UNITED STATES ARMY CORPS OF ENGINEERS

Missouri River Commercial Dredging Draft EIS

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Appendix A Geomorphic Analyses Technical Details

PREPARED BY

ENTRIX, Inc.
200 First Avenue West, Suite 500
Seattle, WA 98119
T 206.269.0104 ▪ F 206.269.0098

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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).

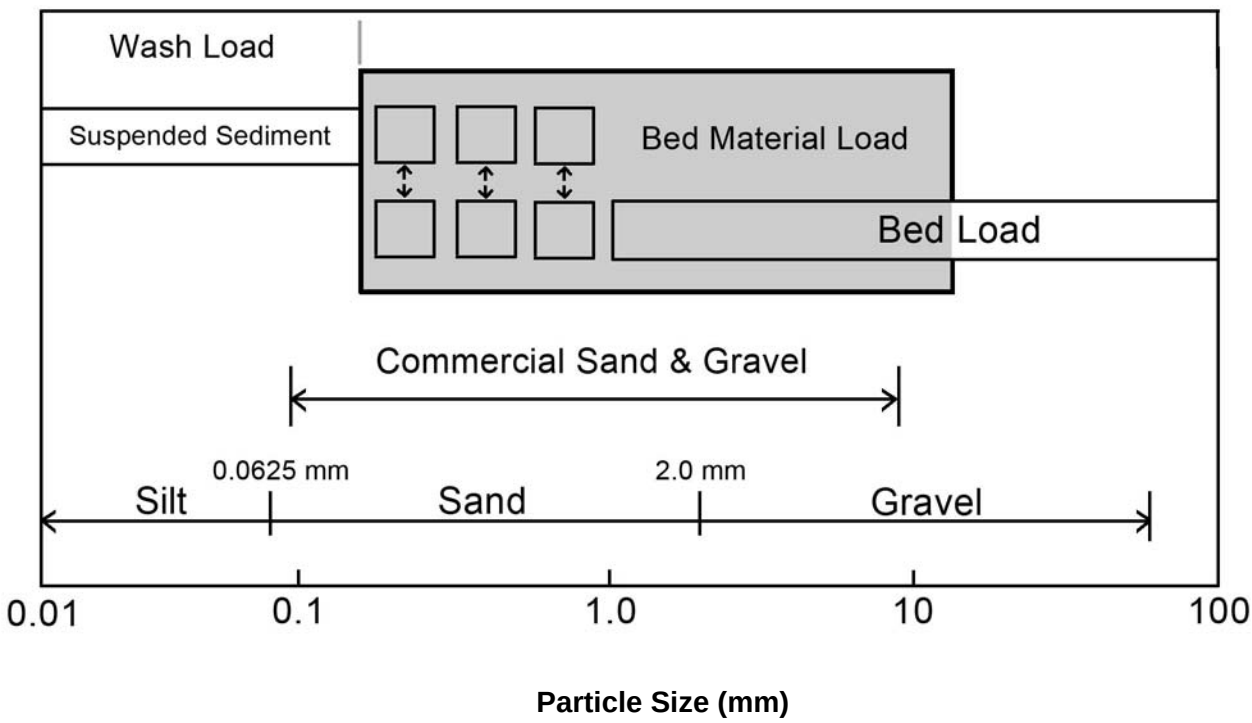

Figure A-1 Illustration of Diffuse Boundaries Defining Sediment Transport Mechanism (Bed Load or Suspended Load) and Sediment Source (Bed Material Load or Wash Load)

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.

