Elkhorn segment (table 13). When the uncertainty of the estimates was considered for main-stem and tributary sediment-transport capacities, the Loup segment was predicted to have net channel degradation as its dominant condition, but the remaining segments' conditions were indeterminate. These results indicate some agreement with the specific-gage analysis for this study (table 10), which indicated the potential for degradation in the Shell segment, but generally insignificant trends in the Elkhorn and Salt segments. The fact that the North Bend streamgage provided some evidence of degradation aligns with the potential for degradation as the dominant condition upstream in the Loup segment, where bed-material transport capacity appears to exceed supplies from upstream and tributaries. Additional investigation, including a more robust, comprehensive treatment of uncertainty is recommended to test hypotheses regarding excess bed-material transport capacity in the Loup segment.

Table 13. Summary of bed-material balance in segments of the lower Platte River, Nebraska, 1970-2011, for grain sizes larger than 0.0625 mm.

Bank storage processes for sediments larger than 0.0625 mm, in general, did not constitute large proportions of the sediment-budget equations, and net differences between bank accretion and erosion were one to two orders of magnitude smaller than either upstream inputs to each segment or inputs from the Loup and Elkhorn Rivers. The computed mean bank adjustments for 1970 to 2003 indicated net accretion of approximately 80,000 tons/yr in the Loup segment, erosion of 50,000 tons/yr in the Shell segment, and an approximate balance of erosion and accretion in the Elkhorn and Salt segments (table 13). In the Shell segment, where net widening was the dominant mean bank-adjustment condition, net contributions from the river banks constituted no more than 2 percent of the total sediment inputs, and if net accretion was not considered at all, bank erosion would have ranged only from 4 to 9 percent of the combined upstream and tributary inputs to each segment.

Comparison of the proportion of total sediment supplies by source and grain size within each segment indicated that the primary sources of sediments composing sandbars (predominantly fine-to-medium sand) vary by segment, but in all cases, bank erosion, being considered a source before bank accretion occurs, contributes a proportionally small mass of sediment of this grain size (figs. 12 and 13). As a percentage of the total sediment supply, when estimates of sediment contributions from large tributaries and upstream segments were made with the Engelund-Hansen (1967) equation, bank erosion constituted no more than 3 percent of the total fine-sand supplies, no more than 4 percent of the total medium-sand supplies, and no more than 20 percent of any sand-size class in any segment (fig. 12). As a percentage of the total sediment supply, when estimates of sediment contributions from large tributaries and upstream segments were made with the Yang (1967) equation, bank erosion constituted no more than 8 percent of the total fine-sand supplies, no more than 9 percent of the total medium-sand supplies, and no more than 15 percent of any sand-sized class in any segment (fig. 13). By contrast, depending on the equation used, large tributaries contributed between 0 and 76 percent of fine- and medium-sand supplies, and upstream segments contributed between 19 and 98 percent of these size classes. Tributary contributions of fine and medium sand to the LPR were least substantial in the Shell and Salt segments, because the sediment discharges from Shell and Salt Creeks contain relatively small proportions of sand. In these segments where tributaries contributed small amounts of sand, sediment discharges from main-stem segments upstream contributed between 90 and 98 percent of total fine- and medium-sand supplies (figs. 12 and 13).

Figure 12. Estimated sources of bed sediment as a percentage of total supply by grain-size class to segments of the lower Platte River, Nebraska, 1970-2011.

Figure 13. Estimated sources of bed sediment as a percentage of total supply by grain-size class to segments of the lower Platte River, Nebraska, 1970-2011.

The riverbanks, despite being relatively small sources of sediments in sandbars composition before accretion was considered, were proportionally large sources of gravel-sized sediment in each segment (figs. 12 and 13). When the Engelund-Hansen (1967) equation was used to estimate large-tributary and upstream-segment sediment supplies, bank erosion constituted between 6 and 37 percent of the total supply of very fine gravel, 12 to 72 percent of the total fine gravel, and 29 to 99 percent of the total supply of coarse gravel (fig. 12). When the

Yang (1973) equation was used to estimate large tributary and upstream segment sediment supplies, bank erosion constituted between 14 and 73 percent of the total supply of very fine gravel, 17 to 89 percent of the total fine gravel, and 30 to 99 percent of the total supply of coarse gravel (fig. 12). The gravel derived from the riverbanks may have been emplaced in flood-plain or terrace deposits laid down by a hydrologic regime that pre-dates the current hydrologic regime (that is, the hydrologic regime before reductions in flood magnitudes of the central Platte River that largely correspond to construction of large storage reservoirs upstream). Moreover, the gravel layers in modern river banks may be indicative of the relative importance of basal gravels for sandbar formation (Leopold and Wolman, 1957), stability, and subsequent burial during flood-plain accretion.

Limitations of Study and Implications for Future Scientific Investigations

The study summarized in this report has substantial uncertainties and limitations, ranging from uncertainties associated with representativeness of sampled grain sizes of the tributaries, riverbed, and riverbanks, to the large uncertainties associated with empirical sediment-transport equations. Also, some inaccuracy is inherent with the digitized GIS datasets used for estimations of annual bank erosion and accretion. The selected method of statistical comparison of sediment GSD of sandbars with various hypothesized sources is a simplification of the fluvial-sediment system, and did not account for the mixing of sources, which inevitably occurs downstream from river confluences. Likewise, the predictive application of sediment transport equations using the hydraulic geometries of the LPR at streamgages, all of which are located at bridge crossings, may not be representative broadly of the hydraulic geometry throughout the LPR. The sediment budgets developed using the HEC model and SIAM tool also contain inherent uncertainty because the models were informed by channel geometry and hydraulics deemed to be of poor quality (see appendix 2 for a discussion of model hydraulics). Because of the poor hydraulic simulations of the HEC model for the most prevalent streamflow conditions, the uncertainty of the sediment-budget estimates from SIAM is likely to be substantial, but quantification of the uncertainty of a sediment budget from a HEC model with poor hydraulic simulations was not considered a useful exercise for the study. Finally, the predictive use of the selected sediment-transport equations, which are widely known to have substantial uncertainty (Reid and Dunne, 1996) under the best known applications, yields additional uncertainty in both approaches to sediment-budget analyses. An attempt was made to provide measures of uncertainty in the sediment budgets, but these measures were not comprehensive, and a more randomized treatment of grain sizes, channel hydraulic geometry, water temperatures, and streamflow would better quantify the uncertainty of the estimates of bed-material transport capacity in the tributaries and main-stem segments.

Although the estimates of total mass and the relative proportions of the total supply of fine and medium sand delivered from the riverbanks seem to indicate that bank erosion is not a primary source of sediments to sandbars, these results do not necessarily preclude the importance of the process of bank erosion to the formation of sandbars. Bank erosion, if not proportionally balanced by deposition within a reach, widens a channel and causes irregularities in the bank shape. Irregularities in channel width, which are a primary consequence of spatially variable bank-erosion rates, cause reach-to-reach shifts in bed-material transport capacity by affecting unit stream power along sequences of channel expansions and contractions (Ashworth, 1996). In addition, riverbanks of the LPR were determined to be a primary source of gravel to several of the studied segments. Basal gravel potentially has relative importance for sandbar formation and stability similar to the mechanism proposed by Leopold and Wolman (1957). Thus, despite clear indications that riverbank erosion is not a primary source of sediments to sandbars, the process of bank erosion itself may be important by causing changes to reach-scale channel hydraulics or gravel supply that may favor stalling of macro-scale bedforms and formation of emergent sandbars.

Because of the limitations associated with sediment budgets described in this report, formulating a framework of the fluvial-sediment system in the LPR upon which to develop further understanding of the effects of bank protections, or other infrastructure features, on the formation and persistence of emergent sandbars is difficult. Nevertheless, there are areas where both approaches to the sediment budget agreed, such as a negative bed-material imbalance in the Loup segment that indicates a dominant bed-material condition of net erosion. The results of both analyses were particularly consistent for mean conditions which, disregarding uncertainty, indicated a supply deficit in the Loup and Salt segments, and a sediment supply surplus in the Elkhorn segment. These consistent results align with geomorphic and engineering reasoning and imply the need for further refinement of the sediment budgets. For example, the negative balance in the Loup segment's budget may be small enough to be accommodated through exchanges of sediment between channel storage in emergent sandbars and bed-sediment discharge components, but that exchange implies more rapid erosion of emergent sandbars to accommodate the sediment-budget imbalance.

Refinement of the SIAM sediment-budget simulations, which estimated sediment transport capacities using hydraulics computed at numerous transects within a segment, is an obvious area for potential improvement of the study presented in this report. Improvement of the SIAM simulations necessitates refinement of the HEC model by, for example, updating model geometry to allow for hydraulic simulation of high-frequency streamflows, which were poorly simulated with the existing model. Recently collected and in-progress collection of high-resolution topographic datasets for the LPR from airborne laser mapping (LiDAR) are available from the Nebraska Department of Natural Resources and (or) U.S. Army Corps of Engineers. Such detailed elevation models, in combination with strategic bathymetric surveys of selected parts of the LPR channel, may allow substantial improvement to the channel geometry used in the existing HEC model.

Summary

The lower Platte River (LPR) corridor provides important habitats for two state- and federally listed bird species: the interior least tern (terns; *Sternula antillarum athallassos)* and the piping plover (plovers; *Charadrius melodus)*. Sandbars are the primary on-river nesting habitat for terns and plovers, and the geometry, abundance, and persistence of these important habitat features is driven by interactions between the hydrology, sediment transport, and channel geomorphology of the LPR. An understanding of the interactions and relative balance between sediment supplies, sediment storage, and the sediment transport capacity of the Platte River is crucial to understanding the interactions between the physical and biological processes in the LPR ecosystem, and thus is important to informed planning and management in the LPR corridor.

In cooperation with the U.S. Army Corps of Engineers (USACE) and the Lower Platte River Corridor Alliance (LPRCA), the U.S. Geological Survey (USGS) initiated a study of the sediment sources of sandbars in the LPR to create a framework for understanding how changes in sediment supply from various sources may affect sandbar formation. A particular focus of the study was to understand if further reductions in sediment inputs from bank erosion would substantially affect mass contributions of sediments important to the composition of sandbars in the LPR.

The study evaluated sediment-transport processes in the LPR relative to the potential for sandbar formation with two primary approaches. First, a sedimentologic analysis, performed at the reach scale, was used to characterize the longitudinal variation in grain sizes composing the riverbed, riverbanks, and sandbars along the LPR, and a simple, quantitative analysis was used to compare grain-size distributions (GSD) of sandbars in each reach with five hypothesized sediment sources: bed material from the sampling reach immediately upstream; bed material from within the sampling reach; coarse-fraction bank material from the upstream sampling reach; coarse-fraction bank material from within the sampling reach; and bed material from the nearest upstream large tributary. Second, a sediment-budget analysis was done at the segment scale from 1970 to 2011 to investigate the longitudinal balance of sediment supplies, sediment storage, and sediment transport capacity in four segments of the LPR for a range of sediment grain sizes, including those grain sizes shown to be most commonly composing sandbars. Sediment budgets were developed for four discrete segments of the LPR, each bounded by large tributaries and designated by the name of the tributary at the upstream boundary: Loup, Shell, Elkhorn, and Salt. Two different methods were used to construct sediment budgets. The first method estimated bed-material transport capacity of the study segments using the U.S. Army Corps of Engineers 1-dimensional hydraulic model HEC-RAS, and computed sediment budgets using the Sediment Impacts Analysis Methods (SIAM) tool in HEC-RAS. The second method estimated bed-material transport capacity of the segments using an at-a-station sediment-transport capacity approach, and computed the sediment budgets manually.

GSD from samples indicated that grain sizes in sandbars, the riverbed, and the coarse fraction of the riverbanks from the central Platte and lower Platte River were composed primarily of very fine to very coarse sand, and these sediments generally became finer downstream from the mouth of the Loup River. Median grain diameters indicated that the riverbed generally was coarser and the coarse fraction of the riverbanks was generally finer than median diameters of sediment in sandbars along the length of the LPR. Median root-mean-square-differences (RMSD) from comparisons of sandbar grain-size distributions with those of the five hypothesized sources ranged from 6.0 to 13.5 percent, but were consistently smaller for within-reach and upstream riverbed comparisons, indicating that overall grain-size distributions of sandbars were most similar to grain sizes in the riverbed; however, RMSD between replicate sandbar sample GSDs ranged from 0.8 to 23.6 percent, and averaged 12.7 percent. Median RMSD values exceeding 10 percent occurred only for comparisons between sandbars and tributary riverbed samples. These results indicate that median RMSD values calculated for comparisons with other hypothesized sources' GSDs are generally within the range shown for natural spatial variation in grain-size distributions from sandbars, and the sedimentologic analysis generally was not sensitive enough to detect whether or not the primary source of sediment in sandbars was the riverbed or riverbanks.

Composite GSDs of samples from sandbars indicated that most of the sediments composing sandbars in the LPR were fine to medium sand [between 0.125 and 0.5 mm (millimeter) in diameter]. The percentage of the total sample mass from sandbars that was fine-to-medium sand ranged from 61 percent in the Elkhorn segment, to 79 percent in the Loup segment. Summed totals of estimated annual bed-material discharges from large tributaries ranged from 7.2 to 17.0 million tons per year (million tons/year) for all bed-material grain sizes, and 4.6 to 11 million tons/yr for sediments coarser than mud. Grain-size specific estimates of bed-material discharges from large tributaries indicated that the Elkhorn and Loup Rivers are the two largest contributors of fine and medium sand to the LPR. The central Platte River also contributes substantial fine and medium sand, but is distinguished by its proportionally larger contributions of coarse and very coarse sand and fine gravel. Estimates of bed-material discharges from Shell and Salt Creeks indicated that these two basins do not contribute substantially to the sand-size load of the main-stem segments and, thus, likely play a minor role as contributors of sediment to sandbars.

Average sediment mass contributions from bank erosion to the LPR from 1970 to 1993 and 1993 to 2003 were one to two orders of magnitude less than sediment discharges from large tributaries and, in three of the segments, were more than offset or approximately balanced by bank accretion. Mean bank-adjustment conditions from 1970 to 2003 indicated that the Loup and Salt segments were accreting bank sediments at rates of 34,000 and 45,000 tons/yr, respectively, and the Shell and Elkhorn segments were eroding bank sediments at rates of 27,000 and 1,000 tons/yr, respectively; however, when uncertainty of the mean estimates was considered, three of the four study segments had “indeterminate” bank-adjustment conditions.

Specific-gage analysis was used to examine trends in stage and mean-bed altitude with time at three streamgages in three segments of the LPR. Results from specific-gage analysis indicated that the riverbed has been either degrading or stable during the study period. Significant negative trends in stage were detected for streamgages at North Bend and Louisville. Significant negative trends in mean riverbed altitude were detected at North Bend and Louisville. No trends were detected for stage and streambed altitude for the Ashland streamgage, and the 10- and 90-percent exceedance flows at Louisville. No trends were detected for streambed altitude at

North Bend for the 10- and 90-percent exceedance levels. The fact that at some sites, trends were detected for river stage with no trends detected for riverbed altitude, or no trends for other streamflow frequencies, precludes a conclusion of overall riverbed instability.

Large sediment imbalances between segments of the LPR were indicated by the sediment budget estimated using the HEC model and the SIAM sediment budget tool; however, the hydraulic simulations from the HEC model were considered to be of low quality, and this resulted in irregular sediment budget results for segments of the LPR computed with the SIAM tool. Of particular concern were two longitudinal patterns in the SIAM estimates of sediment-transport capacity: decreasing or equal sediment-transport capacity in the downstream direction, and within-segment sediment imbalances equal to or greater than published values of median annual suspended-sediment transport in the LPR. The magnitude of sediment imbalances computed for each segment indicates that channel hydraulics potentially were poorly simulated by the HEC model, and improvements to model geometry may be required to refine the model to more accurately simulate channel hydraulics for higher-frequency streamflows.

The sediment budget computed using at-a-station estimates of annual bed-material discharge in each segment of the LPR resulted in more reasonable longitudinal patterns of sediment transport and sediment imbalances that were more proportional with large tributary discharges of bed sediment, allowing a more coherent picture of the fluvial-sediment system. At-a-station estimates of annual bed-sediment transport capacity increased in the downstream direction, from a range of 3.6 to 7.1 million tons/yr in the Loup segment, to 3.9 to 12.7 million tons/yr in the Salt segment. Compilation of sediment budgets for each segment, for grain sizes larger than 0.0625 mm, using the at-a-station estimates of annual bed-material discharge indicated sediment imbalances between adjacent segments, but these imbalances were “too close to call" in most segments when the uncertainty intervals were considered. Channel conditions (degradation or aggradation) were predicted using mean values; results indicated degradation as the dominant condition for the Loup, Shell, and Salt segments, and aggradation as the dominant condition for the Elkhorn segment; however, when the uncertainty of the estimates was considered, only the Loup segment was predicted to have net channel-degradation conditions, and the remaining segments were considered to have indeterminate conditions.

