UNITED STATES ARMY CORPS OF ENGINEERS

Missouri River Commercial Dredging Draft EIS

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Appendix A
Geomorphic Analyses
Technical Details

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Abbreviations & Acronyms

ADCP	Acoustic Doppler current profiler
AMLE	Adjusted Maximum Likelihood Estimation
BSNP	Missouri River Bank Stabilization and Navigation Project
cfs	cubic feet per second
CRP	Construction Reference Plane
D_{10}	the particle size where 10 percent of the sediment is finer than the D_{10} particle size
EIS	environmental impact statement
LOADEST	Load Estimator
HBED	Hydroacoustic Bed Elevation Data
LOMR	lower Missouri River
MEP	modified Einstein procedure
mg/l	milligrams per liter
mm	millimeters
RM	river mile
Ro	Rouse number
SEMEP	Series Expansion of the Modified Einstein Procedure
SEP	standard error of prediction
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

A.1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) has received permit applications from eight companies to dredge sand and gravel from selected locations between river mile (RM) 0.0 and RM 447.7 on the lower Missouri River (LOMR) for commercial uses. As part of its review of the permit applications, the USACE is preparing an environmental impact statement (EIS). The EIS examines the potential environmental impacts of the proposed dredging activities and any related actions.

The USACE has previously found that the river bed has lowered along significant portions of the LOMR because of river bed degradation, a geomorphic process (USACE 2009). Among the important secondary impacts of river bed degradation are effects on infrastructure and flood control structures on the LOMR.

This appendix describes the data sources and methods used to analyze potential impacts of dredging on river bed degradation. This includes the analysis performed to estimate bed material load as a component of the sediment budget, the analysis of hydroacoustic bed elevation data, and an analysis to determine whether segments at three gage locations were in equilibrium. The data and details in this appendix support the geomorphic descriptions and analyses in Sections 3.4 and 4.2 of the Draft EIS.

The bed material load is composed of sediment very similar in size to the sediment removed from the LOMR by commercial dredging. Bed material load is composed of sediment from the river bed that moves along the river bed as bed load and in the water column as suspended sediment. The portion of the bed material load transported as bed load versus the amount transported in suspension depends primarily on the velocity of the water flowing in the river. Because the bed material load is composed of the same material as the river bed, understanding this aspect of the sediment budget is key to understanding why some segments of the river are degrading and others are aggrading.

Because of its particle size, some portion of the suspended sediment is always transported in suspension (the wash load) versus being transported as part of the bed material load. Determining the boundary between when particles will be transported solely as wash load and when they will be transported as part of the bed material load is an important factor in the sediment budget analysis (see Figure A-1 and Section A.2 below for details). As discussed below, the majority of the Missouri River's sediment supply is clay and silt-size wash load that is transported in continuous suspension and is not available as a sediment supply for maintaining the river bed or for removal by dredging.

The amount of sediment moving as bed load is difficult to measure. Little bed load data are available for the LOMR, although it is known that migrating dunes on the river bed transport a significant amount of sediment (Gaeuman and Jacobson 2007). In the absence of adequate data regarding bed load transport, equations based on flow, channel geometry, and other variables are typically used to estimate bed material load.

More data are available regarding suspended sediment. U.S. Geological Survey (USGS) gages at Nebraska City (RM 562.6), St. Joseph (RM 448.2), Kansas City (RM 366.1), and Hermann (RM 97.9) have recorded suspended sediment data since the 1940s. The most up-to-date data from the USGS (unpublished) were used to estimate bed material loads in this analysis.

One previous study includes bed material load estimates on the LOMR. It was prepared in 1999 as part of a USACE dredging project to build the L-385 levee (West Consultants 1999). It used methods similar to this analysis and yielded similar results for a reach of the river between St. Joseph and Kansas City (see Section A.5.2).

A.1.1 Organization of the Appendix

This appendix is divided into the following sections:

- Particle Size – Section A.2 analyzes particle sizes in the river bed and in suspension to determine how sediment of different sizes moves in the LOMR system. The delineation between sediment that occurs only in suspension (wash load) versus sediment that interacts with the bed (bed material load) is important for estimating bed material loads.
- Sediment Loads – Section A.3 reviews the available sediment load data. Most of the available data are for suspended sediment, which is composed of wash load and a portion of the bed material load. The amount of bed material in suspension is used by some bed material load equations to estimate the total bed material load.
- Bed Material Load Estimates – Section A.4 describes the hydraulic models developed at locations with suspended sediment data in order to estimate the total bed material load. Data from the hydraulic models were used in the bed material load equations at four USGS gage locations. The four locations were selected based on available data.
- Estimates of Accuracy and Comparison with Other Studies – Section A.5 places the results of the bed material load estimates in context with flows and watershed characteristics on the LOMR. The

results of the estimates are compared with results from previous studies and measured suspended sediment data.

- Results Compared to Flows and Drainage Area – Section A.6 compares the bed material load estimates generated from this study with reported results from other studies.
- Analysis of Bed Elevation Change Using Hydroacoustic Data – Section A.7 describes the methods used to analyze USACE hydroacoustic data collected throughout the LMOR in 1998, 2007, 2008, and 2009 to detect trends in river bed elevation change.
- Equilibrium Slope Analysis – Section A.8 describes the analysis performed to estimate whether the channel slope and dimensions at the St. Joseph, Kansas City, and Hermann gages are close to equilibrium conditions with regard to sediment supply.

A.2 PARTICLE SIZES OF MATERIAL IN THE RIVER BED AND SUSPENDED IN THE WATER COLUMN

Determining the dominant particle size fraction in the river bed and in the sediment suspended in the water column was necessary for a comparison with the size fraction removed by commercial dredging. Delineating the distribution of river bed sediment sizes is also important for determining how sediment is transported in the river, either along the river bed as bed load or in suspension as suspended sediment.

The Wentworth particle size scale defines particle sizes smaller than 0.063 millimeters (mm) as silt or clay, particles sizes between 0.063 and 2.0 mm as sand, and particle sizes from 2 to 64 mm as gravel (Figure A-1). Figure A-1 shows the relationship between particle size and its: (1) transport mechanism and (2) source.

In general, clay, silt, and fine sand particles are transported in suspension in the Missouri River's water column. Turbulent eddies keep these particles suspended in the flow, allowing minimal interaction with the active channel bed. Deposition of the suspended load primarily occurs in low-velocity zones typical of backwater areas and on floodplains. The source of sediment transported in suspension is largely wash load that predominantly consists of sediment derived from sources other than the bed, such as channel bank erosion and runoff from contributing hill slopes. The upper limit of wash load particle size, or "D_{10}" of the bed sediment, has been defined as that grain size where 10 percent of the bed material (bed substrate) mixture is finer (Einstein 1950). Although the exact value can vary at different locations on the river, the emphasis is that wash load particle sizes are rarely found in the bed material. The volume of wash load transported in the river is principally limited by the supply of material, not the transport capacity related to the river's available energy. Because wash load is transported in suspension at nearly the same velocity as the river's flow, it can be transported through the system during one runoff event. Importantly, increases or decreases in wash load rarely result in significant morphological responses or appreciable changes in channel stability (Biedenharn et al. 2006).

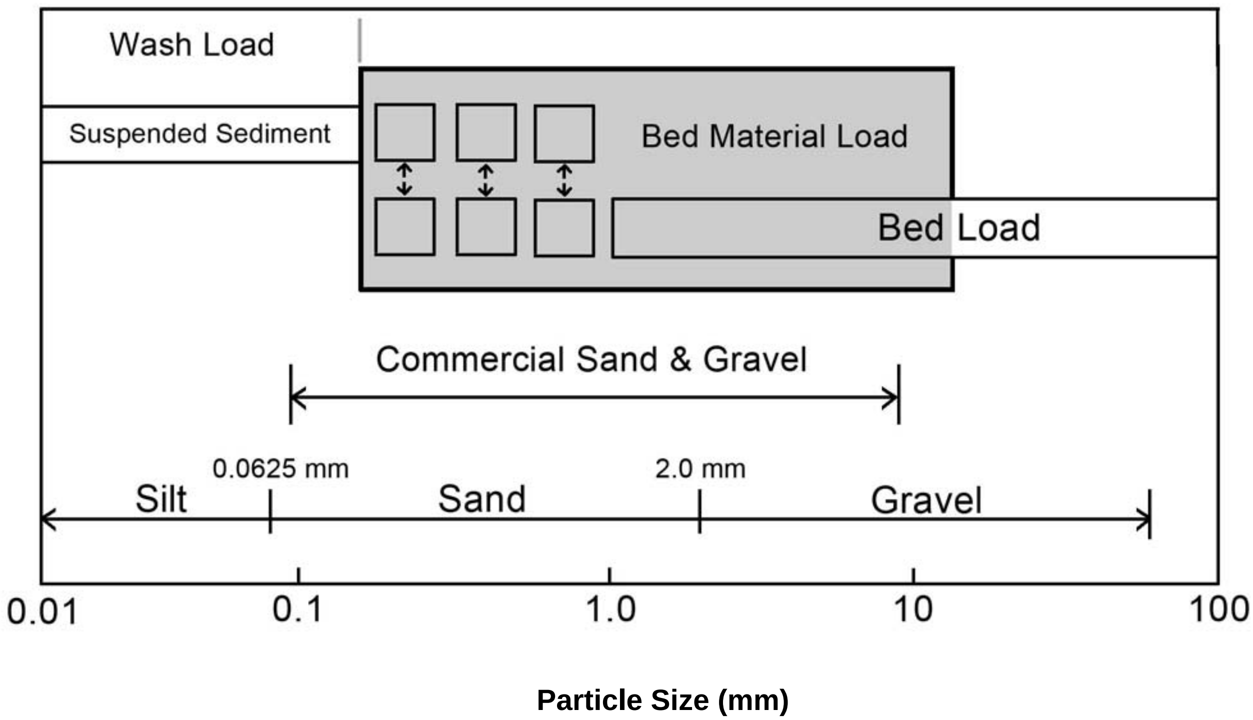

Figure A-1 Illustration of Diffuse Boundaries Defining Sediment Transport Mechanism (Bed Load or Suspended Load) and Sediment Source (Bed Material Load or Wash Load)

In general, medium to coarse sand and gravel particles are transported as bed load in migrating dunes on the Missouri River. Bed load consists of particles moving along or near the bed by rolling, sliding, or saltating (hopping) depending on flow strength and random flow turbulence. The source of bed load is scour of the bed material; thus, the same particle sizes moving as bed load compose the vast majority of the particle sizes in the bed substrate. Unlike wash load, the river's capacity to transport particles as bed load is limited by the amount of energy available to move the sediment. Because bed load particles are constantly interacting with the channel bed, changes in bed load transport rates directly influence channel morphology and channel stability. An imbalance of the river's capacity to transport sediment with its bed material supply results in morphologic change. If the energy available to transport bed material exceeds the sediment supply, the river will scour the bed; conversely, if the energy for transport is less than the sediment supply, sediment will deposit on the bed.

Bed material load refers to sediment derived from the bed material (bed substrate). Bed material can be transported as bed load or as suspended load depending upon particle size and flow strength. The sum of the bed material load and wash load is termed the “total sediment load.”

The arrows in Figure A-1 indicate that the boundaries between suspended load and bed load transport mechanisms are diffuse and are related to flow strength. At low to moderate flows, turbulent eddies may not have sufficient energy to transport fine and medium sand particles in suspension; consequently, the sand is transported as bed load. As flow strength increases with higher flow, turbulent eddies will bring the sand from the bed up into suspension in the water column.

Determining the boundary between when particles will be transported predominantly in suspension versus as bed load is a key factor in the sediment supply analysis. As discussed below, the majority of the Missouri River’s total sediment supply is clay and silt-size wash load that is largely transported in continuous suspension, with little importance to channel stability. To quantify the percentage of the total sediment load that is bed material load, and thus important to channel morphology and stability, it is necessary to determine more specific boundaries between wash load and bed material load. To accomplish this task, Rouse number (*Ro*) calculations were performed at four locations on the Missouri River. This analysis is presented in Section A.3.3.

When sediment samples are collected and analyzed, a particle size distribution is created by calculating the cumulative percent of the sediment finer than a given grain size (Figures A-2 through A-6 are examples). At certain points on the cumulative scale, the particle size can be significant to geomorphic processes. For example, the D_{10} (which is the particle size where 10 percent of the sediment is finer than the D_{10} particle size) is significant because in large, alluvial rivers it often represents the portion of the sediment that is transported primarily as wash load and has minimal interaction with the river bed (Einstein 1950, Biedenharn et al. 2006). Similarly, the D_{50} refers to the median particle size where 50 percent of the sediment is finer than the D_{50} particle size and indicates the mid-point in the size distribution of particles in a sample.

A.2.1 Measured River Bed Sediment Particle Sizes

Several times a year, the USGS collects and analyzes river bed sediment at the main gage sites on the LOMR, including those at Nebraska City, St. Joseph, Kansas City, and Hermann. Every 4–6 years, the

USACE also samples bed sediment longitudinally every few miles along the LMOR at locations in the left, center, and right of the channel bed. The plots in Figures A-2 through A-6 show the average particle size cumulative frequency curves based on the USGS and USACE bed material sample data. These curves are created by calculating the cumulative percent of the sediment finer than a given grain size. The particle size at certain points on the cumulative scale can be significant to geomorphic processes. As noted, the D_{10} often represents the portion of the sediment that is transported primarily as wash load and has minimal interaction with the river bed; and the D_{50} refers to the median particle size where 50 percent of the sediment is finer than the D_{50} particle size, indicating the mid-point in the size distribution of particles in a sample. These gradations are representative of the typical bed sediment sizes at three gage locations on the LOMR, and one site above the Project area at Nebraska City (see Table 3.4-14 in the main volumes).

Detailed results of all the USGS bed sediment samples from 2001 to 2009 and the most recent 2004 USACE results are plotted for the Nebraska City, St. Joseph, Kansas City, and Hermann gages in Figures A-2 through A-5. Table A-1 lists the standard deviations of each particle size class used to create the average gradation in Figures A-2 through A-5. These figures show the size distribution of bed sediment for each year the USGS sampled as colored lines, and the thick black line represents the average of the USGS measurements. The red and green lines show the USACE measurements for locations near the USGS gage sites, except for the Nebraska City gage for which USACE data are not available. The curves are different shapes for the USGS and USACE data because different sieve sizes were used to determine the particle size distribution. The maximum particle size for the USGS data for the St. Joseph, Kansas City, and Hermann gages is 2 mm. The plots show that the particle size gradations for the USGS and USACE data are similar. Figure A-6 shows representative bed material particle size gradations used in the sediment transport modeling compared to Missouri State Concrete Sand minimum (blue line) and maximum (red line) specification gradations. These curves represent the target particle sizes dredged from the river bed for use in concrete sand.

Table A-1 Standard Deviations of the "Percent Finer Than" Values for the Particle Size Classes Used To Estimate the Average Gradation in Bed Material Cumulative Frequency Curves in Figures A-2 through A-5 (%)

	Location			
Particle Size	Nebraska City	St. Joseph	Kansas City	Hermann
0.062 mm (clay/silt)	0.00	0.08	0.42	0.08
0.125 mm (very fine sand)	0.32	0.50	0.81	0.28
0.25 mm (fine sand)	6.05	9.91	11.28	9.63
0.5 mm (medium sand)	13.31	9.70	10.91	15.62
1 mm (coarse sand)	9.93	3.68	7.38	14.81
2 mm (very coarse sand)	5.82	2.62	7.61	10.76

Note: mm = Millimeter(s).

The cumulative frequency curves for the minimum concrete sand specifications are similar to the representative bed sediment gradations, indicating that the river's bed sediment tends to be similar or finer than the minimum sand specification, and that the upper specification for concrete sand is coarser than the typical bed sediment at those locations.

A.2.2 Measured Suspended Sediment Particle Sizes

Measurements of suspended sediment describe the range of sediment sizes transported in the water column. More data are available for suspended sediment loads than for bed load; however, only a portion of the suspended sediment is considered bed material load and is large enough to be dredged for commercial sand and gravel production. This section reviews available data for suspended sediment and suspended sand.

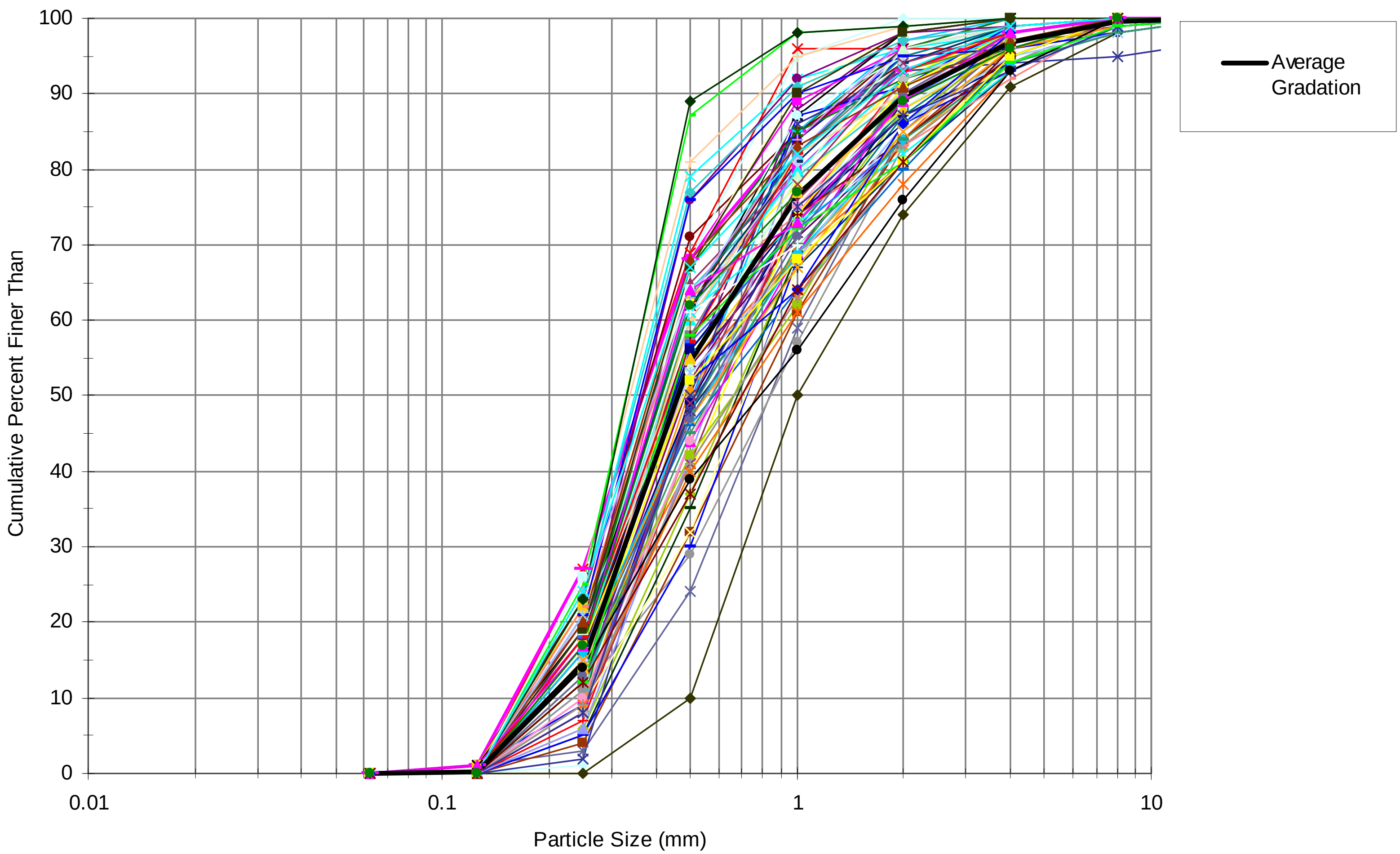

Figure A-2 USGS Bed Material Samples – Nebraska City Gage #06807000 (2001–2009)

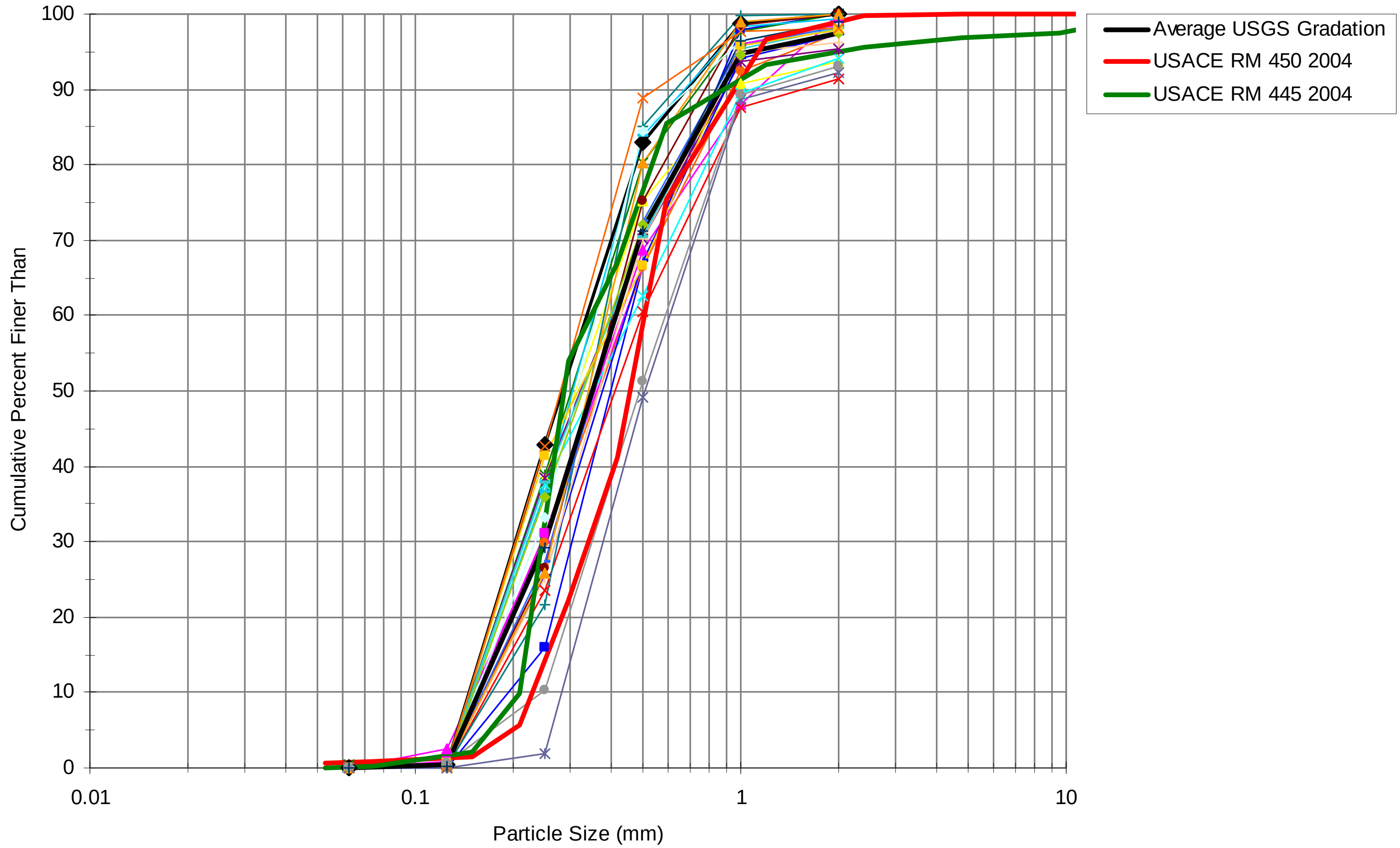

Figure A-3 USGS and USACE Bed Material Samples – St. Joseph Gage #06818000 (2002–2009)

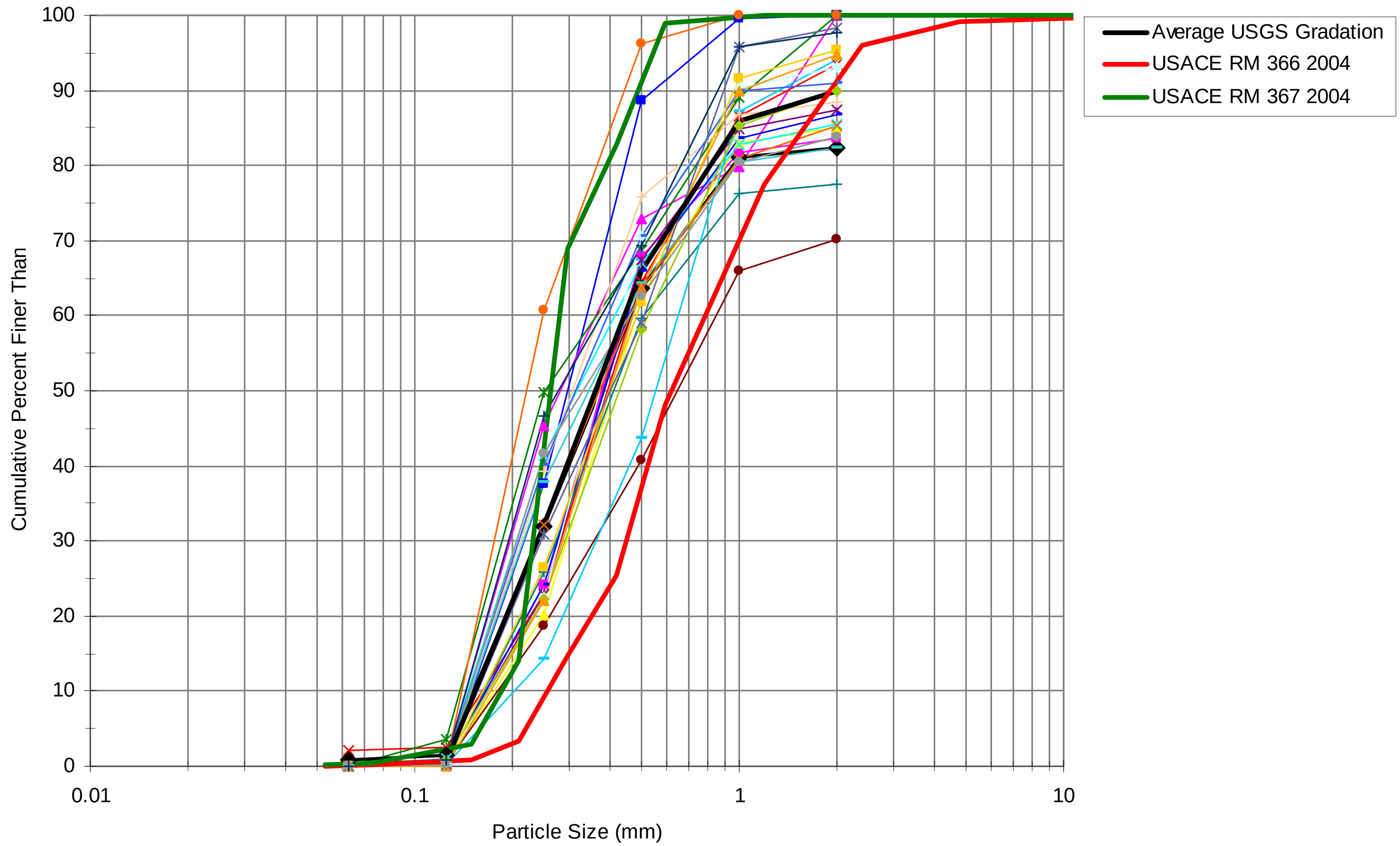

Figure A-4 USGS and USACE Bed Material Samples – Kansas City Gage #06893000 (2002–2009)

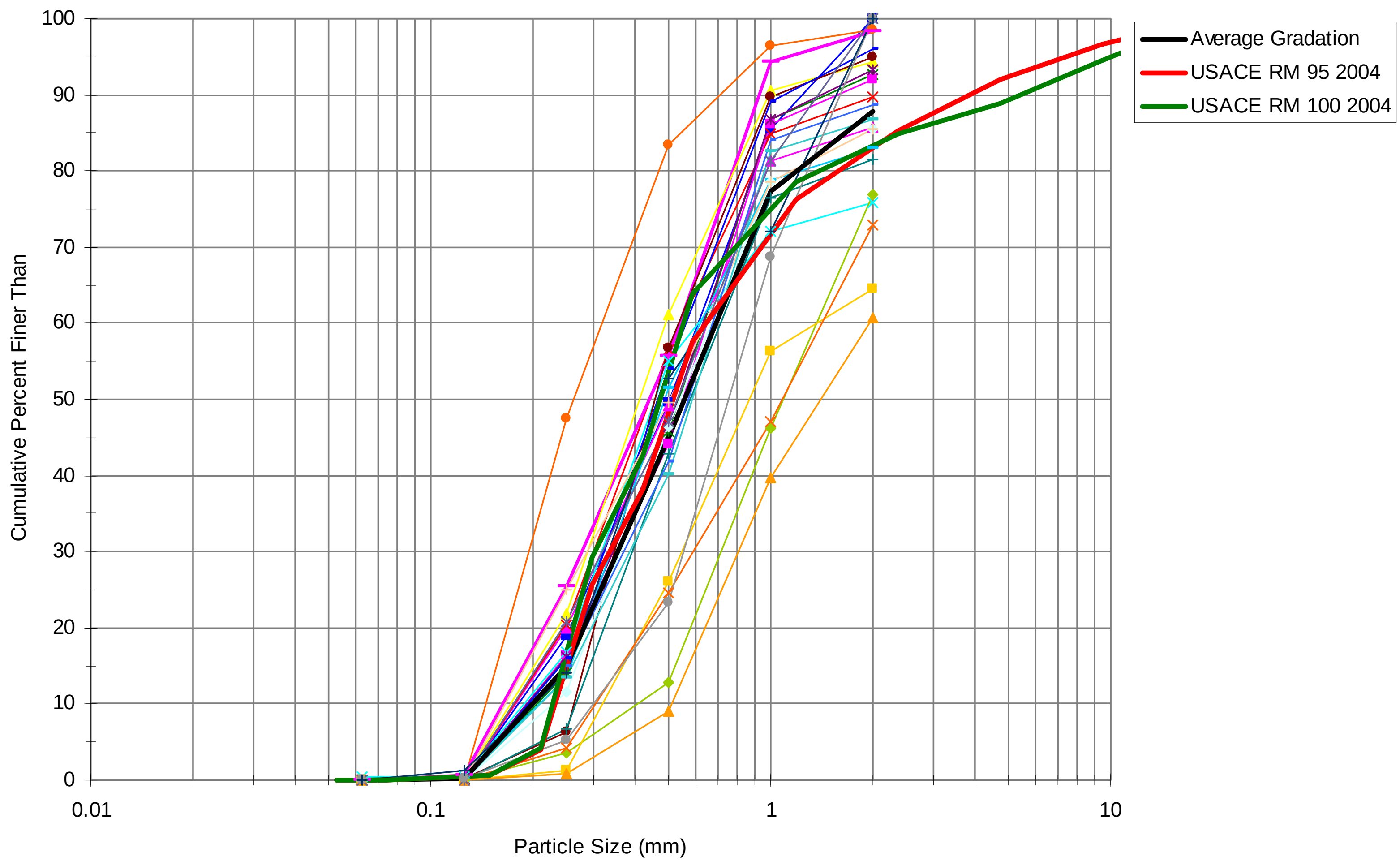

Figure A-5 USGS and USACE Bed Material Samples – Hermann Gage #06934500 (2002–2009)