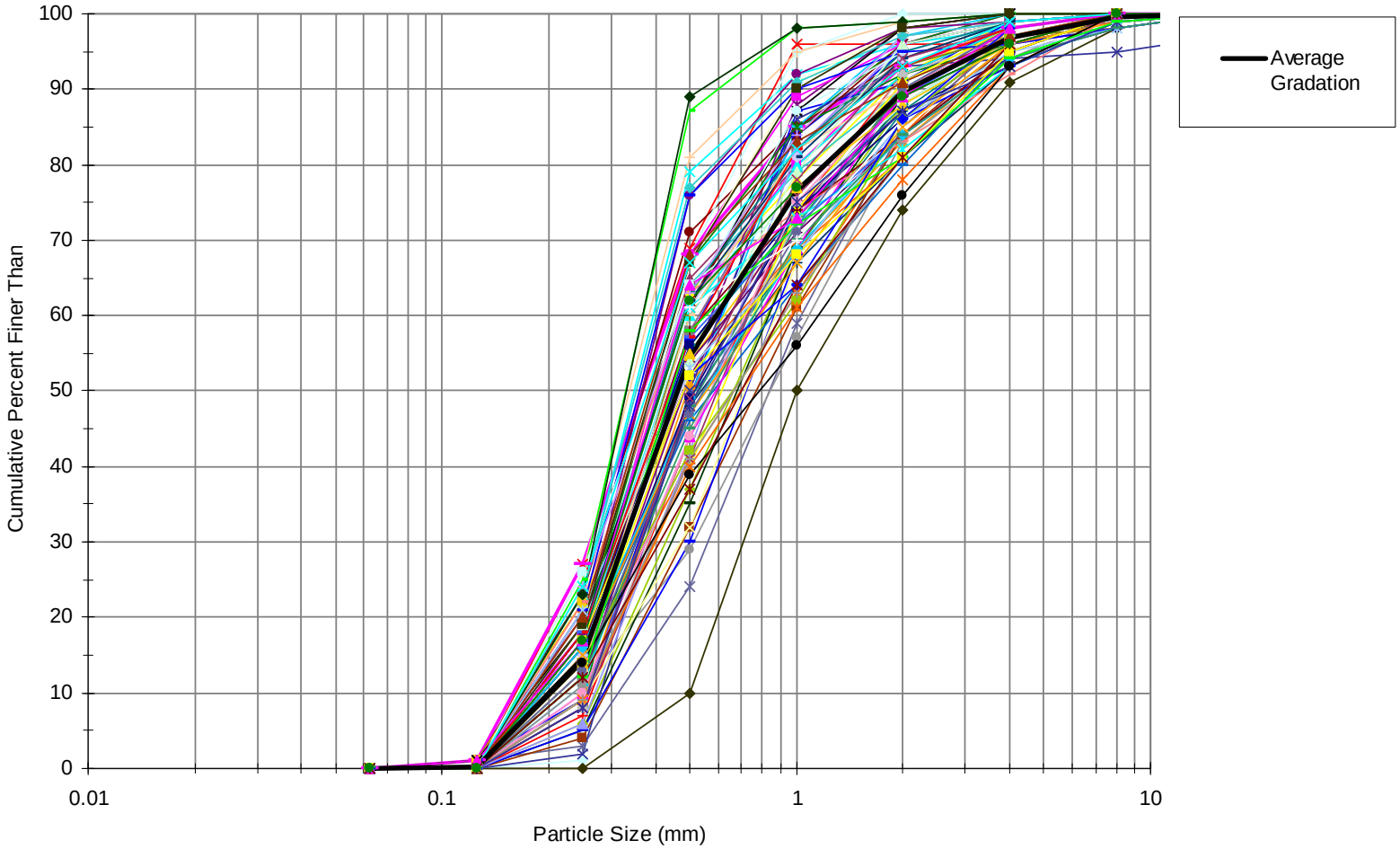

Figure A-2 USGS Bed Material Samples – Nebraska City Gage #06807000 (2001–2009)

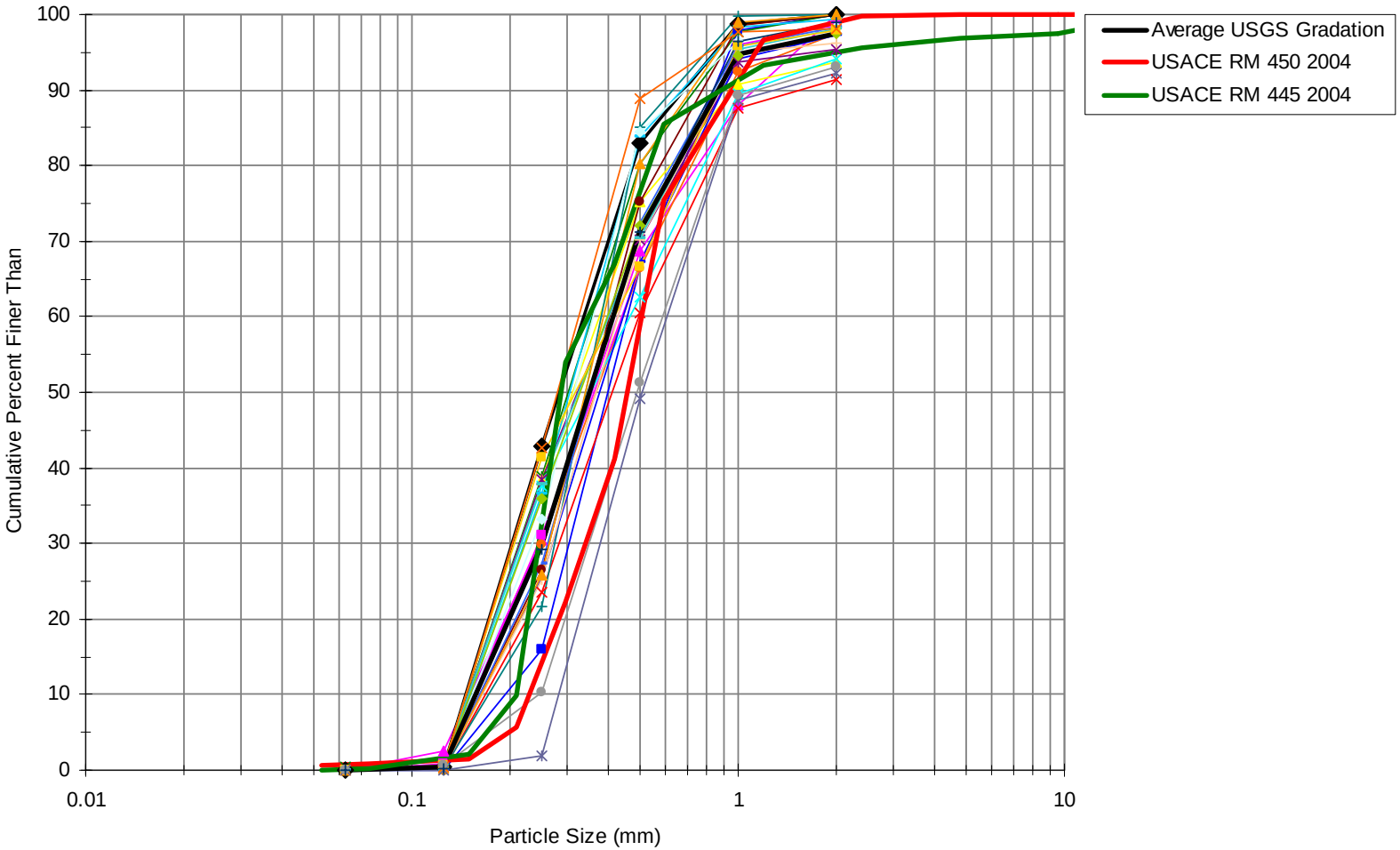

Figure A-3 USGS and USACE Bed Material Samples – St. Joseph Gage #06818000 (2002–2009)