Bank storage processes for sediments larger than 0.0625 mm, in general, did not constitute large proportions of the sediment budget components, and net differences between bank accretion and erosion were one to two orders of magnitude smaller than either upstream sediment inputs to each segment or sediment inputs from the Loup and Elkhorn Rivers. Comparison of the proportion of total sediment supplies by source and grain size within each segment indicated that the primary sources of sediments composing sandbars (predominantly fine and medium sands) vary by segment, but in all cases, bank erosion, being considered a source before bank accretion occurs, contributes no more than 4 to 9 percent of sediments of these diameters, and no more than 20 percent of any sand-sized sediments in any segment. By contrast, large tributaries contributed between 0 and 76 percent of fine to medium sands, and upstream segments contributed between 19 and 98 percent, to segments of the LPR. In segments where tributaries contributed very little sand, the upstream segment contributed between 90 and 98 percent of the total supply of fine to medium sands. Despite contributing a proportionally small mass of the sediment size composing sandbars in the LPR, bank erosion was estimated to contribute between 6 and 73 percent of the total supply of very-fine gravel, 12 to 89 percent of the total fine gravel, and 29 to 99 percent of the total coarse gravel supplies to the LPR.

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Appendix 1: Summary of Aggregated HEC-RAS Model of the Lower Platte River

The HEC-RAS model (HEC model) used as the platform for running the SIAM bed-material sediment budget analysis presented in this report was constructed by aggregating channel geometry and hydraulic inputs from three separate existing hydraulic models, each representing a different segment of the LPR. The three models were constructed at different times as part of various flood insurance studies (U.S. Army Corps of Engineers, 1998). The aggregated model, as well as detailed descriptions of each of the three model components, was provided to the USGS by the USACE, Omaha District. The aggregated HEC model spans from the mouth of the Platte River to just over 2 miles upstream from the Loup River confluence (fig. 1). The three major model components were constructed chronologically, and spatially, from downstream to upstream and, for the purposes of this report, are hereafter referred to as "lower," "middle," and "upper" in reference to their relative positions within the aggregated model. Brief descriptions of each model component are provided in this report for context and documentation.

The lower model component of the aggregated HEC model spans the segment of the LPR extending from the mouth to just upstream from the Elkhorn River confluence (fig.1). The lower model component originally was constructed using the USACE HEC-2 backwater computer program, but was migrated to the HEC-RAS program for the aggregated model. Cross-sectional geometry data for the lower component came from three primary sources depending on location within the segment and proximity to bridges. Geometry data from the mouth of the LPR to State Route 50 originated from a study conducted in 1975 by the Nebraska Natural Resources Commission. Geometry data from State Route 50 to Interstate 80 originated from a 1978 USACE flood insurance study (FIS). Cross-section geometry data upstream from Interstate 80 originated from a Nebraska Department of Natural Resources (NDNR) photogrammetric analysis using aerial photographs from 1997. A limited number of the cross sections used in the lower model component were obtained from on-the-ground surveys performed by the NDNR. From the documentation provided, the 100-year and 500-year flood events were modeled and, based on a 1998 USACE hydrologic analysis of the Platte River (U.S. Army Corps of Engineers, 1998), the streamflows recommended for estimating water-surface elevations of the 10-, 50-, 100-, and 500-year flood events for combined season probability (mixture of open-water and winter season probabilities) were 67,000 ft^3/s, 151,000 ft^3/s, 187,000 ft^3/s, and 300,000 ft^3/s, respectively, at the Platte River near Ashland streamgage, and 114,000 ft^3/s, 205,000 ft^3/s, 250,000 ft^3/s, and 405,000 ft^3/s at the Platte River at Louisville streamgage. Thus, for the purposes of this study, it was assumed that the lower model component was calibrated for a streamflow range of 67,000 to 405,000 ft^3/s.

The middle model component of the aggregated model spans the segment of the LPR extending from the Sarpy-Douglas County line to near Fremont, Nebraska (fig.1). The middle model component originally was constructed using the USACE HEC-2 backwater computer program (U.S. Army Corps of Engineers, 1991), but was migrated to the HEC-RAS program for the aggregated model. Cross-sectional geometry data for the middle component came from a NDNR photogrammetric analysis using aerial photographs from 1997 for the segment spanning from the downstream boundary to State Highway 77, and in 1998 for the segment upstream from there. Cross sections of the stream bed near bridges, and a "limited" number of other locations were constructed from surveys conducted by the NDNR. Several of the cross sections did not include streambed elevations, and the USACE used an iterative method to fit different streambed elevations until the modeled water-surface elevation approximately matched that of the water-surface elevation in the aerial photographs. The middle model component was used to model water-surface elevations for the 10-, 50-, 100-, and 500-year streamflow frequencies for the open-water season, ice-affected season (winter), and a combined probability that includes runoff in the presence of ice. The ranges of streamflows for which water-surface elevation were simulated were 49,400 to 133,000 ft^3/s for the open-water season, 48,100 to 210,000 ft^3/s for the ice season, and 62,000 to 220,000 ft^3/s for the combined probability.

The upper model component of the aggregated model spans the segment of the LPR from near Fremont, Nebraska, to near the western boundary of Butler County, just west of the Loup River confluence (fig. 1). The upper model component originally was constructed using the USACE HEC-2 backwater computer program, but was migrated to the HEC-RAS program for the aggregated model. Cross-sectional geometry data for the upper component came from a NDNR photogrammetric analysis using aerial photographs from 1998 and 1999. Cross sections of the streambed near bridges and a “limited” number of other locations were constructed from surveys conducted by the NDNR. Several of the cross sections did not include streambed elevations, and the USACE used an iterative method to fit different streambed elevations until the modeled water-surface elevation approximately matched that of the water-surface elevation in the aerial photographs. The upper model component was used to model water-surface elevations in two hydraulic reaches for the 10-, 50-, 100-, and 500-year streamflow frequencies for the open-water season, ice-affected season (winter), and a combined probability that includes runoff in the presence of ice. The most downstream hydraulic reach spanned from the downstream boundary of the model to the Loup River confluence, and the ranges of streamflows for which water-surface elevation were simulated were 49,400 to 133,000 ft^3/s for the open-water season, 48,100 to 210,000 ft^3/s for the ice season, and 62,000 to 220,000 ft^3/s for the combined probability. The upstream hydraulic reach spanned from the Loup River confluence to the upstream model boundary, and the ranges of streamflows for which water-surface elevations were simulated were 14,500 to 45,100 ft^3/s for the open-water season, 13,100 to 44,600 ft^3/s for the ice season, and 17,500 to 53,000 ft^3/s for the combined probability.

Nineteen bridges were modeled across the lower, middle, and upper modeling components of the aggregated hydraulic model. Bridge geometry data were obtained from a 1978 FIS study, the Papio-Missouri River Natural Resources District, the Nebraska Department of Roads (NDOR), and NDNR. Both normal and special bridge methods were used to model the bridges (U.S. Army Corps of Engineers, 2010a), and bridges were modeled only for unobstructed flow. Bridge contraction and expansion coefficients were set at 0.3 and 0.5, respectively. Contraction and expansion loss coefficients for channel reaches away from bridges or constrictions were set to 0.1 and 0.3, respectively. Channel roughness values varied from 0.017 to 0.025 in the main channel for reaches without islands or backwaters, 0.025 to 0.030 for the backwater part of the Elkhorn River, 0.030 for reaches with wooded islands, and 0.050 to 0.095 for the overbank part of cross sections. Starting Platte River water-surface elevations at the Missouri River confluence were the 10-, 50-, 100-, and 500-year Missouri River flood water-surface elevations from the FIS for Sarpy County that was effective in 2001. Because the model components were generated from downstream to upstream, starting water-surface elevations in the middle and upper modeling components were the water-surface elevations generated for equivalent flow probabilities in the most upstream cross section of the adjoining downstream model component.

Appendix 2: Methods and Simulations of Channel Hydraulics and SIAM Sediment Budget Analysis Using the Aggregated HEC-RAS Model of the Lower Platte River

Before the study described in this report, the aggregated HEC-RAS model of the lower Platte River (HEC model) had not been used to simulate streamflows across all 103 river miles of the study area. For the purposes of this study, three primary simulation types were made using the HEC model to generate sediment budgets using the SIAM tool: trial simulations, testing simulations, and final simulations. Trial simulations were made to identify problem areas within the model, and to evaluate the ability of the model to simulate water-surface elevations at known points, such as streamgages. Testing simulations were made to generate an initial sediment budget with the SIAM tool. Final simulations were made after the U.S. Army Corps of Engineers reviewed the HEC model hydraulics, and suggested areas of model improvement were identified and made. Final model simulations were used to generate the final SIAM sediment budget present in the main body of the report. All simulations assumed sub-critical flow, and thus the model simulated water-surface profiles using a step-backwater approach (U.S. Army Corps of Engineers, 2010a).

Trial simulations used the original aggregated model geometry, and assumed normal depth for downstream boundary conditions, to test the ability of the raw model to simulate water-surface elevations at known points. Eleven water-surface profiles were generated, one for every tenth flow percentile from 0 to 100th percentiles (baseflow to highest streamflow) for the 1970–2011 streamflow record in each of the segments. Initial trial simulations identified several cross sections near the Elkhorn River confluence that did not have ineffective flow areas, and which were causing substantial errors in the calculation of sub-critical flow water-surface profiles. After ineffective flow areas were added to the problem cross sections, water-surface profiles were generated for each of the 11 flow percentiles, and water-surface elevations were checked against the latest rating curves from 5 USGS streamgages (streamgages 06796000, 06796500, 06796550, 06801000, 06805500; fig. 1). Absolute differences between simulated and known water-surface elevations ranged from -1.46 to 0.51, and the median difference was -0.45. Root-mean-square differences between simulated and known water-surface elevations at the 5 locations ranged from 0.09 to 1.29, and median RMSD was 0.63.

Testing simulations were made to generate water-surface profiles (saved as “plan” files in HEC-RAS) for testing the SIAM sediment budget tool. For each simulation, 15 water-surface profiles were generated for each of the four segments, one for each of the select streamflow exceedance percentiles (0, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, and 99th daily exceedance percentiles) used to simulate tributary contributions to the lower Platte River. For each exceedance profile, known water-surface elevations (referenced to the National Geodetic Vertical Datum of 1929, or NGVD 29) were designated at USGS streamgages 06796000, 06796500, 06796550, 06801000, 06805500 (fig. 1) using the latest rating relations for each gage (*http://waterdata.usgs.gov/nwisweb/cgi-src/get_ratings?site_no*=; accessed April 30, 2013). Water-surface elevations also were generated for each of the exceedance frequencies for the Missouri River at Omaha (USGS streamgage 06610000) and the Missouri River at Nebraska City (USGS streamgage 06807000), and these profiles were interpolated to the mouth of the Platte River to generate downstream boundary conditions for each profile in the HEC-RAS model. The ratings included adjustments to the base, also known as “shifts.” In the case of the 0 percent exceedance profile, known water-surface elevations could not be set at the Leshara

(USGS streamgage 06796500) and Venice (USGS streamgage 06796550) streamgages because the respective rating tables did not include streamflows of such high magnitude.

The water-surface profiles generated from testing simulations were used in the test SIAM analysis by converting the exceedance frequencies for the representative streamgages in each sediment reach into annualized frequencies (percent of time a flow is equaled or exceeded in a single year) by multiplying the fraction of percent in each exceedance category by 365 days. Sediment inputs to each sediment reach were grain-size specific estimates from tributary contributions, bank erosion, and bank accretion (see *Methods Used to Estimate Sediment Supply by Grain-size from Large Tributaries and Bank Erosion* section). Test computations from SIAM used the Engelund-Hansen (1967) and Yang (1973) sediment-transport equations, and the tributary inputs used for each of the computations were the estimates that used each specific equation. Test computations in SIAM assumed a water temperature of 68^{o}F (20^{o}C) and used the default settling velocity estimations specific to each equation.

The test SIAM computations are shown in table 14. Test computations indicated a substantial negative sediment balance in the Loup sediment reach (-22.6 to -10.7 million tons/yr), and a substantial positive sediment balance in the Elkhorn sediment reach (8.5 to 21.4 million tons/yr). In the Shell sediment reach, the Engelund-Hansen (1967) equation indicated a slight positive sediment balance (0.5 million tons/yr), and the Yang (1973) equation indicated a slight negative balance (-0.09 million tons/yr). In the Salt sediment reach, both SIAM computations indicated negative balance, ranging from -6.1 million tons/yr to -8.6 million tons/yr.

Table 14. Summary of test sediment balance computed for segments of the lower Platte River, Nebraska, 1970–2011, using the U.S. Army Corps of Engineers Sediment Impact Analysis Methods tool.

The large sediment imbalances produced in the test SIAM computations for the Loup and Elkhorn segments were approximately equivalent to or more than double the median of recently (Heimann and others, 2011) published estimates of annual suspended-sediment transport at the most downstream gaging station on the lower Platte River, the Platte River near Louisville (USGS streamgage 06805500, fig. 1). Because of the large sediment imbalances, it was assumed that simulated channel hydraulics in the HEC model were of poor quality. The HEC model was subsequently reviewed by the U.S. Army Corps of Engineers, Omaha District, to evaluate if the model was adequately simulating hydraulics, and to identify any areas of the model that could be improved. The review recommended several areas for improvement and troubleshooting strategies, many of which were interrelated. The USGS focused on two of the recommendations for model improvement, because they were deemed to potentially be the source of the poor quality hydraulic simulations. First, the review cited ineffective flow areas within cross sections as a potential primary source of the poor hydraulics, and recommended adding ineffective flow areas at locations where large variations in channel width were occurring. Second, the review recommended removing known water-surface elevations, and allowing the model to solve independently. The review also indicated that the model was defaulting to critical depth, and that these defaults were likely contributing to the poor simulations of hydraulics. The USGS assumed that the defaults to critical depth were a result of a combination of the mixed geometries of the aggregated model (appendix 1), as well as the lack of ineffective flow areas.

To refine the HEC model, the USGS entered or changed ineffective flow areas in 63 of the 336 cross sections within the geometry file of the aggregated HEC model. Additionally, known water-surface elevations were removed from the steady flow file. Final simulations of the 15 water-surface profiles were made, SIAM computations were repeated, and the final sediment budget compared to the test sediment budget. Despite refinements to approximately 20 percent of the channel cross sections, the final sediment budget (see *Sediment Budgets Using a One-Dimensional Hydraulic Model and Automated Sediment Budget Tool* section) did not differ substantially from the test sediment budget. Because of the lack of improvement in the final sediment budget, a review of the hydraulics in the refined model was made, and the review indicated that the model hydraulic simulations were of poor quality for most streamflows below approximately 14,000 ft^3/s, and improvements to the model would likely require substantial refinement of the model geometry, a task that was outside the scope of the study. A summary of the evaluation of channel hydraulics in the aggregated HEC model is given in appendix 3 of this report.

Appendix 3: A Brief Evaluation of Hydraulic Simulations in the Aggregated HEC-RAS Model of the Lower Platte River

The aggregated HEC-RAS model (HEC model) of the LPR originally was calibrated for simulations of streamflows of 10-year return frequency or greater. For the purposes of the sediment budget constructed using the SIAM tool, simulations were made with the HEC model to generate water-surface profiles across the range of daily average flow magnitudes for 1970 to 2011 (fig. 4), and thus, most of the streamflows simulated for the SIAM sediment budget were of lower magnitude than those the model was originally designed to simulate. Refinements were made to the aggregated model geometry and steady flow files after review by the U.S. Army Corps of Engineers suggested areas to improve the quality of hydraulic simulations (see appendix 2 of this report for a summary of model simulations).

The aggregated HEC model with refined geometry was used to simulate 15 water-surface profiles, which were subsequently used as inputs for final SIAM sediment-budget computations. Because the final SIAM computations did not indicate a substantial improvement of model simulations, a review of the hydraulics of the aggregated HEC model with refined geometry was made to provide some indication of where the model could be improved. One of the indications of the quality of simulated hydraulics is the ability of the model to simulate sub-critical conditions continuously upstream to downstream. For a given streamflow simulation, sub-critical flow is indicated at a cross section by a Froude number less than 1.0 (Dingman, 2009). HEC-RAS simulates sub-critical flow by solving the energy equation using a step-backwater approach, for which the elevation of the water surface at a downstream cross section is used to solve for flow depth at an upstream cross section (U.S. Army Corps of Engineers, 2010a). If a sub-critical answer cannot be determined after a pre-determined number of iterations, the software defaults to the answer with the lowest valid energy, even if that answer produces a Froude number larger than 1.0 (supercritical flow), violating the assumption of sub-critical flow. Thus, the number of times the model defaults to a critical or supercritical answer is an indicator of the quality of the hydraulic simulations, particularly if the streamflow being simulated is known to be sub-critical.