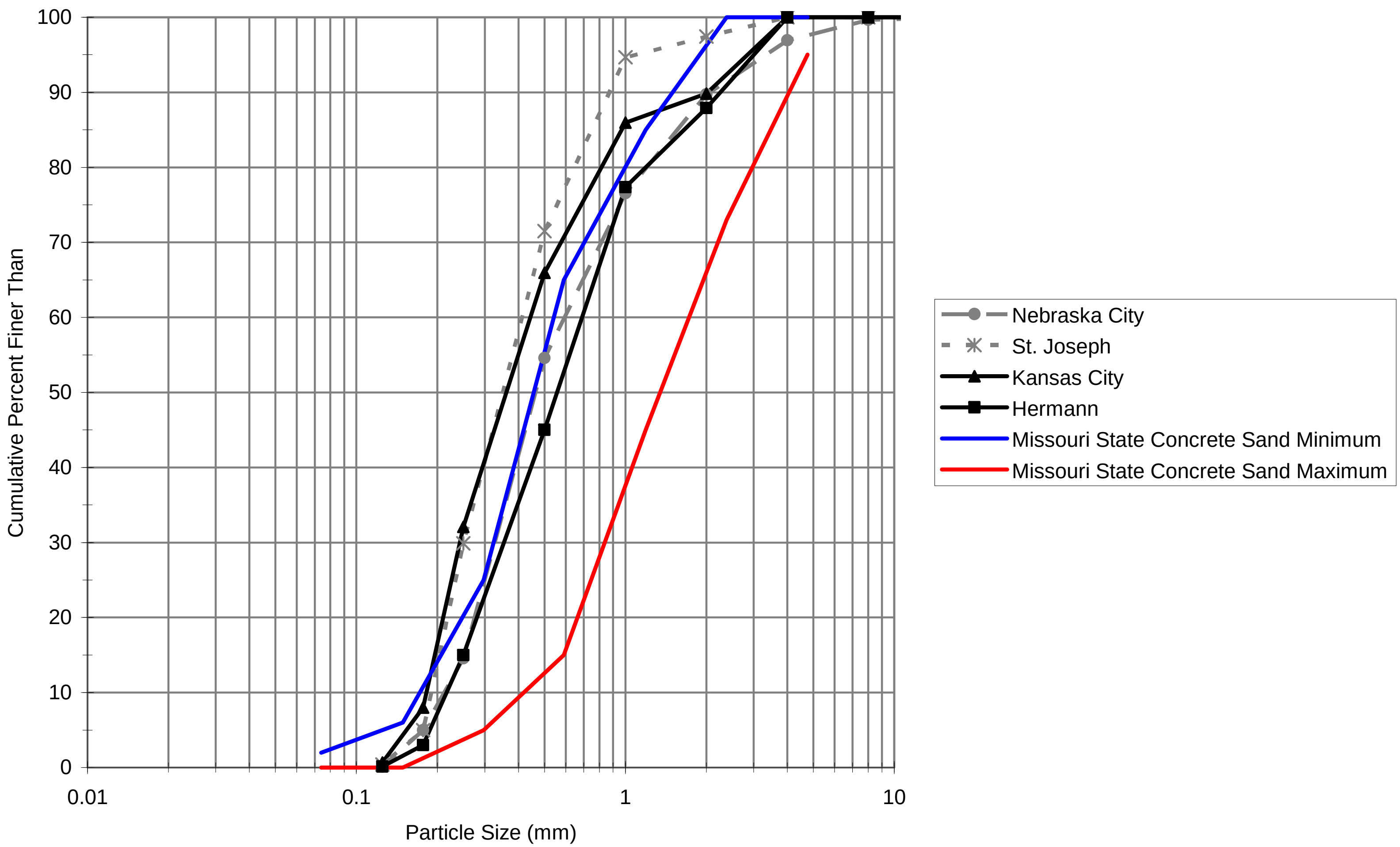

Figure A-6 Representative Bed Material Particle Size Gradations at Missouri River Gaging Sites (2001–2009)

The USGS periodically collects and analyzes the particle sizes of the suspended sediment when measuring suspended sediment loads at gage sites. All of the most recent particle size data (available dating from 1981 to1991 at Nebraska City, from 1994 to 2005 at St. Joseph, from 1994 to 2002 at Kansas City, and from 1994 to 2005 at Hermann) are plotted as cumulative frequency distribution curves in Figures A-7 through A-10. The colored lines in the plot represent each year of data, and the average of all the gradations is plotted as a thick, solid black line. The D_{10} of the river bed is shown on each plot for comparison purposes and indicates that the finest 10 percent of the river bed is coarser than approximately 85–90 percent of the suspended sediment. Table A-2 lists the standard deviations of each particle size class used to create the average gradation in Figures A-7 through A-10.

The average gradations for each location are plotted in Figure A-11 to show the representative particle size cumulative frequency curves for each location. At each gage location, the D_{50} value is finer than the finest particle size analyzed by the USGS, which is the boundary between silt and very fine sand at 0.063 mm. Thus, the median grain diameter for suspended sediment is in the clay/silt fraction.

Table A-2 Standard Deviations of the "Percent Finer Than" Values for the Particle Size Classes in the Suspended Sediment Cumulative Frequency Curves in Figures A-7 through A-10 (%)

	Nebraska City	St. Joseph	Kansas City	Hermann
0.062 mm (clay/silt)	15.8	15.6	16.0	10.7
0.125 mm (very fine sand)	12.8	14.1	15.1	10.3
0.25 mm (fine sand)	3.5	5.2	4.6	4.9
0.5 mm (medium sand)	0.6	1.2	0.6	2.4
1 mm (coarse sand)	0.1	0.2	0.0	1.6
0.062 mm (clay/silt)	15.8	15.6	16.0	10.7

Note: mm = Millimeter(s).

In Figures A-12 through A-15, the percent sand in suspended sediment loads was plotted against river discharge at the time of measurement for the years with available data. The results do not indicate a strong correlation between percent sand content and discharge. The Kansas City plot (Figure A-14) shows that, when flows exceed approximately 85,000 cubic feet per second (cfs), the sand content remains less than 30 percent—suggesting that the supply of sand may be limited relative to transport capacity.

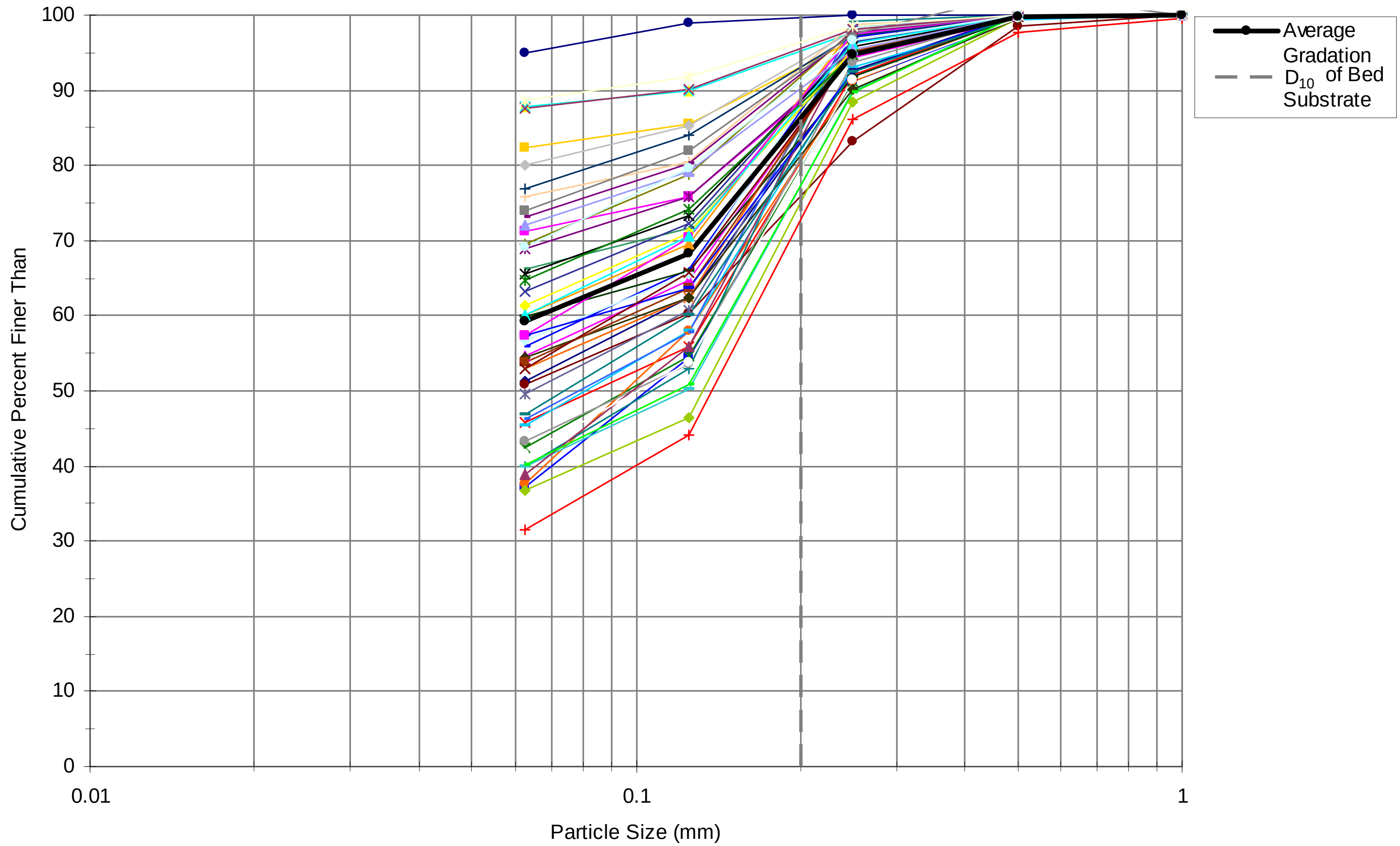

Figure A-7 USGS Total Suspended Sediment Particle Size Gradations – Nebraska City Gage #06807000 (1981–1991)

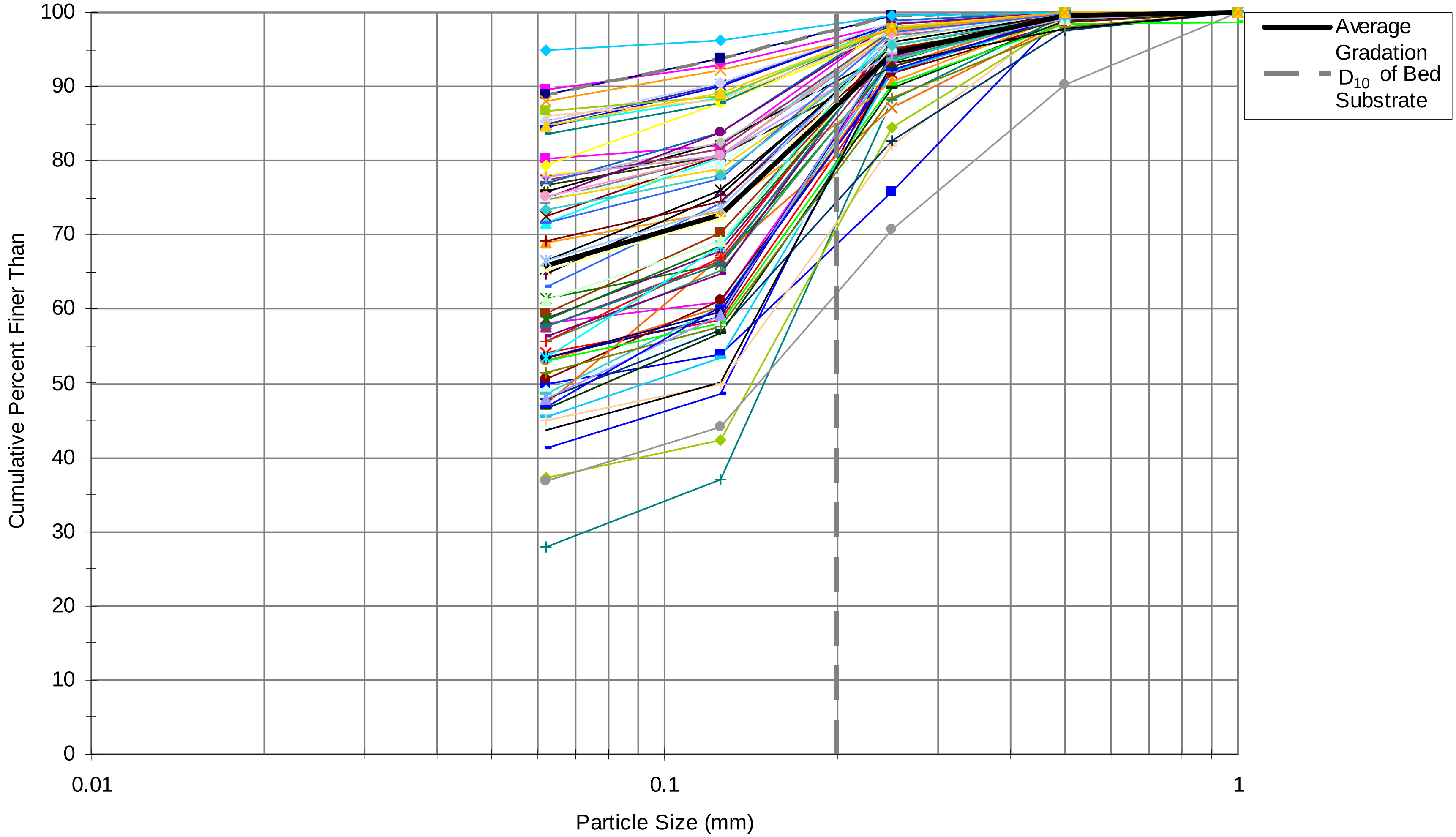

Figure A-8 USGS Total Suspended Sediment Particle Size Gradations – St. Joseph Gage #06818000 (1994–2005)

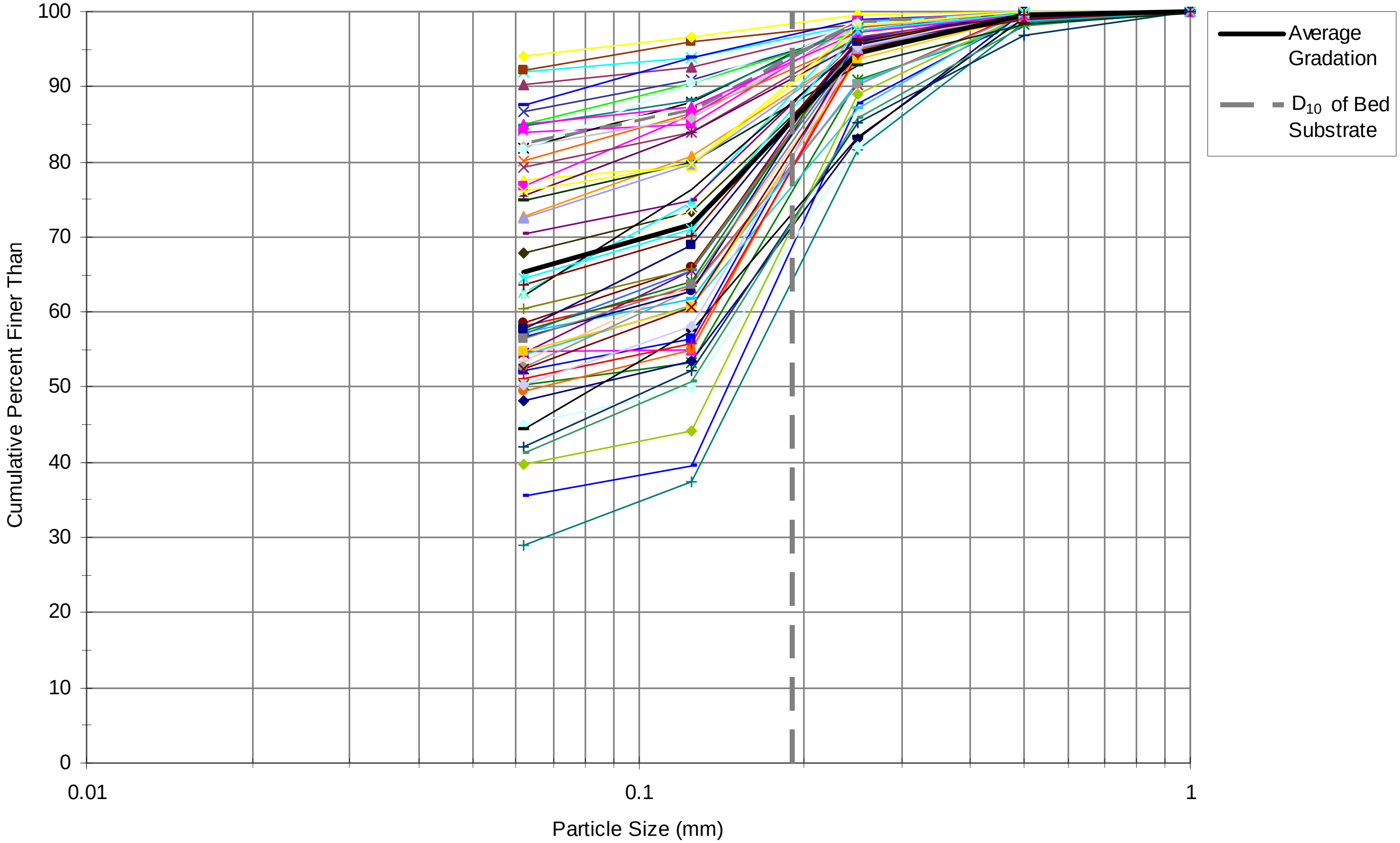

Figure A-9 USGS Total Suspended Sediment Particle Size Gradations – Kansas City Gage #06893000 (1994–2002)

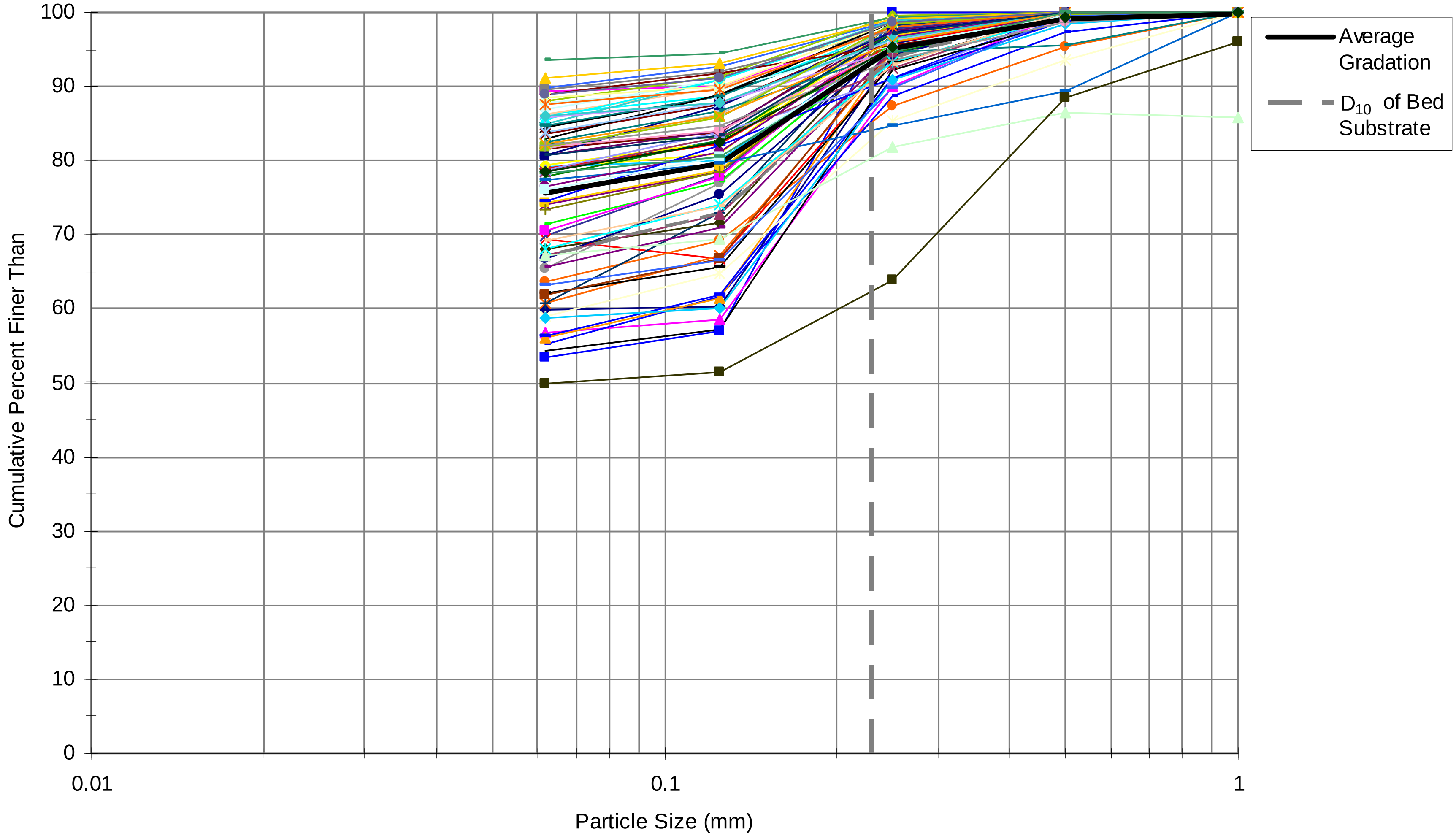

Figure A-10 USGS Total Suspended Sediment Particle Size Gradations – Hermann Gage #069345000 (1994–2005)

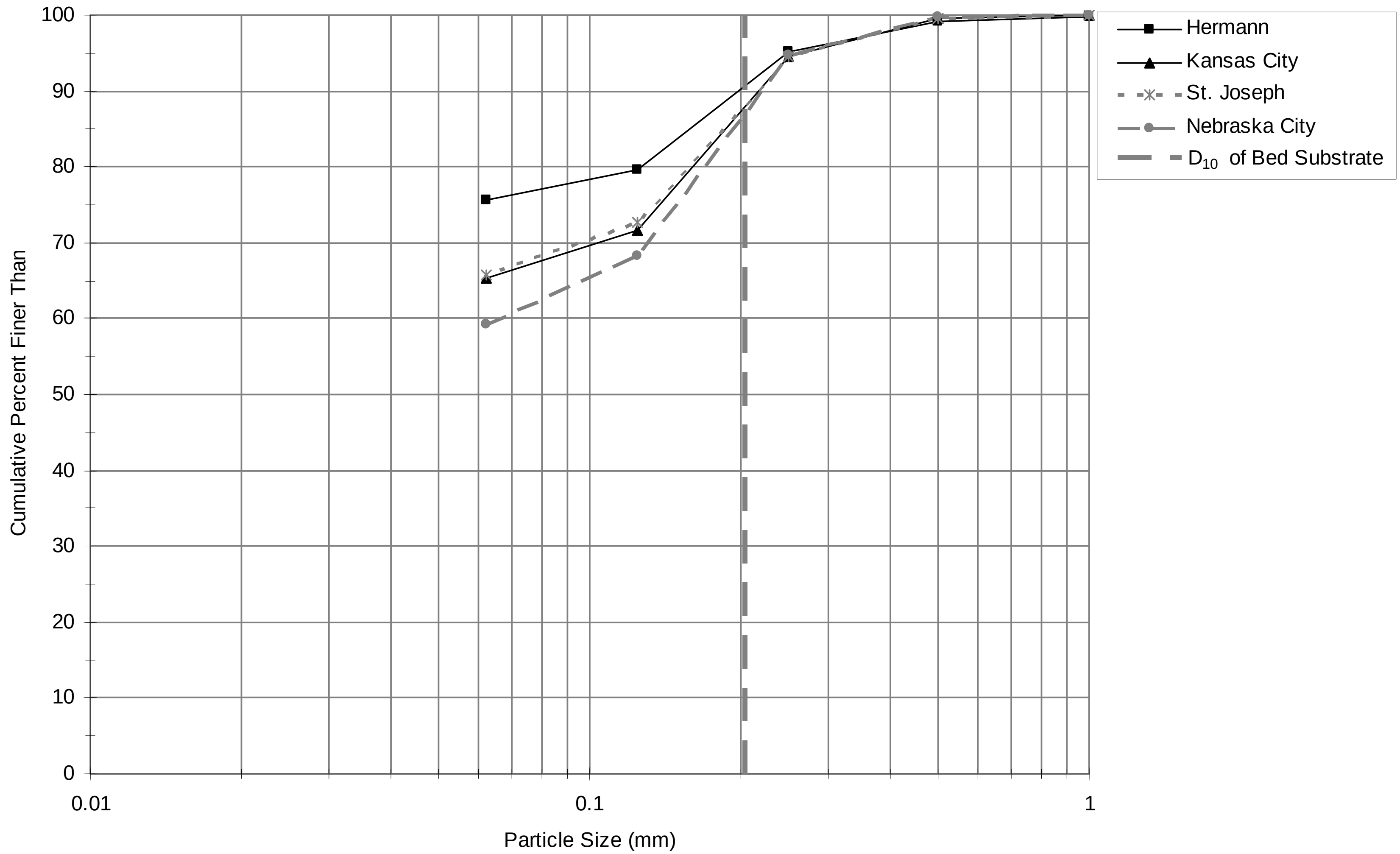

Figure A-11 Representative Total Suspended Sediment Particle Size Gradations at Missouri River Gage Sites

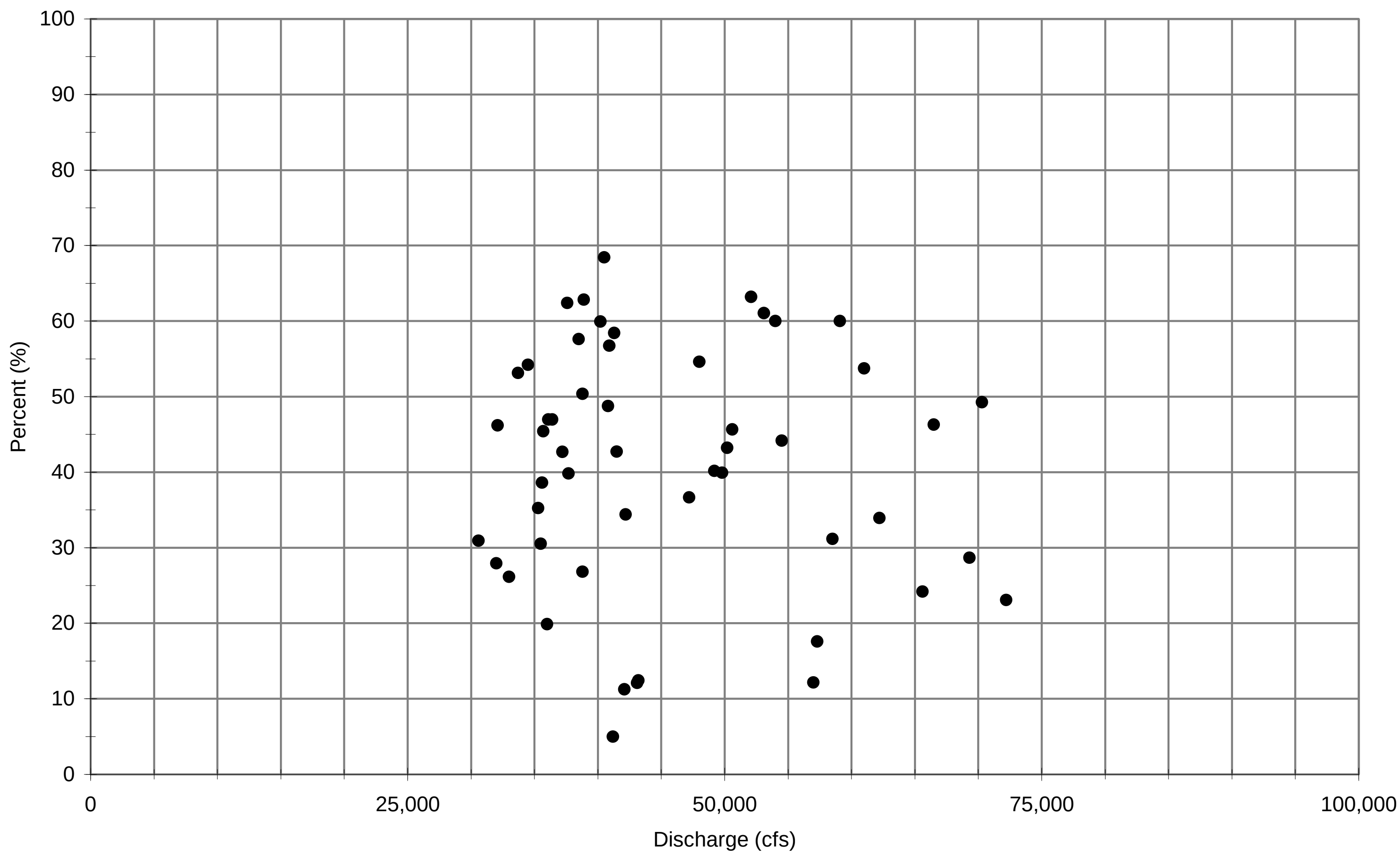

Figure A-12 USGS Total Suspended Sediment Percent Sand Content – Nebraska City Gage #06807000 (1981–1991)