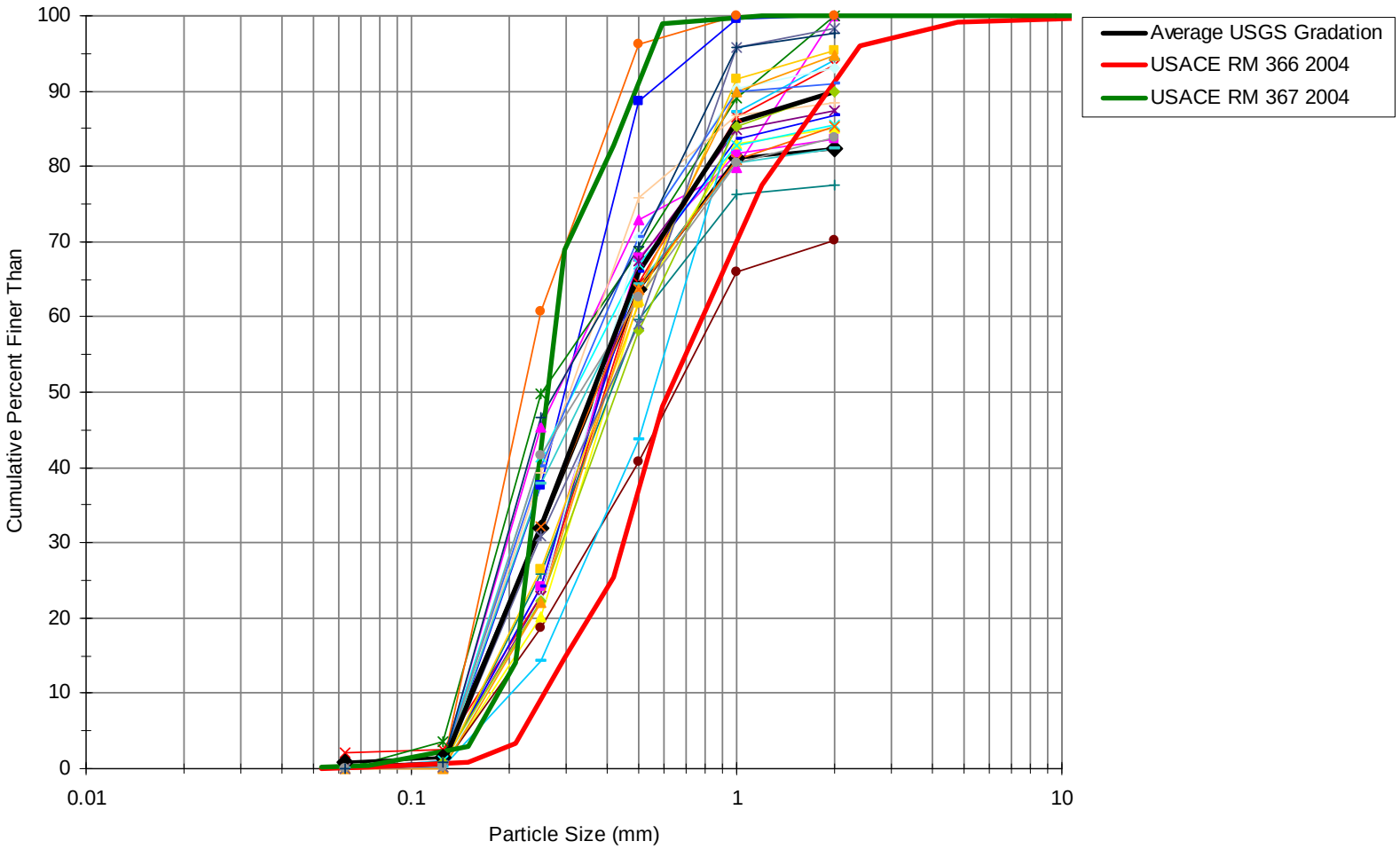

Figure A-4 USGS and USACE Bed Material Samples – Kansas City Gage #06893000 (2002–2009)

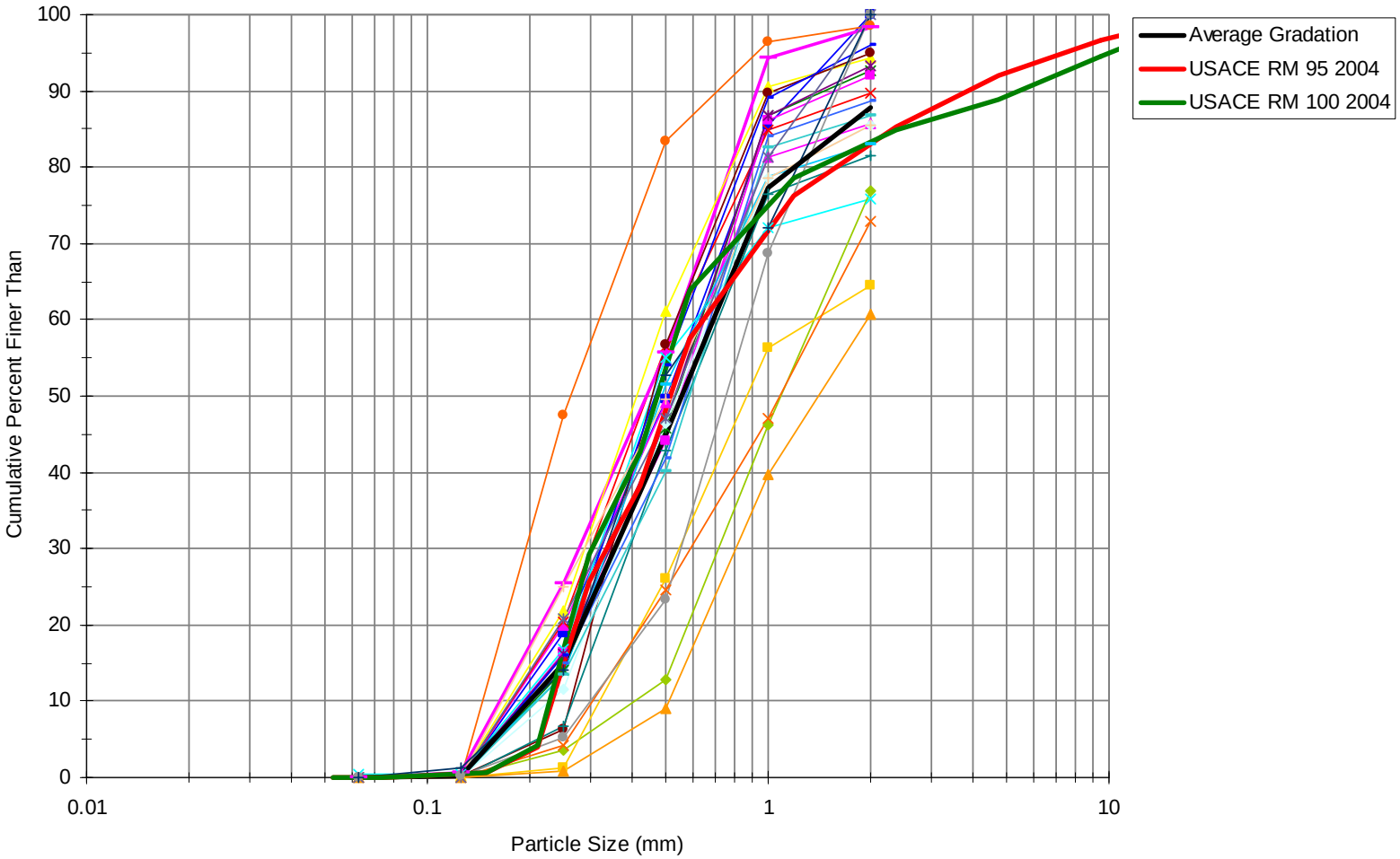

Figure A-5 USGS and USACE Bed Material Samples – Hermann Gage #06934500 (2002–2009)