The hydraulic outputs from the 15 simulated water-surface elevations were examined to determine whether or not certain cross sections or certain streamflows were consistently producing Froude numbers near 1.0, causing the model to produce default, supercritical water-surface elevations. Two primary patterns emerged from the examination of model outputs: higher-frequency (lower-magnitude) streamflows consistently produced increased Froude numbers, and certain cross sections consistently produced increased Froude numbers. The number of cross sections with Froude numbers greater than 0.95 for the entire range of exceedance frequencies simulated using the aggregated HEC-RAS model is shown in figure 14. The range of Froude numbers greater than 0.95 for the range of streamflows simulated using the aggregated HEC-RAS model is shown in figure 15, as is the range of Froude numbers greater than 0.95 for two other recent flood-hazard studies performed by the U.S. Army Corps of Engineers that simulated flood flows along shorter reaches along the lower Platte River, using the same model geometries as the original aggregated model. Both the range and number of Froude numbers greater than 0.95 increase for flow exceedance greater than 5 percent (streamflows exceeded 5 percent of the time during 1970–2011), and at least 10 percent, and as much as 20 percent of the cross sections produced Froude numbers greater than 0.95 for simulated streamflows less than approximately 14,000 ft^3/s. The range of Froude numbers produced for streamflows greater than approximately 14,000 ft^3/s were similar to the range and number of increased Froude numbers produced for previously published flood-hazard analyses, indicating the HEC model was performing at least as well as previous analyses at greater magnitude streamflows, and that model geometry and hydraulic assumptions such as channel roughness, were less adequate for simulations of lower-magnitude, higher-frequency streamflows.

Figure 14. Bar chart showing number of cross sections with Froude numbers greater than 0.95 for the range of streamflow exceedance frequencies simulated in the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska.

Figure 15. Graph showing range of Froude numbers greater than 0.95 for streamflows simulated in the aggregated HEC-RAS hydraulic model of the lower Platte River, and two previously published models which used the same geometry but simulated only higher-magnitude streamflows.

Analysis of the locations of cross sections consistently producing Froude numbers approaching 1.0 indicated that these cross sections tended to cluster in the Loup and Shell segments, in the upper and middle model components (fig. 16). Although several cross sections in the Elkhorn and Salt segments (both in the lower model component) produced Froude numbers approaching critical depth of 1.0, the problematic cross sections in the Elkhorn and Salt segments did not tend to cluster, indicating longer sections of river had sub-critical hydraulic solutions in those segments.

Figure 16. Bar chart showing the number of simulations for which a Froude number at a cross section was greater than 0.95 for the range of streamflows simulated in the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska.

The cross sections of the aggregated HEC-RAS model had two general types of channel bottom topographies: flat-bottomed and natural-bottomed (fig. 17). Bed elevations associated with flat-bottomed cross sections were determined iteratively during the development and calibration of individual model components, and were more abundant in cross sections representing the middle and upper model components (see appendix 1 of this report for model component descriptions). Bed elevations of natural-bottomed cross sections were determined from photogrammetry or within-channel surveys, and were most abundant in cross sections in the downstream model component. Although specific analysis to identify whether or not problematic cross sections tended to be those with flat bottoms, it is likely that the interspersion of flat-bottomed and natural-bottomed cross sections in the middle and upper model components produced substantial flow irregularities between cross sections, triggering hydraulic defaults. Because a substantial number of cross sections in the upper and middle modeling components tended to be at or near critical flow for the entire range of streamflows, these same locations would be expected to have increased estimated sediment-transport capacities. Thus, the large imbalances in the sediment-budget calculations using the SIAM tool were potentially the result of a cascade of sediment originating in the Loup sediment reach, transported through the Shell sediment reach, and deposited within the Elkhorn sediment reach, where cross sections with natural-bottom topography were more abundant.

Figure 17. Graph outputs from HEC-RAS showing examples of two different types of channel-bottom topographies used in cross sections of the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska: (*A*) flat-bottomed, and (*B*) natural-bottomed.

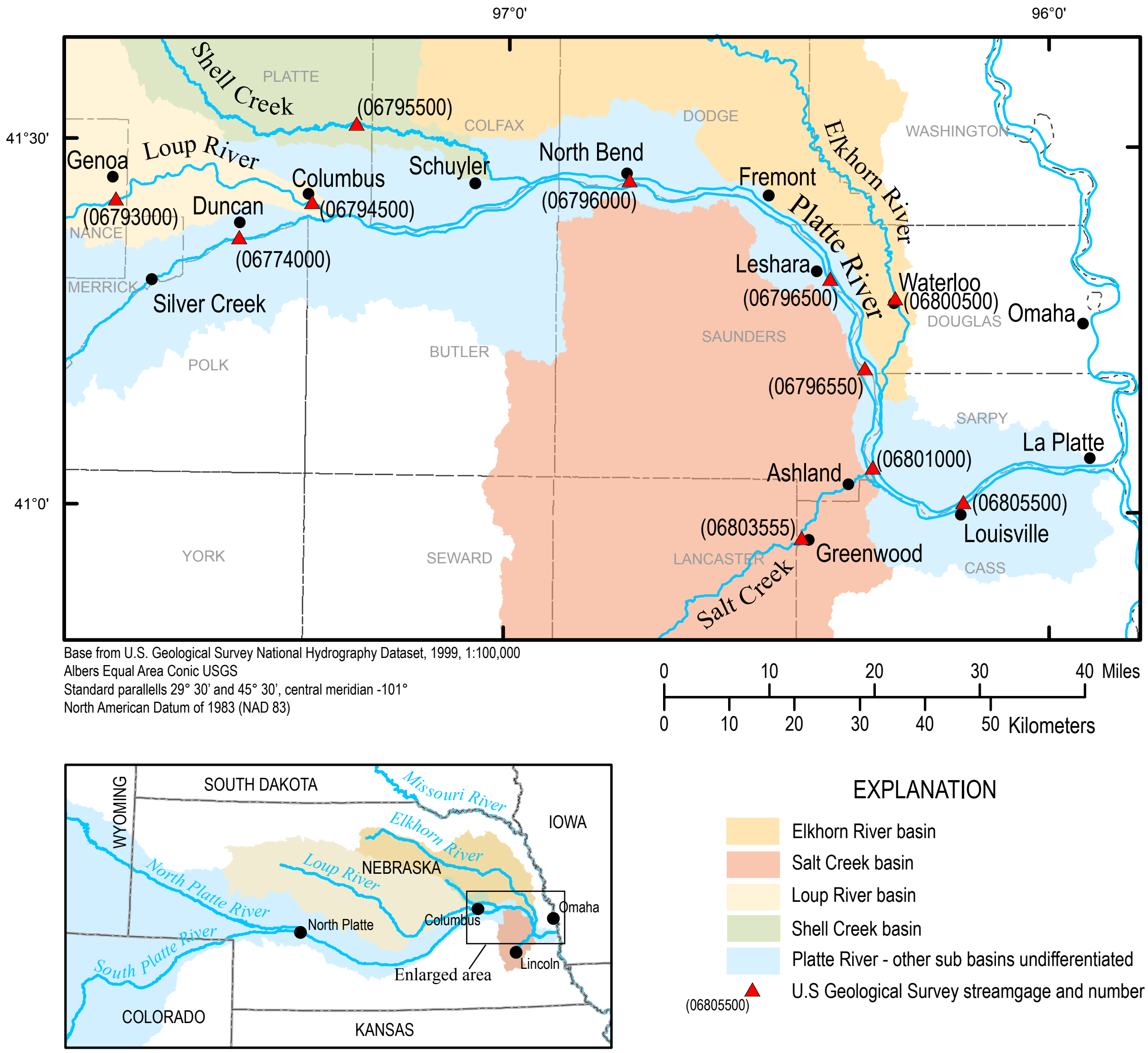

Figure 1. The Platte River Basin in eastern Nebraska, locations of selected U.S. Geological Survey streamgages, and large tributary basin boundaries.

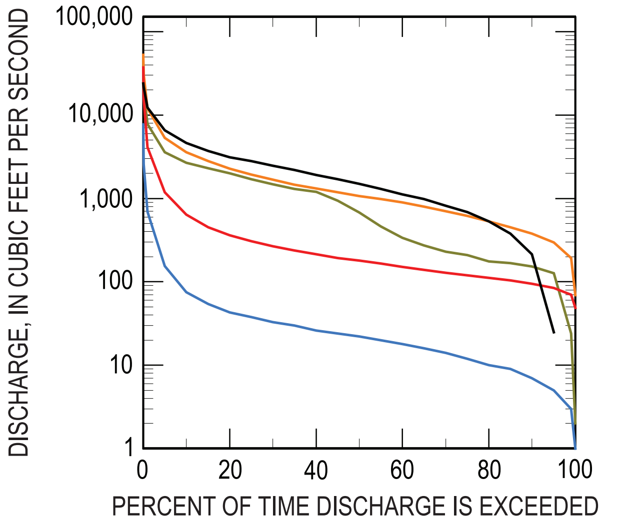

FIGURE 2. Streamflow cumulative-exceedance frequency curves of daily average streamflows at selected U.S. Geological Survey streamgages on large tributaries of the lower Platte River, 1970 to 2011. All streamgages are located in the state of Nebraska.

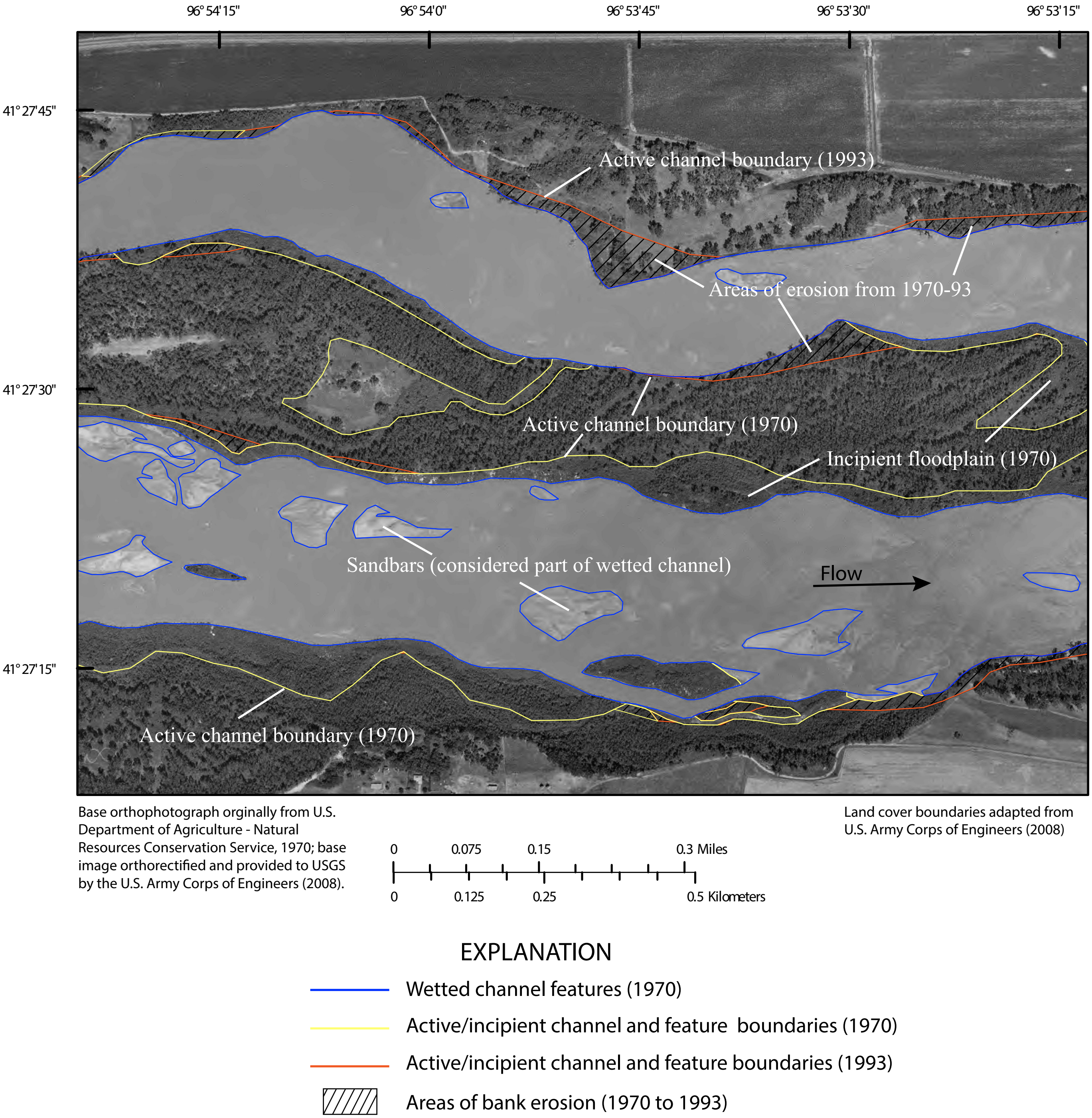

Figure 3. Example of bank-line differencing of polygon features used to estimate bank erosion and accretion rates for segments of the lower Platte River, Nebraska, 1970 to 1993.

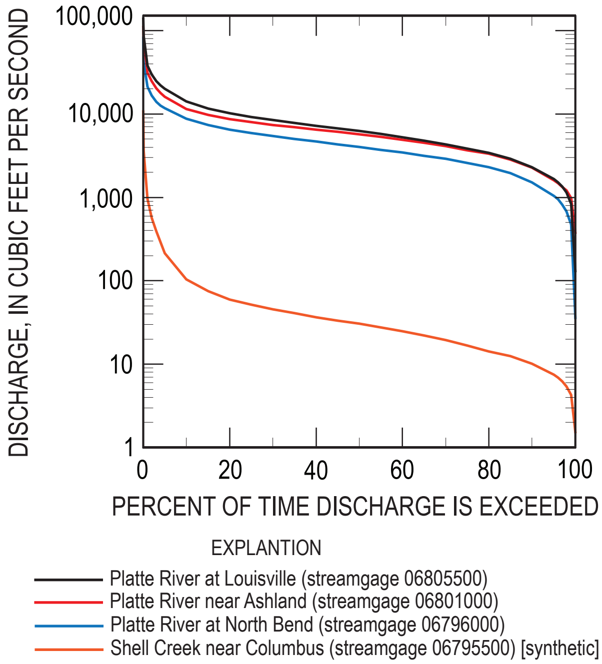

Figure 4. Streamflow cumulative-exceedance frequency curves of daily average streamflows at selected U.S. Geological Survey streamgages in the lower Platte River Basin, Nebraska (USGS, 2012). Period of record used for each curve was water years 1970 through 2011. The synthetic curve for the Loup segment is indistinguishable from the curve for Platte River at North Bend streamgage at the scale shown here.