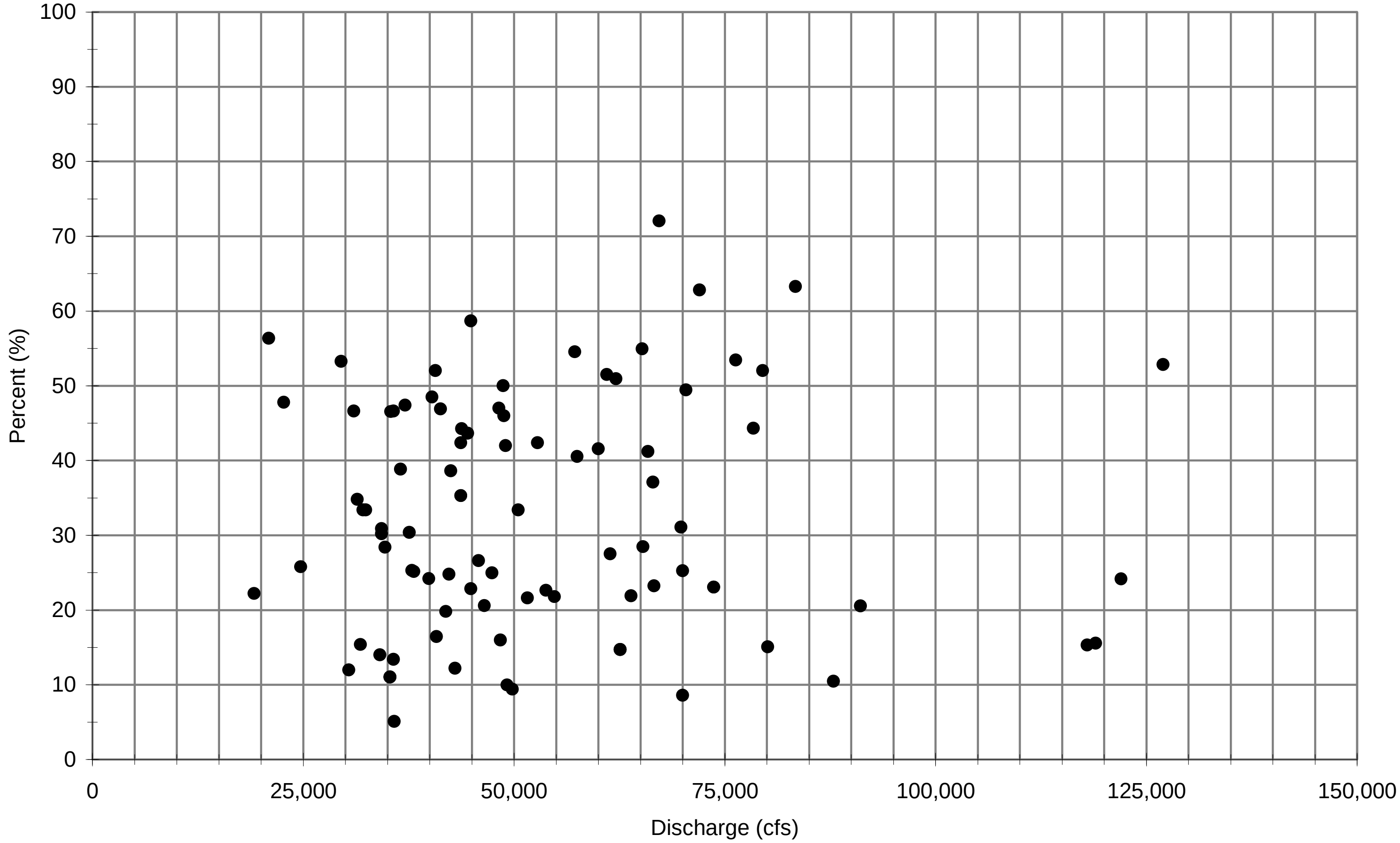

Figure A-13 USGS Total Suspended Sediment Percent Sand Content – St. Joseph Gage #06818000 (1994–2005)

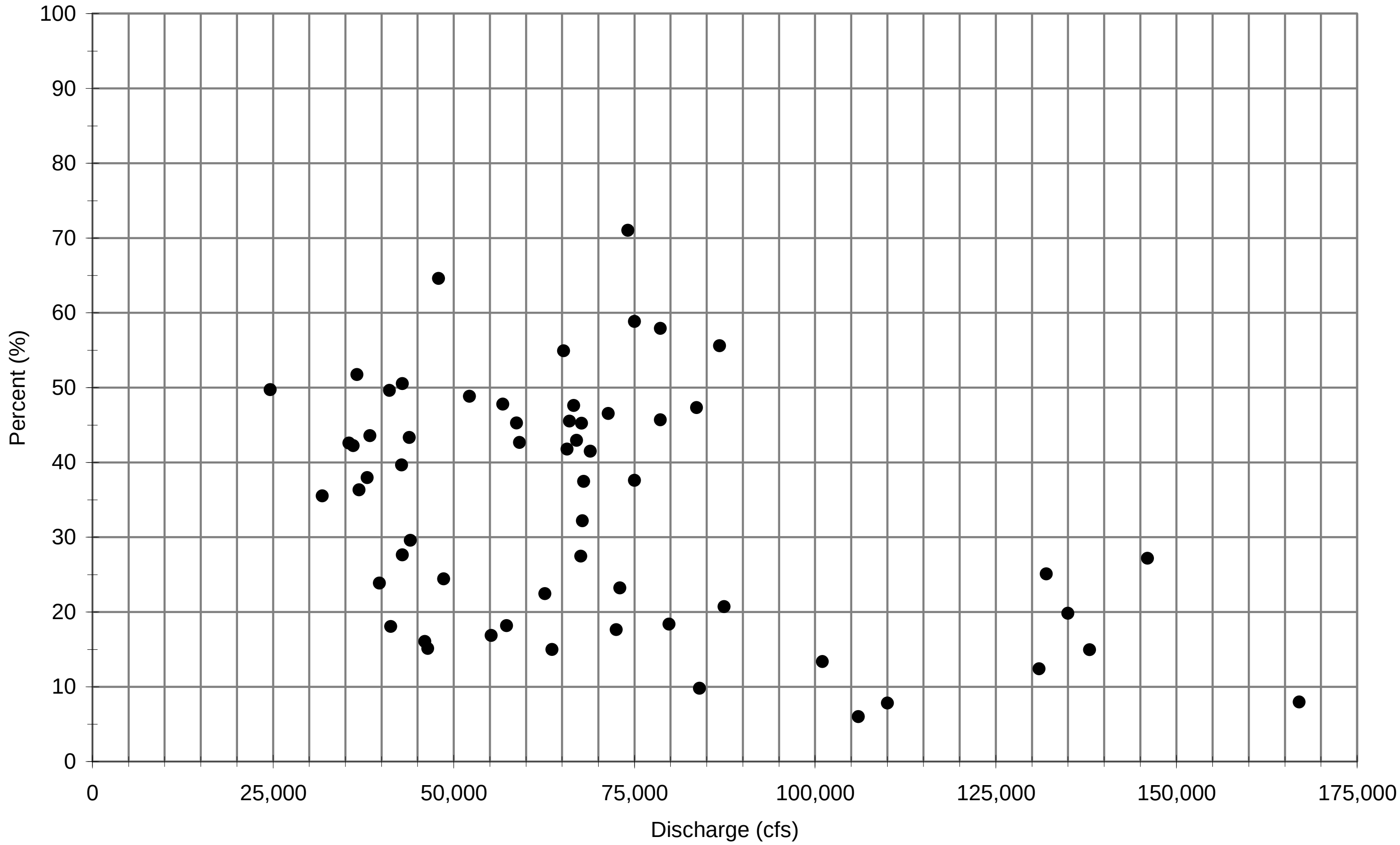

Figure A-14   USGS Total Suspended Sediment Percent Sand Content – Kansas City Gage #06893000 (1994–2002)

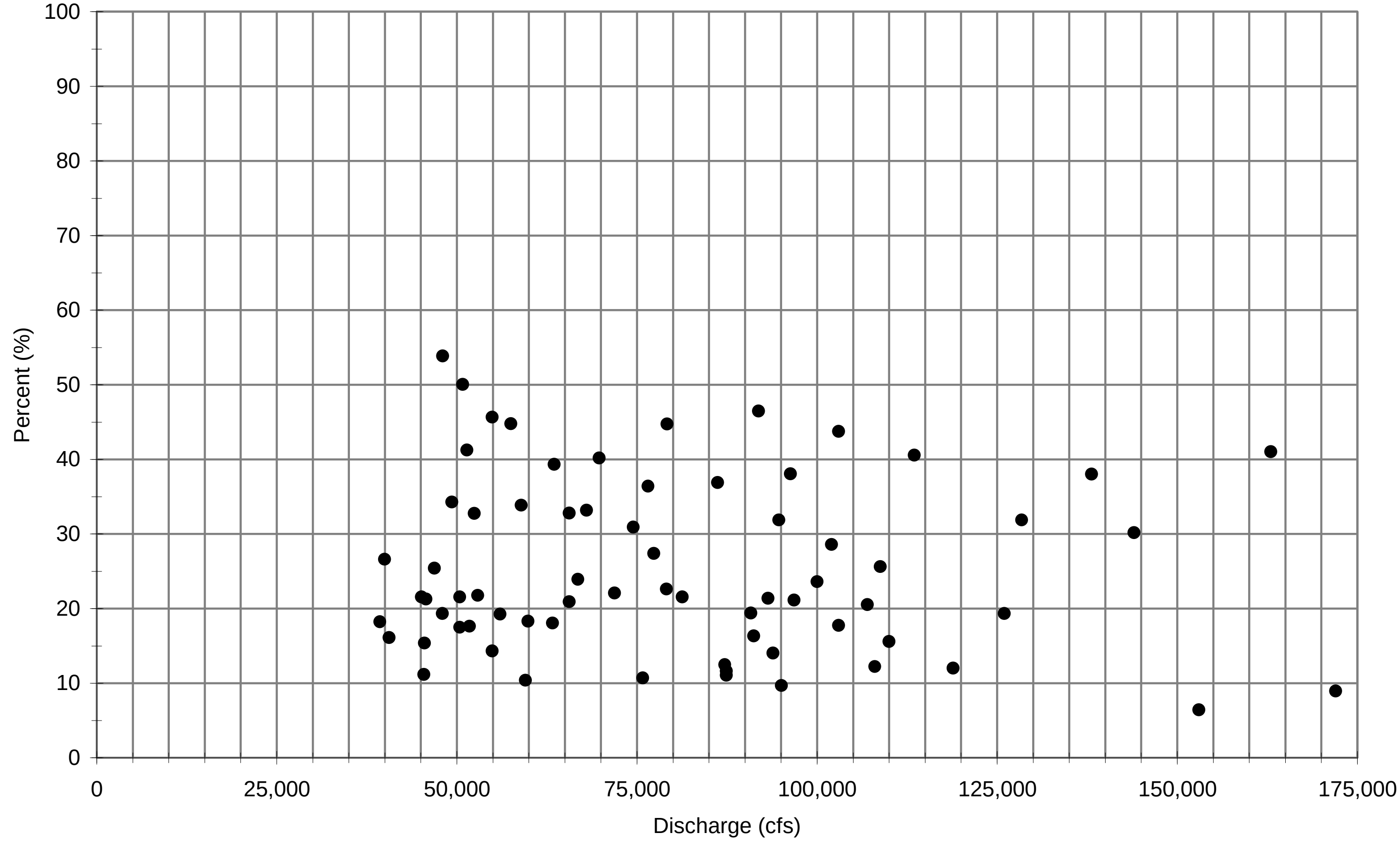

Figure A-15 USGS Total Suspended Sediment Percent Sand Content – Hermann Gage #06934500 (1994–2005)

A.3 SEDIMENT LOADS

A.3.1 Methods of Measuring Suspended Sediment Loads

Measurements of suspended sediment have been collected at various locations on the Missouri River over the past 100 years. Suspended sediment measurements are typically made at channel cross sections by the USGS, at bridges near their gaging stations. A suspended sediment sampler is lowered through the water column to collect either depth-integrated or point samples of suspended sediment. Samples are collected at multiple verticals along the sampling cross section, and then the sample is composited into a cross section average sample. The concentration (typically reported in milligrams per liter [mg/l]) of collected sediment particles is determined, from which a daily suspended sediment load (typically reported in tons of sediment per day) associated with the flow during the time of measurement can be calculated. Because of the configuration of the sampler, it cannot be lowered completely to the bed (see Figure A-16). Consequently, a small portion (typically less than 0.5 foot) of the flow depth is not sampled, creating an “unsampled zone.” On the Missouri River, the unsampled zone is typically only 1–3 percent of the total flow depth, depending on flow. Because the concentration of transported sediment is typically greatest near the river bed, however, the amount of sediment in transport in the unsampled zone can be high relative to the size of the unsampled zone. In particular, the coarser fraction of the bed material load that is transported along or near the bed may not be captured by the suspended sediment sampler.

Bed load sampling on large rivers such as the Missouri is difficult with a traditional bed load sampler, such as a Helley-Smith model. Because the bottom of the channel cannot be seen and the river bed elevation is constantly changing due to sand dune migration, high inaccuracies can be associated with Helley-Smith or similar-type bed load sampling. Thus, only a few measurements of the bed load component of the total sediment load have been made. Rather than measuring the bed load, it is more common on the Missouri River to use numerical techniques that relate the particle sizes composing the bed substrate and the hydraulic energy of the river’s flow to calculate the amount of bed material transported in the unmeasured and measured sediment sampling zones.

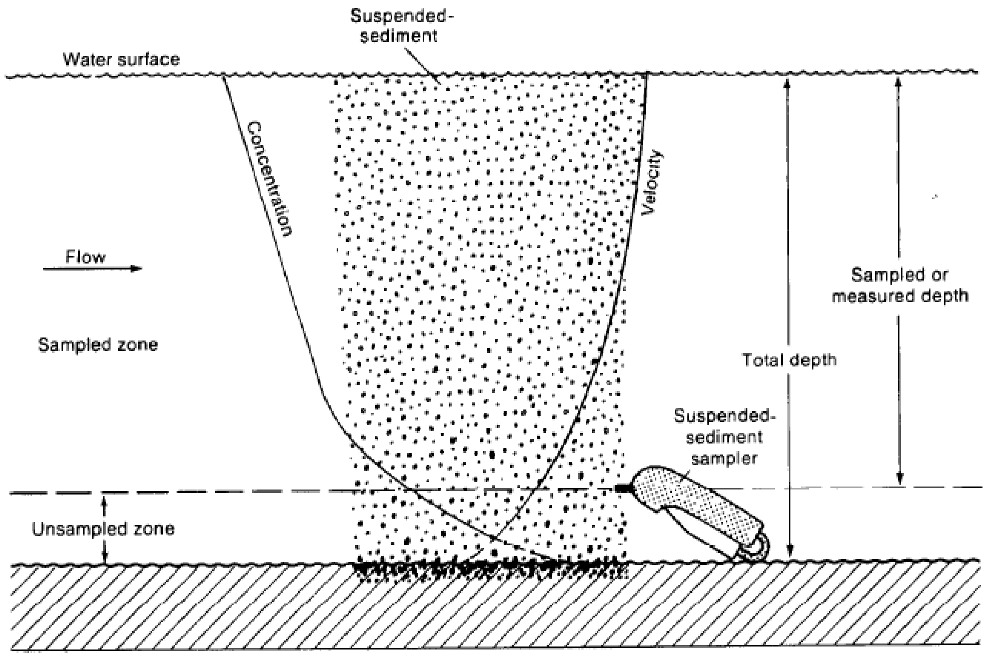

Figure A-16 Measured and Unmeasured Suspended Sediment Sampling Zones

Source: Edwards and Glysson 1999.

A.3.2 Existing Measurements of Suspended Sediment

The USGS is currently working with the USACE to compile, analyze, and calculate total suspended sediment and suspended sand loads using all available measured data on the LOMR and its major tributaries (USGS 2009). The USGS is compiling all known measurements of suspended sediment, including measurements by the USACE and the USGS and other measurements reported in concentrations and daily loads. The effort also includes compilation of all information on bed material and suspended sediment particle size gradations. The compiled data are being examined for inconsistencies and are being converted from point-sample data to depth-integrated data using flow velocities. This study is a major contribution to the record of measured suspended sediment and to understanding sediment loading on the LOMR.

Using these data, the USGS has calculated annual total suspended sediment and suspended sand loads at the St. Joseph, Kansas City, and Hermann gage locations. Calculations were made only at these locations because they were the only gages on the LOMR with sufficient measurement records. Because sediment is not measured every day of the year, the USGS used the measured data to estimate the sediment load for the days when sediment was not measured. The USGS used the USGS-developed LOADEST (Load Estimator) software (Runkel et al. 2004) for these estimates. LOADEST is a program commonly used to estimate annual loads from measured concentrations. To calculate annual loads, the USGS first used LOADEST to calculate a sediment rating curve of sediment load against discharge using all measured sediment concentration values and corresponding discharges in a specific year. The rating curve was used to estimate the sediment load for each mean daily discharge for the year. Summation of the estimated loads for each mean daily discharge in the year produced an annual load. A 3-year moving average then was used to calculate the annual load for the given year. For example, to determine the annual load for year 2004, sediment rating curves and annual loads for years 2003, 2004, and 2005 were developed using each year's respective measured concentrations and mean daily discharge record. The annual loads for all 3 years were averaged to obtain the 3-year moving average for 2004. The USGS used the measured suspended sediment particle size data to determine the percent of the total suspended load that is sand-size sediment. The annual sand loads then were calculated using the same LOADEST procedure as described for the total suspended load.

Results from the USGS study are presented in Table A-3. These are unpublished preliminary results made available by the USGS for use in this analysis. Total suspended annual loads are displayed for water years 1994–2008[1]. The suspended sand loads were not available after 2005 at the St. Joseph and Kansas City gages because insufficient particle size information was available to calculate sand loads. Therefore, the suspended sand averages are shown for years 1994–2005 in Table A-3 to provide a consistent time comparison. It should be noted that the suspended sand loads include both wash load (fine-grained sand) and bed material load (coarse-grained sand). The upper and lower 95-percent confidence intervals and the standard error of prediction (SEP) also are presented in the table to show the variability in the data. The confidence intervals and SEP were generated by the USGS in LOADEST. Runkel et al. (2004), the authors of the LOADEST model, state that:

> "Calculation of the SEP begins with an estimate of parameter uncertainty (the Standard Error) and adds the unexplained variability about the model (random error). Because SEP incorporates parameter uncertainty and random error, it is larger than Standard Error and provides a better description of how closely estimated loads correspond to actual loads." (p. 6)

The values shown in Table A-3 for Nebraska City were based on USGS published daily total suspended load values at the Nebraska City gage. Since these data are available, the LOADEST

[1] A water year is different from a calendar year in that it runs from October 1 through September 30 and is commonly used in hydrologic analyses in North America. For example, water year 2008 began on October 1, 2007, and concluded on September 30, 2008.

analysis was not performed for the Nebraska City location. Because the annual loads were obtained by summing all the daily loads, trend lines did not need to be fit to the data; therefore, no error estimates are given. Suspended sand loads are not reported because particle size data have not been available at the Nebraska City gage since 1991.

Table A-3 USGS Preliminary Annual Total Sediment and Suspended Sand Loads Based on Measured Data at Four Gage Locations on the Lower Missouri River

Water Year	Total Suspended Sediment Load (tons)
Nebraska City Gage[a]	
1994	26,211,430
1995	29,085,000
1996	51,447,590
1997	41,179,300
1998	38,692,400
1999	31,539,700
2000	14,220,600
2001	22,966,140
2002	11,192,140
2003	14,685,110
2004	16,315,440
2005	14,343,880
2006	9,329,500
2007	22,087,110
2008	33,751,800
Average Total Suspended Sediment (1994–2008)	**25,136,476**

Table A-3 USGS Preliminary Annual Total Sediment and Suspended Sand Loads Based on Measured Data at Four Gage Locations on the Lower Missouri River (continued)

Water Year	Total Suspended Sediment Load (tons)	Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand	Lower 95% Confidence Interval for Total Suspended Sediment (tons)	Upper 95% Confidence Interval for Total Suspended Sediment (tons)	Standard Error of Prediction for Total Suspended Sediment (tons)
St. Joseph Gage						
1994	23,690,291	9,538,417	40%	20,415,338	27,338,474	1,767,188
1995	41,501,678	11,635,319	28%	33,260,284	51,163,860	4,573,361
1996	42,722,155	16,176,130	38%	37,268,880	48,487,140	2,863,222
1997	62,776,097	23,959,685	38%	54,185,619	72,334,572	4,632,608
1998	50,433,838	16,697,396	33%	43,136,864	58,605,875	3,948,838
1999	74,486,708	16,006,959	21%	59,026,179	92,755,380	8,617,106
2000	16,607,801	7,709,083	46%	14,179,267	19,229,616	1,289,214
2001	39,802,233	9,051,823	23%	29,244,077	52,944,338	6,061,541
2002	14,293,862	4,607,988	32%	11,511,180	17,545,225	1,541,272
2003	20,472,436	4,768,702	23%	16,932,263	24,532,325	1,940,712
2004	37,872,119	5,198,606	14%	22,833,082	58,924,512	9,269,505
2005	19,666,152	2,847,506	14%	16,318,756	23,496,130	1,832,715
2006	11,453,830	--	--	9,885,989	13,198,396	845,509
2007	26,905,009	--	--	18,013,257	38,686,606	5,296,645
2008	35,652,160	--	--	21,562,791	55,333,631	8,672,769
Total Suspended Sediment Average (1994–2008)	**34,555,758**			**27,184,922**	**43,638,405**	**4,210,147**
Suspended Sand Average (1994–2005)		***10,683,135***	***29%***			

Table A-3 USGS Preliminary Annual Total Sediment and Suspended Sand Loads Based on Measured Data at Four Gage Locations on the Lower Missouri River (continued)

Water Year	Total Suspended Sediment Load (tons)	Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand	Lower 95% Confidence Interval for Total Suspended Sediment (tons)	Upper 95% Confidence Interval for Total Suspended Sediment (tons)	Standard Error of Prediction for Total Suspended Sediment (tons)
Kansas City Gage						
1994	30,071,383	7,562,101	25%	26,711,676	33,733,858	1,792,072
1995	60,883,646	9,204,014	15%	49,201,876	74,499,829	6,461,579
1996	51,833,151	11,496,452	22%	45,856,443	58,058,415	3,113,990
1997	89,916,705	15,586,251	17%	74,622,902	107,413,543	8,372,952
1998	64,962,777	11,182,991	17%	55,573,688	75,476,478	5,080,661
1999	158,825,288	11,311,009	7%	99,914,460	240,146,669	35,979,693
2000	18,582,887	4,234,603	23%	16,165,945	21,145,173	1,270,869
2001	47,313,068	6,941,695	15%	38,105,920	58,070,252	5,099,470
2002	14,382,525	3,482,254	24%	12,080,939	16,993,367	1,254,220
2003	18,059,993	3,545,394	20%	15,387,035	21,061,767	1,448,661
2004	30,676,860	5,396,230	18%	25,374,588	36,565,674	2,857,614
2005	27,488,343	4,301,219	16%	21,876,947	34,099,099	3,122,337
2006	15,044,932	--	--	12,777,500	17,597,041	1,230,380
2007	56,276,239	--	--	36,191,520	83,604,648	12,158,467
2008	46,550,446	--	--	33,497,949	62,710,548	7,473,647
Total Suspended Sediment Average (1994–2008)	**48,724,550**			**37,555,959**	**62,745,091**	**6,447,774**
Suspended Sand Average (1994–2005)		***7,853,684***	***18%***			

Table A-3 USGS Preliminary Annual Total Sediment and Suspended Sand Loads Based on Measured Data at Four Gage Locations on the Lower Missouri River (continued)

Water Year	Total Suspended Sediment Load (tons)	Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand	Lower 95% Confidence Interval for Total Suspended Sediment (tons)	Upper 95% Confidence Interval for Total Suspended Sediment (tons)	Standard Error of Prediction for Total Suspended Sediment (tons)
Hermann Gage						
1994	52,906,783	22,815,078	43%	41,995,758	65,784,607	6,077,422
1995	108,788,187	27,800,344	26%	89,450,488	131,056,280	10,624,884
1996	71,316,053	16,648,097	23%	61,323,997	82,030,564	5,285,498
1997	100,818,569	30,546,649	30%	88,459,852	114,410,166	6,623,119
1998	77,723,362	22,896,373	29%	68,332,604	88,036,135	5,028,725
1999	110,341,112	29,901,720	27%	93,554,030	129,258,348	9,115,087
2000	14,698,826	4,380,979	30%	12,999,898	16,469,012	885,333
2001	72,344,565	15,456,483	21%	59,147,338	87,602,486	7,267,043
2002	45,960,346	8,007,942	17%	33,360,137	61,774,578	7,268,713
2003	10,677,631	2,885,998	27%	8,926,244	12,671,044	956,151
2004	42,544,685	9,704,181	23%	32,952,967	53,782,093	5,322,799
2005	58,036,214	11,506,182	20%	43,385,207	76,058,777	8,354,233
2006	8,175,245	2,408,194	29%	6,298,546	10,436,478	1,057,549
2007	36,822,836	13,975,437	38%	28,128,638	47,360,279	4,915,707
2008	55,505,753	26,694,551	48%	36,116,491	81,282,456	11,578,362
Total Suspended Sediment Average (1994–2008)	**57,777,344**			**46,962,146**	**70,534,220**	**6,024,042**
Suspended Sand Average (1994–2005)		***16,879,169***	***27%***			

[a] The values shown for the Nebraska City gage are based on U.S. Geological Survey published daily total suspended load values at the Nebraska City gage. Because these data are available, the LOADEST analysis was not performed for the Nebraska City location. Because the annual loads were obtained by summing all the daily loads, trend lines did not need to be fit to the data; therefore, no error estimates are given. Suspended sand loads are not reported because particle size data have not been available at the Nebraska City gage since 1991.

Source: Unpublished U.S. Geological Survey data made available for the analysis.

A.3.3 Suspended Bed Material Load

The total suspended sediment data presented in the previous section includes particle sizes ranging from clay to coarse sand. However, all of the clay and silt and some of the finer sand in the measured suspended sediment loads remain in permanent suspension as wash load and should not be considered bed material load. The wash load portion must be subtracted from the measured suspended sediment load to obtain a better estimate of the suspended bed material load. The values shown in Table A-4 represent the bed material load-sized fraction of the suspended sediment load after subtracting the wash load; they range from 6 percent at the Hermann gage to 15 percent at the Kansas City gage and are indicated on Figures A-7 through A-10 by the intersection of “D_{10} of the substrate” with the “average gradation” on each graph. The fractions were obtained by retaining only sediment coarser than the river bed D_{10} from the suspended sediment loads for the indicated time periods with sediment size data

Table A-4 Percentage of Total Suspended Sediment Load with Particle Sizes Coarser Than the Bed Material D_{10}

	Location			
	Nebraska City	St. Joseph	Kansas City	Hermann
Time period of available data	1981–1991	1994–2005	1994–2002	1994–2005
Percent of total suspended load coarser than the bed material D_{10}	13%	13%	15%	6%
Standard deviation	6.7%	8.2%	9.2%	5.3%

To ensure that the river bed D_{10} is a valid estimate of the transition between wash load and bed material load, a separate analysis was conducted based on the “Rouse number” method. The Rouse number is the ratio of particle settling velocity to the shear velocity and indicates whether a particle will be transported and how. Rouse number calculations were performed at the Nebraska City, St. Joseph, Kansas City, and Hermann hydraulic modeling reaches (see Section A.4.1).

Table A-5 shows the dominant sediment transport mechanism expected for a given Rouse number. For Rouse number transport mechanisms, suspended sediment is equivalent to wash load, and bed material load is a combination of the mixed load and bed load categories shown in Table A-5. The values in Table A-5 were determined by Shah-Fairbank (2009) from examination of similar values presented in research by Julien (1998) and Dade and Friend (1998).

Table A-5 Relationship between the Rouse Number and the Dominant Sediment Transport Mechanism

Rouse Number	Dominant Sediment Transport Mechanism
> 12.5	No motion
5 – 12.5	Bed load
1.25 – 5	Mixed load[a]
< 1.25	Suspended load

Note: Values were determined by Shah-Fairbank (2009) from examination of similar values presented in research by Julien (1998) and Dade and Friend (1998).

[a] Combination of bed and suspended loads.

Particle settling velocities were calculated using Dietrich's (1982) equation for natural particles. Output from the hydraulic modeling described in Section A.4.1 was used to perform the Rouse number analysis. Results from the Rouse number calculations are presented in Figures A-17 through A-20 for each hydraulic modeling reach. The graphs show the behavior of different particle sizes at different discharges. For example, 1-mm particles will move as bed load at flows up to approximately 25,000 cfs and as mixed load (as suspended load and as bed load) at higher flows. The Rouse number analysis shows that sand particles finer than approximately 0.25 mm at the Nebraska City, St. Joseph, and Kansas City gages—and finer than approximately 0.2 mm at the Hermann gage—remain in suspension at all discharges and should be considered wash load.