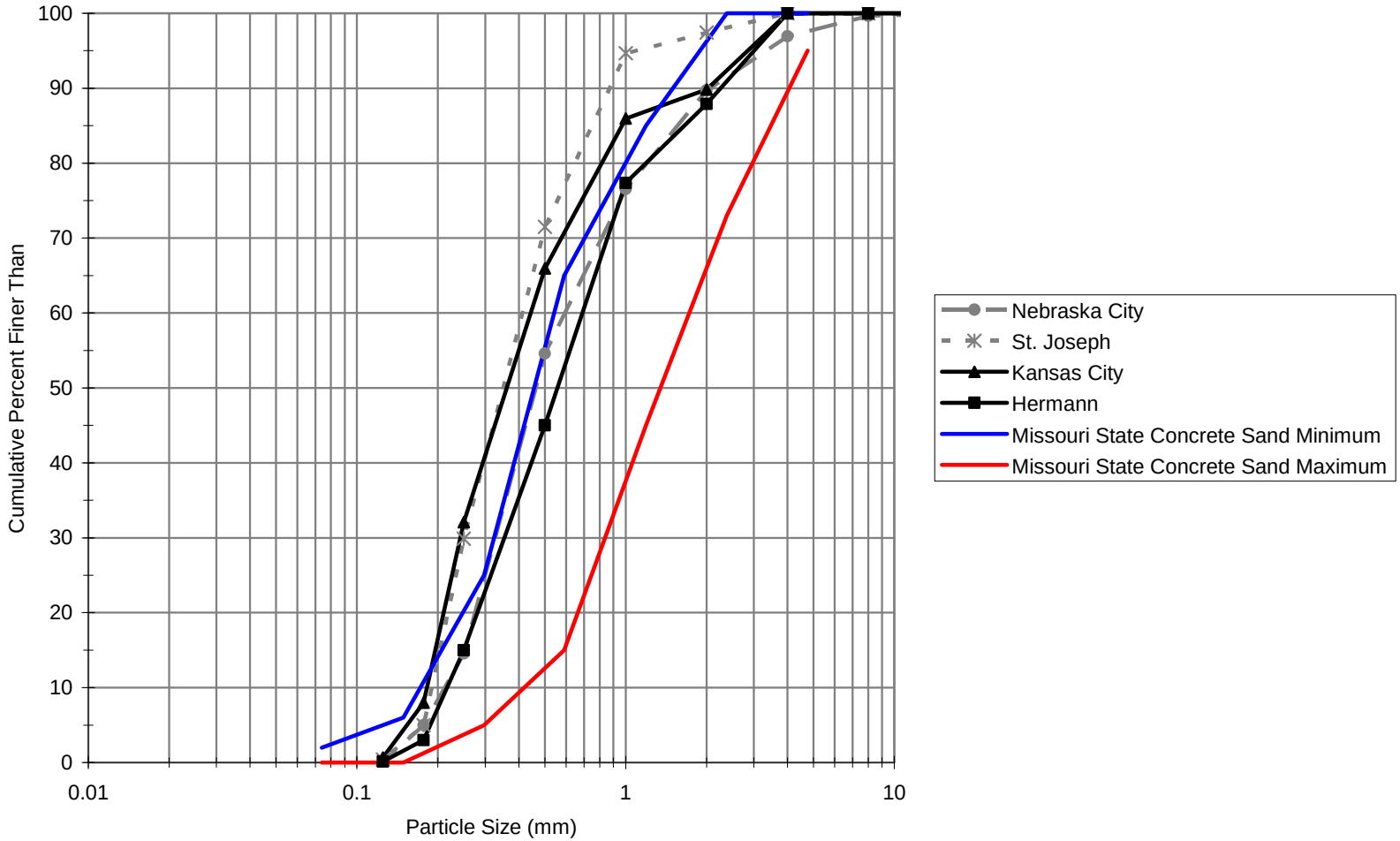

Figure A-6 Representative Bed Material Particle Size Gradations at Missouri River Gaging Sites (2001–2009)

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.