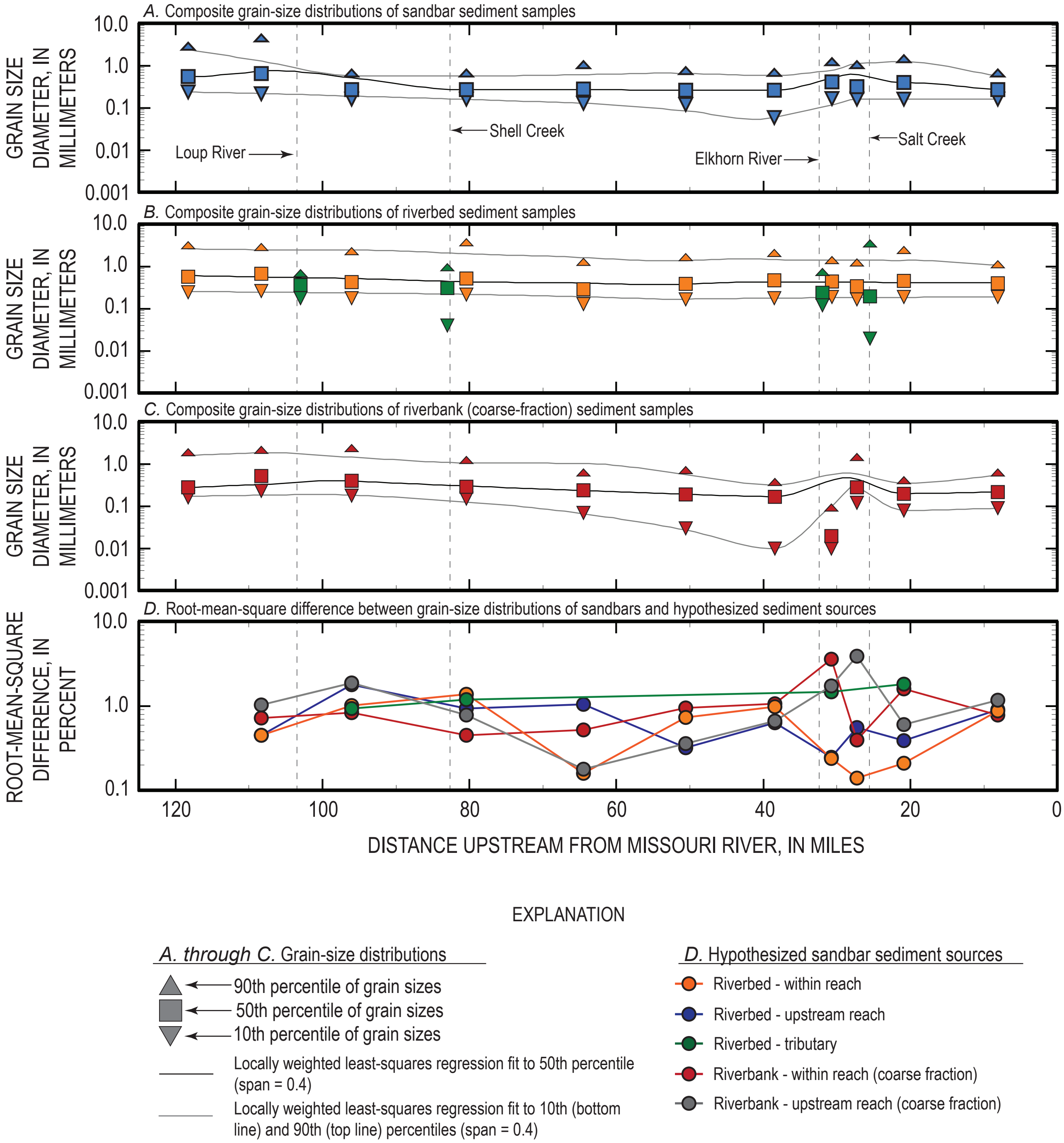

Figure 5. Longitudinal distribution of composite grain-size distributions of sediment samples from sandbars, the riverbed, and riverbanks, and root-mean-square difference between sediment grain-size distributions of sandbars and five hypothesized sediment sources, lower Platte River, Nebraska (sediment grain-size data provided by Dan Pridal, USACE, written commun., January 2012). Data points are centered on sampling reaches described in Schaepe and Alexander (2011). Locally weighted least-squares-regression lines were fit using techniques described in Helsel and Hirsch (2002).

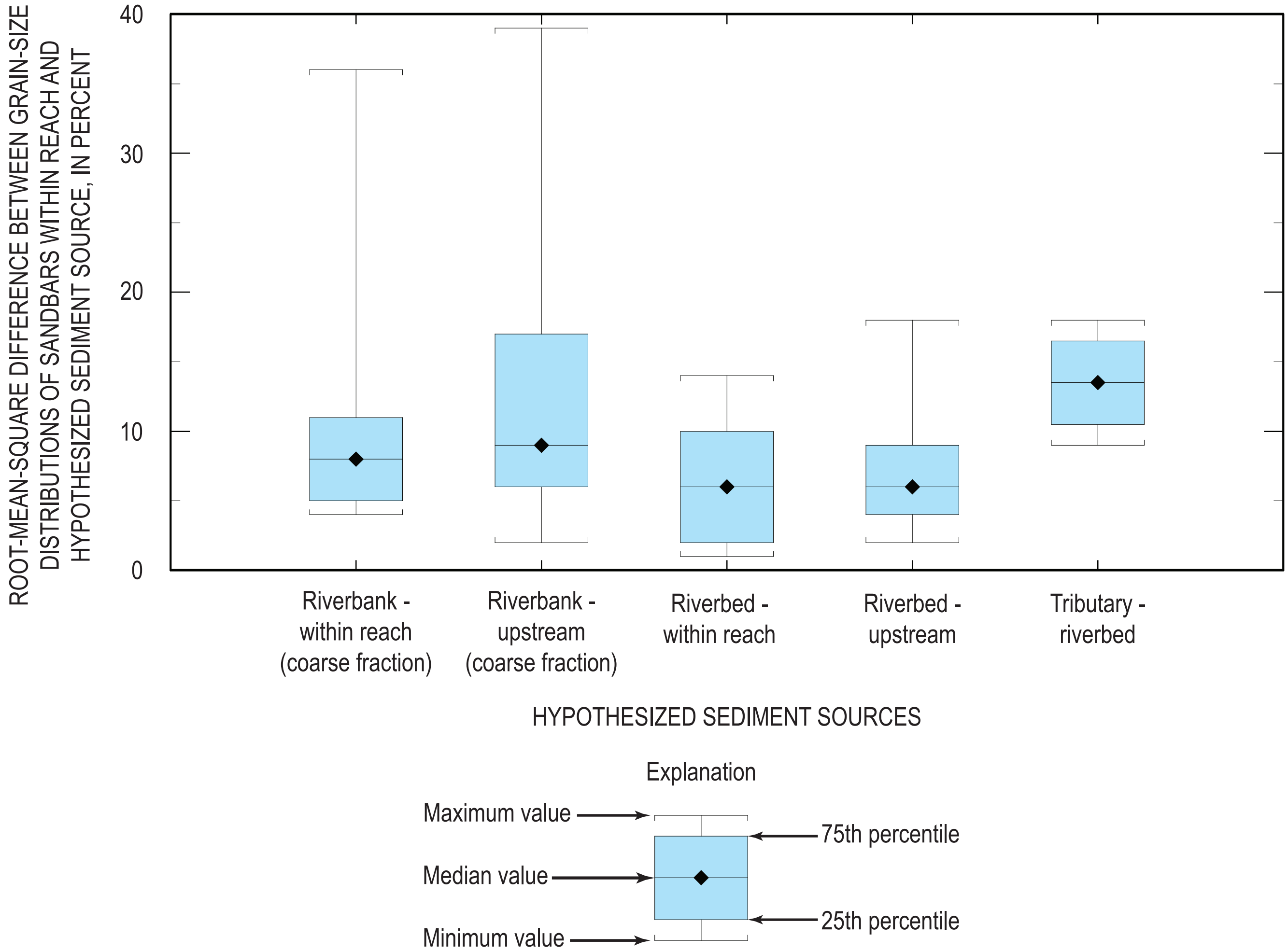

Figure 6. Frequency distributions of root-mean-square differences between sampled grain-size distributions from sandbars and those from five hypothesized sediment sources, lower Platte River, Nebraska.

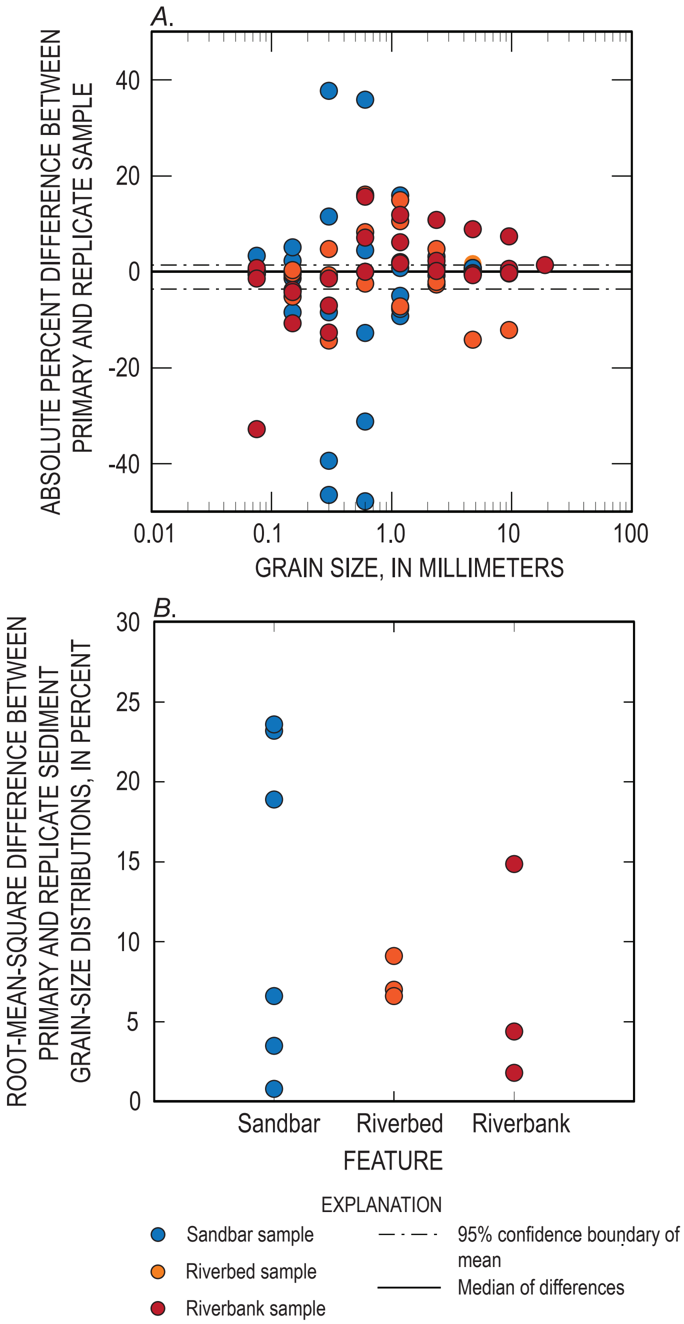

Figure 7. Measured primary and replicate grain-size differences of sediment samples from sandbars, the riverbed, and riverbanks of the lower Platte River, Nebraska: (*A*) absolute differences between percent of sample within individual grain-size intervals and; (*B*) root-mean-square difference between primary and replicate grain-size distributions for sandbar, riverbed, and riverbanks.

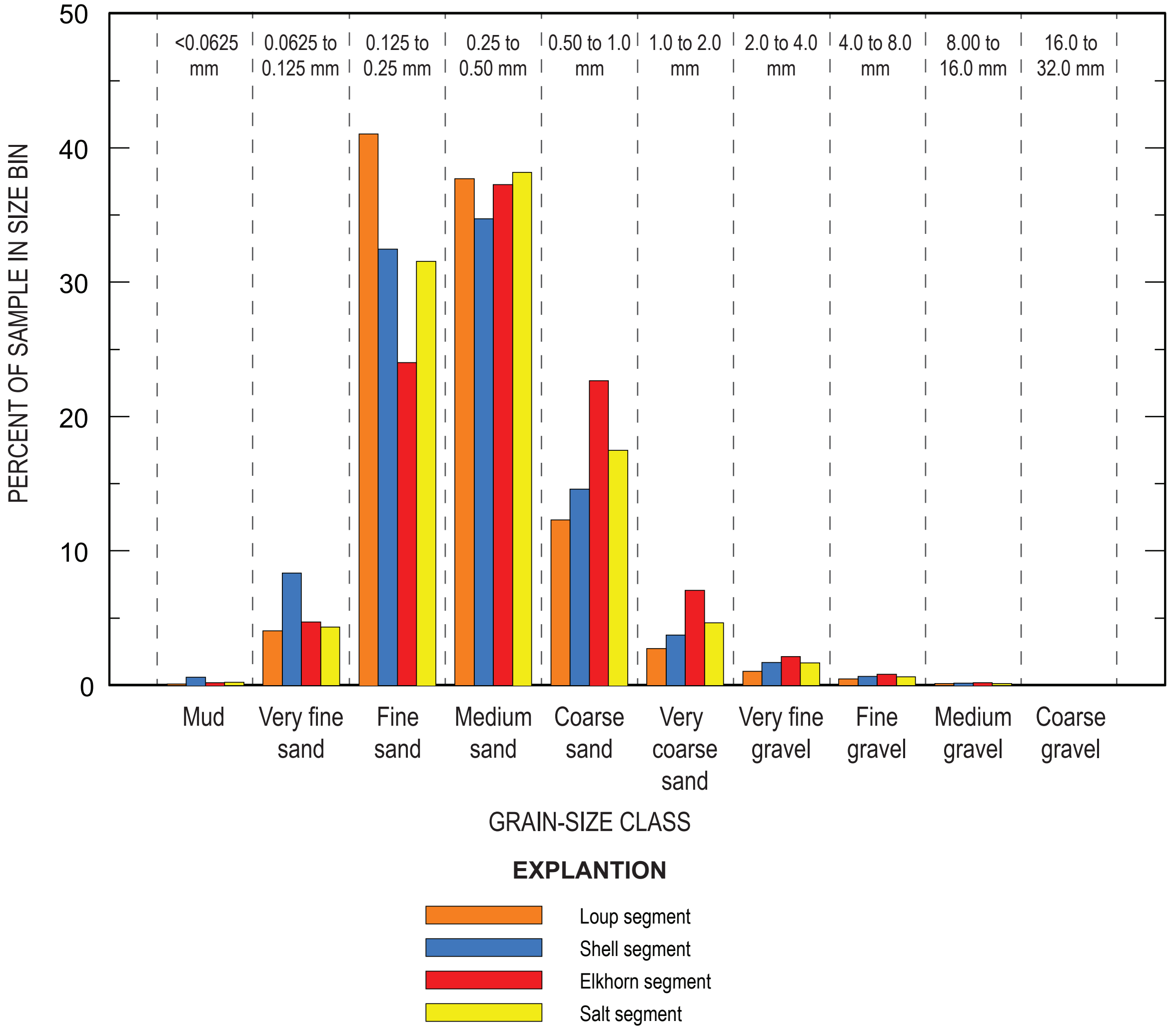

Figure 8. Grain-size-frequency distributions of composite samples from sandbars in segments of the lower Platte River, Nebraska (the data used to generate the composite samples provided by Dan Pridal, USACE, written commun., January 2012; mm, millimeter).

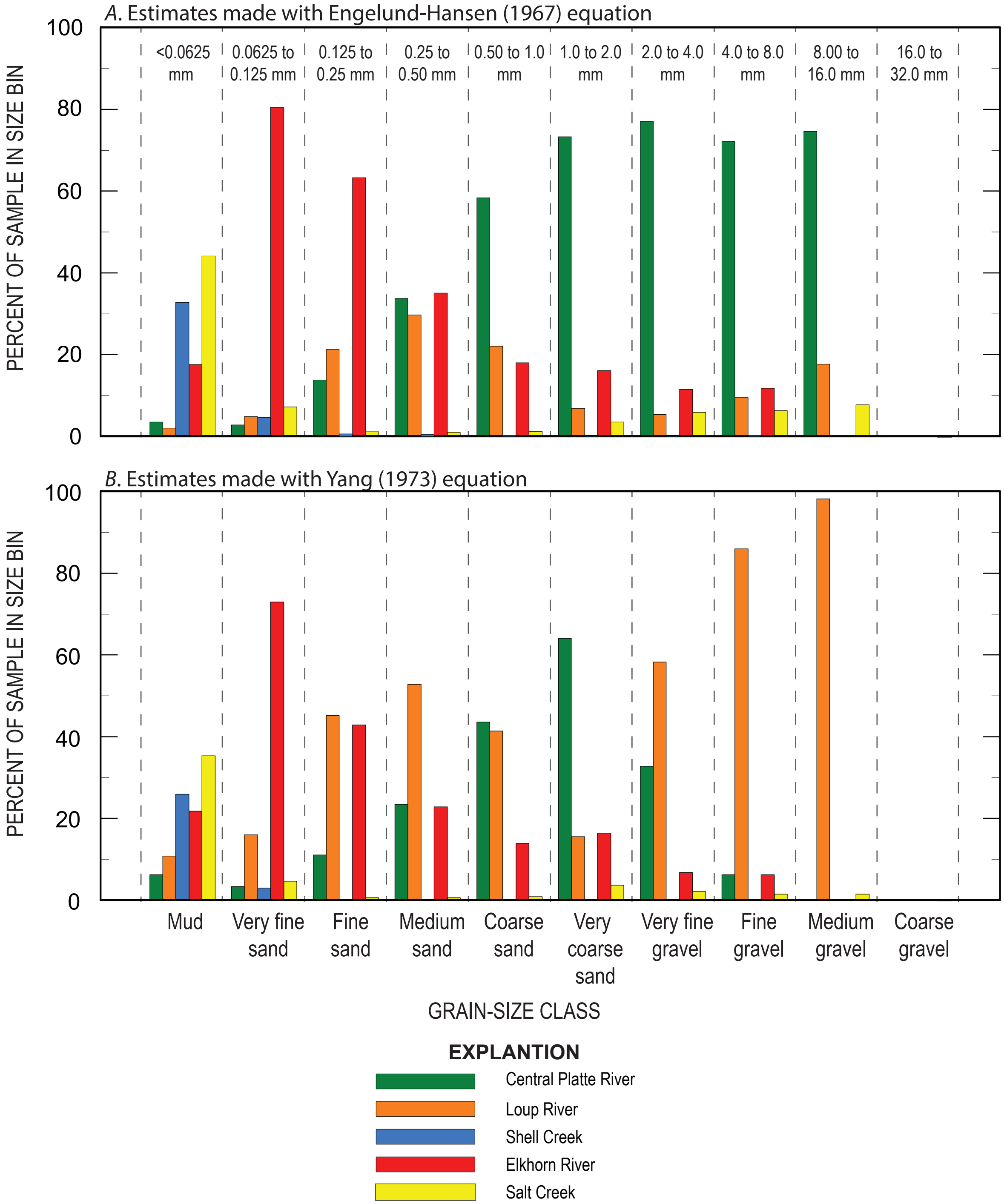

Figure 9. Distribution of total annual tributary bed-material sediment discharge to the lower Platte River, Nebraska, by grain-size class and large tributary, 1970-2011. (Height of all bars in each grain-size class sums to 100 percent; mm, millimeter.)