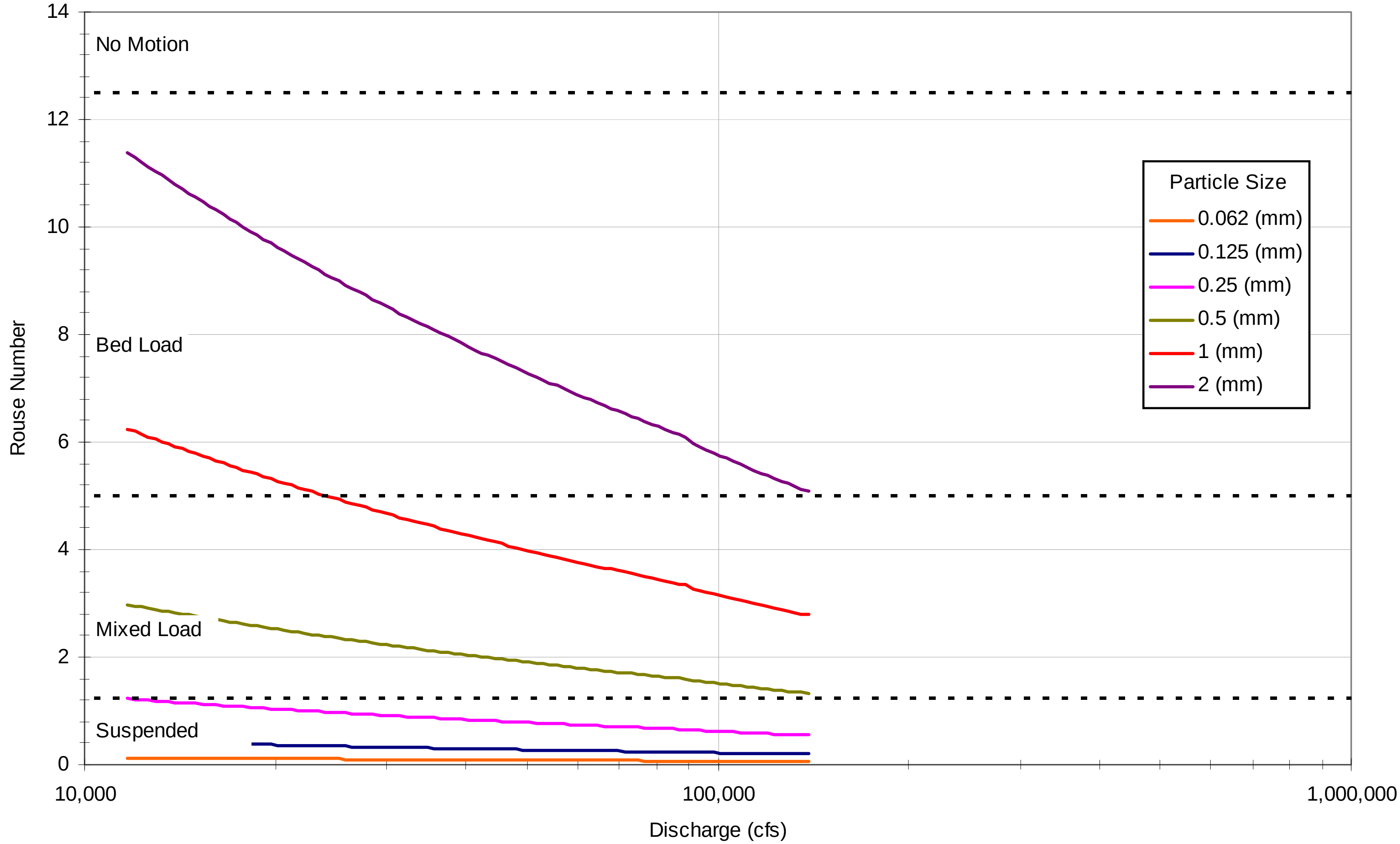

Figure A-17 Mode of Sediment Transport Predicted from Rouse Number Analysis at the Nebraska City Hydraulic Modeling Reach

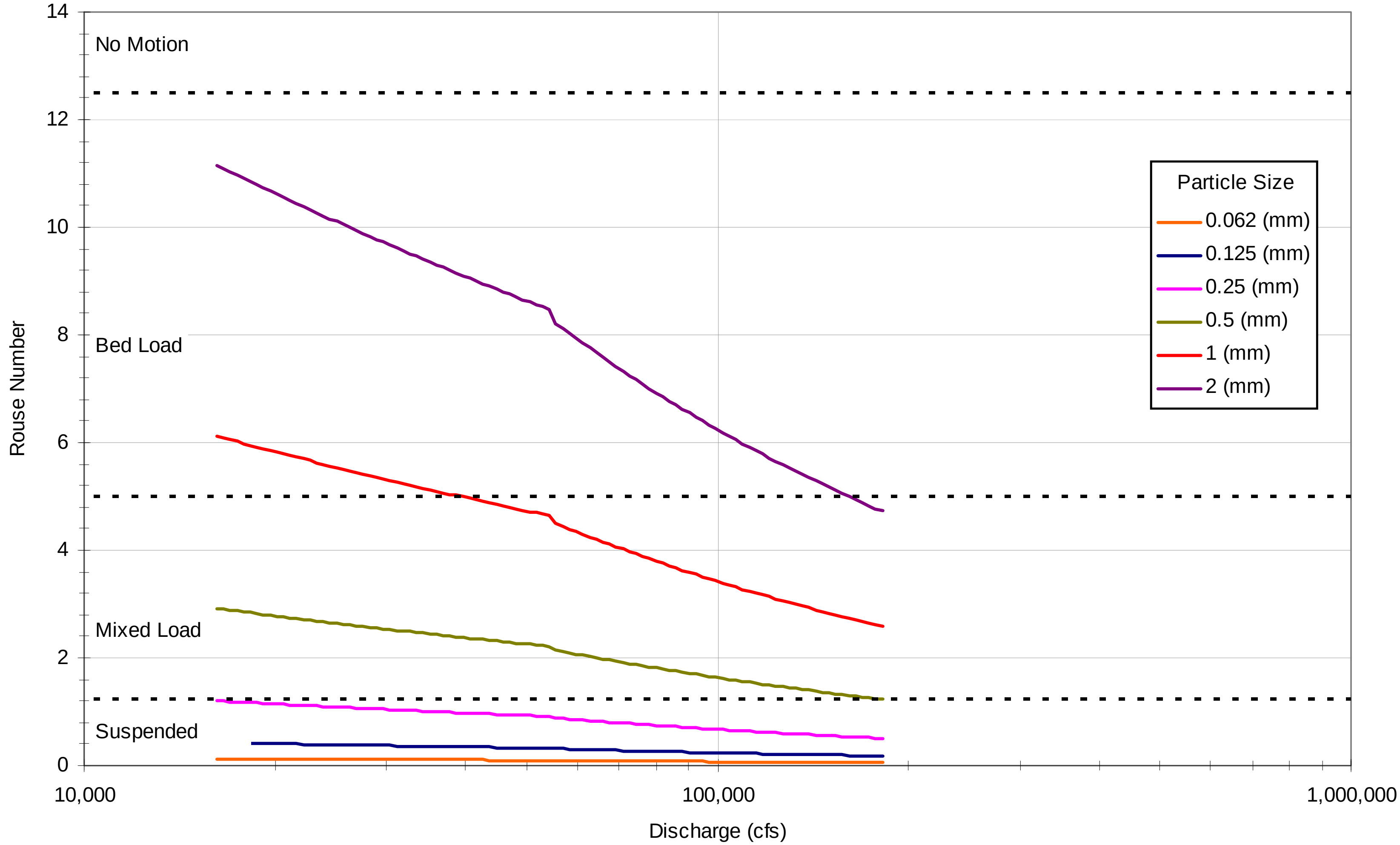

Figure A-18 Mode of Sediment Transport Predicted from Rouse Number Analysis at the St. Joseph Hydraulic Modeling Reach

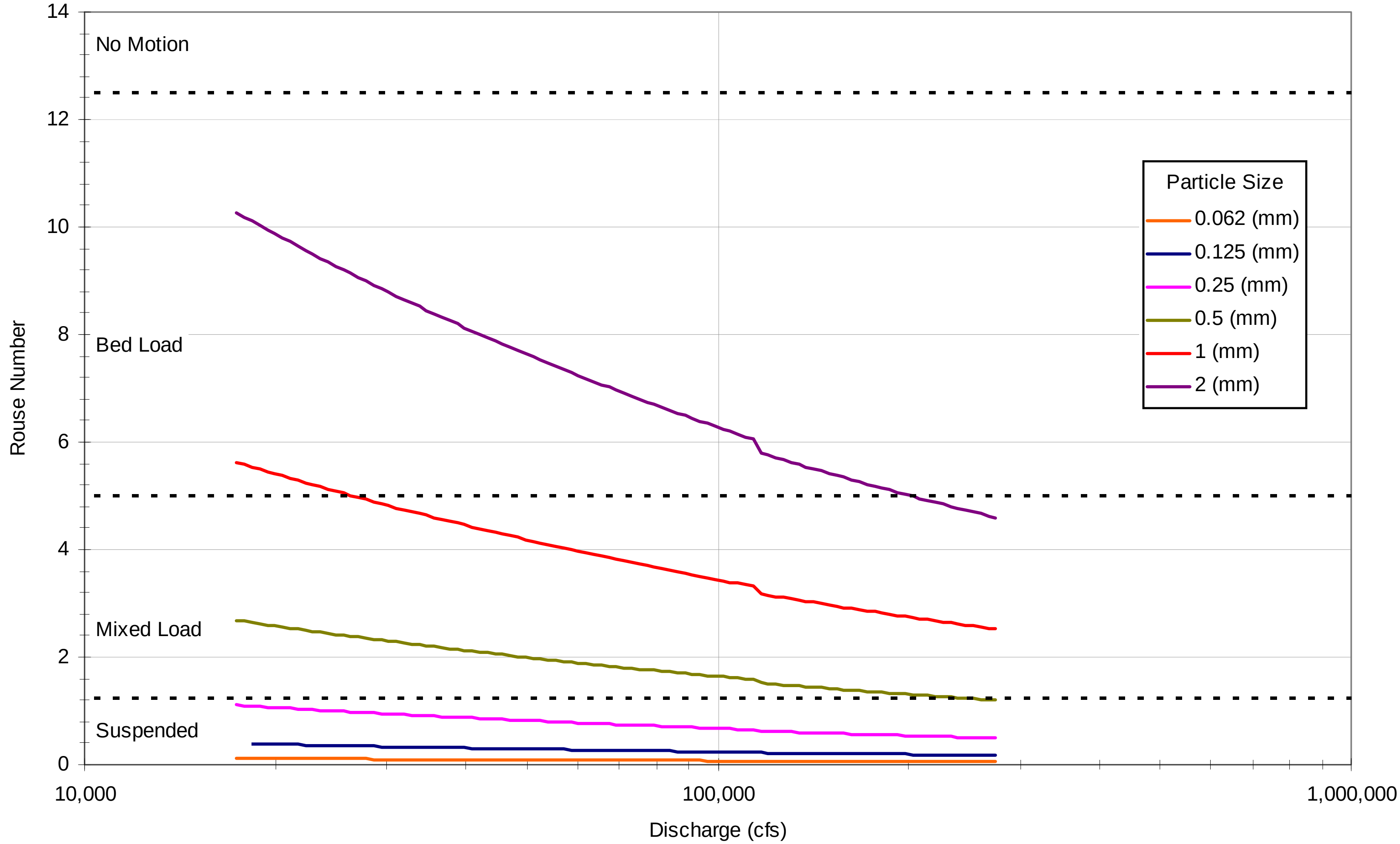

Figure A-19 Mode of Sediment Transport Predicted from Rouse Number Analysis at the Kansas City Hydraulic Modeling Reach

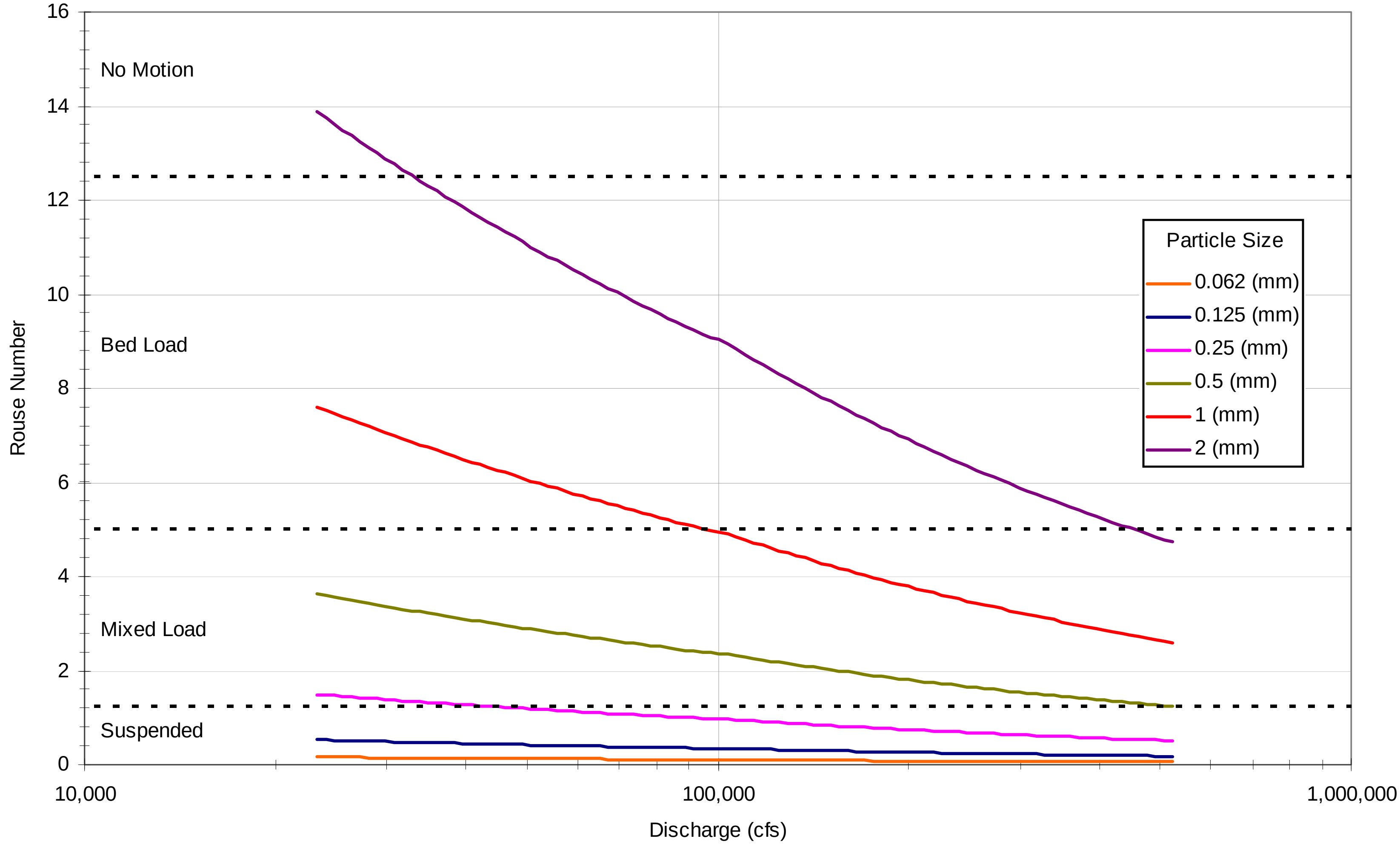

Figure A-20 Mode of Sediment Transport Predicted from Rouse Number Analysis at the Hermann Hydraulic Modeling Reach

A.4 ESTIMATING BED MATERIAL LOADS ON THE LOWER MISSOURI RIVER

The previous sections describe the particle sizes of the sediment in the river bed and in suspension, and summarize the available data for suspended sediment loads and the bed material load-sized sediment. Because no data are available regarding the sediment moving along the bed as bed load and in the bottom portion of the water column in the unsampled zone, values for these components of bed material load must be estimated. Appropriate equations for use on large sand-bed rivers were reviewed and used to calculate bed material loads. Each equation required input of several measured or estimated parameters to calculate the bed material load, including the physical geometry of the channel, a range of flows and velocities, and sediment size distributions and loads. Sufficient data were available from the USGS gage sites at St. Joseph, Kansas City, and Hermann to meet the input requirements of the equations. The gage at Nebraska City, upstream from the Project area, was included because daily suspended sediment load measurements were available for that gage and can be used to check the results of the calculations.

Bed material loads for the LOMR were estimated using the following procedure:

- Modeling reaches were established at the four USGS gage locations using measured channel cross sections;
- A hydraulic model was developed at the modeling reaches and calibrated with measured water stage, flows, and velocities to estimate the amount of energy available to transport sediment;
- A suspended sediment rating curve was developed to determine daily loads based on a range of flows;
- Appropriate equations were selected and used to calculate average bed material loads for two representative time periods; and
- The results were compared with previous studies and existing data on suspended sediment loads.

Each of these steps is described in the following sections.

A.4.1 Hydraulic Modeling to Support Bed Material Load Calculations

A hydraulic model was created to determine the hydraulic properties of the river channel and to define the amount of flow energy available to transport the bed material load. The bed material load equations presented below require hydraulic input values, such as flow velocity, flow depth, and channel width.

The procedure to establish modeling reaches, calibrate the models with measured hydraulic data, and analyze the data for use in the bed material load calculations is described below.

Hydraulic modeling sites were established at the Nebraska City (RM 562.6), St. Joseph (RM 448.2), Kansas City (RM 366.1), and Hermann (RM 97.9) gaging sites to model steady and gradually varied flow conditions using USACE HEC-RAS software. These locations were selected because (1) they are the sites with the most sediment records (as discussed above); and (2) measurement data are available to calibrate the hydraulic and sediment models. The hydraulic output from the models was used in bed material load equations to determine the sediment supply for the LOMR.

At the St. Joseph, Kansas City, and Hermann gages, approximately 1,500-foot-long modeling reaches were created using the 2008 USACE hydroacoustic cross section bed elevation data. These cross sections were supplemented with USGS digital elevation data for the banks and floodplain for elevations outside of the range of the hydroacoustic data (see Table A-6 for details of modeling sites). The Nebraska City modeling site is over 3,500 feet long and uses USGS acoustic Doppler current profiler (ADCP) data supplemented with digital elevation data at higher elevations to create modeling cross sections. Recorded depths in the Nebraska City ADCP data were converted to river bed elevations based on the river's stage at the time of measurement and the distance of the measurement cross section from the gage. At all four locations, the highest-resolution digital elevation data available were used for the cross section upland elevations.

Table A-6 Descriptions of the Four HEC-RAS Modeling Reaches in the Lower Missouri River

	Location			
	Nebraska City	St. Joseph	Kansas City	Hermann
Length	3,600	1,480	1,530	1,430
Number of cross sections	4	7	7	7
Source of bed elevations	USGS ADCP	USACE 2008 Hydroacoustic	USACE 2008 Hydroacoustic	USACE 2008 Hydroacoustic
Source of bank and upland elevations	USGS 1/3 and 1/9 Arc Second NED	USGS 1/9 Arc Second NED	USGS 1/9 Arc Second NED	USGS 10m DEM

Notes:

ADCP = Acoustic Doppler current profiler.
DEM = Digital elevation model.
NED = National elevation dataset.

The modeling cross sections and Missouri River Bank Stabilization and Navigation Project (BSNP) channel engineering features for each location are shown in Figures A-21 through A-24. The figures illustrate the locations of the cross section survey points used in the model, as well as physical features such as dikes, revetments, and bridges. The USGS ADCP cross section survey points at Nebraska City (Figure A-21) are so close together that they appear as a thick dark line on the map.

The steady flows modeled in HEC-RAS range from the minimum to maximum mean daily discharge recorded for the period from 1994 to 2009 at each location. This period corresponds with the period analyzed in the sediment transport analysis. Each of the modeling sites was created with the most upstream cross section located near the USGS gage (except for the Nebraska City gage, see below) so that the model could be started downstream and the measured stages at the gage could be used to calibrate the modeled stages at the gage cross section. Table A-7 lists the corresponding stages based on the most recent USGS data of the modeled discharges available online in the USGS National Water Information System (NWISWeb) (USGS 2001).

Table A-7 Discharges and Stages Used at the Modeling Sites in the Lower Missouri River (USGS Gage Data)

Nebraska City		St. Joseph		Kansas City		Hermann	
Discharge (cfs)	Stage (NGVD 29 ft)	Discharge (cfs)	Stage (NGVD 29 ft)	Discharge (cfs)	Stage (NGVD 29 ft)	Discharge (cfs)	Stage (NGVD 29 ft)
10,000	907.9	17,000	790.7	20,000	711.0	23,000	481.7
15,000	909.2	25,000	793.0	25,000	711.9	35,000	485.1
20,000	910.6	37,500	796.6	37,500	714.8	50,000	487.6
25,000	911.9	50,000	799.0	50,000	717.4	63,000	489.6
30,000	913.1	62,500	801.4	62,500	719.9	75,000	491.4
35,000	914.4	75,000	803.3	75,000	721.8	100,000	494.5
40,000	915.5	87,500	805.2	87,500	723.4	150,000	499.4
50,000	917.6	100,000	806.6	100,000	725.0	200,000	503.0
60,000	919.6	125,000	809.2	125,000	727.6	250,000	506.1
80,000	922.7	150,000	811.5	150,000	730.4	300,000	509.1
100,000	925.2	175,000	813.2	175,000	732.9	350,000	511.1
125,000	927.4	182,000	813.4	200,000	735.4	400,000	512.6
139,000	928.7			250,000	739.9	523,000	516.8
				275,000	740.8		

Notes:

cfs = Cubic feet per second.
ft = Feet.
NGVD = National geodetic vertical datum.

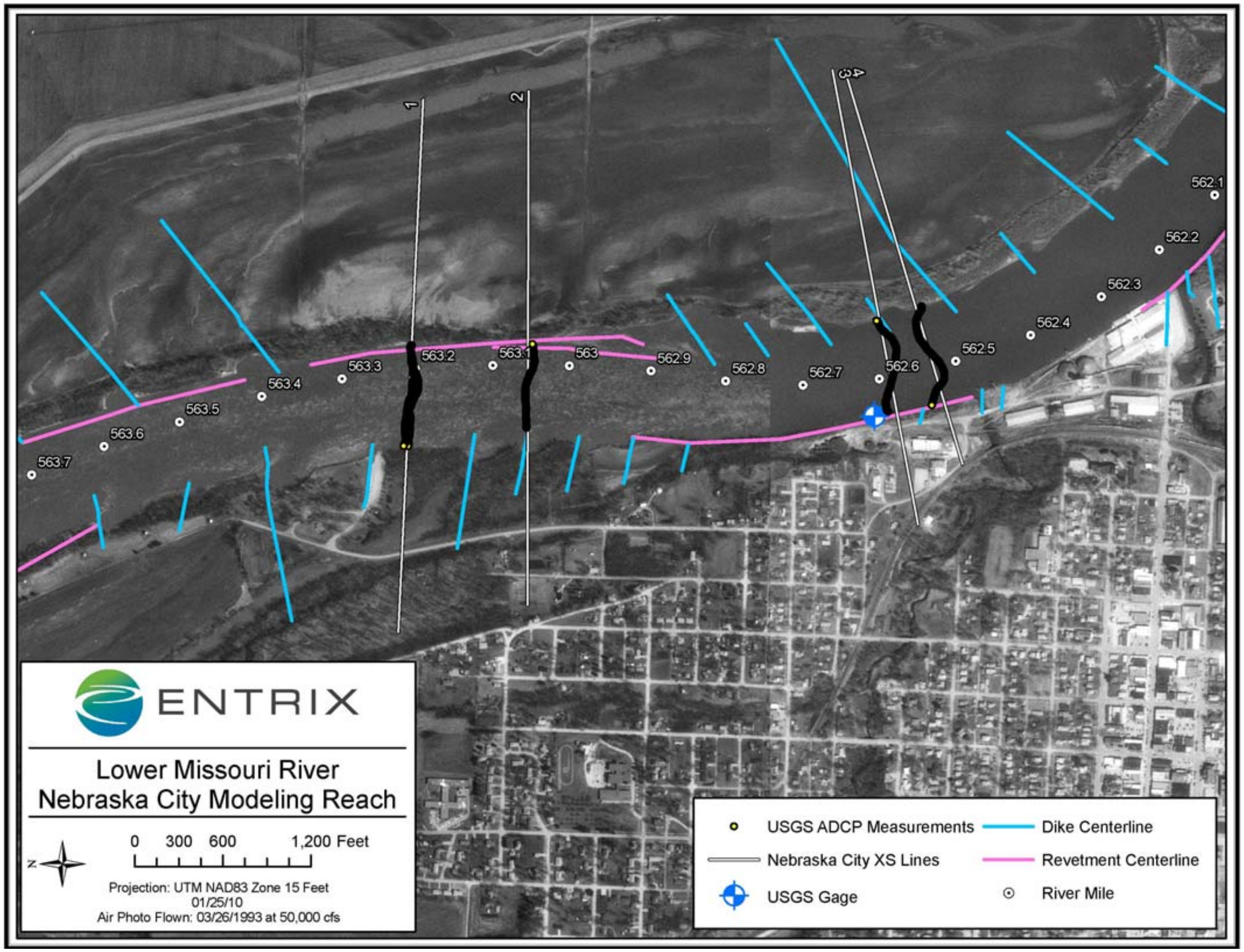

Figure A-21 Overview of the Nebraska City Hydraulic Modeling Reach

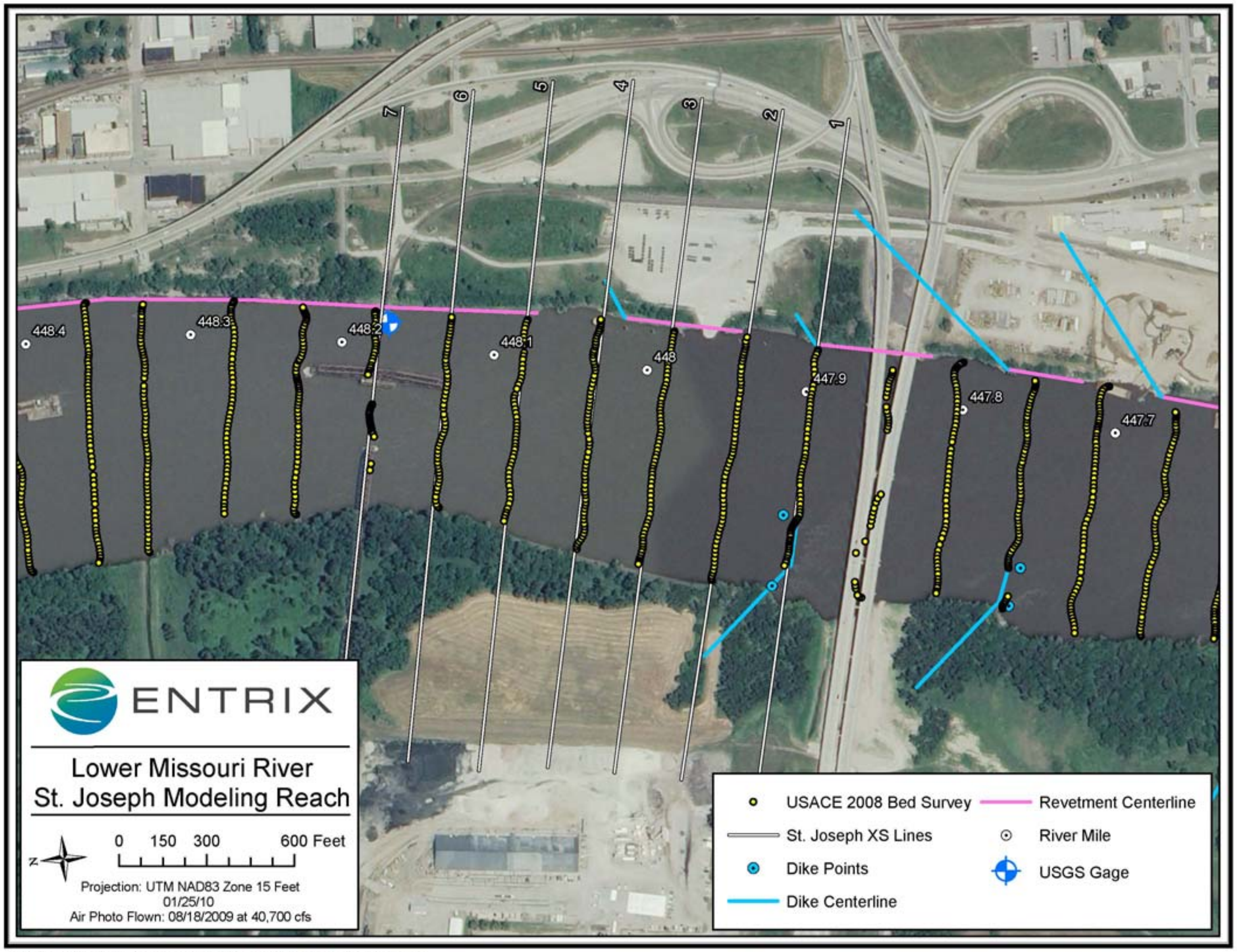

Figure A-22 Overview of the St. Joseph Hydraulic Modeling Reach

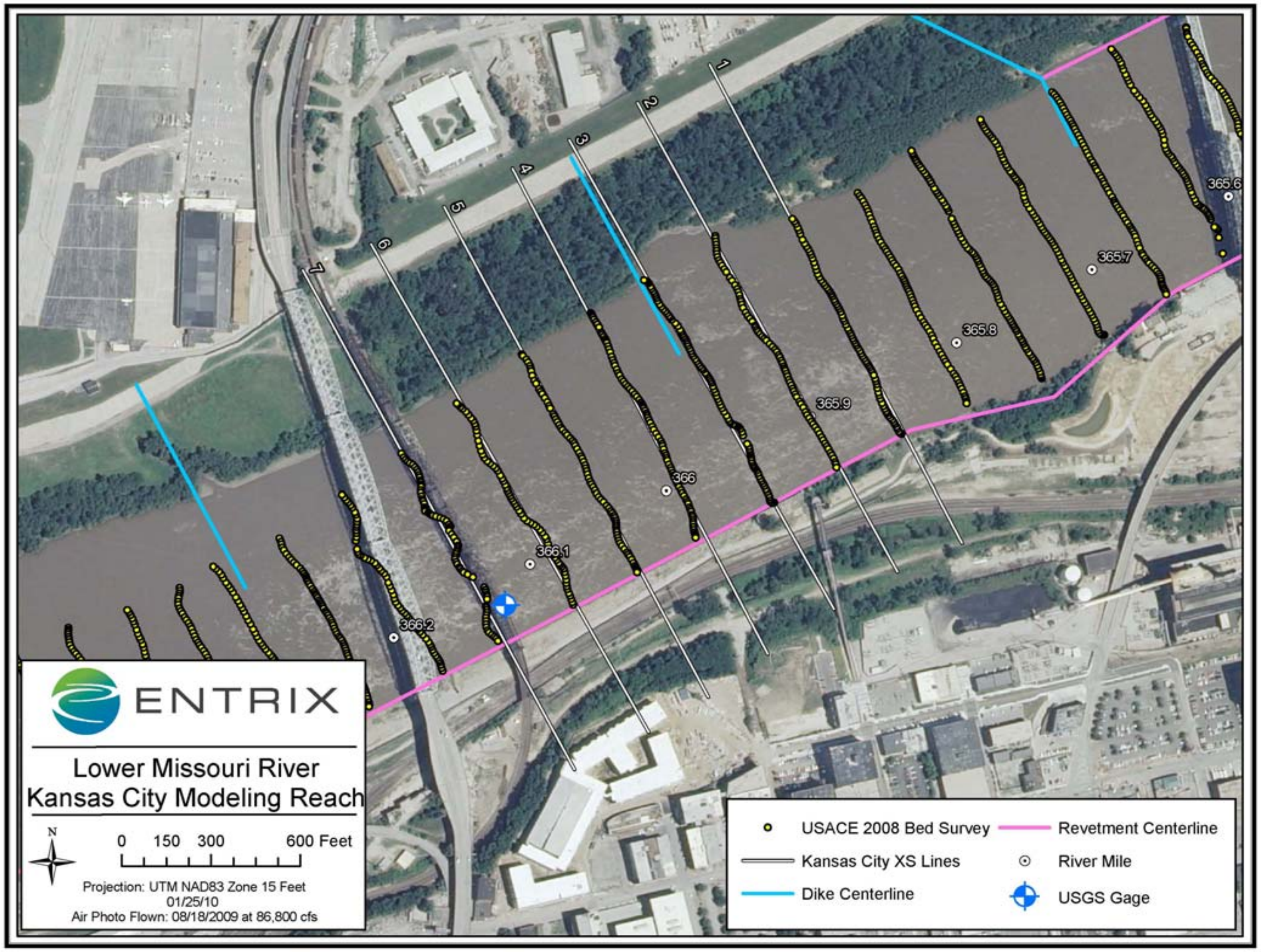

Figure A-23 Overview of the Kansas City Hydraulic Modeling Reach

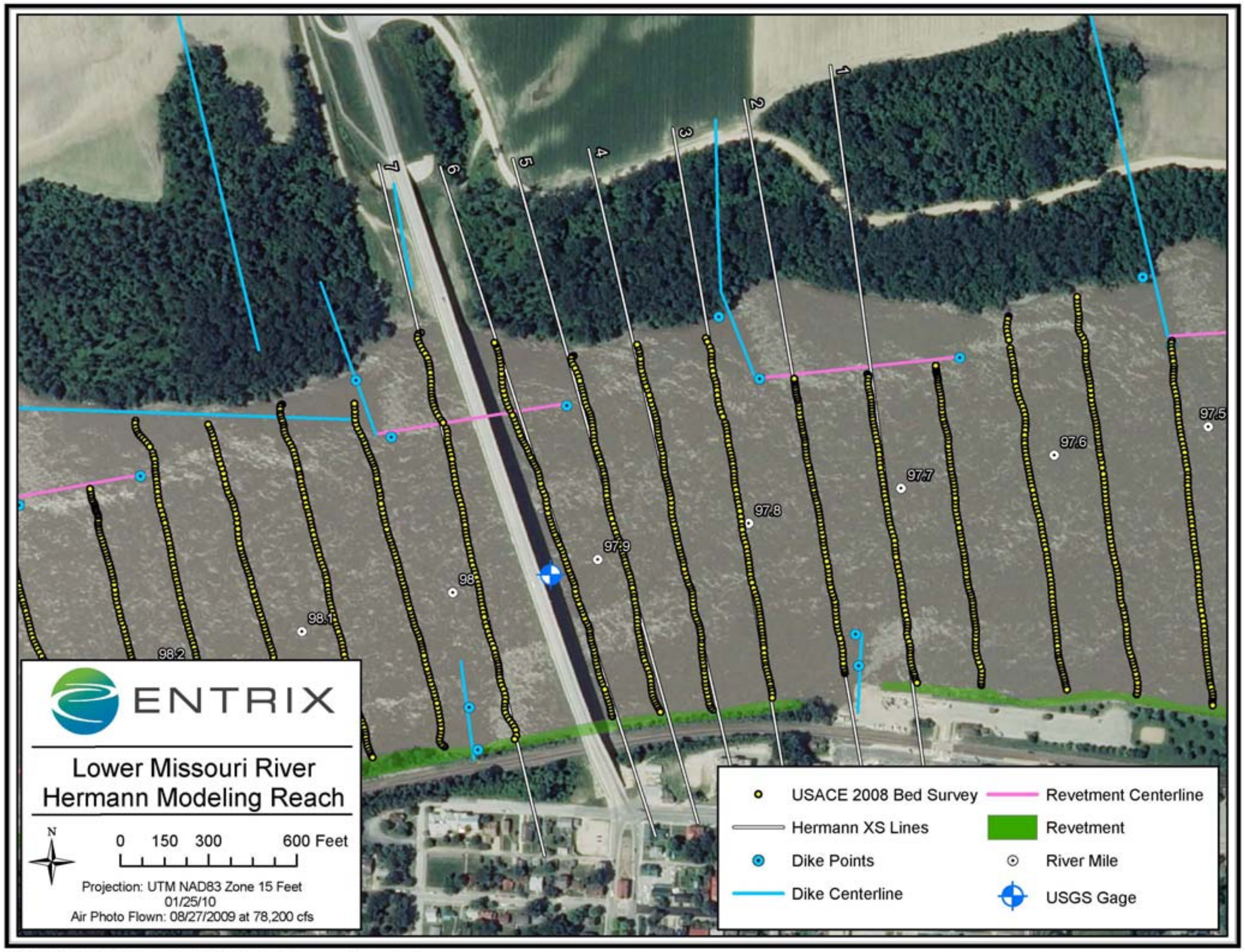

Figure A-24 Overview of the Hermann Hydraulic Modeling Reach

Because the Nebraska City gage is located in the middle of the modeling reach, observed water surface elevations for the most upstream cross section were created by increasing the stage at the gage based on the distance and slope of the river. Manning's roughness values[2] of 0.03 in the active channel and 0.08 in vegetated channel margins produced the best match between measured and modeled water surface elevations. A review of the plotted model output indicated that the modeled and measured water surface elevations were typically within a few tenths of a foot from each other, indicating that the model accurately replicates measured water surface elevations.