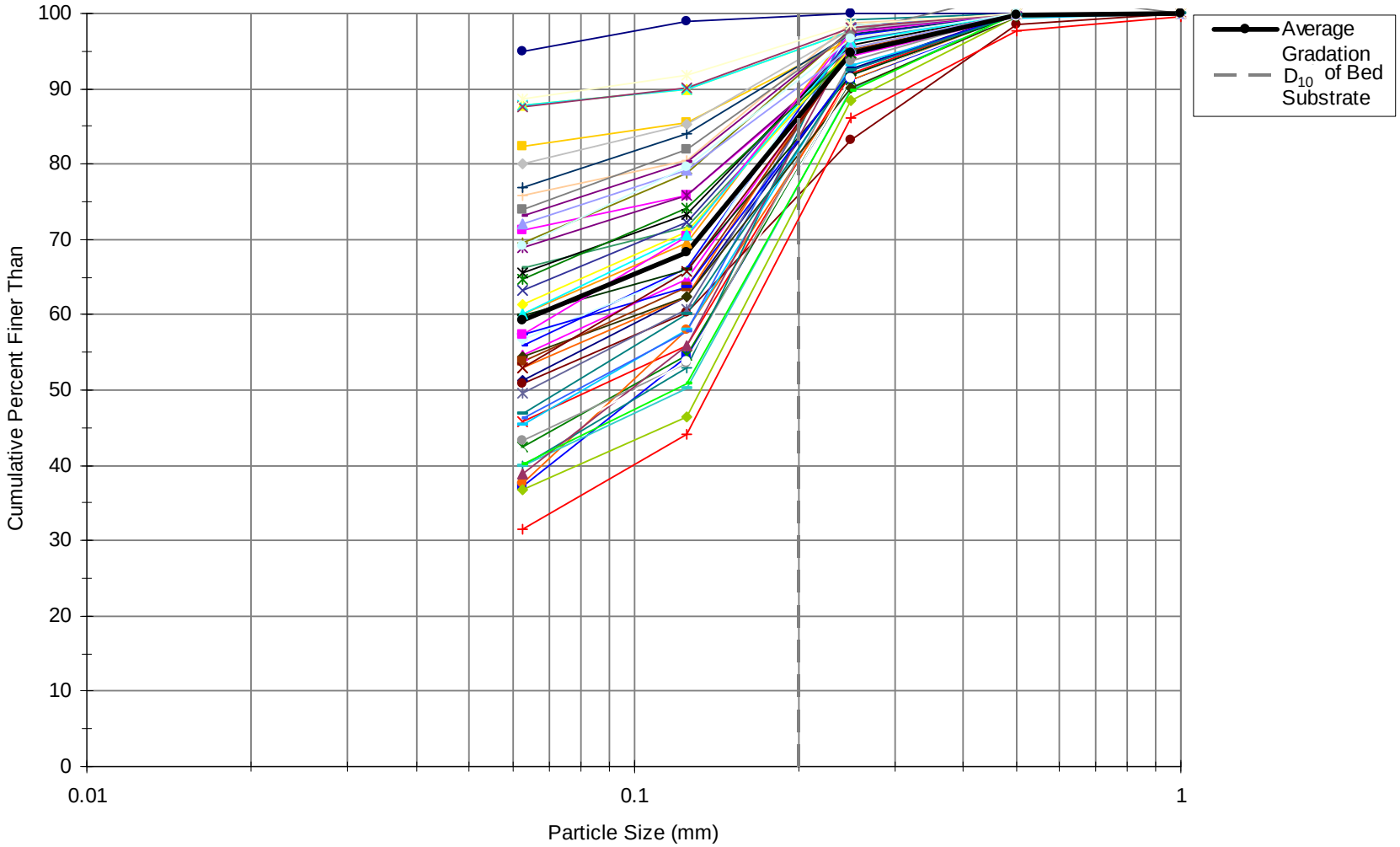

Figure A-7 USGS Total Suspended Sediment Particle Size Gradations – Nebraska City Gage #06807000 (1981–1991)

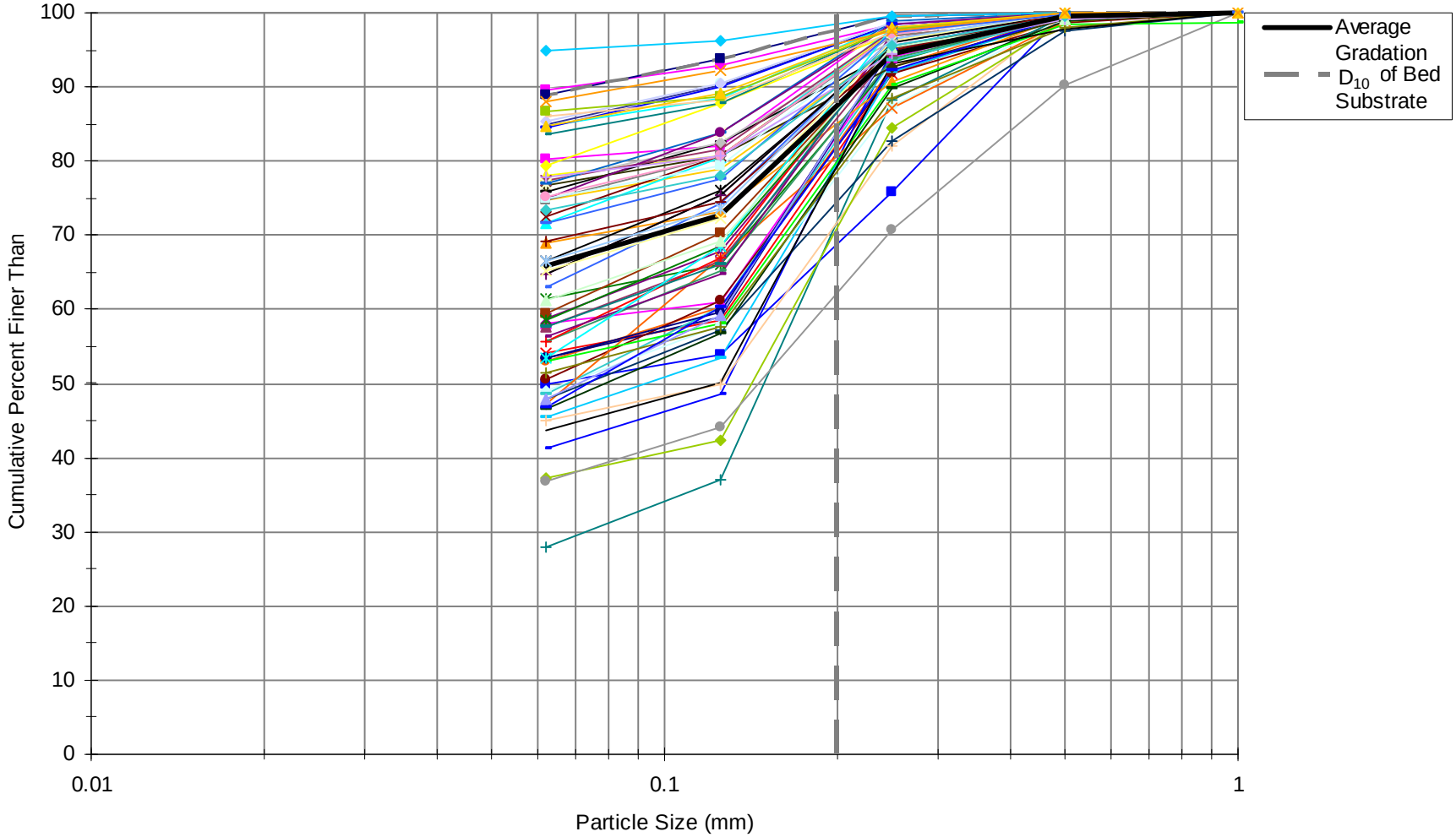

Figure A-8 USGS Total Suspended Sediment Particle Size Gradations – St. Joseph Gage #06818000 (1994–2005)