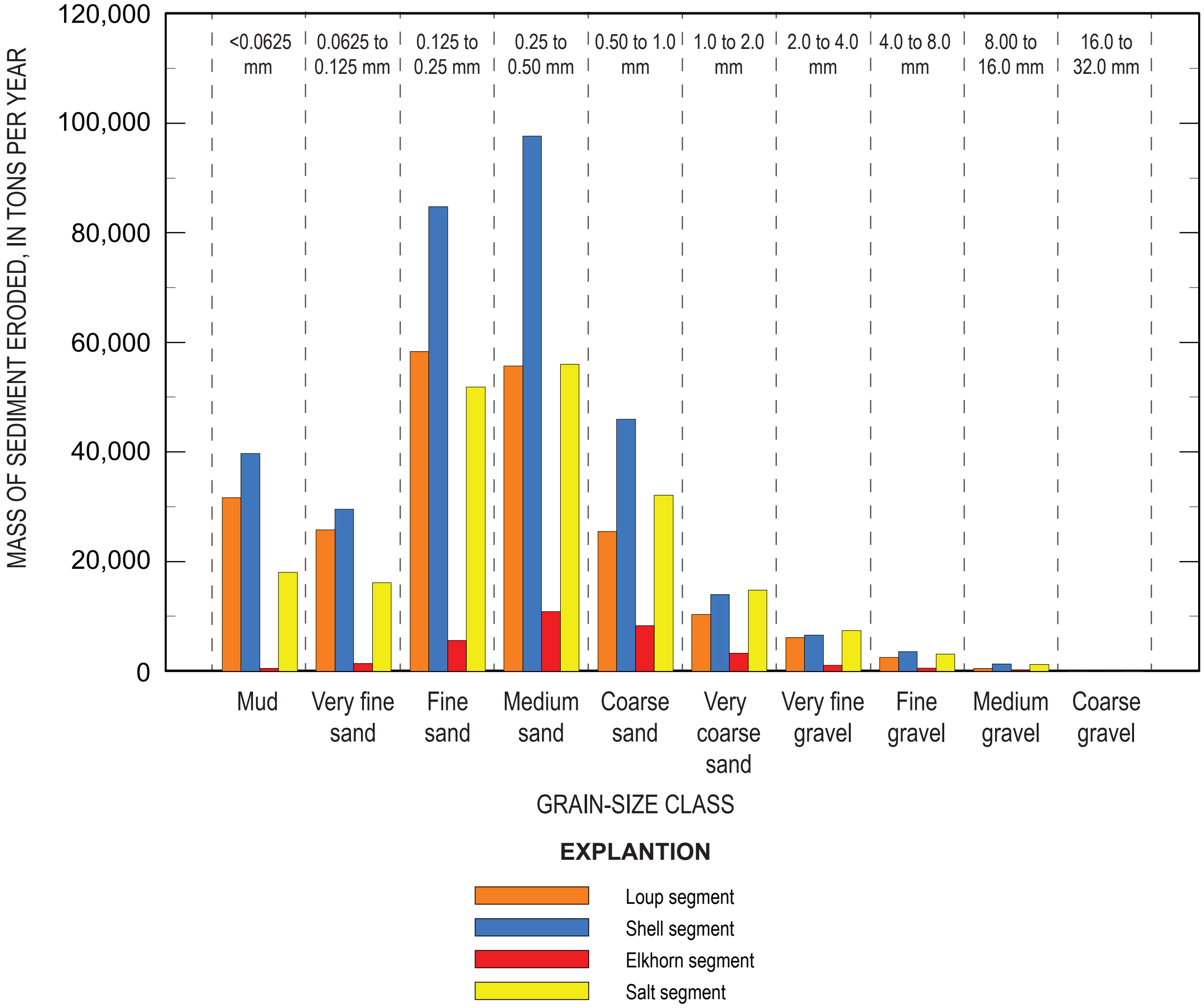

Figure 10. Distribution of estimated sediment delivery from bank erosion in the lower Platte River, Nebraska, by grain-size class and river segment, 1970-2011. (Plotted values are gross bank erosion, and neglect any offset from bank accretion; mm, millimeter.)

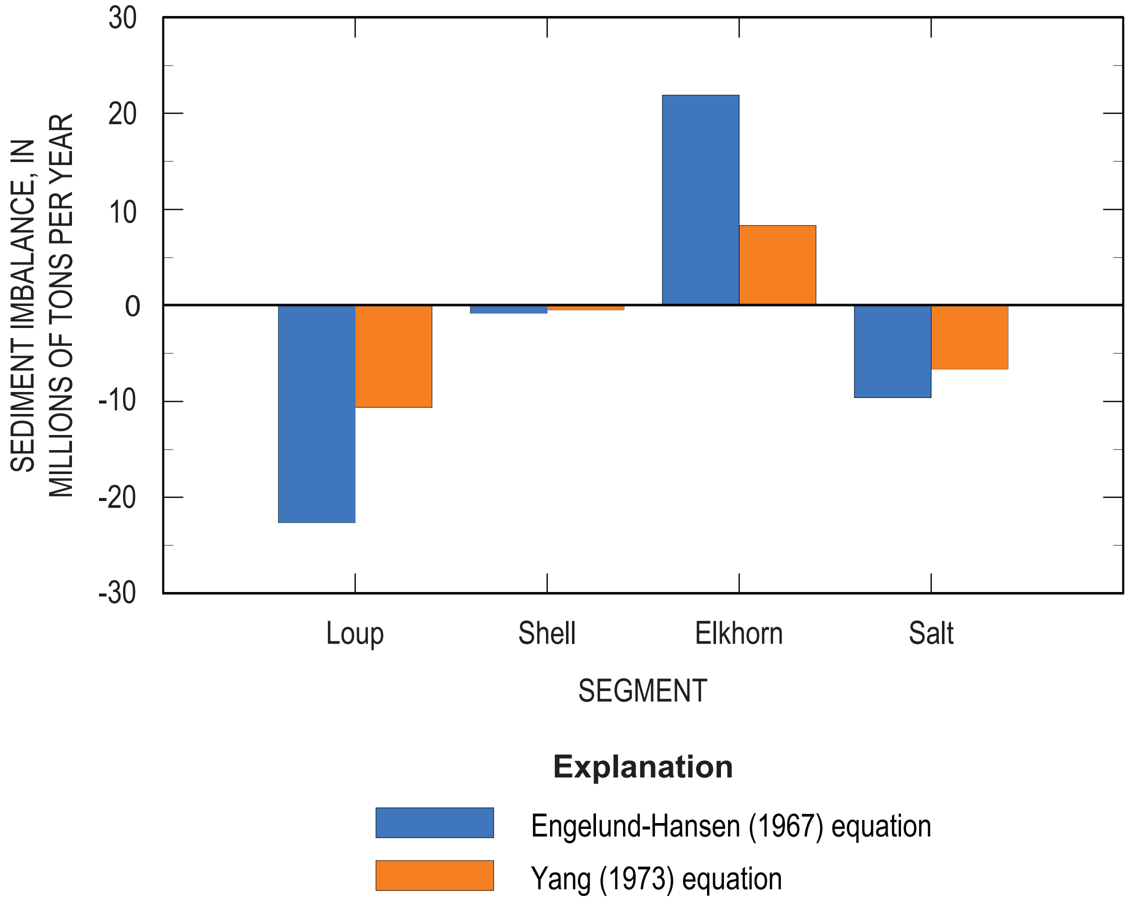

Figure 11. Bed-material imbalances in segments of the lower Platte River, Nebraska, 1970-2011, by sediment-transport equation, as estimated using the U.S. Army Corps of Engineers' Sediment Impact Analysis Methods tool. (Positive imbalance corresponds to aggradation; negative imbalance corresponds to degradation.)

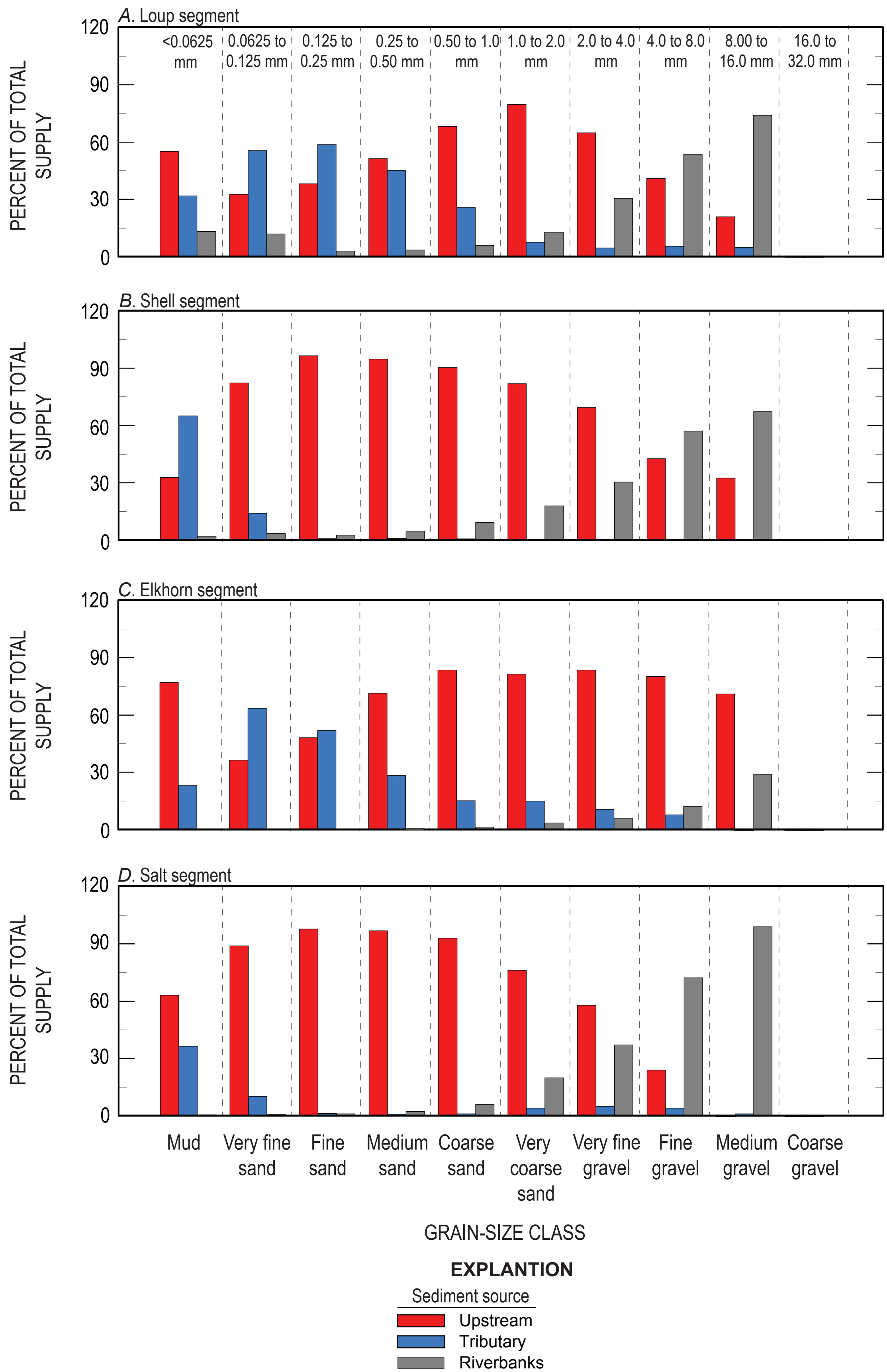

Figure 12. Estimated sources of bed sediment as a percentage of total supply by grain-size class to segments of the lower Platte River, Nebraska, 1970-2011. Bed-material discharges from upstream and tributary sources were estimated by applying the Engelund-Hansen (1967) equation at representative streamgages. (mm, millimeter.)

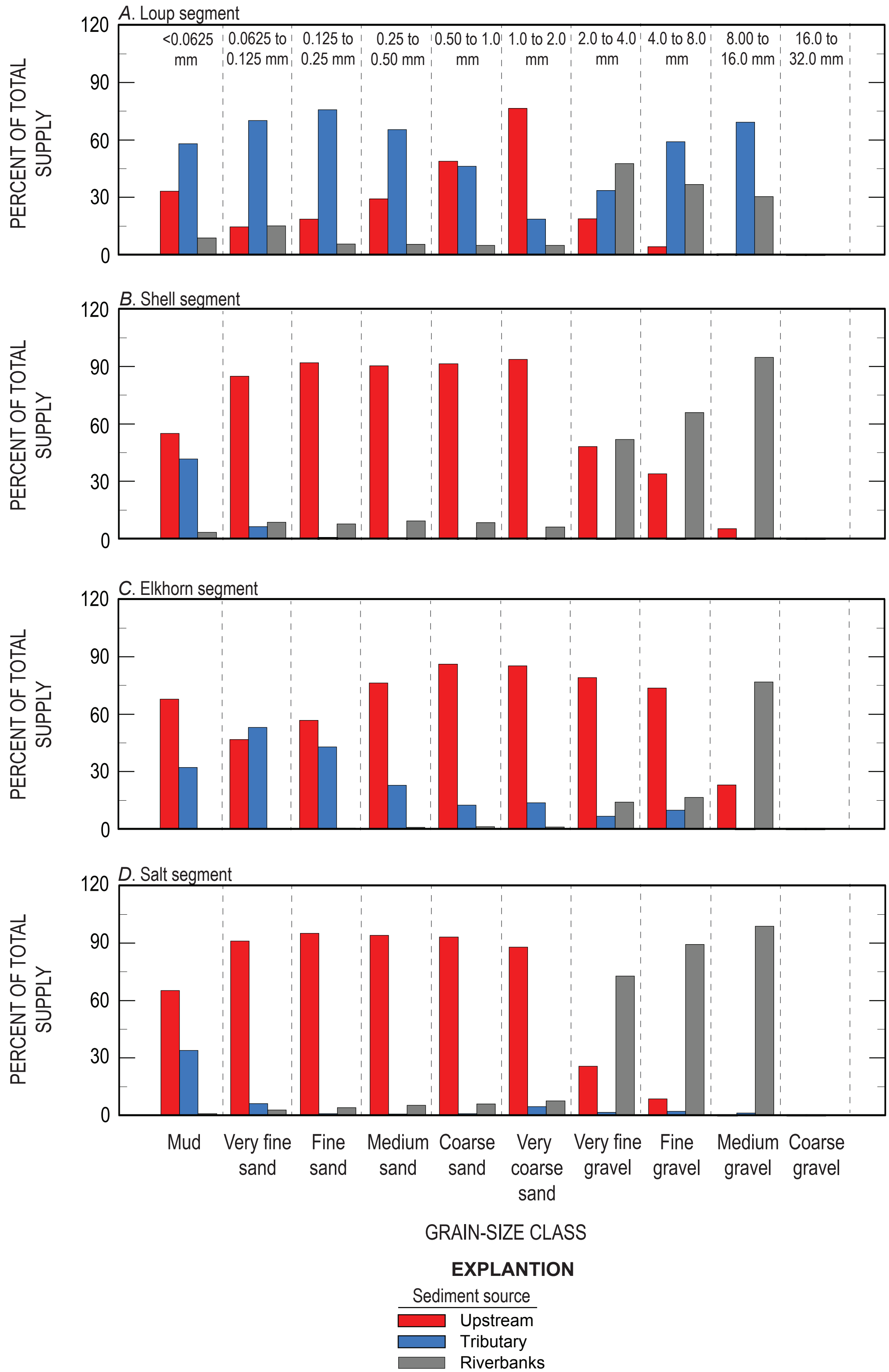

Figure 13. Estimated sources of bed sediment as a percentage of total supply by grain-size class to segments of the lower Platte River, Nebraska, 1970-2011. Bed-material discharges from upstream and tributary sources were estimated by applying the Yang (1973) equation at representative streamgages. (mm, millimeter.)