Example cross section plots from the Hermann reach showing modeled water surface elevations and Manning's "n" roughness values are shown in Figure A-25. The cross sections were plotted without vertical exaggeration to show their dimensions at a one-to-one scale. The red circles on the cross sections represent the boundaries chosen to delineate the channel in HEC-RAS from the left and right overbank areas. The "channel" was defined as the width over which bed material load is transported. The channel designated for bed material load transport did not include BSNP infrastructure such as dikes or revetments. Including these structures in the wetted width of the channel would have created unrealistic bed material load transport rates. For example, at cross section six at Hermann (see Figure A-24), the left descending bank (looking downstream) is set approximately 300 feet from the left edge of water at the revetment or L-dike centerline, which is 300 feet from the left edge of water. Even though water flows over the dikes at higher flows, the low velocities and bed load are disconnected from the main channel because the revetment barrier prevents this zone from transporting appreciable volumes of bed material load. At cross sections without BSNP infrastructure, the entire wetted width of the channel bed was used (see cross section four in Figure A-24). The hydraulic output specific to the HEC-RAS channel was used in the sediment transport calculations because it defines the energy available in the zone where bed material load is moving.

Measured and modeled velocities and measured and modeled water surface elevations were compared to determine the accuracy of the model. The USGS periodically measures the discharge at their gaging stations to verify and update stage-discharge rating curves. These data are available online in NWISWeb (USGS 2001). In addition to reporting the measured discharge and other factors related to the measurement, the USGS reports the mean flow velocity and channel width at the time of measurement.

[2] Manning's roughness "n" is an empirical coefficient used to estimate the resistance of a river to the flow of water and is used in the Manning's equation, which is a relationship between flow rate and parameters such as channel slope, channel size and shape, channel roughness, and flow depth.

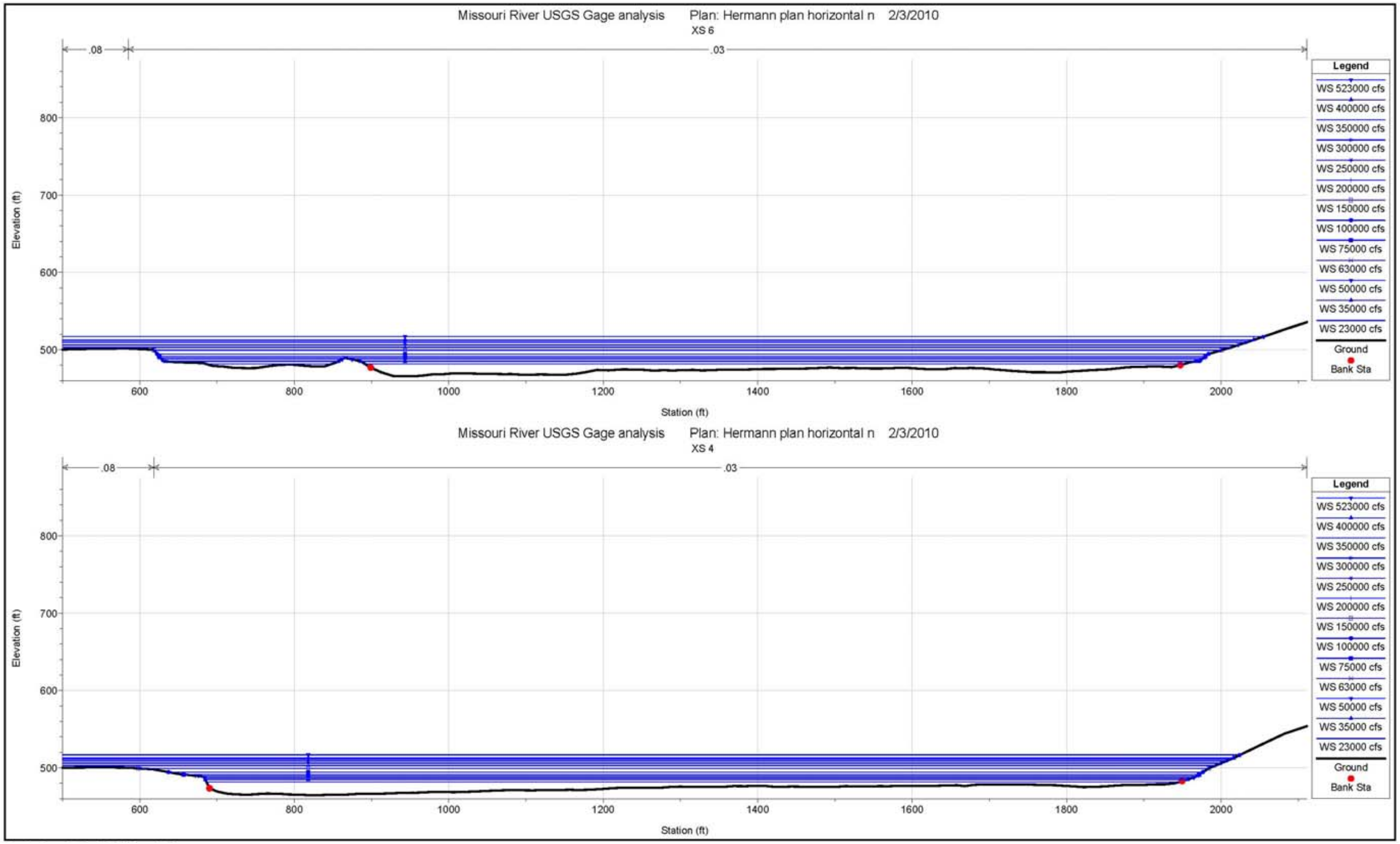

Figure A-25 Example HEC-RAS Cross Section Plots Showing Bed Material Transport Widths for a Cross Section with (XS 6 top) and without (XS 4 bottom) Missouri River Bank Stabilization and Navigation Project Revetments

Historically, the USGS measured discharges by lowering flow meters from a crane mounted on a bridge at or near the gaging site. In recent years, the USGS has changed from bridge measurements to ADCP measurements taken from boats moving on a transect across the channel. The transect is near the gage, but not always at the same exact river location. The measurement location may vary between measurements, depending on flow level. Therefore, when comparing the trend of mean velocities with time, it was noted that the crane measurements were not exactly comparable to the ADCP measurements because they were not all collected at precisely the same cross section. They were determined to be sufficiently similar for the purposes of the analysis and are the only data available.

Plots showing mean flow velocity versus discharge are shown for the St. Joseph, Kansas City, and Hermann gages in Figures A-26 through A-28. Each plot shows measured velocities from 1990 to 2009. All of the measurements taken with a crane were plotted as one series, and all recent ADCP measurements from 2007 to 2009 were plotted as a separate series. The separate plots distinguish between the two measurement methods and show trends in velocity for the previous 2 years. The plots also show the modeled results for comparison purposes.

The modeled results were found to compare well with the measured data. At St. Joseph, Kansas City, and Hermann, the modeled velocities follow the trend of the 2007–2009 measured data instead of the older measured velocities dating back to 1990. This is expected because the channel elevation data are based on 2008 surveys, and the stages used to calibrate the model were determined from the most recent stage-discharge curves. At Nebraska City, the modeled velocities were not plotted; they can be directly compared with measured ADCP velocities because the cross sections were generated from depths recorded by the ADCP during the same measurement. Results in Table A-8 show that the modeled velocities are within 0.1–0.2 feet per second of the ADCP velocities.

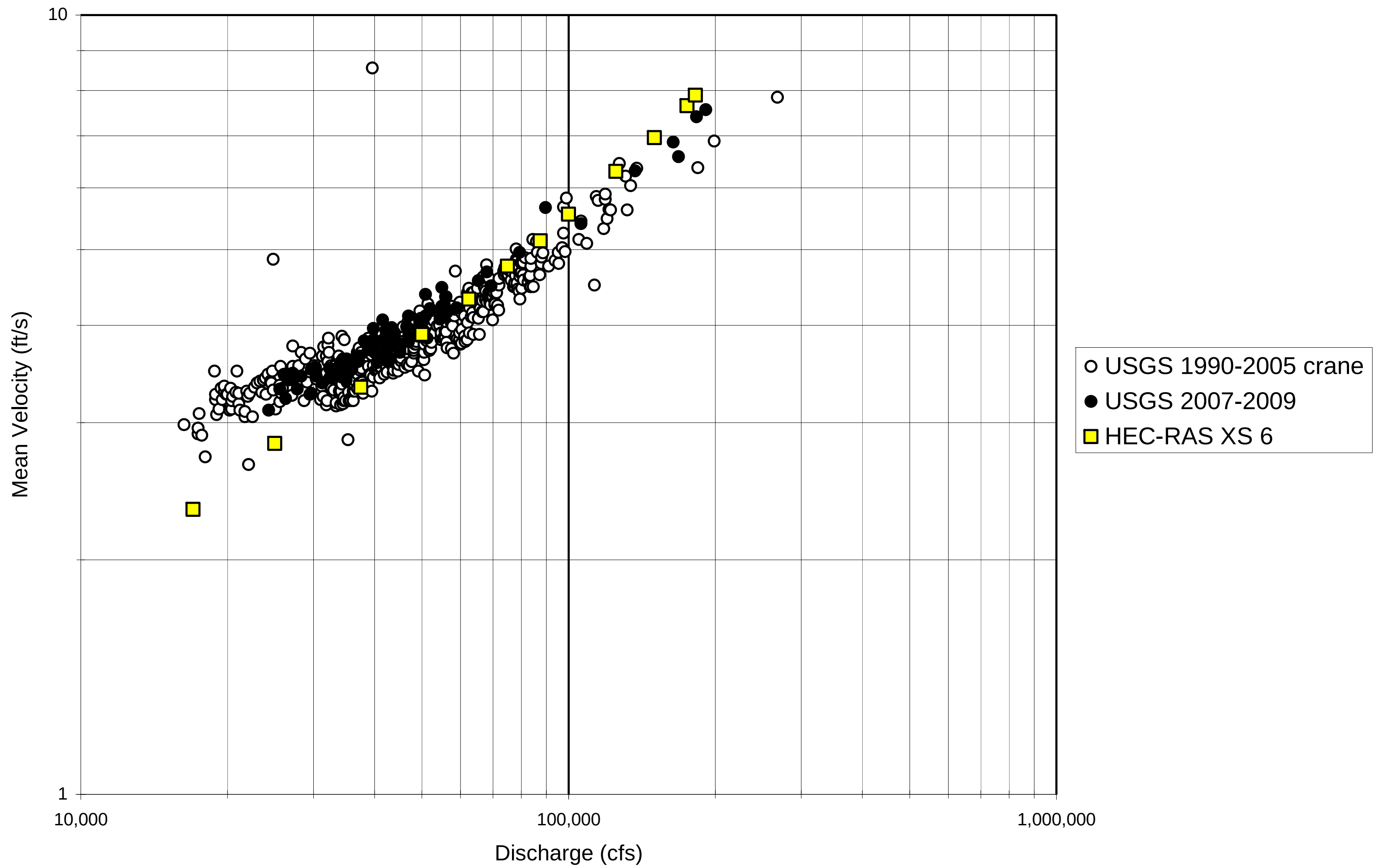

Figure A-26 Comparison of USGG Measured and HEC-RAS Modeled Mean Channel Velocities at the St. Joseph Gage

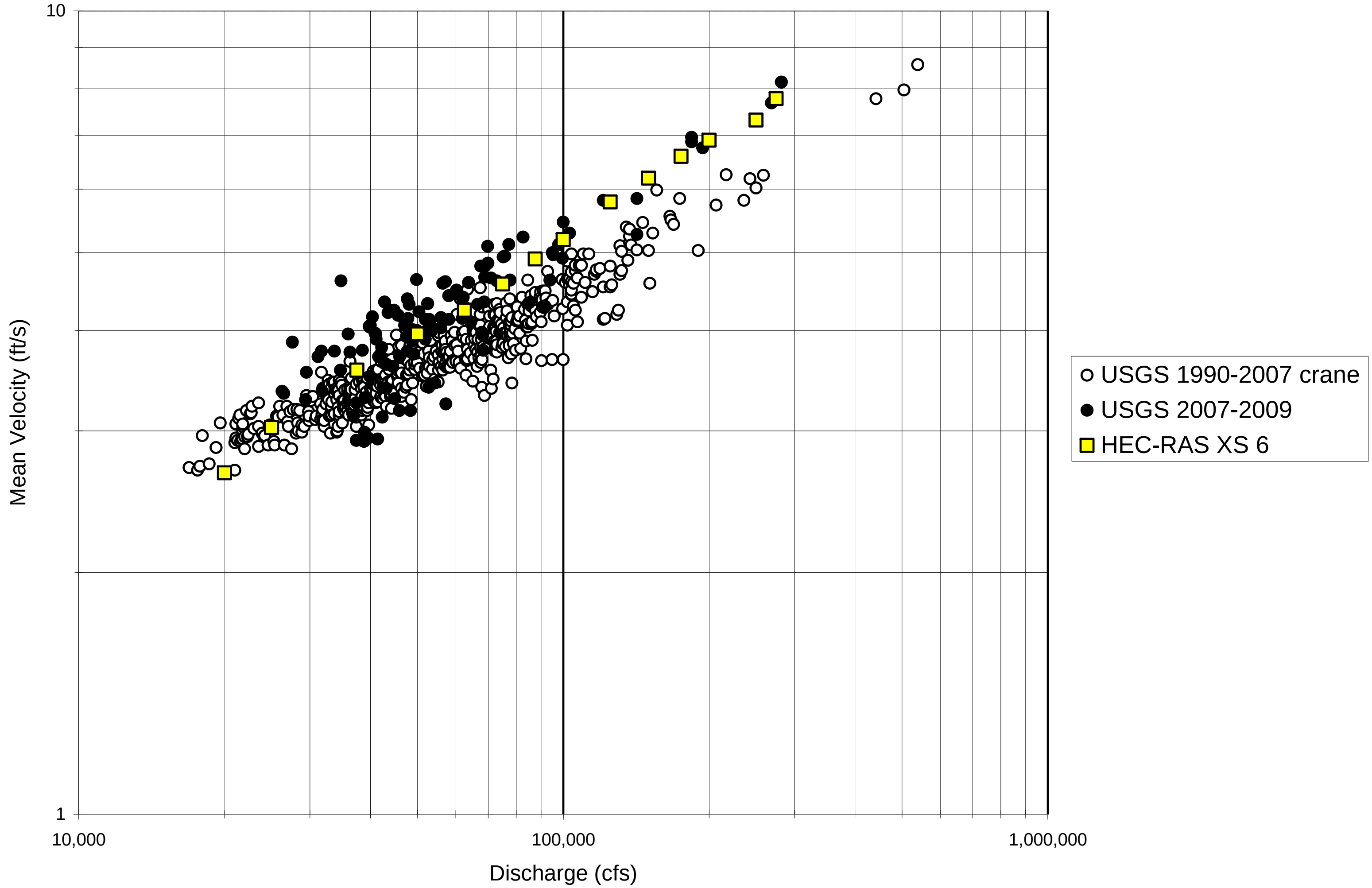

Figure A-27 Comparison of USGG Measured and HEC-RAS Modeled Mean Channel Velocities at the Kansas City Gage

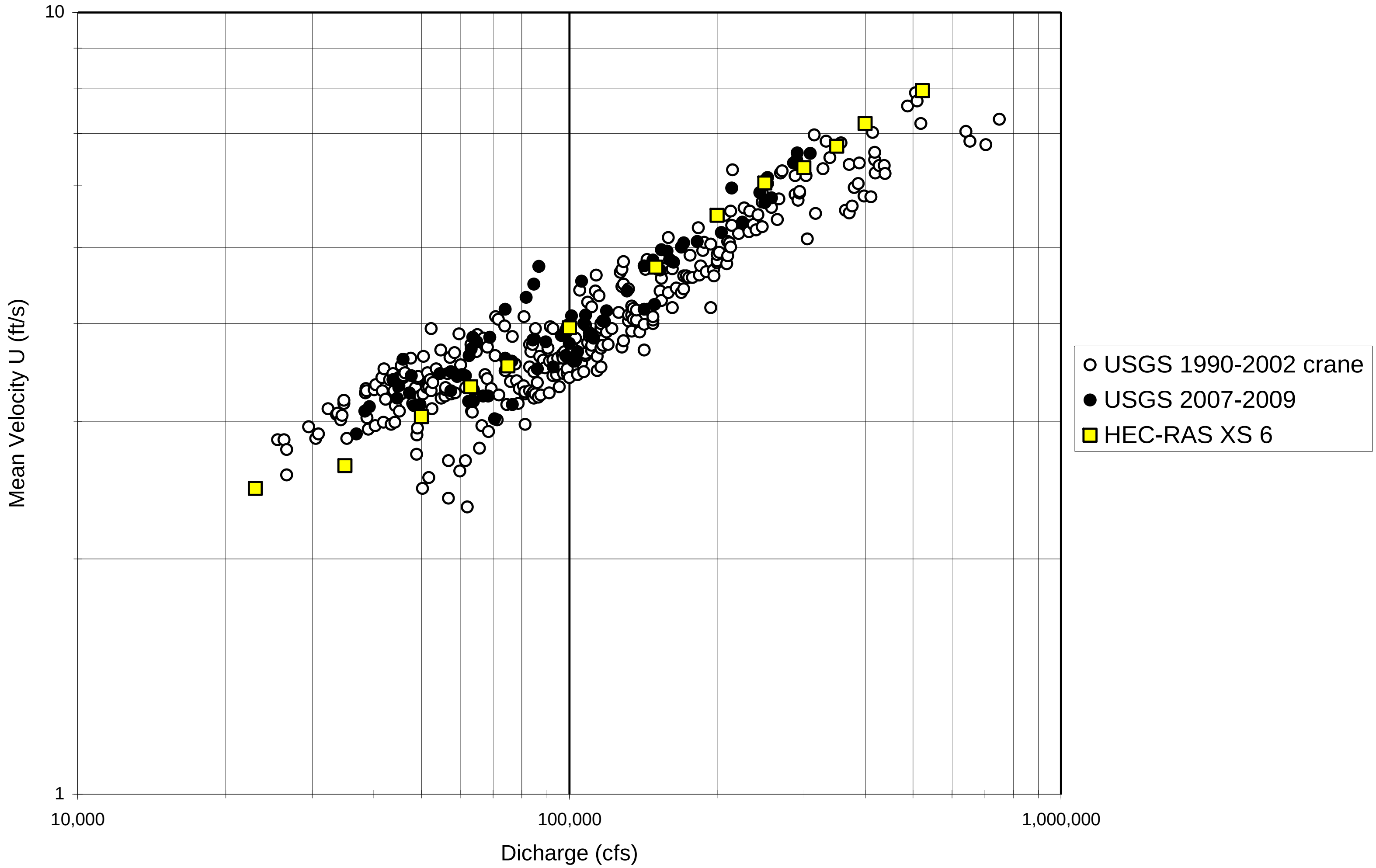

Figure A-28 Comparison of USGG Measured and HEC-RAS Modeled Mean Channel Velocities at the Hermann Gage

Table A-8 Comparison of Measured and Modeled Velocities at the Nebraska City Modeling Reach

		Velocity (feet per second)	
HEC-RAS Cross Section	Discharge (cubic feet per second)	USGS Acoustic Doppler Current Profiler	HEC-RAS Modeled
4	53,700	4.4	4.6
4	78,300	5.5	5.4
3	39,700	4.3	4.3
2	109,000	6.1	6.0
1	116,000	6.3	6.2

A.4.2 Total Bed Material Load Calculations

This section describes the methods used to calculate total bed material loads based on the output from the hydraulic models and the measured sediment particle size data presented above. Total bed material loads were calculated at the four gage locations using five different equations:

1. Ackers and White (1973) with HR Wallingford (1990) adjusted coefficients;
2. Engelund and Hansen (1967);
3. Molinas and Wu (2001);
4. Yang (1973); and
5. Series Expansion of the Modified Einstein Procedure (SEMEP) (Shah-Fairbank 2009, Guo and Julien 2004).

All five equations predict total bed material load, which is the sum of the bed load and bed material component of the suspended load. These five equations were selected for the analysis because they are commonly used by both researchers and practitioners to estimate total bed material loads on large sand-bed rivers with relatively uniform bed sediment, such as the Missouri River (García 2008, Molinas and Wu 2000). Because there is no consensus in the field of sediment transport on which equation is the best predictor of bed material load transport, all five equations were used in the study to show the range of loads predicted. As discussed below, an average result of the equations was used to form the result.

Descriptions of the equations and the actual equations are presented below. The notation for the equations is based on Parker (2005).

A.4.2.1 Ackers and White (1973) with HR Wallingford (1990) Adjusted Coefficients

This equation is based on Bagnold's stream power concept, in which general physical principles are used to state that the energy to transport sediment is determined by the available power of the flow. Ackers and White applied dimensional analysis to express sediment mobility using dimensionless parameters (García 2008). Several of the equation's parameters were originally determined using best-fit laboratory data. In 1990, HR Wallingford developed new coefficients for the original equation to prevent it from overestimating transport for fine sediments less than approximately 0.2 mm. The revised coefficients were used in this study.

q_t - unit volume total bed material transport rate per unit width [L2/T] is

$$q_t = \frac{1}{(R+1)} \frac{X_t}{(1-X_t)} q_w$$, and

flux-based mass concentration of total bed material sediment X_t [1] is

$$X_t = \frac{R+1}{\hat{H}} (Cz)^n C_{aw} \left(\frac{F_{gr}}{A_{aw}} - 1 \right)^m$$, where

the sediment mobility number F_{gr} is

$$F_{gr} = \sqrt{\tau^*} (Cz)^{1-n} \left(\frac{1}{\sqrt{32}\, \ell og_{10}(10\hat{H})} \right)^{1-n}$$, and

the dimensionless Chezy resistance coefficient C_z [1] is

$$C_z = \frac{U}{u_*}$$, and

$$\hat{H} = \frac{H}{D}$$

The coefficients are defined as:

$$n = \begin{cases} 1.00 - 0.56\,\ell og_{10}\left(\mathbf{Re}_p^{2/3}\right) & , \quad 1 < \mathbf{Re}_p^{2/3} \le 60 \\ 0 & , \quad 60 < \mathbf{Re}_p^{2/3} \end{cases}$$

$$m = \begin{cases} \dfrac{6.83}{\mathbf{Re}_p^{2/3}} + 1.67 & , \quad 1 < \mathbf{Re}_p^{2/3} \le 60 \\ 1.78 & , \quad 60 < \mathbf{Re}_p^{2/3} \end{cases}$$

$$A_{aw} = \begin{cases} 0.23\mathbf{Re}_p^{-1/3} + 0.14 & , \quad 1 < \mathbf{Re}_p^{2/3} \le 60 \\ 0.17 & , \quad 60 < \mathbf{Re}_p^{2/3} \end{cases}$$

$$\ell og_{10} C_{aw} = \begin{cases} 2.79\,\ell og_{10}(\mathbf{Re}_p^{2/3}) - 0.98[\ell og_{10}(\mathbf{Re}_p^{2/3})]^2 - 3.46 & , \quad 1 < \mathbf{Re}_p^{2/3} \le 60 \\ -1.60 & , \quad 60 < \mathbf{Re}_p^{2/3} \end{cases}$$

Where:

$R = (\rho/\rho_s - 1)$, sediment submerged specific gravity [1]
ρ = water density [M/L^3]
ρ_s = sediment material density [M/L^3]
$Re_p = \sqrt{RgD}\,D/\nu$ [1]
g = acceleration of gravity [L/T^2]
D = grain size [L]
ν = kinematic viscosity of water [L^2/T]
q_w = water discharge per unit width [L^2/T]
U = depth- or cross sectionally-averaged flow velocity [L/T]
$u_* = \sqrt{\tau_b/\rho}$, shear velocity [L/T]
H = cross sectionally averaged flow depth [L]
$\tau_b = \rho g H S_f$, bed shear stress [M/L/T^2]
S_f = down-channel friction slope [1]
$\tau^* = \tau_b/(\rho RgD)$, Shields number [1]

A.4.2.2 Engelund and Hansen (1967)

This equation applies Bagnold's stream power concept and the similarity principle in which a series of non-dimensional parameters are obtained to characterize sediment transport. The relatively simple equation was formulated from a small set of laboratory data but has been shown to perform well as a field predictor (García 2008).

q_t - unit volume total bed material transport rate per unit width [L^2/T] is

$$q_t = q_t^* \sqrt{RgD}D$$, where

Einstein number q^*_t for total bed material load [1] is

$$q_t^* = \frac{0.05}{C_f}(\tau^*)^{5/2}$$, and

the total resistance coefficient C_f [1] is

$$C_f = \frac{2(gR_hS_f)}{U^2}$$, and

the Shields number τ^* [1] is

$$\tau^* = \frac{\tau_b}{\rho RgD} = \frac{u_*^2}{RgD}$$

Where:

g = acceleration of gravity [L/T^2]
R_h = hydraulic radius [L]
S_f = down-channel friction slope [1]
U = depth- or cross sectionally-averaged flow velocity [L/T]
$\tau^* = \tau_b/(\rho RgD)$, Shields number [1]
$\tau_b = \rho gHS_f$, bed shear stress [$M/L/T^2$]
$R = (\rho/\rho_s - 1)$, sediment submerged specific gravity [1]
ρ = water density [M/L^3]
ρ_s = sediment material density [M/L^3]
D = grain size [L]
H = cross sectionally averaged flow depth [L]
$u_* = \sqrt{\tau_b / \rho}$, shear velocity [L/T]

A.4.2.3 Molinas and Wu (2001)

Molinas and Wu state that many sediment transport equations are derived from laboratory studies with shallow flow depths where Reynolds numbers are much lower; Froude numbers are much higher; and water surface slopes are steeper when compared to conditions in large, natural rivers (Molinas and Wu

2001). Molinas and Wu (2001) used the universal stream power concept to develop a bed material load equation for large sand-bed rivers. An advantage of their equation is that the energy slope (S_f) is not a required input, which can be difficult to accurately measure on large low-gradient rivers (Molinas and Wu 2001).

q_t - unit volume total bed material transport rate per unit width [L^2/T] is

$q_t = .0027 q_w C_t$, where

flux-based volume total bed material concentration C_t [ppm] is

$$C_t = \frac{1430\left(0.86+\sqrt{\Psi}\right)\Psi^{1.5}}{0.016+\Psi}$$, and

Ψ = universal stream power [1] is defined as

$$\Psi = \frac{U^3}{gRHv_s\left[\log_{10}\left(\frac{H}{D}\right)\right]^2}$$

Where:

U = depth- or cross sectionally-averaged flow velocity [L/T]
g = acceleration of gravity [L/T^2]
R = $(\rho/\rho_s - 1)$, sediment submerged specific gravity [1]
ρ = water density [M/L^3]
ρ_s = sediment material density [M/L^3]
H = cross sectionally averaged flow depth [L]
ν_s = particle terminal fall velocity in quiescent water [L/T]
D = grain size [L]
q_w = water discharge per unit width [L^2/T]

A.4.2.4 Yang (1973)

This equation is based on dimensional analysis and unit stream power theory, with coefficients determined from multiple regression analysis of laboratory flume data (García 2008). Yang and Molinas (1982, as cited in García 2008) report good results when comparing the Yang (1973) equation with 166 river measurements, although no large rivers were included in the analysis (García 2008).

q_t - unit volume total bed material transport rate per unit width [L^2/T] is

$$q_t = \frac{1}{(R+1)}\frac{X_t}{(1-X_t)}q_w$$, and

Flux-based mass concentration of total bed material sediment X_t [1] is

$$\ell og_{10}(X_t \cdot 10^6) = 5.435 - 0.286\ell og_{10}(\mathbf{R}_f\mathbf{Re}_p) - 0.457\ell og_{10}\left(\frac{u_*}{v_s}\right) + \left[1.799 - 0.409\ell og_{10}(\mathbf{R}_f\mathbf{Re}_p) - 0.314\ell og_{10}\left(\frac{u_*}{v_s}\right)\right]\ell og_{10}\left(\frac{US_f}{v_s} - \frac{U_cS_f}{v_s}\right)$$

where

$$\frac{U_c}{v_s} = \begin{cases} \dfrac{2.5}{\ell og_{10}\left(\dfrac{u_*D}{\nu}\right) - 0.06} + 0.66 & , \quad 1.2 < \dfrac{u_*D}{\nu} < 70 \\ 2.05 & , \quad 70 \le \dfrac{u_*D}{\nu} \end{cases}$$

and

$$\mathbf{R}_f = \frac{v_s}{\sqrt{RgD}}, \quad \mathbf{Re}_p = \frac{\sqrt{RgD}\,D}{\nu}$$

Where:

R = ($\rho/\rho_s - 1$), sediment submerged specific gravity [1]
ρ = water density [M/L^3]
ρ_s = sediment material density [M/L^3]
Re_p = $\sqrt{RgD}\,D/\nu$ [1]
g = acceleration of gravity [L/T^2]
D = grain size [L]
ν = kinematic viscosity of water [L^2/T]
q_w = water discharge per unit width [L^2/T]
v_s = particle terminal fall velocity in quiescent water [L/T]
u_* = $\sqrt{\tau_b/\rho}$, shear velocity [L/T]
τ_b = $\rho g H S_f$, bed shear stress [$M/L/T^2$]
H = cross sectionally averaged flow depth [L]

S_f = down-channel friction slope [1]
U = depth- or cross sectionally-averaged flow velocity [L/T]

A.4.2.5 Series Expansion of the Modified Einstein Procedure (SEMEP) (Shah-Fairbank 2009, Guo and Julien 2004)

Hans Albert Einstein (1950) developed a method to determine a channel's total sediment load by calculating the bed load transport and integrating the suspended sediment discharge equation to compute the amount of sediment in transport in the channel's unmeasured zone. Suspended sediment discharge was determined by integrating the product of the theoretical velocity profile (Keulegn 1938, as cited in Shah-Fairbank 2009) and suspended sediment concentration profile (Rouse 1937, as cited in Shah-Fairbank 2009).