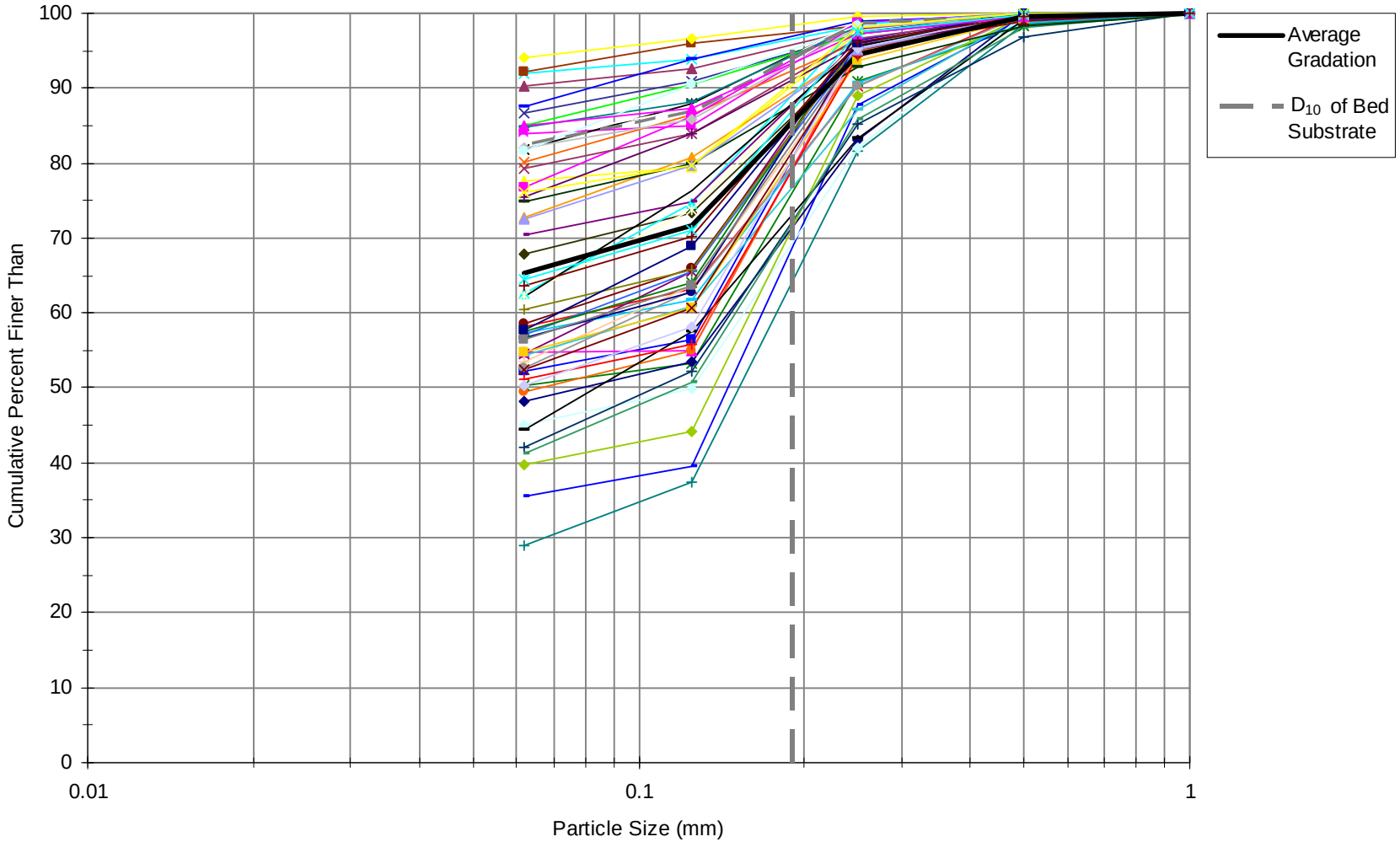

Figure A-9 USGS Total Suspended Sediment Particle Size Gradations – Kansas City Gage #06893000 (1994–2002)

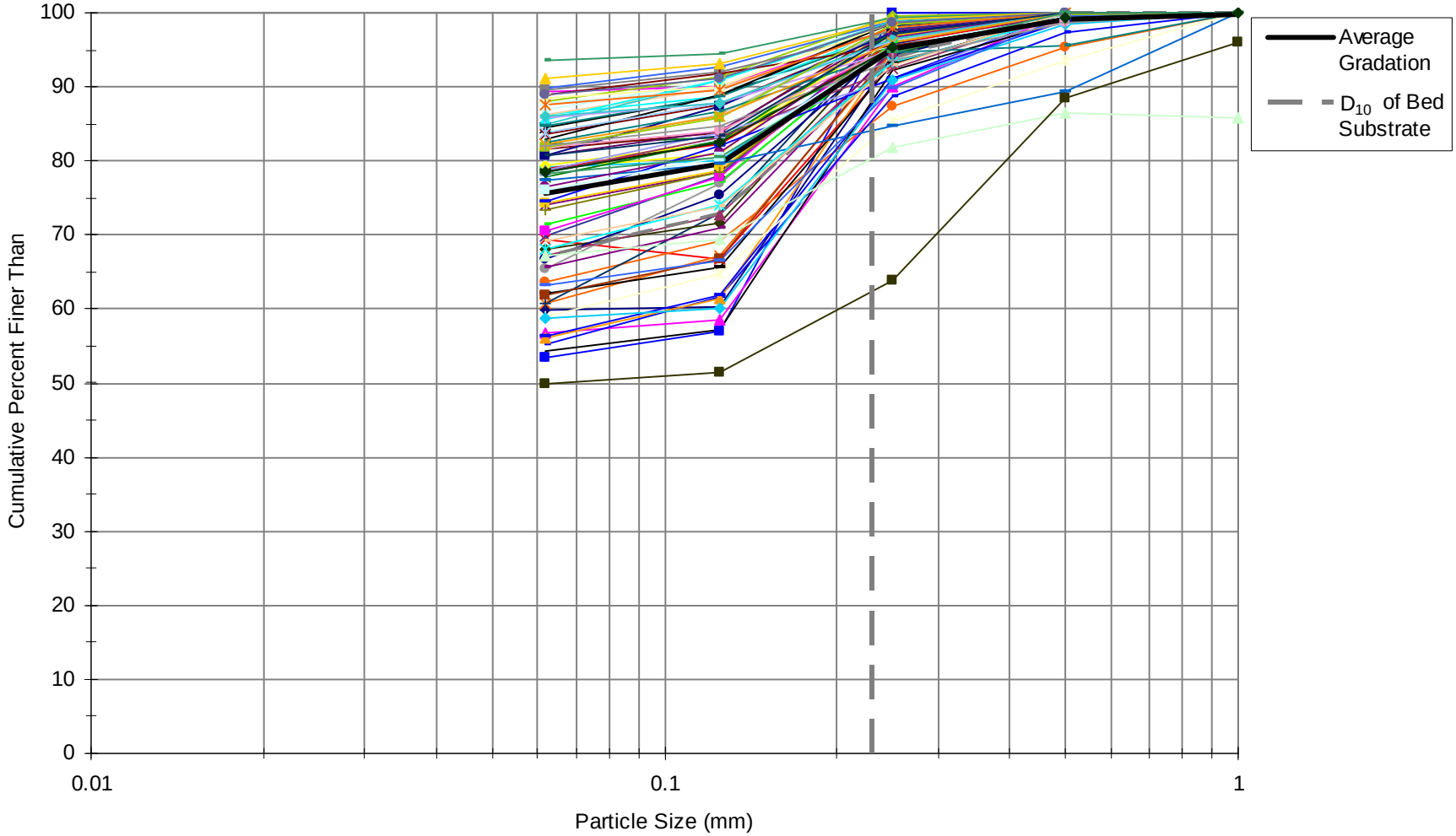

Figure A-10 USGS Total Suspended Sediment Particle Size Gradations – Hermann Gage #069345000 (1994–2005)