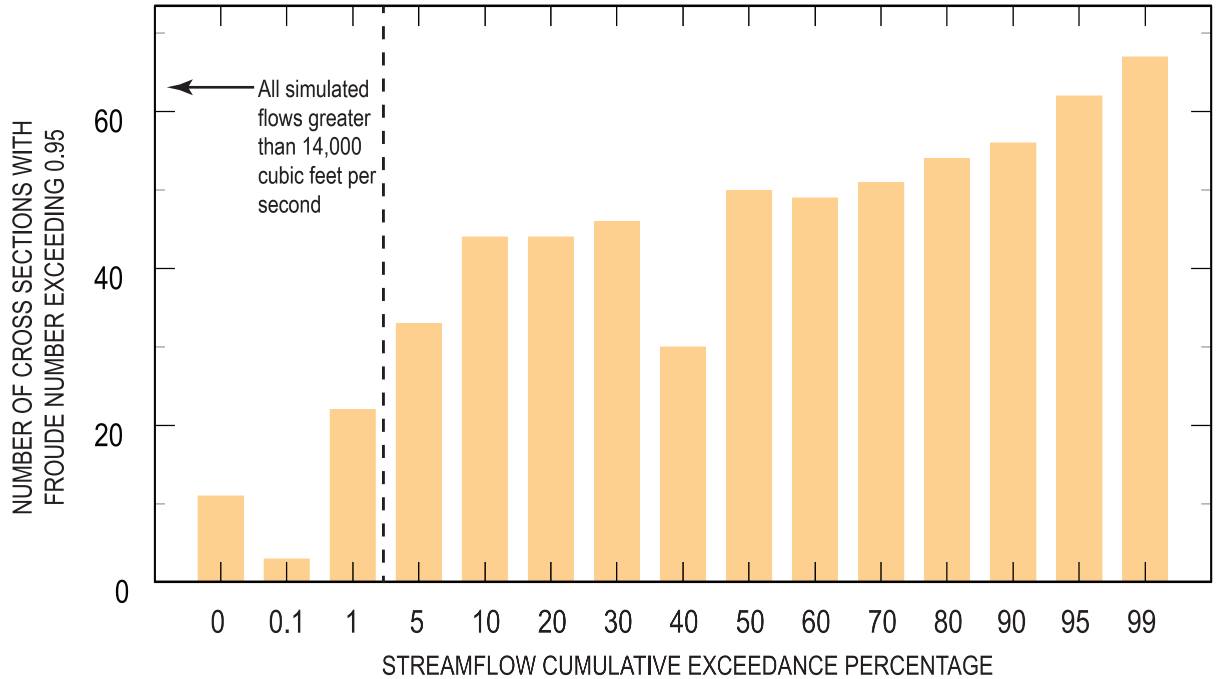

Figure 14. Number of cross sections with froude numbers greater than 0.95 for the range of streamflow exceedance frequencies simulated in the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska.

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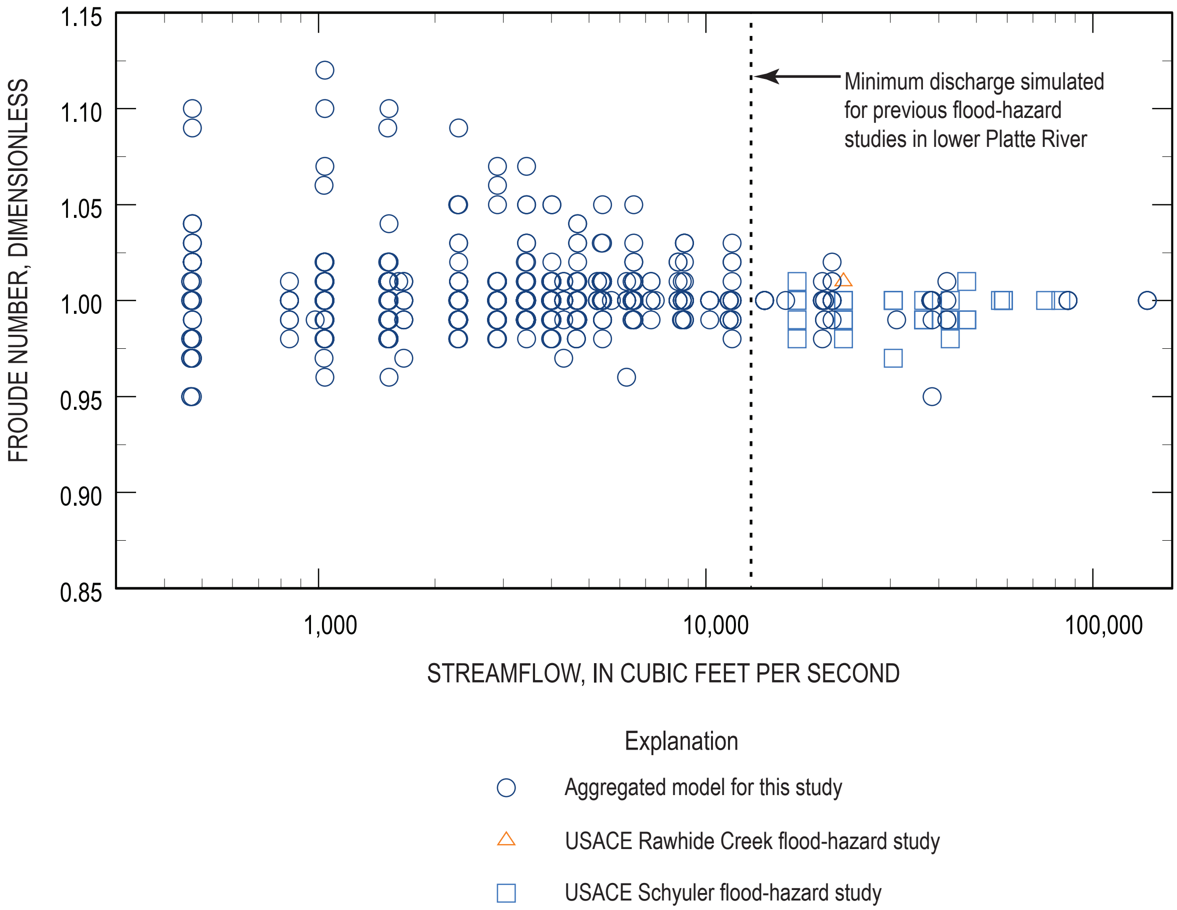

Figure 15. Range of Froude numbers greater than 0.95 for streamflows simulated in the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska, and two previouly published models which used the same geometry but simulated only higher-magnitude streamflows (Data for USACE flood hazard studies provided by Dan Pridal, USACE, written communication, January 2012. USACE, U.S. Army Corps of Engineers.)

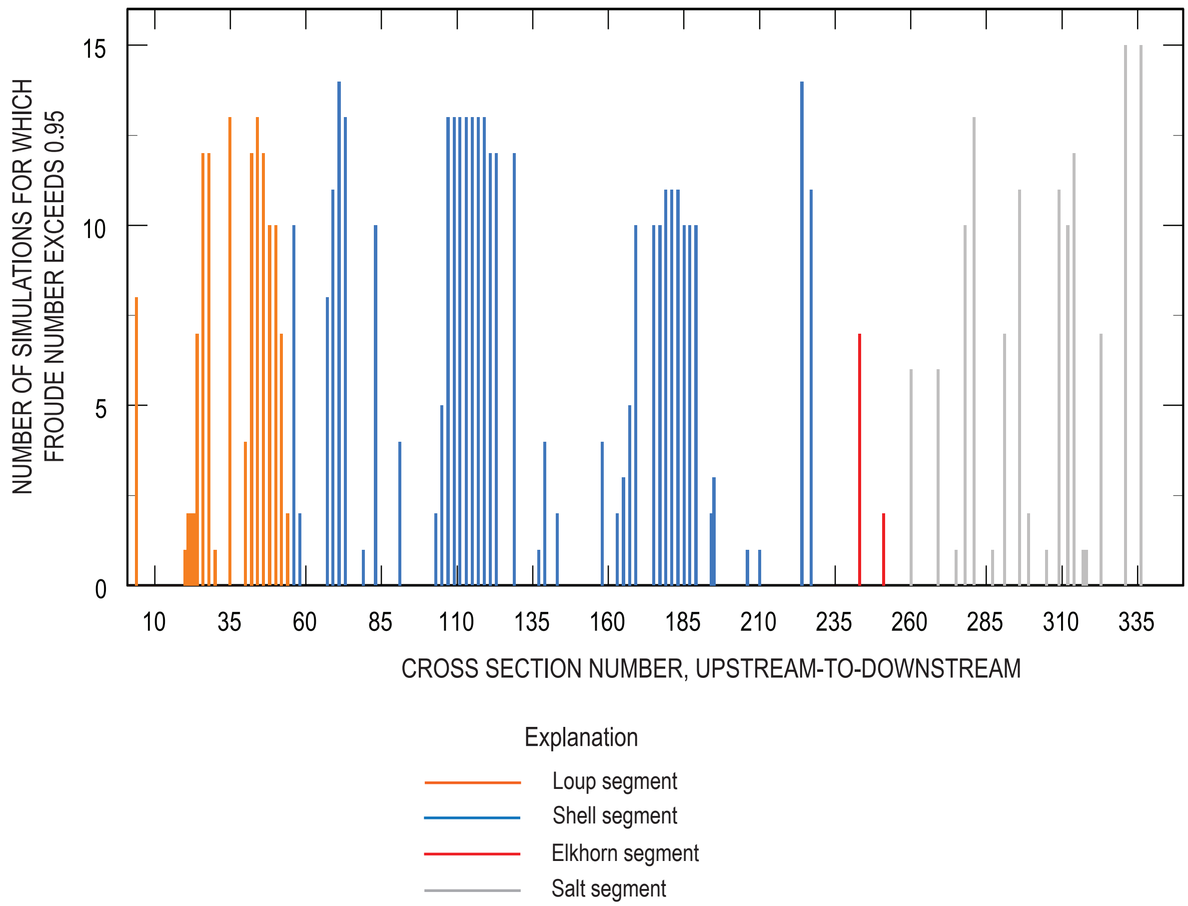

Figure 16. Number of simulations for which a Froude number at a cross section was greater than 0.95 for the range of streamflows simulated in the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska.

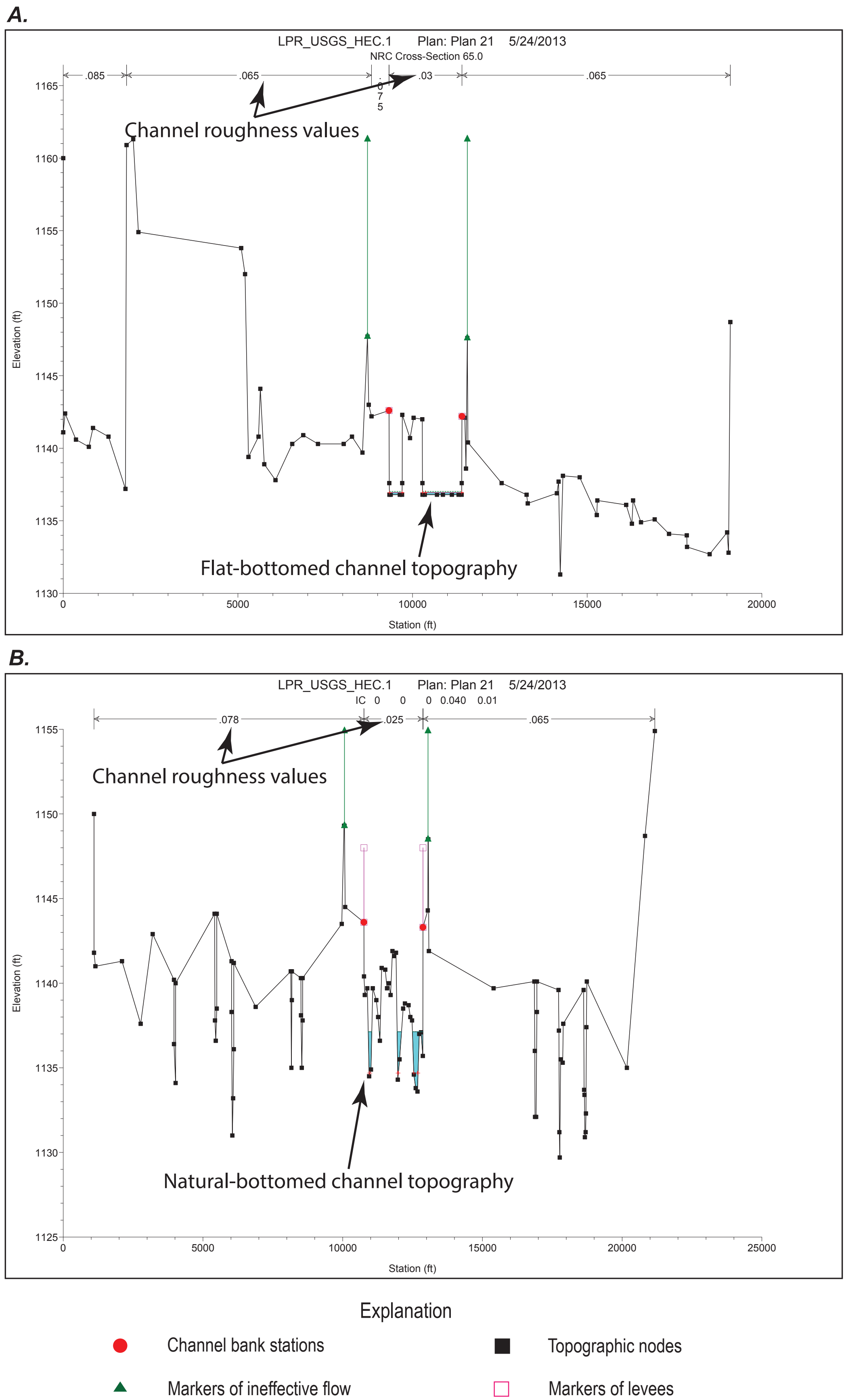

Figure 17. Graph outputs from HEC-RAS showing examples of two different types of channel-bottom topographies used in cross sections of the aggregated HEC-RAS hydraulic model of the lower Platte River, Nebraska: (*A*) flat-bottomed, and (*B*) natural-bottomed.

Table 1. Lower Platte River, Nebraska, sediment sampling reaches of Schaepe and Alexander (2011).

[River miles are referenced to the river mouth; Hwy, highway; NA, Not applicable]

Sampling reach identifier	Number of sampling sites[1]	Platte River reach description	Reach location, in river miles	Reach length, in miles
UA	1	Silver Creek, Hwy 139 bridge to midpoint between Silver Creek, Hwy 139 and Columbus, Hwy 81 bridge	123.1 to 113.2	9.9
UB	1	Midpoint between Silver Creek, Hwy 139 bridge and Columbus, Hwy 81 bridge to confluence with Loup River	113.2 to 103.3	9.9
1A	2	Confluence with Loup River to Schuyler, Hwy 15 bridge	103.3 to 88.6	14.7
1B	2	Schuyler, Hwy 15 bridge to North Bend, Hwy 79 bridge	88.6 to 72.4	16.2
1C	2	North Bend, Hwy 79 bridge to Fremont, Hwy 77 bridge	72.4 to 56.9	15.5
1D	2	Fremont, Hwy 77 bridge to midpoint between Fremont, Hwy 77 bridge and the Elkhorn River confluence	56.9 to 44.9	12
1E	2	Midpoint between Fremont, Hwy 77 bridge and the Elkhorn River confluence to the Elkhorn River confluence	44.9 to 32.8	12.1
2A	1	Elkhorn River confluence to midpoint between Elkhorn River confluence and Salt Creek confluence	32.8 to 29.4	3.4
2B	1	Midpoint between Elkhorn River confluence and Salt Creek confluence to Salt Creek confluence	29.4 to 25.9	3.5
3A	1	Salt Creek confluence to Louisville streamgage	25.9 to 16.5	9.4
3B	2	Louisville stream gage to the Platte River mouth	16.5 to 0	16.5
		Tributary	**Sample site location**	
NA	3	Loup River	1 within Platte River valley boundary, 2 upstream from Platte River valley boundary	
NA	3	Shell Creek	1 within Platte River valley boundary, 2 upstream from Platte River valley boundary	
NA	3	Elkhorn River	1 near Platte River confluence, 2 a minimum of 5 miles upstream from Platte River confluence	
NA	3	Salt Creek	1 within Platte River valley boundary, 2 upstream from Platte River valley boundary	

[1]For each sampling site on the main channel of the Platte River, 3 bed-material, 3 sandbar-material, and 2 bank-material samples were taken; for each sampling site on tributaries, three bed-material and 1 bank-material samples were taken.