The Einstein (1950) method is beneficial when the majority of the transported sediment is near the bed. Colby and Hembree (1955) developed a modified Einstein procedure (MEP) that is better suited than the original Einstein (1950) method for application at cross sections in sand-bed rivers where the majority of the sediment is transported in suspension throughout the water column. The MEP requires measurement of suspended sediment that is then extrapolated throughout the unmeasured zone to determine total sediment load. Numerous improvements have been made to the MEP, including the update of Colby and Hubbell (1961) and Burkham and Dawdy (1980).

Shah-Fairbank (2009) developed a new version of the MEP that includes improvements to make it more user-friendly and to eliminate some of the empiricism of selecting input parameters.

Four of the stated (Shah-Fairbank 2009) major improvements to the MEP include:

1. Incorporation of an algorithm developed by Guo and Julien (2004) to quickly and accurately solve the Einstein integrals based on a series expansion method.
2. Basing total sediment discharge calculations on the median particle size of the suspended sediment (D_{50ss}) rather than dividing the bed material and suspended sediment gradations into particle size classes.
3. Determining Rouse numbers directly for depth-integrated suspended sediment samples by calculating particle fall velocities based on D_{50}, shear velocity, and assuming a constant value for the von Kármán constant. Therefore, it is no longer necessary to determine Rouse numbers for each overlapping class and fit power regressions to the data.

4. Use of measured suspended sediment discharge and Rouse numbers to calculate the bed load component of the total sediment discharge directly instead of using Einstein's probability of entrainment.

The SEMEP equation differs from the other four equations in that it calculates the amount of bed material in transport using a relationship between the material in the bed substrate and the particle size and concentration of material measured in suspension. It is designed to estimate the actual amount of sediment in transport rather than an equilibrium sediment load, which is the maximum amount of sediment that could be transported at a location if the sediment was available. The equation uses measured total suspended sediment concentrations, bed (D_{10}, D_{50}, D_{65}) and suspended sediment (D_{50}) particle sizes, and channel hydraulics to determine the amount of sediment being transported in the unmeasured zone (see Figure A-16). The unmeasured zone includes bed load and suspended sediment in transport near the channel bottom beneath the maximum depth that a suspended sediment sampler can sample (typically less than 0.5 foot). The bed material portion of the total suspended load is based on the percent of the total suspended load that is coarser than the D_{10} of the bed material. The MEP, on which the SEMEP is based, is well established and a recommended approach where most of the sediment is transported in suspension (as on the LOMR) and where the sand supply may be restricted (Hicks and Gomez 2003). The MEP was used in the only other study to calculate bed material loads on the LOMR, the 1999 *Missouri River Levee Unit L-385 Sediment Analysis* (West Consultants 1999).

Suspended sediment concentrations on the Missouri River at the four gaging locations are known because of the point-sampler and depth-integrated measurements made by the USGS. If a sample was collected with a point-sampler, then integrating the point concentration and point velocity data produces the unit measured sediment discharge q_m [M/LT]

$$q_m = \int_{d_n}^{H} c u_y \, dy$$

Where:

d_n = nozzle distance from the bed, unmeasured depth [L]
H = cross sectionally averaged flow depth [L]
c = flux-based volume suspended sediment concentration [ppm]
u_y = point velocity at depth y [L/T]
y = vertical distance from water surface [L]

The Rouse number Ro is calculated from

$$Ro = \frac{v_s}{\kappa u_*}$$

Where:

ν_s = suspended sediment D_{50} particle terminal fall velocity in quiescent water [L/T]
κ = von Kármán constant (set at 0.4)
$u_* = \sqrt{ghS_f}$, shear velocity [L/T]
g = acceleration of gravity [L/T^2]
h = flow depth [L]
S_f = down-channel friction slope [1]

Once q_m and Ro are known, then unit bed load discharge q_b is determined directly from q_m by using the Guo and Julien (2004) algorithm to solve the Einstein integrals with series expansion

$$q_m = 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left(\frac{30h}{y_0}\right) J_{1a} + J_{2a} \right\}$$

Where:

$E = 2D_{50}/h$
D_{50} = median bed grain size [L]
y_0 = vertical distance where velocity is zero = D_{65}

and where the integrals J_{1a} and J_{2a} are

$$J_{1a} = \int_A^1 \left(\frac{1-y'}{y'}\right)^{Ro} dy'$$

$$J_{2a} = \int_A^1 \ln y' \left(\frac{1-y'}{y'}\right)^{Ro} \ln y' \, dy'$$

Where:

$A = d_n/h$
$y' = y/h$

The total suspended sediment discharge q_s that includes the unmeasured zone is then determined by integrating the measured suspended sediment load from the water surface to the top of the bed load layer, defined as twice the depth of the bed sediment D_{50}

$q_s = 0.216 q_b \frac{E^{Ro-1}}{(1-E)^{Ro}} \left\{ \ln\left(\frac{30h}{y_0}\right) J_1 + J_2 \right\}$, where the integrals J_1 and J_2 are

$$J_1 = \int_E^1 \left(\frac{1-y'}{y'}\right)^{Ro} dy'$$

$$J_2 = \int_E^1 \ln y' \left(\frac{1-y'}{y'}\right)^{Ro} dy'$$

The total sediment discharge q_t is then determined from

$$q_t = q_b + q_s$$

As stated above, the SEMEP equation requires input of total suspended sediment load. As evident in the scatter of the USGS measured total suspended sediment and suspended sand load data plotted in Figures A-29 through A-32, a given discharge can have wide variability in the measured load. A best-fit line through the scattered data was created to develop a rating curve in which only one sediment load is associated with any given discharge. The best-fit line reduced the scatter into one typical load for a given discharge to represent the 1994–2009 data.

Two methods were used to develop the sediment rating curves, and an analysis was performed on each rating curve to determine which curve provides the best fit to the measured data. As discussed above, the USGS used LOADEST (Runkel et al. 2004) to calculate annual total suspended sediment and suspended sand loads. In the first method, all the USGS total suspended sediment and mean daily discharge measurements from 1994 to 2008 at the four gages were input into LOADEST so that LOADEST could determine the best-fit rating curve to the sediment and discharge data using the Adjusted Maximum Likelihood Estimation (AMLE) technique (Runkel et al. 2004). In the second method, the same discharge and sediment data were used to develop power function rating curves in spreadsheet software. The power function rating curves were visually fit to the data using multiple linear segments to provide a better fit with the data, as opposed to using one power function for all the data that can lead to overestimates or underestimates (Simon et al. 2004). Figures A-29 through A-32 show the resulting rating curves developed with AMLE and power functions for the gage locations. For each sediment rating curve, the total load obtained by summing the predicted load for each mean daily discharge for years 1994–2008 was compared with the sum of all the 1994–2008 annual total sediment loads reported as preliminary values by the USGS (or against the published daily loads at Nebraska City).

Results of the rating curve analysis are presented in Table A-9. The sediment loads are reported as 1994–2008 average annual loads. The percent difference is listed between the average annual load obtained by summing the individual mean daily loads predicted by each rating curve and the USGS preliminary annual loads (or published daily loads at Nebraska City). The loads predicted by the rating curve with the lowest percent difference were used as the total suspended sediment load input in the SEMEP analysis. The coefficient of determination r^2 values of the selected rating curve for each gage are also listed in Table A-9 to show how well the measured data fits the best-fit trend line. The results show that the power functions produced the best results at the St. Joseph, Kansas City, and Hermann gages, in which the rating curve values are within 6 percent of the USGS preliminary values. At Nebraska City, the LOADEST AMLE rating curve provides the best fit to the measured data and therefore was selected for the SEMEP analysis.

The SEMEP calculation requires the D_{50} of the suspended sediment load (as does the Molinas and Wu equation). As described above, the recent USGS particle size analysis of their measured suspended loads did not include the clay and silt fraction, which typically represents more than one-half of the total suspended load. Therefore, older suspended sediment particle size curves created by the USACE on the LOMR were analyzed to determine the D_{50} of the suspended load. Figure A-33 is an example of a curve in which the D_{50} of the measured suspended load is fine silt. The USGS analyzed all the mechanical analysis curves available to determine the suspended sediment D_{50}. The results used in the SEMEP calculation are listed in Table A-10. Because no data were available at Nebraska City, the D_{50} from St. Joseph (0.018 mm) was used.

Values used in the SEMEP calculation for the percent of the total suspended load coarser than the D_{10} of the bed material are listed in Table A-4. Because the percent sand content in the total suspended load does not show a correlation with discharge, the same average gradation for each location was used for the entire range of discharges modeled with the SEMEP.

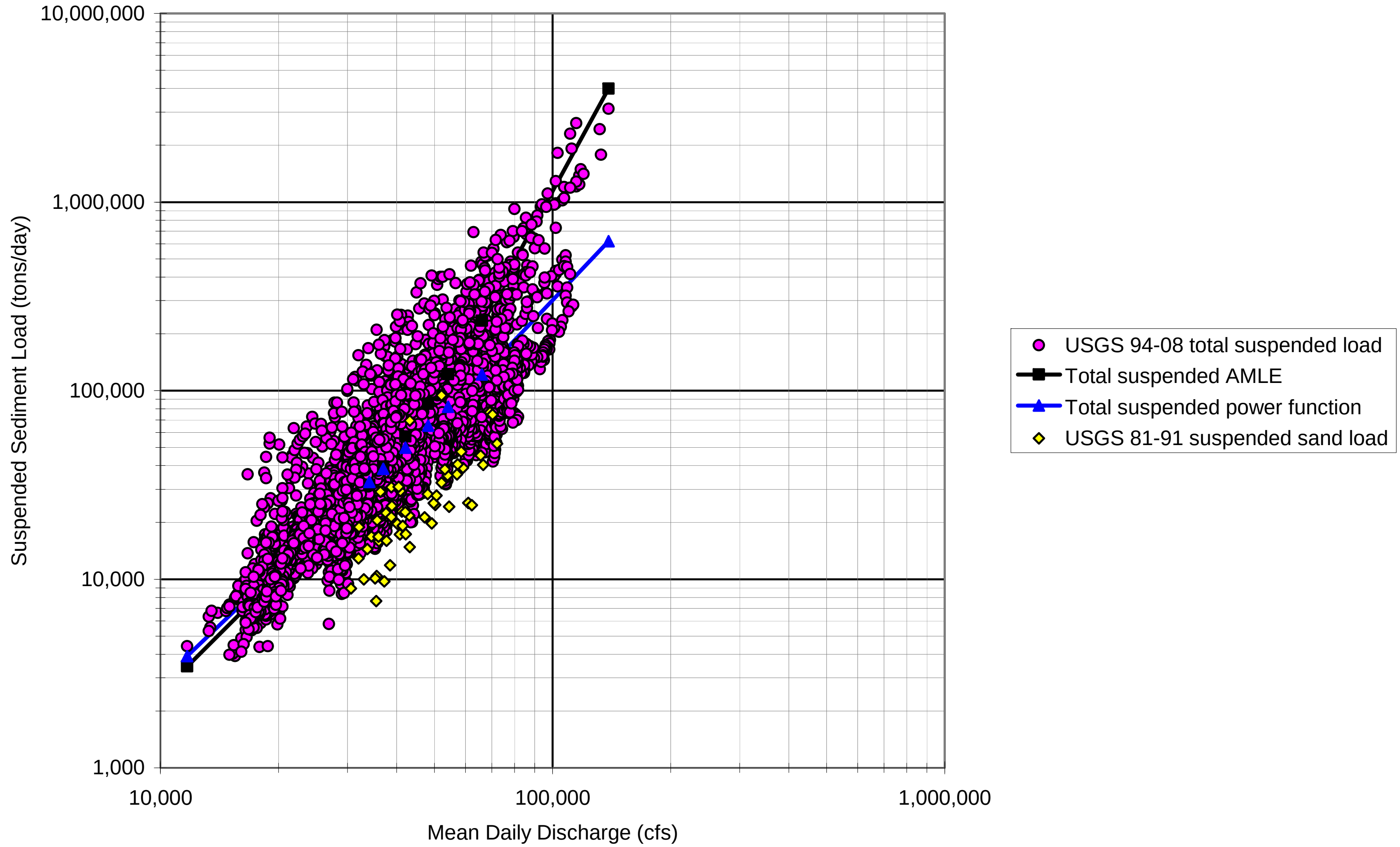

Figure A-29 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the Nebraska City Gage

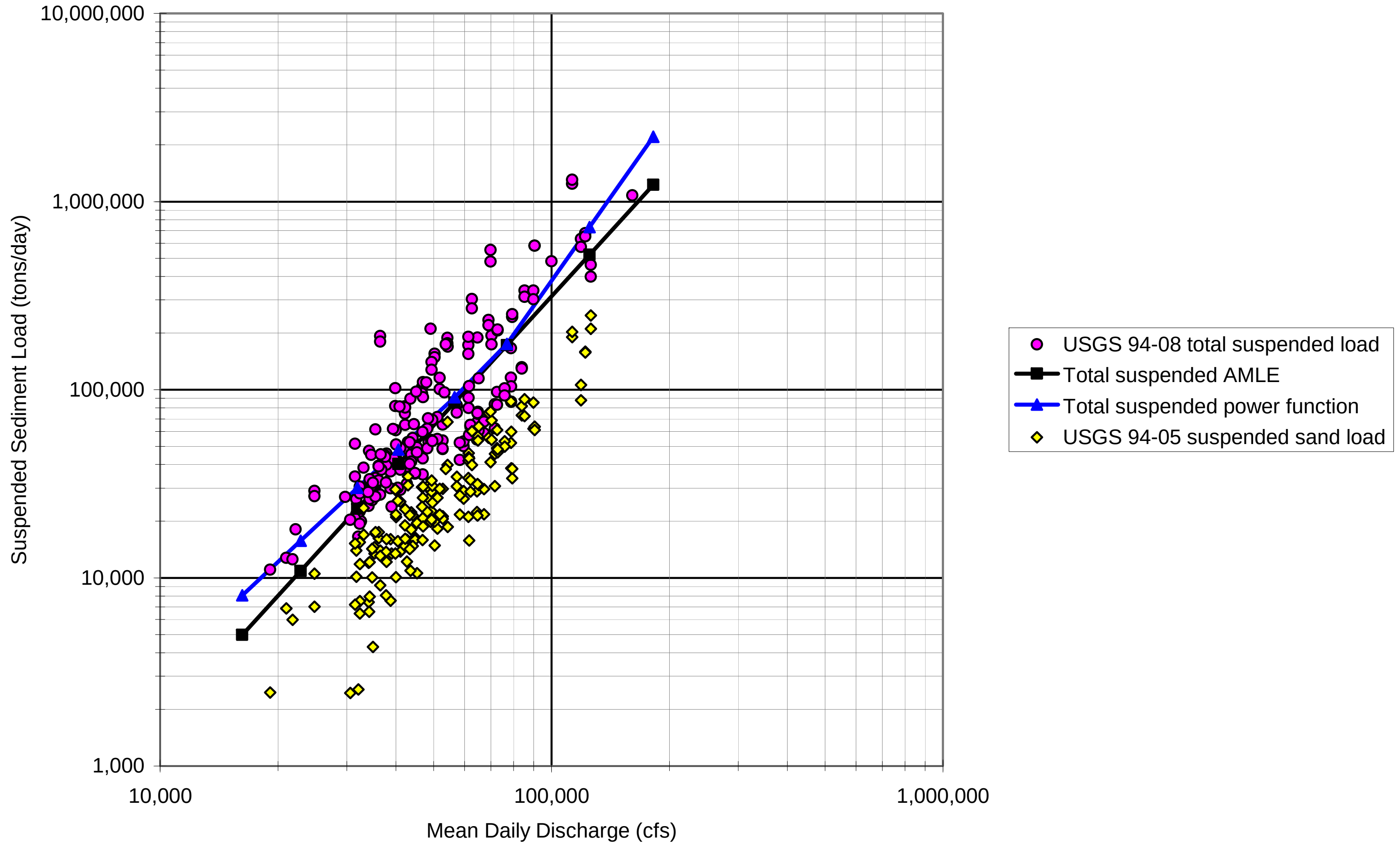

Figure A-30 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the St. Joseph Gage

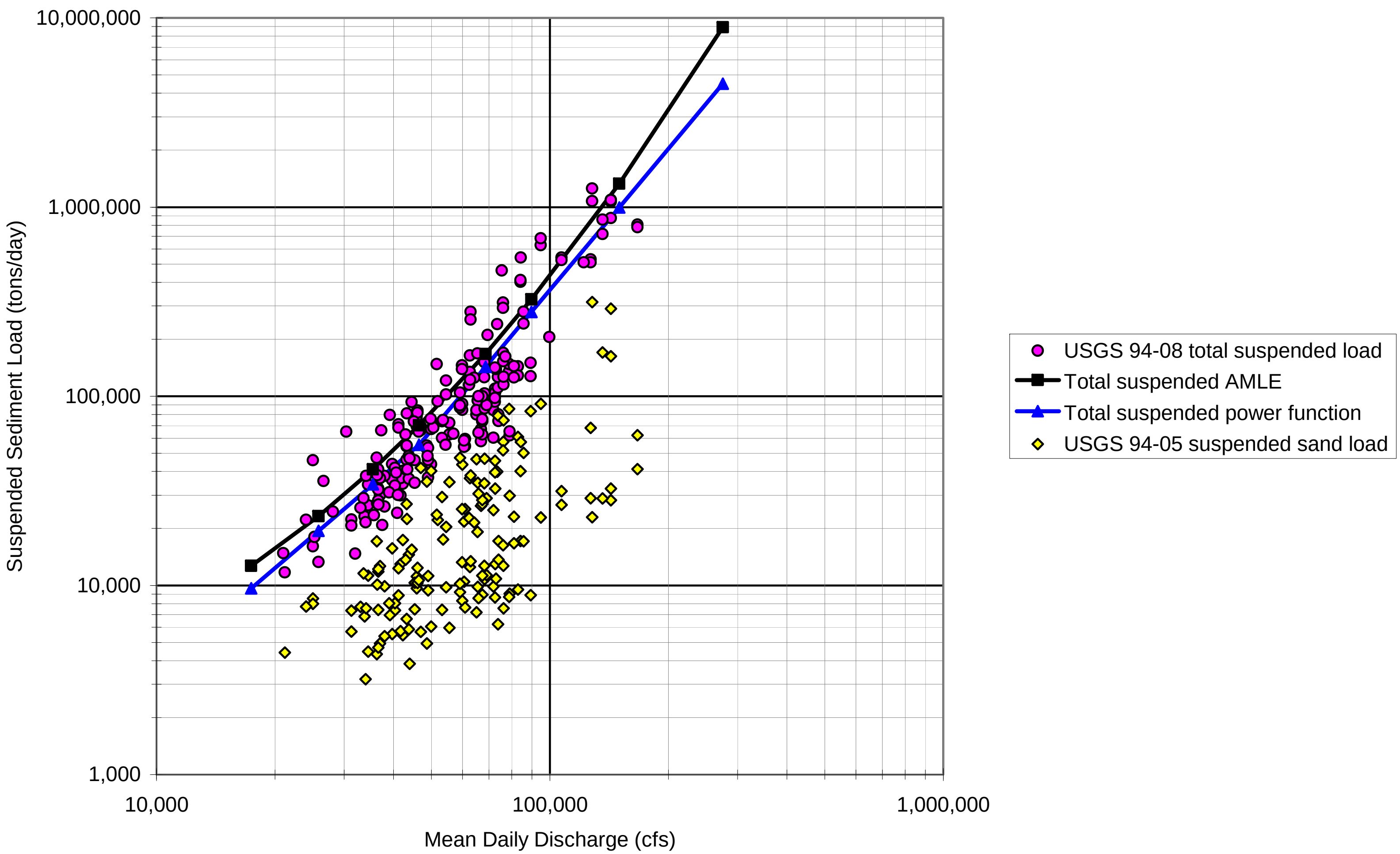

Figure A-31 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the Kansas City Gage

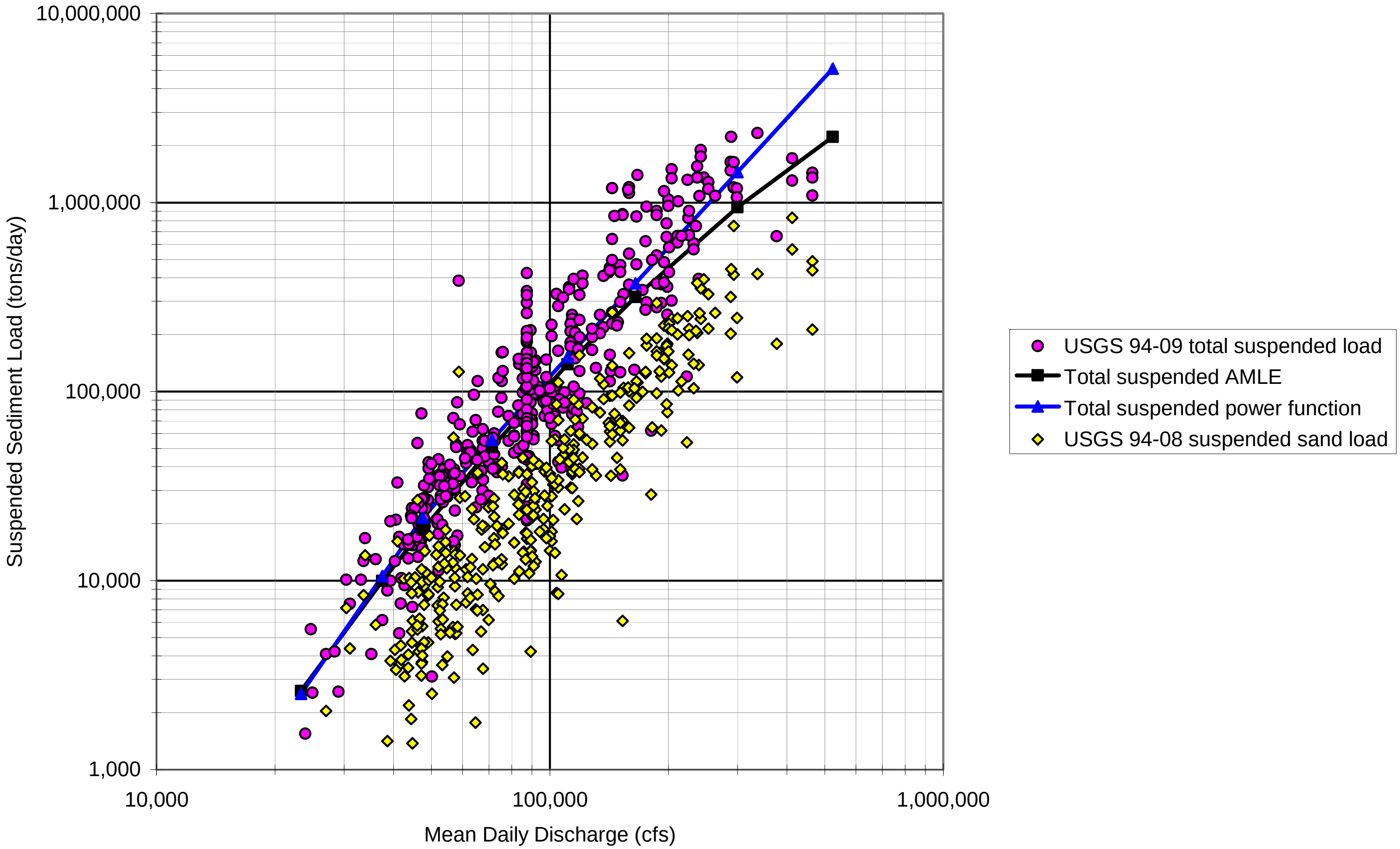

Figure A-32 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the Hermann Gage

Table A-9 Comparison of Sediment Rating Curve Predictions for Average Annual Total Suspended Sediment Loads (1994–2008)

Method	Nebraska City (tons/year)	Percent Difference of Rating Curve from USGS	St. Joseph (tons/year)	Percent Difference of Rating Curve from USGS	Kansas City (tons/year)	Percent Difference of Rating Curve from USGS	Hermann (tons/year)	Percent Difference of Rating Curve from USGS
USGS published data	25,136,476	-	N/A	-	N/A	-	N/A	-
USGS preliminary data	-	-	34,555,758	-	48,724,550	-	57,777,344	-
AMLE rating curve	22,726,508	**-9.6%**	31,492,698	-8.9%	44,779,810	-8.1%	52,237,144	-9.6%
Power function rating curve	20,511,116	-18.4%	32,561,942	**-5.8%**	48,467,340	**-0.5%**	57,402,506	**-0.6%**
r^2 of selected rating curve	-	0.81	-	0.63 (lower trend) 0.57 (upper trend)	-	0.69 (lower trend) 0.62 (upper trend)	-	0.59 (lower trend) 0.65 (upper trend)

Notes:

N/A = No data available.

Bolded items indicate rating curve selected (Adjusted Maximum Likelihood Estimate [AMLE] or power function) for input in the Series Expansion of the Modified Einstein Procedure (SEMEP) analysis.

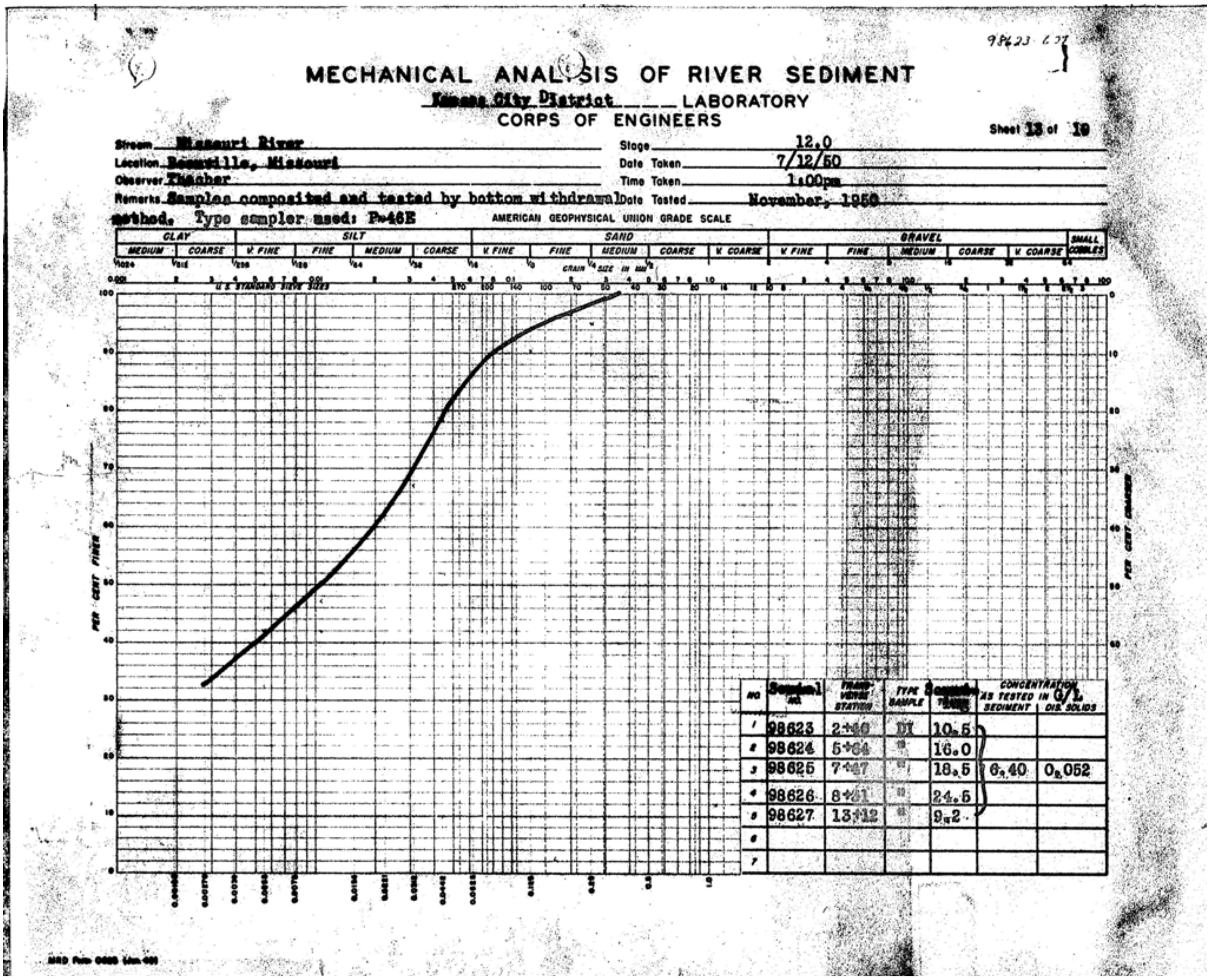

Figure A-33 Example of USACE Mechanical Analysis Curve That Includes Particle Size Analysis for the Clay and Silt Fraction of the Suspended Load

Table A-10 Suspended Sediment D_{50} Values Obtained from USACE Mechanical Analysis Curves

	Location		
	St. Joseph	Kansas City	Hermann
Years	1948–1950; 1963–1965	1949; 1963–1965	1963–1965
Number of samples	88	12	6
Average D_{50} (mm)	0.018	0.016	0.012
Particle class	Silt	Silt	Silt
Standard deviation (mm)	0.004	0.011	0.0016

Note: mm = Millimeter(s).

The unmeasured depth d_n, or distance of the sediment sampler's nozzle from the bed when lowered to its maximum depth, was set at 4.3 inches in the SEMEP calculations. This corresponds to the nozzle distance specified for the P-61 sediment sampler (Edwards and Glysson 1999), which was the sampler model most commonly used to collect the suspended sediment measurements.

As is commonly done (Molinas and Wu 2000), the Yang, Ackers and White, and Engelund and Hansen equations were used in fractional form to estimate the transport for each particle size fraction D_i of the bed material at the gage location rather than the D_{50}. Table A-11 illustrates the geometric mean D_i determined from the class sizes used in the fractional analysis.

Table A-11 Grain Sizes Classes Used in the Fractional Bed Material Load Equations

Grain Size (millimeters)	Class (millimeters)	D_i (millimeters)
32	16–32	22.63
16	8–16	11.31
8	4–8	5.66
4	2–4	2.83
2	1–2	1.41
1	0.5–1	0.71
0.5	0.25–0.5	0.35
0.25	0.177–0.25	0.21
0.177	0.125–0.177	0.15

The transport rates for each particle fraction were summed to obtain the total bed material load from

$$q_t = \sum_{i=1}^{N} q_{ti}$$

Where:

q_t = bed material load per unit width
N = number of size fractions in the sediment mixture
i = size fraction within a mixture

The bed material particle size gradations (Figure A-6) and average hydraulic output (including channel depths, velocities, shear stresses, energy slopes, and widths) for the several cross sections that comprise the HEC-RAS modeling reach at each location were used in the calculations. Because hydraulics, and thus bed material load estimates, can vary between nearby cross sections, the average of several cross sections was used to best represent the typical hydraulic conditions in the reach.