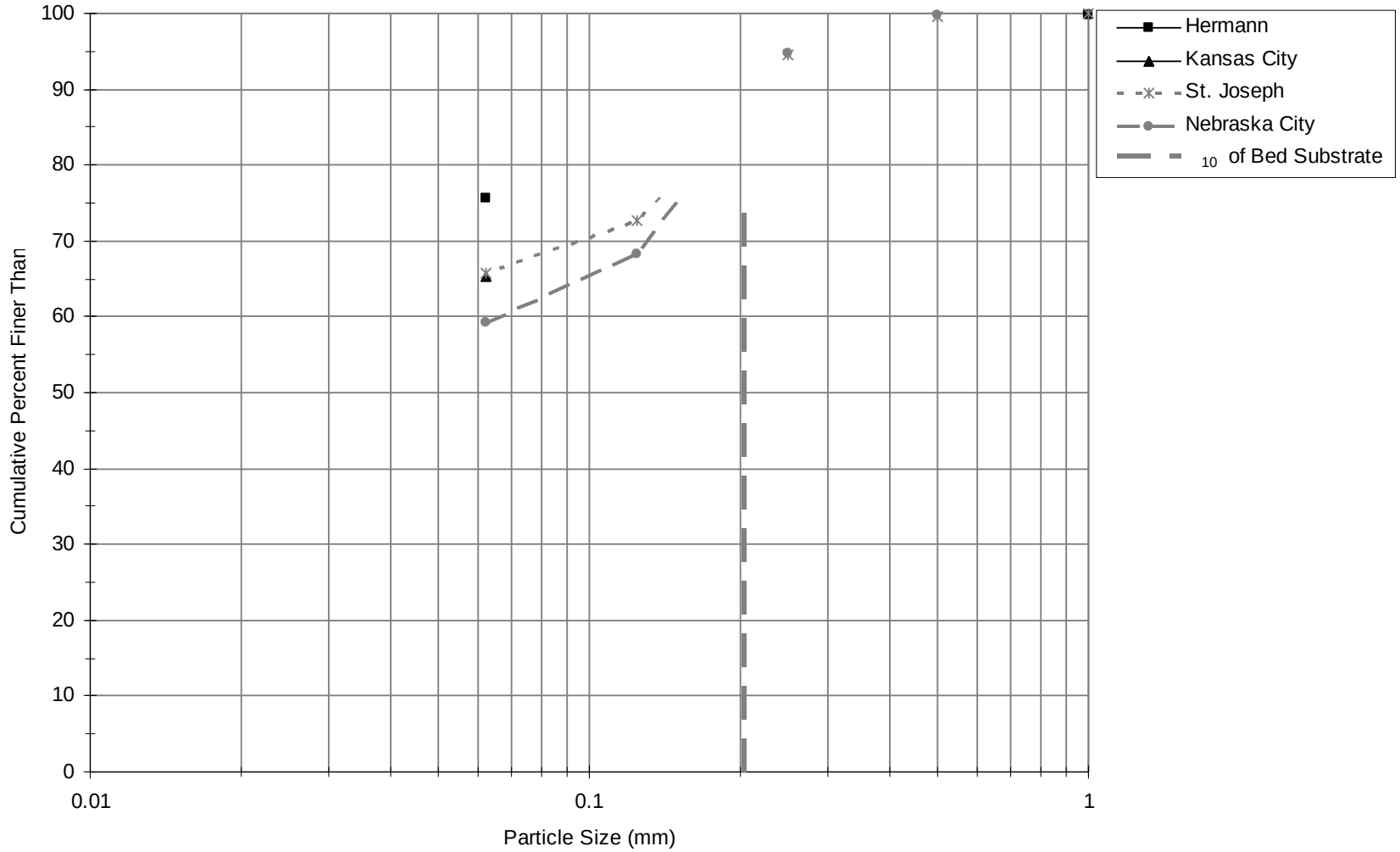

Figure A-11 Representative Total Suspended Sediment Particle Size Gradations at Missouri River Gage Sites