Table 2. Streamgages used to represent channel hydraulic geometry and streamflow for at-a-station estimations of annual bed-material sediment discharge of large tributaries to the lower Platte River, Nebraska, by river segment.

[fig., figure; mi^2, square miles; --, data not available; USGS, U.S. Geological Survey]

Segment[1]	U.S. Geological Survey streamgage number and name (fig. 1)		Daily streamflow period of record used		Total drainage basin area[2]	Drainage area at gage[3]	Contributing drainage area at gage[4]	Gage location	Percent of drainage basin represented by gage[5]
			Start date	End date	(mi^2)	(mi^2)	(mi^2)	(miles upstream from mouth)	
Loup									
	6774000	Platte River near Duncan	10/1/1969	9/30/2011	59,440	59,300	54,630	10.2	100
	6793000	Loup River near Genoa	10/1/1969	9/30/2011	15,080	14,320	5,620	27.2	95
	6794500	Loup River at Columbus	10/1/1969	10/10/1978	15,080	15,200	6,230	2.7	101
Shell									
	6795500	Shell Creek near Columbus[6]	10/1/1969	9/30/2011	480	294	--	30.0	61
Elkhorn									
	6800500	Elkhorn River at Waterloo	10/1/1969	9/30/2011	7,000	6,900	5,870	12.2	99
Salt									
	6803555	Salt Creek at Greenwood	10/1/1969	9/30/2011	1,650	1,050	--	12.6	64

[1] Segment is a length of river consisting of multiple reaches spanning between two primary tributaries and named for the upstream tributary.

[2] Total area of drainage of river basin determined from USGS Watershed Boundary Dataset (*http://nhd.usgs.gov/wbd.html*).

[3] Drainage area upstream from gaging station. Available from USGS National Water Information System (*http://waterdata.usgs.gov/nwis*).

[4] Drainage area upstream from gaging station estimated to contribute to runoff. Available from USGS National Water Information System (*http://waterdata.usgs.gov/nwis*).

[5] Determined as the ratio of drainage area at streamgage to total drainage basin area, expressed as a percentage; exceedance of 100% likely indicates differences in precision of drainage area data between USGS Watershed Boundary Dataset and data available from USGS National Water Information System.

[6] This gage is missing daily records from 10/1/1975 to 09/30/1977.

Table 3. At-a-station hydraulic geometry relations for selected streamgages on large tributaries to the lower Platte River, Nebraska.

[All data from U.S. Geological Survey National Water Information System; period of record for each streamflow-gaging station expressed in water years; period of record used for hydraulic geometry analysis may differ from total available period of record for streamflow gage listed; ft^3/s, cubic feet per second; *W,* channel wetted top width; *a* , width coefficient; *b,* width exponent; *D* , average channel depth; *c* , depth coefficient; *f* , depth exponent; *U,* average current velocity; *k* , velocity coefficient; *m* , velocity exponent; Q, streamflow; <, less than]

Parameter or statistic	U.S. Geological Survey streamgage name and number					
	Platte River near Duncan, (06774000)[1]		**Loup River at Columbus (06794500)[2]**	**Shell Creek near Columbus (06795500)**	**Elkhorn River at Waterloo (06800500)**	**Salt Creek at Greenwood (06803555)**
	Period of record used for analysis					
	1970 to 2011		1953 to 1978	1970 to 2011	1970 to 2011	1993 to 2011
	Measurements used in hydraulic geometry analysis					
	56	206	451	392	176	367
	Maximum streamflow of included measurements, in ft^3/s					
	480	16,700	81,400	3,590	53,100	39,800
	Minimum streamflow of included measurements, in ft^3/s					
	2	517	8	2	125	66
	Width coefficients and exponents (equation 10; $W = aQ^b$)					
a	6.5	530	16	8.7	75	79
b	.74	.05	.41	.26	.15	.10
p value[3]	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
COD[4]	.93	.05	.77	.84	.59	.33
	Depth coefficients and exponents (equation 11; $D = cQ^f$)					
c	.35	.01	.17	.28	.07	.04
f	.06	.66	.32	.46	.50	.61
p value[3]	<.0001	<.001	<.0001	<.0001	<.0001	<.0001
COD[4]	.11	.92	.76	.88	.95	.93
	Velocity coefficients and exponents (equation 12; $U = kQ^m$)					
k	.44	.23	.38	.43	.20	.31
m	.19	.28	.27	.27	.35	.28
p value[3]	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
COD[4]	.78	.89	.83	.69	.91	.85
	Product of coefficients					
	1.00	1.02	1.02	1.02	1.00	1.01
	Sum of exponents					
	1.00	1.00	1.00	.99	1.00	1.00

[1]Two hydraulic geometry curves were generated for this streamgage: one for streamflows smaller than 500 ft^3/s, and one for streamflows larger than 500 ft^3/s because of substantial change in slope of data identified in scatterplots.

[2]The hydraulic geometries at this streamgage were determined to be statistically insignificantly different than those from a streamgage with a period of record spanning the study period of 1970 to 2011, the Loup River near Genoa (USGS station no. 06793000).

[3]Probability (*p*- value) that regression slope is zero (no correlation between discharge and geometric variable); values less than 0.10 indicate model significance at the 90-percent confidence level, based on hypothesis test using Student's t distribution (Helsel and Hirsch, 2002).

[4]Coefficient of determination for least-squares estimate of regression equation (Helsel and Hirsch, 2002).

Table 4. Summary of sediment-sample sources and composite grain-size distributions for the riverbed, riverbanks, and large tributaries of segments of the lower Platte River, Nebraska.

[mm, millimeters; D_{10}, grain diameter at the 10th percentile of the distribution; D_{50}, median grain diameter; D_{90}, grain diameter at the 90th percentile of the distribution]

Feature or tributary to segment	Source sites used for composited characteristic grain size (Schaepe and Alexander, 2011)[1]	Grain sizes (mm)			Percent grain class			Folk and Ward (1957) statistics		
		D_{10}	D_{50}	D_{90}	Gravel[2] (percent)	Sand[3] (percent)	Clay[4] (percent)	Mean grain diameter (mm)	Mean grain diameter sediment class	Sorting
Loup Segment										
riverbed	1A1, 1A2, 1B1	0.17	0.44	2.48	12	88	0	0.51	Coarse Sand	Poorly Sorted
riverbanks	1A1, 1A2, 1B1	0.02	0.19	0.84	3	77	19	0.16	Fine Sand	Very Poorly Sorted
sandbars	1A1, 1A2, 1B1	0.14	0.27	0.73	2	98	1	0.28	Medium Sand	Moderately Sorted
Central Platte riverbed	UA, UB	0.25	0.67	2.88	15	84	0	0.73	Coarse Sand	Poorly Sorted
Loup riverbed	Loup River - A, B, C	0.16	0.35	0.87	3	97	0	0.36	Medium Sand	Moderately Sorted
Shell Segment										
riverbed	1B2, 1C1, 1C2, 1D1, 1D2, 1E1, 1E2	0.16	0.44	2.07	10	89	0	0.50	Medium Sand	Poorly Sorted
riverbanks	1B2, 1C1, 1C2, 1D1, 1D2, 1E1, 1E2	0.02	0.24	0.93	4	79	17	0.21	Fine Sand	Very Poorly Sorted
sandbars	1B2, 1C1, 1C2, 1D1, 1D2, 1E1, 1E2	0.11	0.28	0.84	3	94	4	0.29	Medium Sand	Poorly Sorted
Shell Creek riverbed	Shell Creek - A, B, C	0.01	0.05	0.41	1	42	57	0.05	Very Coarse Silt	Very Poorly Sorted
Elkhorn Segment										
riverbed	2A, 2B	0.15	0.37	1.25	5	95	0	0.39	Medium Sand	Poorly Sorted
riverbanks	2A, 2B	0.15	0.42	1.43	5	94	1	0.43	Medium Sand	Poorly Sorted
sandbars	2A, 2B	0.14	0.36	1.02	3	96	1	0.37	Medium Sand	Poorly Sorted
Elkhorn River riverbed	Elkhorn River - A, B, C	0.12	0.23	0.76	2	97	1	0.25	Medium Sand	Poorly Sorted
Salt Segment										
riverbed	3A, 3B1, 3B2	0.16	0.40	1.26	5	95	0	0.42	Medium Sand	Poorly Sorted
riverbanks	3A, 3B1, 3B2	0.04	0.28	1.16	5	84	11	0.27	Medium Sand	Poorly Sorted
sandbars	3A, 3B1, 3B2	0.14	0.32	0.89	2	96	1	0.33	Medium Sand	Poorly Sorted
Salt Creek riverbed	Salt Creek - A, B, C	0.01	0.19	3.06	16	50	34	0.18	Fine Sand	Very Poorly Sorted

[1] See tables 1 and 2 of Schaepe and Alexander (2011) for reach descriptions and summary of sampling sites.

[2] Gravel is defined as grain sizes larger than 2 millimeters and less than 64 millimeters in diameter.

[3] Sand is defined as grain sizes larger than 0.0625 millimeters and smaller than 2 millimeters in diameter.

[4] Mud is defined as grain sizes smaller than 0.0625 millimeters in diameter (silt and clay).

Table 5. Average bank heights in segments of the lower Platte River, Nebraska.

[n, sample size; Avg, average; est., estimated; Adj., adjusted; 90% exceedance discharge, flow exceeded 90 percent of the time over period of record from 1970 to 2011 at representative streamgage; --, not applicable]

Segment	n	Avg. bank height above est. stage of median discharge (feet)	Avg. bank height above est. stage of 90% exceedance discharge (feet)	Adj. avg. bank height above est. stage of 90% exceedance discharge[1] (feet)
Loup[2]	3	5.5	6.4	5.5
Shell[2]	7	4.2	5.1	4.4
Elkhorn[2]	3	5.3	6.3	5.4
Salt[2]	4	6.1	7.3	6.2
Salt[3]	86	5.0	6.2	--

[1]Bank heights in this column adjusted using the ratio of average heights above 90% exceedance in the Salt sediment reach for samples from Schaepe and Alexander (2011) to those of Alexander and others (2013).

[2]Bank height samples for this estimate taken from Schaepe and Alexander (2011).

[3]Bank height samples for this estimate taken from Alexander and others (2013).

Table 6. At-a-station hydraulic geometry relations for selected streamgages in the lower Platte River, Nebraska.

[All data from U.S. Geological Survey National Water Information System; period of record for each streamflow-gaging station expressed in water years; period of record used for hydraulic geometry analysis may differ from total available period of record for streamflow gage listed; ft^3/s, cubic feet per second; *W*, channel wetted top width; *a* , width coefficient; *b*, width exponent; *D* , average channel depth; *c* , depth coefficient; *f* , depth exponent; *U*, average current velocity; *k* , velocity coefficient; *m* , velocity exponent; Q, streamflow; <, less than.]

Parameter or statistic	U.S. Geological Survey streamgage name and number					
	Platte River at North Bend, (06796000)[1]		Platte River near Ashland, (06801000)[2,3]		Platte River at Louisville, (06805500)[1,4]	
	Period of record used for analysis					
	1970 to 2011		1988 to 2011		1973 to 2011	
	Measurements used in hydraulic geometry analysis					
	219	207	99	181	174	289
	Maximum streamflow of included measurements, in ft^3/s					
	4,990	73,400	3,990	90,300	4,930	134,000
	Minimum streamflow of included measurements, in ft^3/s					
	146	5,000	1	4,010	160	5,010
	Width coefficients and exponents (equation 10; $W = a\,Q^b$)					
a	24	370	5.8	300	9.4	360
b	.45	.12	.62	.14	.55	.12
p value[5]	<.0001	<.001	<.0001	<.0001	<.0001	<.0001
COD[6]	.46	.09	.98	.34	.60	.31
	Depth coefficients and exponents (equation 11; $D = c\,Q^f$)					
c	.15	.03	.26	.03	.18	.02
f	.29	.51	.24	.51	.29	.57
p value[5]	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
COD[6]	.36	.72	.89	.89	.35	.92
	Velocity coefficients and exponents (equation 12; $U = k\,Q^m$)					
k	.57	.11	.68	.14	.58	.17
m	.17	.37	.14	.33	.16	.31
p value[5]	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
COD[6]	.42	.81	.75	.86	.34	.82
	Product of coefficients					
	2.05	1.00	1.01	1.09	1.00	1.03
	Sum of exponents					
	.91	1.00	1.00	.99	1.00	1.00

[1]Two hydraulic geometry curves were generated for this streamgage: one for streamflows smaller than 5,000 ft^3/s, and one for streamflows larger than 5,000 ft^3/s because of substantial change in slope of data identified in scatterplots.

[2]Two hydraulic geometry curves were generated for this streamgage: one for streamflows smaller than 4,000 ft^3/s, and one for streamflows larger than 4,000 ft^3/s because of substantial change in slope of data identified in scatterplots.

[3]This gage has a period of record spanning from 1928 to 2011, but a gap in the record from 1953 to 1988.

[4]This streamgage was moved in 1972 to a different location when a new bridge was constructed nearby; the hydraulic geometry represents the streamgage location from 1972 to 2011.

[5]Probability (*p*- value) that regression slope is zero (no correlation between discharge and geometric variable); values less than 0.10 indicate model significance at the 90-percent confidence level, based on hypothesis test using Student's t distribution (Helsel and Hirsch, 2002).

[6]Coefficient of determination for least-squares estimate of regression equation (Helsel and Hirsch, 2002).

Table 7. Summary of estimates of annual bed-material discharge from large tributaries to segments of the lower Platte River, Nebraska, 1970-2011.

[Slight inequities in accounting may be shown because of rounding. mm, millimeters; Eng-Han, estimate of annual bed-material discharge made using Engelund-Hansen (1967) equation; Yang, estimate of annual bed-material discharge made using Yang (1973) equation]

Tributary basin	Bed-material discharge equation used	Estimated sediment mass within grain-size interval, in tons per year: 0.0625	0.125	0.25	0.5	1	2	4	8	16	Total estimated sediment discharge (tons/year)	Total estimated sediment discharge, less muds
Loup segment												
Central Platte River	Eng-Han	139,000	70,700	745,000	795,000	290,000	63,600	12,900	1,900	100	2,120,000	1,980,000
	Yang	122,000	24,800	191,000	296,000	253,000	157,000	2,400	300	0	1,050,000	924,000
Loup River	Eng-Han	77,600	119,300	1,142,000	698,000	110,000	6,000	900	300	0	2,150,000	2,080,000
	Yang	216,000	118,900	775,000	663,000	240,000	38,000	4,300	4,100	1,000	2,060,000	1,845,000
Shell segment												
Shell Creek	Eng-Han[1]	2,340,000	217,000	54,700	18,000	2,800	300	100	0	0	2,630,000	293,000
	Yang[1]	919,000	39,900	8,400	4,600	1,800	700	0	0	0	970,000	55,000
Elkhorn segment												
Elkhorn River	Eng-Han	697,000	2,030,000	3,412,000	825,000	89,300	13,900	1,900	300	0	7,070,000	6,370,000
	Yang	427,000	541,000	736,000	288,000	80,500	40,300	500	300	0	2,110,000	1,690,000
Salt segment												
Salt Creek	Eng-Han[1]	2,310,000	245,000	78,300	32,000	8,100	4,100	1,300	200	0	2,680,000	370,000
	Yang[1]	936,000	47,500	13,600	9,900	7,100	12,500	200	100	0	1,030,000	91,000
Total, large tributaries												
	Eng-Han	5,560,000	2,680,000	5,430,000	2,370,000	500,000	88,000	17,100	2,700	200	16,650,000	11,090,000
	Yang	2,620,000	772,000	1,720,000	1,260,000	582,000	249,000	7,400	4,800	1,000	7,220,000	4,600,000

[1]Estimate of annual bed-material discharge was adjusted upward by scaling drainage area at location of estimate to total drainage area of basin.

Table 8. Selected previously published estimates of annual sediment discharge from large tributaries to the lower Platte River, Nebraska.

[All values shown in tons per year; --, not applicable]

Tributary	Missouri River Basin Commission (1975)[1]	Simons and Associates (2000)[2]	Kircher (1983)[2]	Lyons-Randle (1988)[2]	Randle and Samad (2003)[2]	Loup Power District (2011)[3]
Central Platte	1,865,400	845,000	826,000	706,000	374,000	--
Loup River	7,435,400	--	--	--	--	1,758,000
Shell Creek	154,600	--	--	--	--	--
Elkhorn River	4,709,700	--	--	--	--	--
Salt Creek	1,974,000	--	--	--	--	--

[1] Estimate made using modified Einstein (1950) procedure; estimate likely includes substantial washload.

[2] Estimate made using equation from indicated reference, made at Grand Island, Nebraska; published by Randle and Samad (2003).

[3] Estimate made using the Yang (1973) equation.

Table 9. Estimates of riverbank erosion and accretion in segments of the lower Platte River, Nebraska, 1970-2011.