Results of the SEMEP analysis are listed in Tables A-12 through A-15 for each gage. The total sediment load (Q_t) is the sum of the measured (Q_m) and unmeasured sediment loads (Q_{um}), and includes all the material moving in transport as either suspended load or bed load. The fraction of the total sediment load composed of wash load and bed material load is also listed. The total amount of sediment moving in the unmeasured zone is typically 1–2 percent and is inversely related to flow magnitude. The bed material load as a percentage of total sediment load is also listed in Tables A-12 through A-15. Depending on flow magnitude, the bed material load is generally less than 14–16 percent of the total load, except for Hermann where it is 6–8 percent.

A.4.3 Total Bed Material Load Equation Results

Total bed material load transport rating curves for the four gages are displayed in Figures A-34 through A-37. The curves show how much sediment (in tons/day) each equation predicts can be transported for a given discharge (in cfs). The Yang, Ackers and White, Molinas and Wu, and Engelund and Hansen equations all predict similar total bed material loads. The SEMEP equation consistently predicts less total bed material load than the other transport capacity equations at low to moderate discharges. At Nebraska City and Kansas City, SEMEP predicts higher loads for high-flow events.

The bed material rating curves were used to calculate sediment loads for each mean daily discharge for the period from 1994 to 2009. The mean daily loads were summed to obtain average annual loads, which are summarized in Table A-16. The period from 2000 to 2009 was selected for analysis because it is comparable to detailed dredging data from the same period, but the mean annual flows in this period tend to be lower than the long-term mean (see Figure 3.4-14 in the main volume of the Draft EIS). The period from 1994 to 2009 includes higher than average flows during the 1990s and, when combined with the drier years from 2000 to 2009, represents average conditions.

Although each of the five equations uses different methods and makes different assumptions, each is calculating the same value—the total amount of bed material transported by the Missouri River at the four gage locations. The SEMEP calculation yielded similar results as the other four equations for each gage location, except for the Hermann gage, for which SEMEP yielded slightly more than one-half of the average of the other four equations (Table A-16). Because the SEMEP equation uses measured suspended sediment data and represents an actual estimate of bed material load rather than transport capacity, it was given greater weight when compared with the other four equations. To obtain a representative value of the bed material load at each gage location, a weighted average was used that combines the average of the four transport-based equations with the result of the SEMEP equation. The SEMEP result averaged with the average of the other four equations is reported in Table A-16.

Table A-12 Results of the SEMEP Calculations at the Nebraska City Hydraulic Modeling Reach

Discharge (cfs)	Measured Sediment Load Q_m (tons/day)	Unmeasured Sediment Load Q_{um} (tons/day)	Total Sediment Load ($Q_t = Q_{um}+Q_m$) (tons/day)	Percent Unmeasured Q_{um}/Q_t (%)	Wash Load Q_w (tons/day)	Bed Material Load Q_{bm} (tons/day)	Percent Bed Material Load Q_{bm}/Q_t (%)
11,700	3,447	110	3,557	3.1%	2,999	558	15.7%
34,100	31,614	547	32,161	1.7%	27,504	4,657	14.5%
37,000	39,437	652	40,089	1.6%	34,310	5,779	14.4%
42,150	56,999	875	57,874	1.5%	49,589	8,285	14.3%
48,200	84,922	1,210	86,132	1.4%	73,882	12,249	14.2%
54,125	121,807	1,626	123,432	1.3%	105,972	17,460	14.1%
66,050	234,309	2,797	237,105	1.2%	203,849	33,257	14.0%
139,000	3,983,036	31,355	4,014,391	0.8%	3,465,241	549,150	13.7%

Notes:

cfs = Cubic feet per second.
SEMEP = Series Expansion of the Modified Einstein Procedure.

Table A-13 Results of the SEMEP Calculations at the St. Joseph Hydraulic Modeling Reach

Discharge (cfs)	Measured Sediment Load Q_m (tons/day)	Unmeasured Sediment Load Q_{um} (tons/day)	Total Sediment Load ($Q_t = Q_{um}+Q_m$) (tons/day)	Percent Unmeasured Q_{um}/Q_t (%)	Wash Load Q_w (tons/day)	Bed Material Load Q_{bm} (tons/day)	Percent Bed Material Load Q_{bm}/Q_t (%)
16,200	8,070	196	8,265	2.4%	7,021	1,245	15.1%
22,850	15,721	319	16,040	2.0%	13,677	2,362	14.7%
31,900	30,022	511	30,534	1.7%	26,119	4,414	14.5%
40,600	47,920	720	48,641	1.5%	41,691	6,950	14.3%
56,500	90,950	1,151	92,101	1.2%	79,127	12,975	14.1%
76,900	174,958	1,885	176,843	1.1%	152,214	24,629	13.9%
125,000	730,201	6,112	736,313	0.8%	635,275	101,038	13.7%
182,000	2,204,470	15,198	2,219,668	0.7%	1,917,889	301,779	13.6%

Notes:

cfs = Cubic feet per second.
SEMEP = Series Expansion of the Modified Einstein Procedure.

Table A-14 Results of the SEMEP Calculations at the Kansas City Hydraulic Modeling Reach

Discharge (cfs)	Measured Sediment Load Q_m (tons/day)	Unmeasured Sediment Load Q_{um} (tons/day)	Total Sediment Load ($Q_t = Q_{um}+Q_m$) (tons/day)	Percent Unmeasured Q_{um}/Q_t (%)	Wash Load Q_w (tons/day)	Bed Material Load Q_{bm} (tons/day)	Percent Bed Material Load Q_{bm}/Q_t (%)
17,400	9,623	211	9,834	2.1%	8,179	1,655	16.8%
25,800	19,377	346	19,723	1.8%	16,471	3,252	16.5%
35,500	34,167	516	34,683	1.5%	29,042	5,641	16.3%
46,500	55,197	725	55,921	1.3%	46,917	9,004	16.1%
68,600	142,759	1,532	144,291	1.1%	121,345	22,946	15.9%
89,800	278,484	2,600	281,085	0.9%	236,712	44,373	15.8%
150,000	994,666	7,127	1,001,792	0.7%	845,466	156,326	15.6%
275,000	4,475,737	23,505	4,499,242	0.5%	3,804,376	694,866	15.4%

Notes:

cfs = Cubic feet per second.
SEMEP = Series Expansion of the Modified Einstein Procedure.

Table A-15 Results of the SEMEP Calculations at the Hermann Hydraulic Modeling Reach

Discharge	Measured Sediment Load Q_m	Unmeasured Sediment Load Q_{um}	Total Sediment Load ($Q_t = Q_{um}+Q_m$)	Percent Unmeasured Q_{um}/Q_t	Wash Load Q_w	Bed Material Load Q_{bm}	Percent Bed Material Load Q_{bm}/Q_t
23,300	2,512	66	2,578	2.6%	2,362	217	8.4%
37,500	10,534	211	10,745	2.0%	9,902	843	7.8%
47,500	21,470	376	21,846	1.7%	20,182	1,664	7.6%
71,200	55,486	774	56,260	1.4%	52,157	4,104	7.3%
111,000	151,847	1,653	153,500	1.1%	142,736	10,764	7.0%
165,000	373,026	3,254	376,280	0.9%	350,645	25,635	6.8%
300,000	1,446,781	9,052	1,455,833	0.6%	1,359,975	95,859	6.6%
523,000	5,101,213	23,469	5,124,683	0.5%	4,795,141	329,542	6.4%

Notes:

cfs = Cubic feet per second.
SEMEP = Series Expansion of the Modified Einstein Procedure.

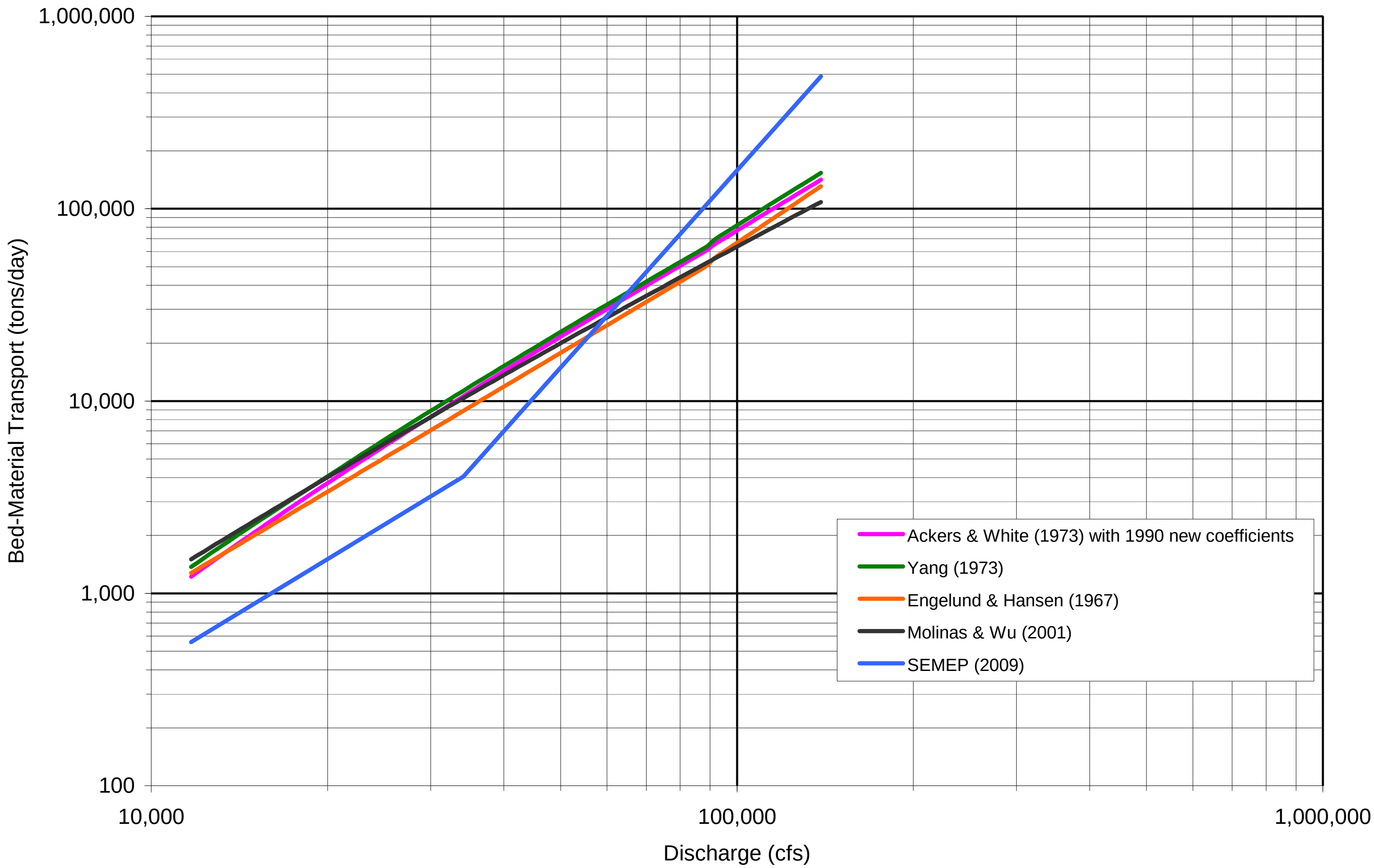

Figure A-34 Total Bed Material Rating Curves Produced by the Five Equations at the Nebraska City Hydraulic Modeling Reach

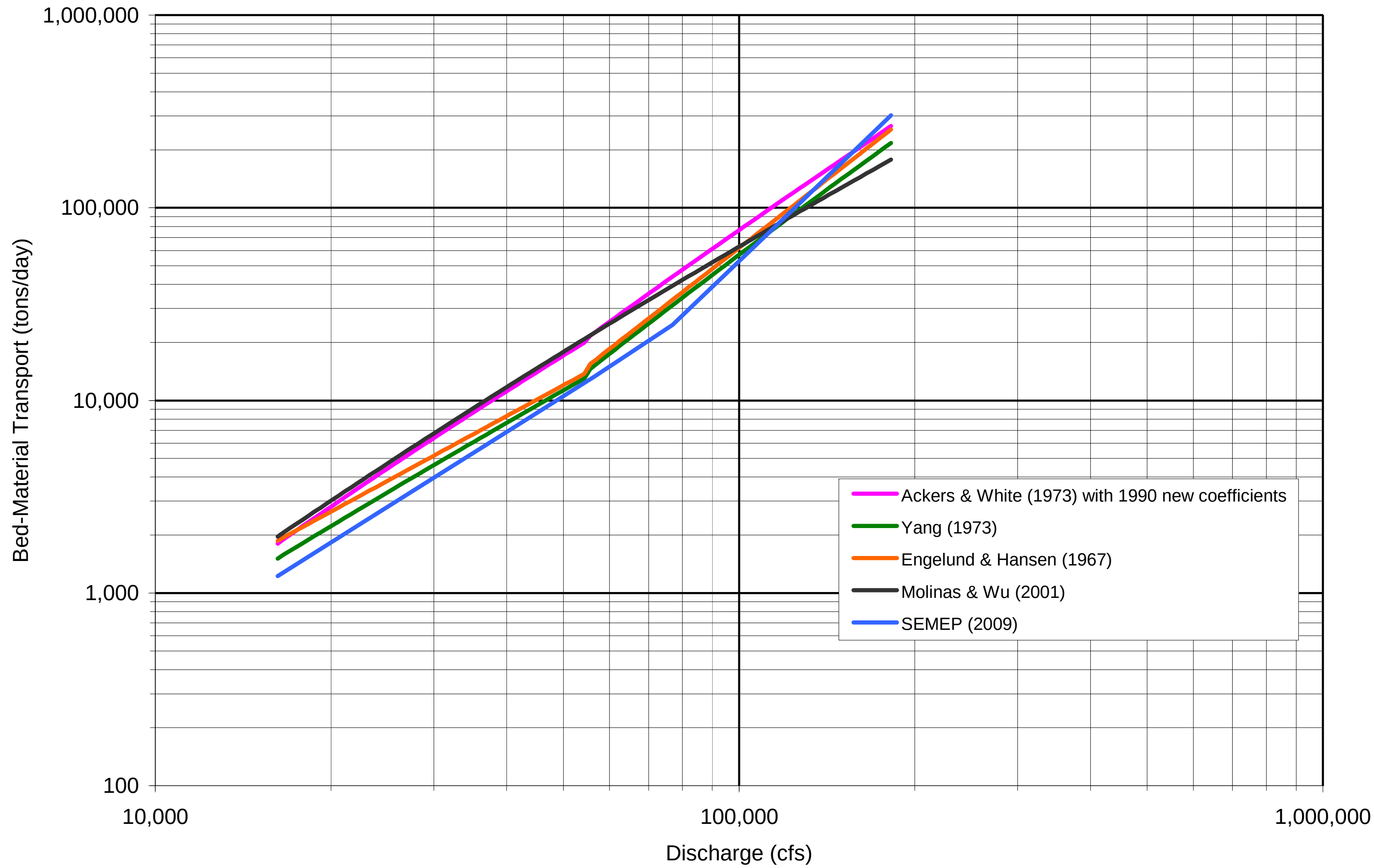

Figure A-35 Total Bed Material Rating Curves Produced by the Five Equations at the St. Joseph Hydraulic Modeling Reach

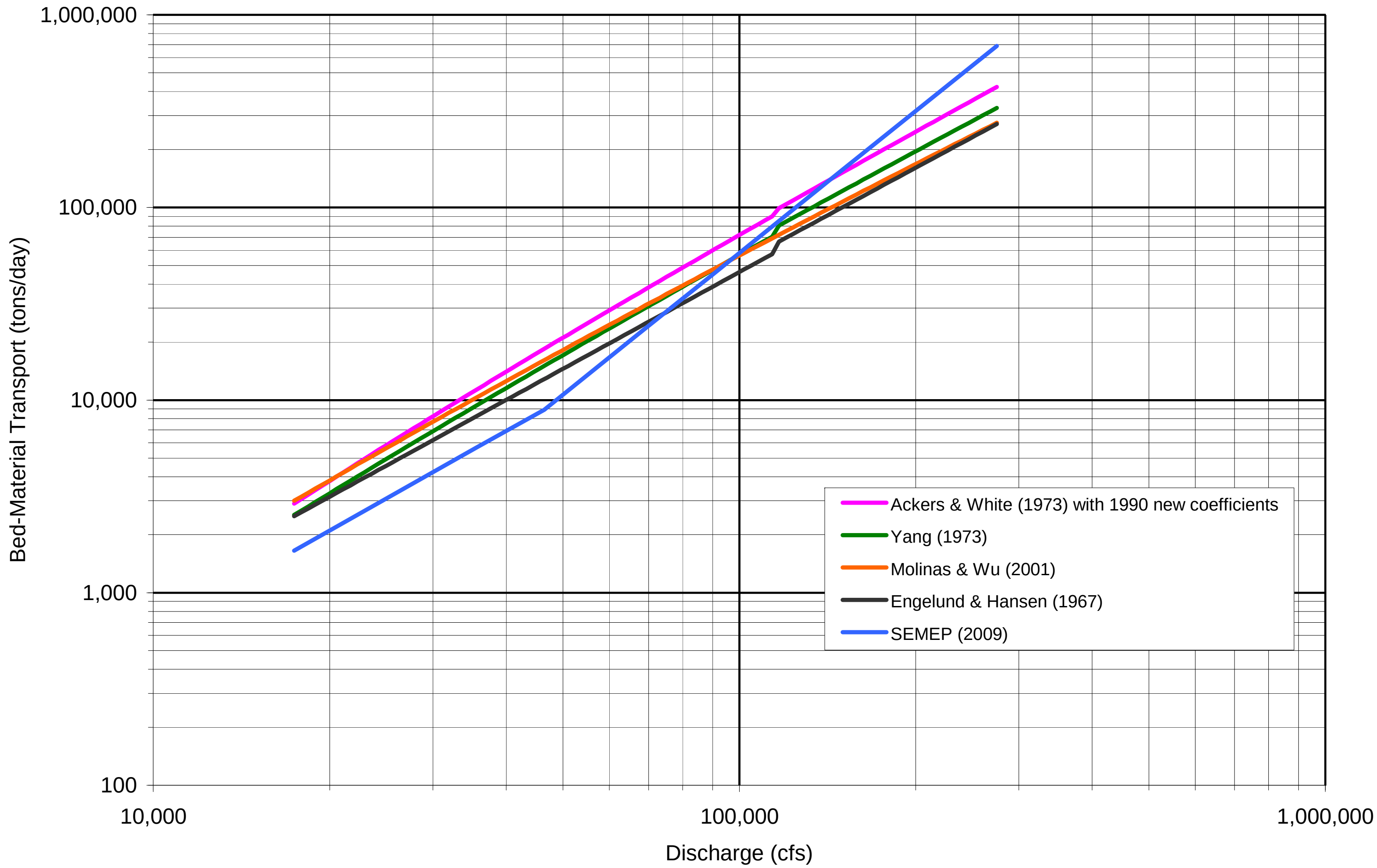

Figure A-36 Total Bed Material Rating Curves Produced by the Five Equations at the Kansas City Hydraulic Modeling Reach

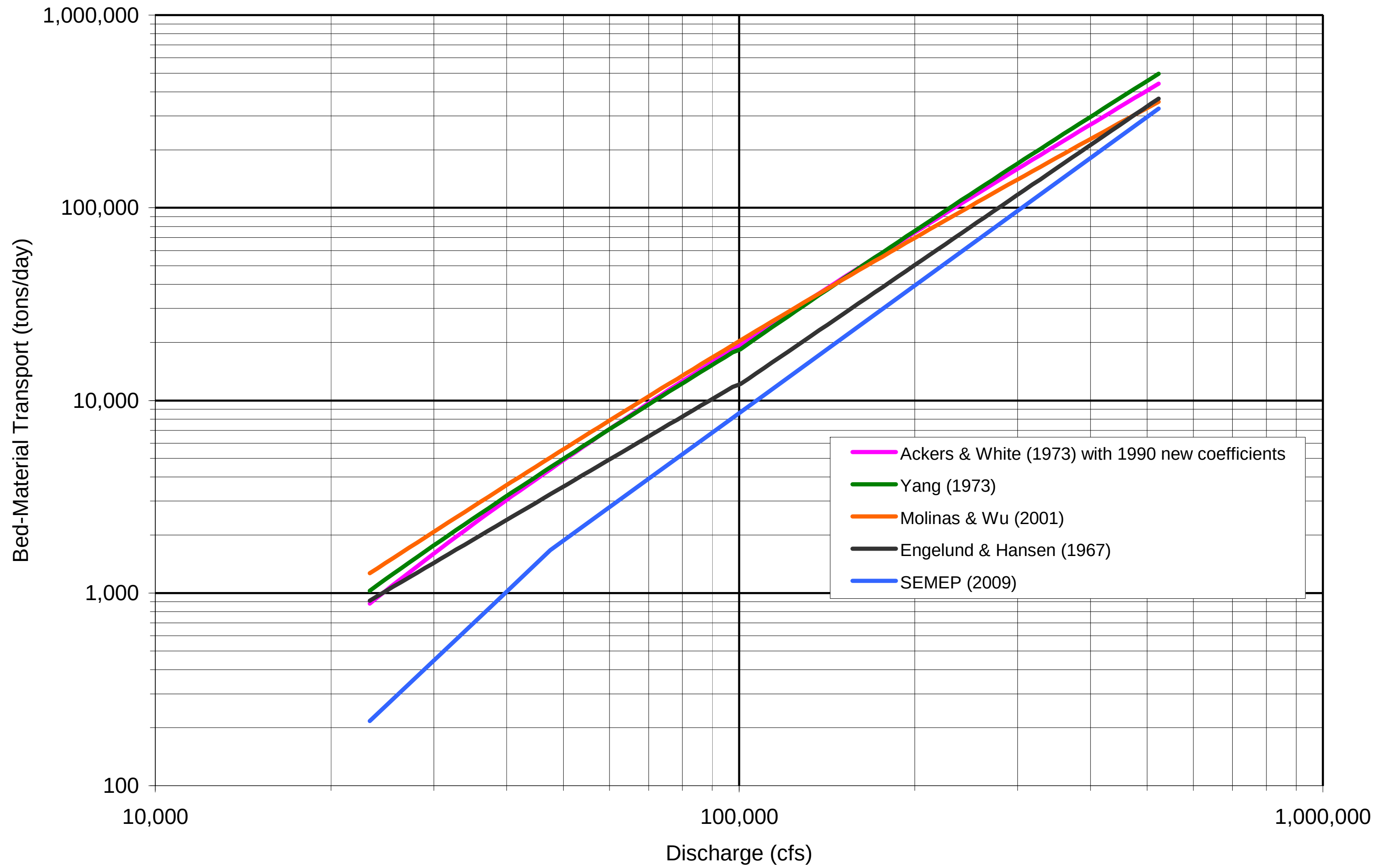

Figure A-37 Total Bed Material Rating Curves Produced by the Five Equations at the Hermann Hydraulic Modeling Reach

Table A-16 Total Bed Material Loads Estimated from Bed Material Load Equations (tons/year)

Location	Ackers & White (1973)	Engelund & Hansen (1967)	Molinas & Wu (2001)	Yang (1973)	Average (AVG) of Four Bed Material Equations (no SEMEP)	SEMEP (2009)	Weighted AVG – AVG of SEMEP and AVG of Four Bed material Equations	SEMEP as Percentage of AVG of Four Bed Material Equations
2000–2009								
Nebraska City	3,858,310	3,345,360	3,735,295	4,289,933	3,807,225	2,442,765	3,124,995	64%
St. Joseph	4,342,438	3,316,504	4,141,181	3,030,405	3,707,632	3,308,508	3,508,070	89%
Kansas City	7,147,775	5,032,985	5,991,383	5,834,135	6,001,569	4,702,736	5,352,153	78%
Hermann	5,303,880	3,726,159	5,187,083	5,301,546	4,879,667	2,517,785	3,698,726	52%
1994–2009								
Nebraska City	5,956,510	5,092,627	5,507,685	6,508,525	5,766,337	5,365,748	5,566,042	93%
St. Joseph	7,144,192	5,455,947	6,467,546	5,020,173	6,021,965	5,410,855	5,716,410	90%
Kansas City	10,584,323	7,305,296	8,550,699	8,576,194	8,754,128	7,650,806	8,202,467	87%
Hermann	7,912,424	5,553,251	7,561,138	7,969,907	7,249,180	3,956,009	5,602,594	55%

Note: SEMEP = Series Expansion of the Modified Einstein Procedure.

A.5 ESTIMATES OF ACCURACY AND COMPARISONS WITH OTHER STUDIES

A.5.1 Estimates of Equation Accuracy in the Literature

Each of the bed material load equations used in this study are equations commonly referenced in the professional literature and used in similar studies by researchers and practitioners. Because of the variability in several of the inputs into the equations, it is not feasible to track and quantify the potential cumulative error of the sediment rating curves in Figures A-34 through A-37.

Previous studies, however, have performed statistical analyses of estimated bed material loads with measured bed material loads to evaluate the accuracy of the equations. Molinas and Wu (2000) calculated correlation coefficients, *R*, by comparing computed versus measured bed material loads. *R* equals 1 when computed loads perfectly match the measured loads. The Engelund and Hansen (1967), Ackers and White (1973), and Yang (1973) equations used in this study were included in the Molinas and Wu (2000) study. Unlike this study, Molinas and Wu (2000) did not use the HR Wallingford (1990) adjusted coefficients, thus their analysis of the Ackers and White (1973) equation is not directly comparable. Molinas and Wu (2000) calculated *R* values of 0.51, 0.63, and 0.75 for the Engelund and Hansen (1967), Ackers and White (1973), and Yang (1973) equations, respectively. Thus, they determined the Engelund and Hansen equation performed the poorest and the Yang equation performed the best.

In a similar study, Molinas and Wu (2001) compared how their newly developed equation presented in the same paper (the equation used in this study), compared with other bed material load equations. The comparison of computed versus measured bed material loads focused on 414 data points from seven large rivers, including the Amazon and Orinoco Rivers, the Atchafalaya River, the Mississippi River, and the Red River. Molinas and Wu (2001) calculated *R* values of 0.58, 0.25, and 0.49 for the Engelund and Hansen (1967), Ackers and White (1973), and Yang (1973) equations, respectively. The authors calculated an *R* value of 0.81 for their own equation (Molinas and Wu 2001). Thus, they determined the Engelund and Hansen and Ackers and White equations performed the poorest and their equation performed the best for large sand-bed rivers. Molinas and Wu (2001) state that, on average, the Ackers and White and Engelund and Hansen overestimate bed material transport, while the Yang equation underestimates transport in large rivers. Again, note that unlike this study, Molinas and Wu (2001) did not use the HR Wallingford (1990) adjusted coefficients, thus their analysis of the Ackers and White (1973) equation is not directly comparable.

Shah-Fairbank (2009) compared how well the SEMEP equation estimated sediment loads compared with measured sediment load data. Only the values where the ratio of shear velocity to particle fall velocity (u^*/ω) are greater than five are considered here since these are the conditions on the LOMR. Comparison of the SEMEP equation's estimate of measured loads on the Platte River produced an *R* value of 0.71. Comparison of the SEMEP estimates against a set of measured sediment loads from 93 streams in the United States produced an *R* value of 0.99 (Williams and Rosgen 1989). Finally, comparison of the SEMEP against measured sediment loads on the Niobrara River produced an *R* value of 0.48. Shah-Fairbank (2009) concluded that the SEMEP equation performs best when the shear velocity to particle fall velocity ratio is greater than five and the sediment discharge is greater than 10,000 tons day. Both of these conditions are typical of the LMOR.

A.5.2 Comparison with Other Studies and Suspended Loads

The results of the bed material load estimates from this analysis were compared to the L-385 study results (West Consultants 1999) and to the bed material load-sized fraction of the suspended sediment loads to determine whether the results were comparable.

The L-385 study estimated bed material loads to determine the impact of dredging up to 3.5 million cubic yards of sediment from the Missouri River for use in levee construction upstream of the confluence with the Kansas River. They used the modified Einstein procedure to calculate the total bed material load. For the 1967–1997 period, which had higher than average mean annual flows at 59,837 cfs (mean annual flow for the period of record is 51,588 cfs), the study estimated an average bed material load of 10.9 million tons per year at Kansas City and 8.95 million tons at St. Joseph (Table A-17). The estimate between 1994 and 2009 for Kansas City and St. Joseph are 8.2 and 5.72 million tons per year, respectively. Given the difference in analysis periods, flows, and the variability in bed material loads, the results from the L-385 study are comparable to the results from the current analysis. One reason that the bed material loads reported in the L-385 study are higher than the current estimates is because the L-385 study considered particles coarser than 0.125 mm to be bed material load, whereas this study considered particle sizes coarser than approximately 0.2 mm to be bed material load.

Table A-17 Bed Material Load and Bed Material Load-Sized Fraction of the Total Suspended Sediment Estimates at Four USGS Gages (million tons/year)

	Period	Location			
		Nebraska City	St. Joseph	Kansas City	Hermann
This Analysis					
Averaged bed material load estimate	2000–2009	3.12	3.51	5.35	3.70
	1994–2009	5.57	5.72	8.20	5.60
Previous Studies					
L-385 study / West Consultants 1999	1967–1997	N/A	8.95	10.9	N/A
Bed Material Load-Sized Fraction of the Total Suspended Sediment					
USGS, preliminary	1994–2008	3.27	4.49	7.31	3.47
Jacobson adjusted (Jacobson et al. 2009)	1994–2006	2.95	3.96	6.93	3.65

Note: N/A = No data available.

Table A-17 also presents unpublished suspended sediment data from the USGS and results from Jacobson et al. (2009) adjusted to include only the bed material load-sized fraction. The bed material load-sized fraction of the suspended sediment load is an estimate of the bed material-sized fraction of the total suspended sediment measurements for each site in which all material finer than the D_{10} was removed. This allows a comparison with the bed material estimates, which also consider all material finer than the bed substrate D_{10} to be wash load. Considering the entire measured suspended sediment load as bed material load would overestimate the bed material load because a large percentage of the suspended sediment load is wash load that is continuously transported as wash load even at low velocities. Because bed material load includes sand that moves as bed load in the unmeasured zone and in suspension, the bed material load should be a higher value than the same-sized fraction moving in suspension. The results in Table A-17 indicate that this is the case for all of the estimated values for similar time periods. The table also shows lower values for the bed material load-sized fraction of the total suspended sediment at the Hermann gage compared to the Kansas City gage, providing verification of the trend from an independent data source.

A.6 COMPARISON OF THE RESULTS TO FLOWS AND DRAINAGE AREA

Table A-18 lists the average of the mean annual flows, the drainage areas, and the bed material loads (based on the weighted average of the SEMEP with the average of the four other equations) for the 1994–2008 period of the four gages used in the sediment analysis. Table A-18 also includes the percent change between the gage locations to allow comparison across the different parameters. For example, the increase in mean annual flow between the Nebraska City gage and the St. Joseph gage is 15 percent, between the St. Joseph gage and the Kansas City gage is 17 percent, and between the Kansas City gage and the Hermann gage is 62 percent.

Table A-18 Mean Annual Flow and Drainage Area Values for the Gages Used in the Sediment Load Analysis

	Location			
	Nebraska City	St. Joseph	Kansas City	Hermann
1994–2008 average mean annual flow (cfs)	40,939	46,895	54,975	89,074
1994–2008 mean annual flow range (cfs)	28,340–66,450	29,790–76,050	34,130–82,660	41,690–135,700
Percent increase in mean annual flow	-	15%	17%	62%
Drainage area (mi^2)	410,000	420,100	484,100	522,500
Percent increase in drainage area	-	2%	15%	8%
1994–2009 bed material load (million tons/yr)	5.57	5.72	8.20	5.60
Percent change in bed material load	-	2.7%	43.4%	-31.7%
1994–2008 Total suspended sediment load (USGS preliminary) (million tons/yr)	25.14	34.56	48.72	57.78
Percent change in total suspended sediment load	-	37.4%	41.0%	18.6%

For the 1994–2009 period, the total bed material load increases from Nebraska City to Kansas City and then decreases appreciably from Kansas City to Hermann (Table A-18). Between Nebraska City and St. Joseph, the bed material load increases approximately 2.7 percent, and between St. Joseph and Kansas City the bed material load increases approximately 43.4 percent. Increases in bed material load with increasing drainage area downstream are typical of large rivers because of the additional inputs of sediment and flow from the contributing watershed. Between Kansas City and Hermann, however, the bed material load estimate decreases by approximately 31.7 percent. For comparison, the measured total suspended load data shows an increase of 37 percent between Nebraska City and St. Joseph, and a 41-percent increase between St. Joseph and Kansas City (Table A-18). Even though the amount of total suspended sediment increases 19 percent between Kansas City and Hermann, the rate of increase is lower than expected considering that the 62-percent increase in mean annual flow between the two locations is approximately four times greater than the flow increases associated with the larger sediment increases upstream.

The increase in mean annual flow and a wider channel over which bed material load can be transported at Hermann compared to Kansas City does not translate into increased bed material load estimates. The reason for the decrease in bed material load between Kansas City and Hermann may be attributable to several factors. First, based on the hydraulic modeling results, the Hermann reach has lower flow velocities and boundary shear stresses at a given flow than the Kansas City reach, which results in lower sediment transport rates. Second, based on river bed particle size analysis, the cross section at the Hermann gage has a coarser bed material than Kansas City, which means that it requires more energy or higher flows to mobilize and transport sediment relative to Kansas City. Figure 3.4-18 in the Draft EIS shows the increasing trend in river bed particle sizes moving downriver. Third, there is a considerable increase in flows from tributaries between the Kansas City gage and the Hermann gage (Table A-18), but limited tributary sediment load data indicates that the Osage and Gaconade Rivers may not be contributing much sediment relative to their flows (see Table 3.4-17 in the Draft EIS). Increased flows from the Osage and Gasconade Rivers without increased sediment inputs would tend to increase transport capacity at equivalent flows. The higher estimated bed material load estimate of the four transport based equations relative to the SEMEP equation at the Hermann site seems to support this conclusion.

A.7 ANALYSIS OF RIVER BED ELEVATION CHANGE USING HYDROACOUSTIC DATA

A.7.1 Availability of Hydroacoustic Data

Several data sets are available for analyzing changes in river bed elevations on the LOMR. Each has strengths and limitations because most data were not collected for the purpose of assessing river-wide aggradation or degradation. Two sources of data have been analyzed and presented by the USACE to estimate aggradation and degradation on the LOMR: (1) long-term average river bed cross section elevation data collected at USGS gage locations; and (2) low-water surface elevation changes adjusted to Construction Reference Plane (CRP) data from 1990 and 2005. The cross section data collected at USGS gage locations provide annual estimates dating back to the late 1920s at five gage sites and back to the late 1940s at a sixth gage site. This dataset provides long-term bed elevation trend data, but at only six locations on the river.

The low-flow water surface elevation data set is based on the change in modeled low-flow water surface elevations between 1990 and 2005 and adjusted to CRP flows. This data set provides information on the change in water surface elevations between two points in time, but for the entire length of the river in the study area. Water surface elevations do not parallel river bed elevations exactly because water elevations result from a combination of factors, including discharge, slope, velocity, and channel roughness. The water surface tends to smooth out the highly variable and changing river bed surface. Because the CRP represents the water surface at relatively low flows (a flow exceeded 75 percent of the time), it can be used to estimate river bed elevation changes over time and over the length of the river.

One limitation of the low-flow data set is that it represents only the change between 1990 and 2005, and does not allow analysis of change within that time period or allow averaging of changing river bed elevations over time.

As part of the environmental impacts analysis, a third data set was analyzed. In 1998 and 1999, hydroacoustic bed elevation data (HBED) were collected along the LOMR in a “serpentine” manner, with approximately 50 feet between survey points (Figure A-38). Hydroacoustic data are collected from a moving boat using sound (similar to SONAR used on submarines) to determine the distance between the instrument and the river bed. The precise location of the boat is tracked using a satellite Global Positioning System (GPS). The 1998 data set contains approximately 200,000 bed elevation survey locations. In 2007, 2008, and 2009, the USACE collected hydroacoustic survey data at the same cross sections established every 250 feet at most locations in the river and every 87 feet at Habitat Monitoring Assessment Program locations, with bed elevation points collected every 0.5 feet (Figure A-38). Due to the large number of data points, only one data point was retained every 10 feet in each cross section. The 2007 database contains records from 11,813 cross sections. The 2008 data were collected only at locations with active dredging. The 2009 data set had not been finalized by the USACE at the time of this analysis, but the draft 2009 data were processed as part of this analysis to obtain results that are comparable to the data from 1999, 2007 and 2008 (see “Methods” below).

All points on each transect within 200 feet of the "sailing line" were selected and averaged to obtain an average bed elevation for each transect and for each year. The sailing line follows the navigation channel and tracks the outside portion of the channel in meander bends where flow strength is greatest and the channel is usually the deepest. The average bed elevation for each transect was then averaged by river mile, and compared by river mile to the survey results from the other years. The results from any given survey year can therefore be compared to other survey years by river mile to determine changes in average bed elevation within 200 feet of the sailing line.

A.7.2 Methods

The USACE made available the hydroacoustic survey data of channel bed elevations for years 1998, 2007, 2008, and 2009. In 1998, the data were collected by a boat moving in a serpentine path along the channel. The cross sections were not perpendicular to the channel centerline. The boat crossed the channel approximately every 300–500 feet along the channel centerline. In 2007, 2008, and 2009, the USACE collected the hydroacoustic data in true cross sections perpendicular to the channel centerline spaced approximately 250 feet apart (Figure A-38).

All of the hydroacoustic survey points have XYZ coordinates of easting, northing, and bed elevation. The 1998, 2007, 2008, and 2009 hydrographic datasets contain 321,222, 1,425,927, 591,862, and 1,927,488 survey points, respectively.

The hydroacoustic survey data were used to generate longitudinal profiles for 1998, 2007, 2008, and 2009 to determine how aggradation and degradation trends vary spatially and in magnitude on the LMOR. The 1998, 2007, and 2009 datasets are nearly continuous throughout the LMOR; while the 2008 dataset has several gaps with no survey data for long reaches of the river.

The first step in creating the longitudinal profile was to select all river bed elevation points within 200 feet of the sailing line for each cross section and use geographic information systems (GIS) software to calculate the river mile location of each data point by assigning the data point to the nearest location on the sailing line and measuring the river mile distance at that location from the river mouth. As a result, the 1998, 2007, 2008 and 2009 survey points can be compared because they use a common distance reference. The 1998, 2007, and 2008 survey points were then imported into Microsoft Access software and sorted by the unique identifier the USACE assigned to each cross section. Because the 2009 data did not have unique cross section identifiers assigned by the USACE,

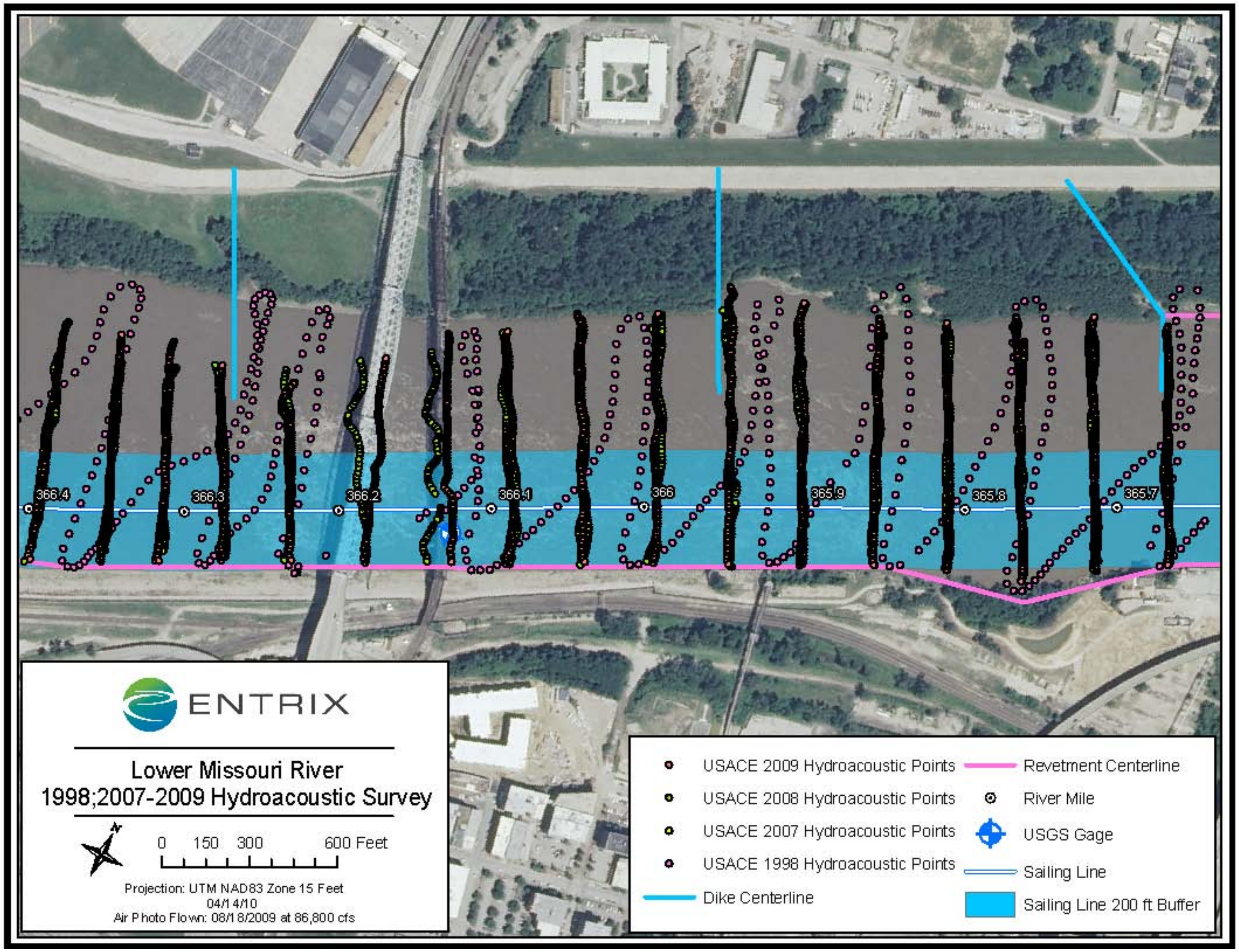

Figure A-38 Hydroacoustic Survey Points in the Kansas City Segment (RM 350 – RM 383) (1998 and 2007–2009)

bed elevation points from the 2009 data were assigned the same cross section identifier as the nearest cross section from 2007. The elevation and river mile distance of all points in each cross section were averaged to obtain an average channel elevation and average river mile distance for all cross section points within 200 feet of the sailing line.

A.7.3 Results

The average elevation points for each transect were imported into Microsoft Excel and then averaged for each river mile. For example, average transect elevations between RM 0 and RM 1 were averaged and reported as RM 1 for the 1998, 2007, 2008, and 2009 data. As an example, Figure A-39 shows average transect elevations for the 1998 and 2009 dataset plotted along with the 1-mile averages for the Kansas City segment.

The average river bed elevation for each river mile for the 1998 data was subtracted from the 2007, 2008, and 2009 data to determine the change in elevation between the two time periods for each river mile. A 5-mile moving average was applied to the difference to smooth the data. Figure A-40 shows a plot of the data averaged by river mile and the 5-mile moving average for the Kansas City segment.

The 5-mile moving average of difference between the 2007, 2008, and 2009 data and the 1998 data then were plotted; they are displayed on Figure A-41. This figure shows the increase (aggradation) or decrease (degradation) in average bed elevation along the entire LOMR for three time periods. The results show areas dominated by aggradation between RM 155 – RM 240, RM 255 – RM 360, and RM 400 – RM 498. Areas dominated by degradation occur near metropolitan areas (RM 0 – RM 100, RM 130 – RM 155, and RM 370 – RM 400) and near the confluence of the Grand River (RM 250). The general trend in average river bed elevations between 2007 and 2009 was aggradation above RM 250 and degradation below RM 250.

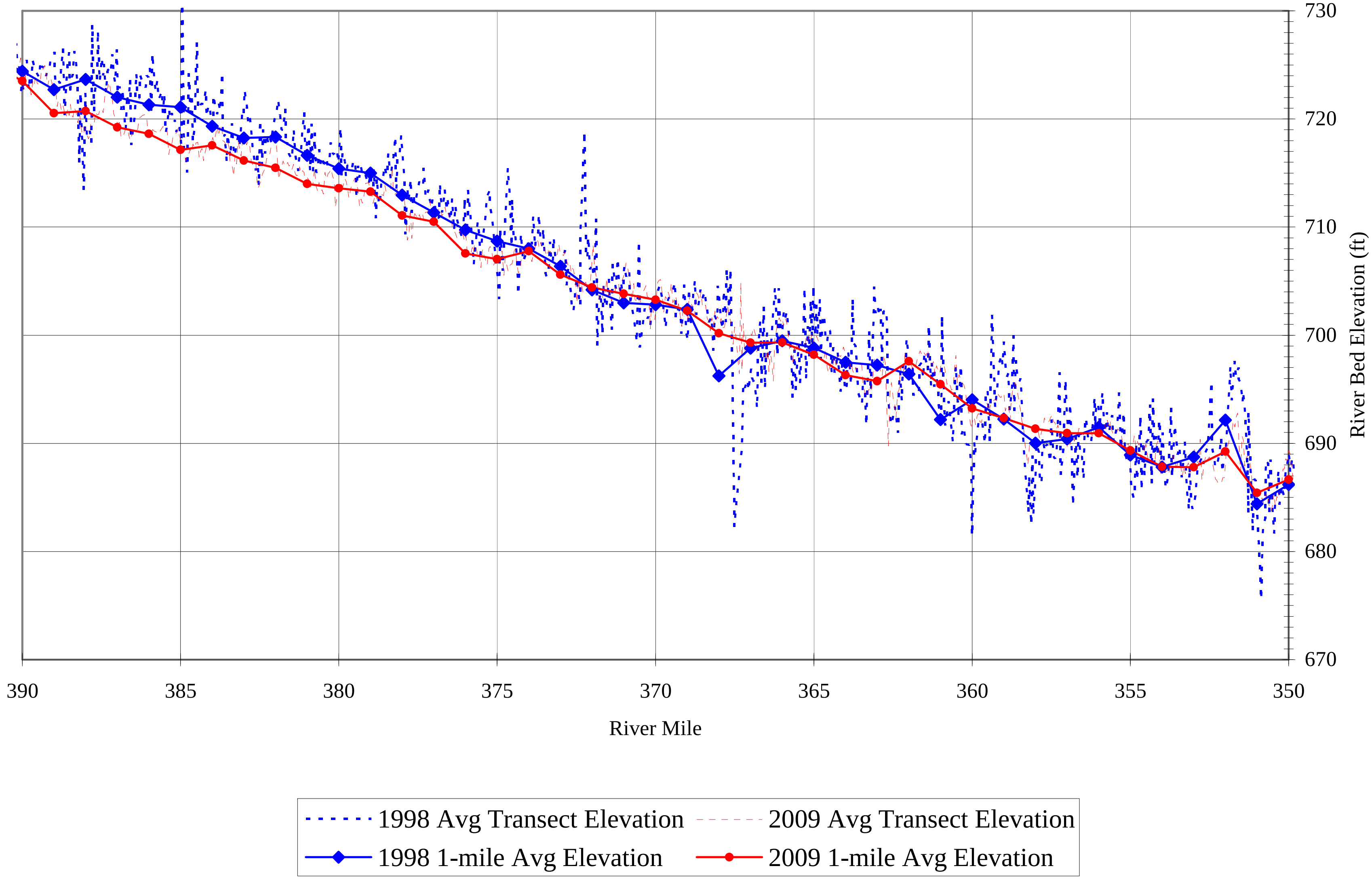

Figure A-39 Average Bed Elevation Points for the 1998 and 2009 Hydroacoustic Surveys Plotted against 1-Mile Average Elevations for the Kansas City Segment

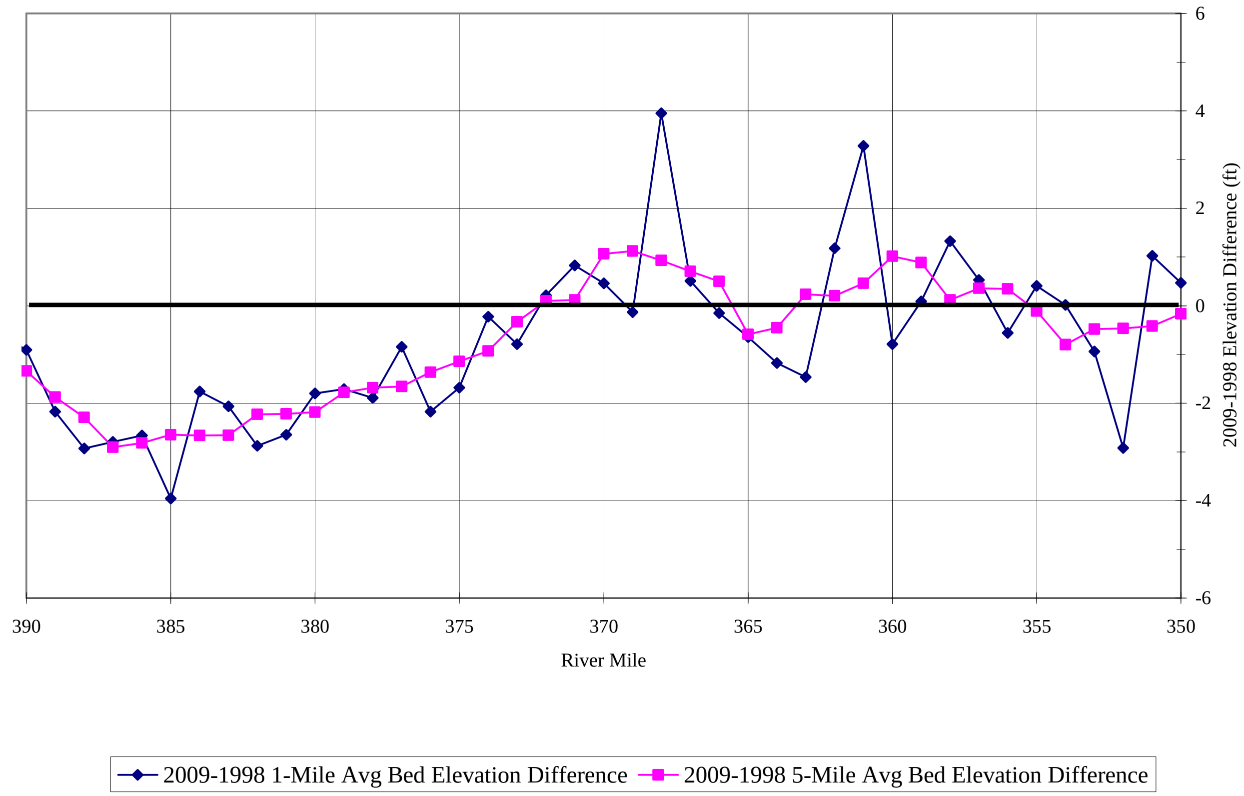

Figure A-40 1-Mile and 5-Mile Averaged Difference between 2009 and 1998 River Bed Elevation Averages for the Kansas City Segment

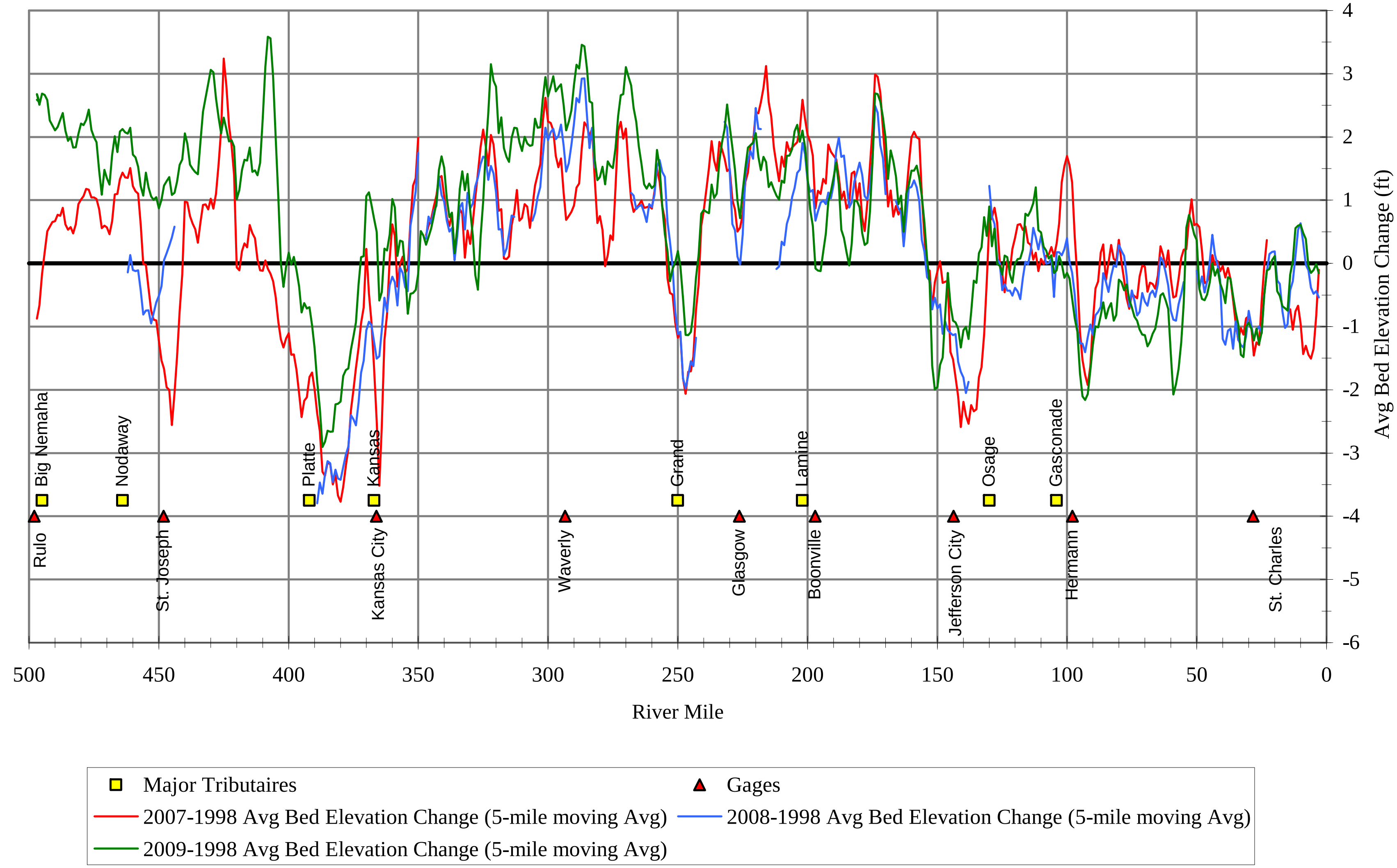

Figure A-41 Change in Average River Bed Elevation between 2007, 2008, and 2009 and 1998 Using 5-Mile Moving Average

A.8 EQUILIBRIUM SLOPE ANALYSIS

The three main data sets available with information regarding past changes in river bed elevations and water surface elevations include the CRP, the HBED, and data from established USGS gage sites. These data sets provide historical information regarding trends and changes in river bed elevations and water surface elevations in response to floods, changes in flows and sediment supply, dredging, and projects such as the BSNP. While these data provide insights regarding past and potential future trends, additional analysis was conducted to help determine whether the river bed at three analysis locations was likely to continue to degrade, aggrade, or remain stable.

The analysis, called "equilibrium slope analysis," indicates whether the bed slope of the LOMR at three gage locations is in equilibrium with the prevailing bed material load and flow regimes. Although the equilibrium slope analysis does not predict the magnitude or rate of change that will occur in the future, it does predict if the existing channel has a stable channel slope, from which conclusions can be drawn about whether the channel is likely to aggrade or degrade. A stable channel slope, or equilibrium slope, is the bed slope required by the Missouri River at a particular location to pass the incoming bed material load with the available flow without the river bed aggrading or degrading.

The equilibrium slope method is commonly used to design new channels. The method used in this analysis is similar to the stable channel design method in SAM hydraulic design software (Copeland 1994, Thomas et al. 2002), available in USACE HEC-RAS software, and the method presented in Wilcock (2004).

In the equilibrium slope analysis, a design flow, bed material supply, and channel width are specified; and iterative calculations are performed to determine the optimal combination of channel depth, slope, and velocity needed to create the hydraulic energy will pass the sediment supply without sedimentation or erosion of the bed. The analysis was performed at the St. Joseph, Kansas City, and Hermann gage locations because bed material loads were calculated for these sites and extensive hydrologic records are available.

The bed material loads predicted by the Ackers and White (1973) equation with HR Wallingford (1990) adjusted coefficients were used in the analysis (see Section A.4.2.1 for more details on this equation, which was one of the five equations used to estimate bed material loads). This equation was selected because the equation can be rearranged to solve for flow velocity (U) instead of bed material transport.

$$q_{bm}^{*} = C\frac{U}{\sqrt{RgD}}\left(\frac{U}{u_*}\right)^n\left(\frac{F_{gr}}{A}-1\right)^m$$

The key inputs needed to perform the equilibrium slope analysis are discharge, bed material load, Manning's n value, median grain diameter of bed substrate (D_{50}), and channel width. The inputs correspond with the value associated with the selected discharge. For example, if the equilibrium slope model is to be run at a 50,000 cfs discharge, then the bed material load calculated by the Ackers and White equation for 50,000 cfs is input as the sediment supply, the back-calculated Manning's n value and channel width are determined from the HEC-RAS hydraulic model results, and the D_{50} (which does not change with discharge) is determined from the analysis of bed substrate measurements made by the USGS and USACE. In some equilibrium slope analyses, hydraulic geometry relationships that relate channel width and discharge are used to select a channel width. In this analysis, however, the channel width is confined at the gaging locations and thus is not an adjustable variable.

All of the calculations were performed in a spreadsheet model in which multiple dependent variables, including velocity, depth, hydraulic radius, and slope, were iterated with each other until a solution was found. The solution represents the combination of channel cross section dimensions, velocity, and channel slope that will pass the bed material load in equilibrium. ***

The model was run at the 25-percent exceedance flow for all three gages. This flow was chosen because it is a relatively high-magnitude flow (approximately equal to the 1-year peak annual return flow) in which a large amount of bed material is in transport and channel-forming processes are occurring. Results from the equilibrium slope analysis are presented in Table A-19. The first group of rows lists the input parameters that include the independent variables associated with the 25-percent exceedance flow. The second group of rows lists the HEC-RAS existing conditions parameters of velocity, depth, slope and mean boundary shear stress (τ_o). These values represent the existing conditions at the gages determined from the calibrated hydraulic model. The third group of rows lists the equilibrium slope output that includes the results of the iterative calculations performed to determine the velocity, depth, and slope needed to pass the bed material supply. The final group of rows list the percent change from the HEC-RAS existing condition to the equilibrium slope estimated results. These percent change values can be interpreted as how different the existing channel is from the estimated equilibrium channel configuration. If there is little difference, the existing channel configuration is at or near the predicted equilibrium condition and can be considered relatively stable. Larger differences indicate that the existing channel configuration is not near the predicted equilibrium condition, and the channel may aggrade or degrade to a more optimal configuration.

Table A-19 Results of Equilibrium Slope Analysis for Three Gage Locations on the Lower Missouri River

	Location		
	St. Joseph Gage	Kansas City Gage	Hermann Gage
Equilibrium Slope Calculation Input Parameters			
Discharge (Q) at 25% exceedance (cfs)	56,500	68,700	111,000
Bed material load (Q_{bm}) (tons/day)	17,168	28,759	16,141
Channel width (ft)	655	525	1,098
Manning's n (dimensionless)	0.028	0.031	0.028
Bed particle size D_{50} (mm)	0.35	0.36	0.55
HEC-RAS Existing Condition			
Velocity (ft/s)	4.2	4.8	4.0
Depth (ft)	19.3	22.5	20.5
Slope (ft/ft)	0.00012	0.00015	0.00010
τ_o (lb/ft^2)	0.15	0.21	0.13
Equilibrium Slope Estimated Results			
Velocity (ft/s)	4.2	5.0	4.1
Depth (ft)	19.9	21.6	22.3
Slope (ft/ft)	0.00013	0.00019	0.00010
τ_o (lb/ft^2)	0.15	0.24	0.13
Percent Difference between Existing and Estimated Results			
Velocity	0.5%	4.0%	3.1%
Depth (ft)	3.4%	-4.1%	8.1%
Slope (ft/ft)	4.2%	21.5%	0.3%
τ_o (lb/ft^2)	1.7%	11.5%	4.6%

At the St. Joseph gage, the predicted equilibrium velocity, depth, and slope are similar to the existing condition. The greatest change is a 4.2-percent difference in slope between the existing and equilibrium conditions. The results indicate that, if conditions remain the same, the channel is relatively stable and unlikely to aggrade or degrade.

At the Hermann gage, the predicted equilibrium channel configuration is similar to the existing condition. The predicted equilibrium channel is 1.8 feet deeper than the existing channel (an

8.1-percent change), and the slopes are nearly identical. The results indicate that, if conditions remain the same, the channel is relatively stable and unlikely to aggrade or degrade.

The greatest differences between the existing condition and the equilibrium condition are at the Kansas City gage. The equilibrium slope estimate predicts a slightly higher velocity (4.0 percent) and slightly lower depth (-4.1 percent). The parameter with the greatest difference between the estimated and actual values is the slope, where the predicted equilibrium slope of 0.00019 is 21.5 percent greater than the existing slope of 0.00015. The model is indicating that the optimal channel configuration to create the energy needed to pass the bed material supply in equilibrium is a steeper and less deep channel. Since the predicted slope is steeper than the existing slope, the slope is inclined to increase from the existing condition.

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