[Slight inequities in accounting may be shown because of rounding. Erosion assumes eroded area is typically mature banks of estimated average height for each reach. Accretion assumes land gained is only 60% of the height of the land lost. Assumption based on calculated ratios of coarse fraction to fine fraction thicknesses reported in Schaepe and Alexander (2011), and bank height estimations performed for this study. Erosion and accretion calculations assume a factor of 1.35 tons of sediment per cubic yard (Marron, 1992); Segment, length of the lower Platte River channel bound at upstream and downstream ends by major tributary, named by upstream tributary; acres/mi/yr, acres per mile per year; Ttons/yr, thousands of tons per year; ±, plus or minus sensitivity or statistical uncertainty of estimate; pred., predicted; --, not applicable; indet., indeterminate condition, defined when no difference between magnitude of bank erosion and accretion can be concluded when the uncertainty of the estimates is considered; eros., defined as net evacuation of sediments from riverbanks or islands; acc., accretion, defined as net depostion of sediment by creation of riverbanks or islands.]

Parameter	Unit of measure	Segment			
		Loup	Shell	Elkhorn	Salt
		1970-1993			
Total eroded area	acres	490	750	50	320
Incremental rate eroded area	acres/mi/yr	1.0	.6	.3	.5
Total rate of erosion	Ttons/yr	256	310	26	190
Total accreted area	acres	870	980	100	520
Incremental accreted area	acres/mi/yr	1.8	.8	.6	.9
Total rate of accretion	Ttons/yr	275	242	29	184
		1993-2003			
Total eroded area	acres	100	370	40	170
Incremental rate eroded area	acres/mi/yr	.5	.7	.6	.7
Total rate of erosion	Ttons/yr	125	354	44	226
Total accreted area	acres	270	420	50	380
Incremental accreted area	acres/mi/yr	1.3	.8	.7	1.5
Total rate of accretion	Ttons/yr	192	240	32	311
		1970-2003			
Mean total rate of erosion	Ttons/yr	216	323	31	201
Mean total rate of erosion, less muds[1]	Ttons/yr	175	269	31	178
Erosion less muds uncertainty ±	Ttons/yr	7	14	1	6
Mean total rate of accretion	Ttons/yr	250	242	30	222
Mean total rate of accretion, less muds[1]	Ttons/yr	246	225	29	177
Accretion less muds uncertainty ±	Ttons/yr	37	34	4	27
Mean adjustment[2]	Ttons/yr	34	-27	-1	45
Pred. adjustment condition[3]	--	indet.	eros.	indet.	indet.
Mean adjustment, less muds[1,2]	Ttons/yr	71	-44	-2	-1
Pred. adjustment condition, less muds[1,3]	--	acc.	eros.	indet.	indet.

[1]Estimate excluding grain sizes smaller than 0.0625 millimeters.

[2]Rate of adjustment predicted by subtracting mean total erosion rate from mean total accretion rate. A positive value indicates net accretion; a negative value indicates net erosion.

[3]Predicted dominant bank adjustment condition when uncertainty of mean total erosion and accretion estimates is considered.

Table 10. Results from specific gage analysis for selected streamgages in the lower Platte River, Nebraska.

[All data from U.S. Geological Survey National Water Information System. Stage, regression analysis of water surface height over time; mean riverbed altitude, regression analysis of mean water depth subtracted from stage plus local altitude datum, a measure of channel bottom elevation; 90 percent exceedance, statistics computed on measurements made within 10 percent of the magnitude of daily flows exceeded 90 percent of the period of record; n, number of measurements used in regression analysis; ft^3/s, cubic feet per second; ft/year, feet per year; <, less than; NA, trend not detected at 0.05 significance level; 50 percent exceedance, statistics computed on measurements made within 10 percent of the magnitude of daily flows exceeded 50 percent of the period of record; >, greater than; 10 percent exceedance, statistics computed on measurements made within 10 percent of the magnitude of daily flows exceeded 10 percent of the period of record.]

Parameter or statistic	U.S. Geological Survey streamgage name and number: Platte River at North Bend, (06796000)		Platte River near Ashland, (06801000)		Platte River at Louisville, (06805500)	
	Stage	Mean riverbed altitude	Stage	Mean riverbed altitude	Stage	Mean riverbed altitude
90-percent exceedance[1]						
sample size (n)	8		7		18	
date range of data	7/28/1971 to 6/24/2002		6/12/1989 to 10/12/2004		9/19/1974 to 8/31/2005	
streamflow range (ft^3/s)	961 to 1,120		2,090 to 2,400		2,100 to 2,500	
tau[2]	-.79	-.50	.43	.62	-.24	.18
p value[3]	<.010	.11	.23	.07	.18	.32
robust slope (ft/year)[4]	-.05	*NA*	*NA*	*NA*	*NA*	*NA*
50-percent exceedance						
sample size (n)	43		26		36	
date range of data	5/12/1970 to 5/27/2009		3/26/1990 to 6/7/2012		3/13/1975 to 5/21/2007	
streamflow range (ft^3/s)	3,620 to 4,410		5,170 to 6,140		5,630 to 6,860	
tau[2]	-.49	-.24	-.01	.06	-.51	-.53
p value[3]	<.001	.02	>0.5	>0.5	<.001	<.001
robust slope (ft/year)[4]	-.01	-.01	*NA*	*NA*	-.02	-.03
10-percent exceedance						
sample size (n)	35		19		18	
date range of data	4/22/1970 to 8/9/2011		7/27/1992 to 3/2/2012		4/1/1980 to 6/11/2003	
streamflow range (ft^3/s)	7,920 to 9,660		10,500 to 12,500		12,800 to 15,200	
tau[2]	-.69	-.10	.02	.09	-.29	.01
p value[3]	<.001	.41	>0.5	>0.5	.10	>0.5
robust slope (ft/year)[4]	-.03	*NA*	*NA*	*NA*	*NA*	*NA*

[1]Statistics shown for 90% exceedance for the Platte River at North Bend were actually computed using the 95% exceedance values because too few measurement data points were available at the 90% exceedance flow magnitude.

[2]Rank-based correlation statistic computed using the method of Kendall (1938), and following procedure of Helsel and Hirsch (2002).

[3]Probability (*p*- value) that there is no correlation between time and variable of interest (stage or mean bed altitude); values less than 0.05 indicate correlation model significance of at least the 95-percent confidence level.

[4] Slope of regression line computed using method of Theil (1950) and following procedure of Helsel and Hirsch (2002).

Table 11. Summary of bed-material balance computed for segments of the lower Platte River, Nebraska, 1970-2011, using the U.S. Army Corps of Engineers' SIAM tool.

[Slight inequities in accounting may be shown due to automatic rounding in SIAM output; SIAM, Sediment Impacts Analysis Methods; tons/yr, tons per year; Engelund-Hansen, estimate of annual bed-material sediment discharge made using Engelund-Hansen (1967) dimensionless equation; Yang, estimate of annual bed-material sediment discharge made using Yang (1973) dimensionless equation]

Sediment-transport prediction equation	Local sediment supply[1] (tons/yr)	Transport capacity (tons/yr)	Bed sediment supply[2] (tons/yr)	Washload supply[3] (tons/yr)	Sediment balance (tons/yr)
Loup segment					
Engelund-Hansen	4,240,000	26,700,000	4,030,000	211,000	-22,600,000
Yang	3,070,000	13,300,000	2,740,000	333,000	-10,600,000
Shell segment					
Engelund-Hansen	2,710,000	27,900,000	27,000,000	2,560,000	-819,000
Yang	1,060,000	13,900,000	13,400,000	1,260,000	-445,000
Elkhorn segment					
Engelund-Hansen	7,070,000	12,400,000	34,200,000	3,260,000	21,900,000
Yang	2,120,000	7,200,000	15,600,000	1,690,000	8,350,000
Salt segment					
Engelund-Hansen	2,650,000	22,300,000	12,700,000	5,560,000	-9,610,000
Yang	1,010,000	13,900,000	7,270,000	2,620,000	-6,610,000

[1] Local supplies are within-reach tributary and bank-erosion contributions; these estimates were done outside of the SIAM tool. Estimates of tributary contributions used the same predictive equations as those shown for the SIAM results. See *Grain-Size Specific Sediment Supplies to the Lower Platte River* section of the report.

[2] Includes part of local supplies that are coarser than muds, plus upstream bed-material contributions.

[3] Supplies of sediment from tributaries, bank erosion, and upstream that are finer than 0.0625 millimeters.

Table 12. Summary of at-a-station estimates of annual bed-material discharge for segments of the lower Platte River, Nebraska, 1970-2011.

[Slight inequities in accounting may be shown due to rounding; mm, millimeters; est., estimated; Eng-Han, estimate of annual bed-material sediment discharge made using Engelund-Hansen (1967) dimensionless equation; Yang, estimate of annual bed-material sediment discharge made using Yang (1973) dimensionless equation]

U.S. Geological Survey streamgage name and number	Bed-material discharge equation used	Estimated sediment mass within grain-size interval, in tons per year										
		0.0625	0.125	0.25	0.5	1	2	4	8	16	Total est. sediment load (tons/year)	Total est. sediment load, less muds (tons/year)
Loup segment												
Platte River near North Bend (06796000)	Eng-Han[1]	639,000	690,000	3,210,000	1,990,000	441,000	63,800	15,000	2,660	630	7,050,000	6,410,000
	Yang[1]	670,000	291,000	1,010,000	936,000	502,000	216,000	6,090	1,830	70	3,630,000	2,960,000
Shell segment												
Platte River near North Bend (06796000)	Eng-Han	675,000	1,150,000	3,150,000	2,080,000	494,000	75,400	15,100	3,260	340	7,650,000	6,980,000
	Yang	692,000	477,000	974,000	963,000	552,000	250,000	5,940	2,200	40	3,920,000	3,220,000
Elkhorn segment												
Platte River near Ashland (06801000)	Eng-Han	0	1,690,000	4,950,000	2,660,000	544,000	61,200	12,400	1,090	0	9,920,000	9,920,000
	Yang	0	550,000	1,260,000	1,050,000	538,000	184,000	2,620	320	0	3,590,000	3,590,000
Salt segment												
Platte River near Louisville (06805500)	Eng-Han	0	856,000	6,620,000	4,250,000	900,000	106,000	14,100	1,657	590	12,740,000	12,740,000
	Yang	0	221,000	1,350,000	1,370,000	729,000	263,000	1,970	400	30	3,940,000	3,940,000

[1]Because of an absence of a streamgage in this segment, the hydraulic geometry of this segment was represented by a streamgage present in the Shell segment.

Table 13. Summary of bed-material balance in segments of the lower Platte River, Nebraska, 1970-2011, for grain sizes larger than 0.0625 millimeters.

[Values shown may have slight inequities when compared with values reported in other tables because of rounding. All numerical values shown in thousands of tons per year; Pred., predicted; Cond., condition; uncert., uncertainty; Eng-Han., estimate of total sand bed-material sediment load made using Engelund-Hansen (1967) dimensionless equation; Yang, estimate of total sand bed-material sediment load made using Yang (1973) dimensionless equation; (+/-), plus or minus sensitivity or statistical uncertainty of estimate not centered; ±, plus or minus sensitivity or statistical uncertainty centered; acc., accretion, defined as net depostion of sediment by creation of riverbanks or islands; erosion, defined as net evacuation of sediments from riverbanks or islands; deg., degradation, defined as net evacuation of sediment from the riverbed resulting in bed lowering; indet., indeterminate condition, defined when no difference in magnitude between channel sediment inputs and outputs, or bank erosion and accretion, can be concluded when the uncertainty of the estimates is considered.]

	Segment inputs		Segment changes in bank storage			Segment outputs	Predicted channel storage cond.	
Prediction equation	Upstream sand input[1]	Tributary sand input[1]	Bank erosion[2]	Bank accretion[3]	Pred. bank adjust. cond.[4]	Output - sand transport capacity[1]	Mean predicted channel cond.[5]	Mean + uncert. cond.[6]
Loup segment								
Eng.-Han.	1,980 (+/-) 660 / 520	2,080 (+/-) 170 / 100	170 ± 10	250 ± 40	acc.	6,410 (+/-) 2,100 / 1,510	deg.	deg.
Yang	920 (+/-) 150 / 140	1,850 (+/-) 110 / 40	170 ± 10	250 ± 40	acc.	2,960 (+/-) 630 / 390	deg.	deg.
Shell segment								
Eng.-Han.	6,410 (+/-) 2,100 / 1,510	290 (+/-) 40 / 30	270 ± 10	220 ± 30	erosion	6,980 (+/-) 5,040 / 4,220	deg.	indet.
Yang	2,960 (+/-) 630 / 390	60 ± 10	270 ± 10	220 ± 30	erosion	3,220 (+/-) 1,490 / 1,410	deg.	indet.
Elkhorn segment								
Eng.-Han.	6,980 (+/-) 5,050 / 4,220	6,370 (+/-) 3,020 / 2,680	30 ± 1	30 ± 4	indet.	9,920 (+/-) 2,790 / 1,960	agg.	indet.
Yang	3,220 (+/-) 1,490 / 1,410	1,690 (+/-) 660 / 500	30 ± 1	30 ± 4	indet.	3,590 (+/-) 600 / 350	agg.	indet.
Salt segment								
Eng.-Han.	9,920 (+/-) 2,790 / 1,960	370 ± 260	180 ± 6	180 ± 30	indet.	12,740 (+/-) 3,540 / 2,460	deg.	indet.
Yang	3,590 (+/-) 600 / 350	90 ± 30	180 ± 6	180 ± 30	indet.	3,940 (+/-) 540 / 570	deg.	indet.

[1] Uncertainty of estimate shown is the sensitivity analysis range of estimated sediment transport rates predicted for finest and coarsest sampled grain-size distributions within segment, and not a statistical uncertainty.

[2] Uncertainty of estimate shown is the 95-percent confidence interval of mean bank height for segment, estimated using the calculated standard error of mean from the largest sample size of bank heights, collected in the Salt segment.

[3] Uncertainty of estimate shown is the 95-percent confidence interval of estimated mean accreted bank height for segment, estimated using the calculated standard error of the mean for coarse fraction of bank height (Schaepe and Alexander, 2011).

[4] If the estimated magnitude of a bank-adjustment process (erosion or accretion) is not included within the uncertainty bounds of the opposite process, an adjustment condition is predicted, otherwise, an indeterminate condition is reported.

[5] Condition predicted by simple differencing between segment sediment output capacity and mean sediment inputs plus the balance of changes in bank storage. If the condition of segment changes in bank storage is deemed "indeterminate," bank storage is not included in the calculation of mean predicted channel-adjustment condition.

[6] If the estimated magnitude of sand-bed material sediment output is not within the uncertainty bounds of sand-bed material sediment inputs, a channel-adjustment condition is predicted, otherwise, an indeterminate condition is reported.

Table 14. Summary of test sediment balance computed for segments of the lower Platte River, Nebraska, 1970-2011, using the U.S. Army Corps of Engineers Sediment Impact Analysis Methods tool.

[Slight inequities in accounting may be shown because of automatic rounding in computed output; tons/yr, tons per year; Engelund-Hansen, estimate of annual bed-material sediment discharge made using Engelund-Hansen (1967) dimensionless equation; Yang, estimate of annual bed-material sediment discharge made using Yang (1973) dimensionless equation]

Sediment transport prediction equation	Local sediment supply[1] (tons/yr)	Reach transport capacity (tons/yr)	Bed sediment supply[2] (tons/yr)	Washload supply[3] (tons/yr)	Sum local supplies (tons/yr)	Reach sediment balance (tons/yr)
Loup segment						
Engelund-Hansen	4,240,000	26,700,000	4,030,000	211,000	4,240,000	-22,600,000
Yang	3,070,000	13,400,000	2,740,000	333,000	3,070,000	-10,700,000
Shell segment						
Engelund-Hansen	2,710,000	26,500,000	27,000,000	2,560,000	6,950,000	542,000
Yang	933,000	13,500,000	13,400,000	1,240,000	4,010,000	-87,600
Elkhorn segment						
Engelund-Hansen	7,070,000	11,400,000	32,900,000	3,260,000	14,000,000	21,400,000
Yang	2,120,000	6,710,000	15,200,000	1,670,000	6,120,000	8,510,000
Salt segment						
Engelund-Hansen	2,650,000	20,400,000	11,800,000	5,560,000	16,700,000	-8,580,000
Yang	1,010,000	12,900,000	6,780,000	2,600,000	7,130,000	-6,110,000

[1] Local supplies are within-reach tributary and bank-erosion contributions. Tributary contributions were estimated independently using the same prediction equations as those shown for the SIAM analysis.

[2] Includes part of local supplies that are coarser than muds, plus upstream bed-material contributions.

[3] Supplies of sediment from tributaries, bank erosion, and upstream that are finer than 0.0625 millimeters.