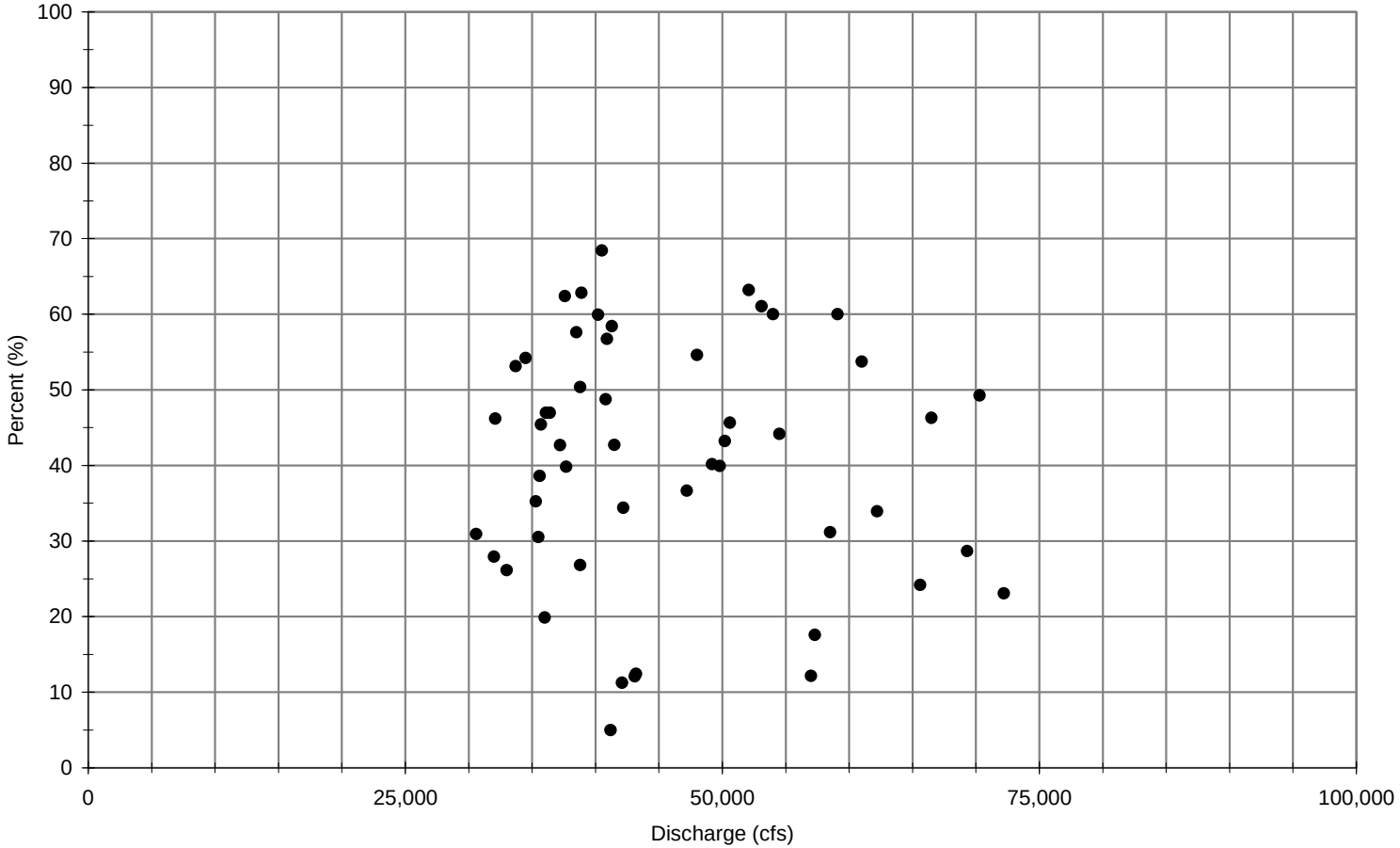

Figure A-12 USGS Total Suspended Sediment Percent Sand Content – Nebraska City Gage #06807000 (1981–1991)

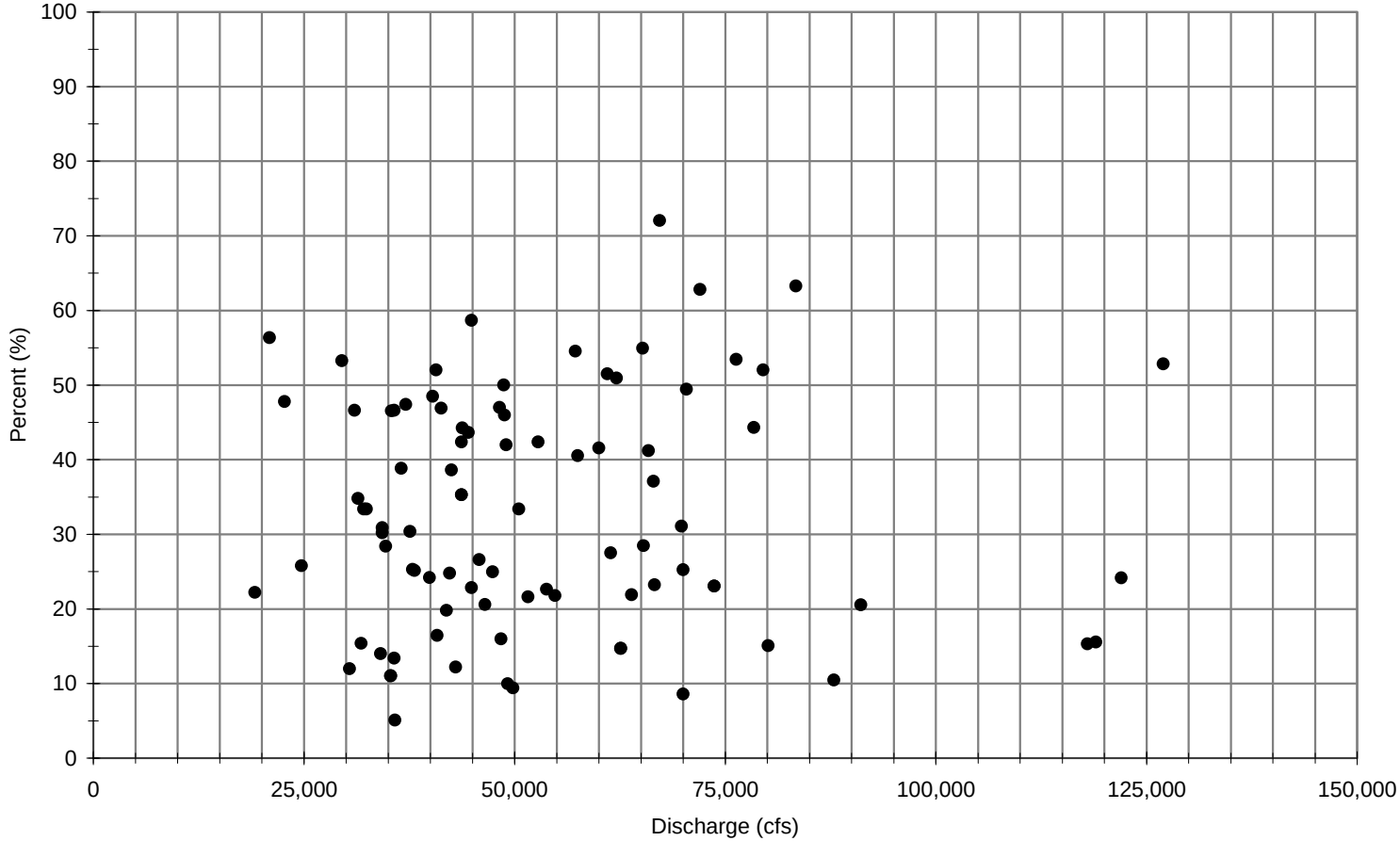

Figure A-13 USGS Total Suspended Sediment Percent Sand Content – St. Joseph Gage #06818000 (1994–2005)

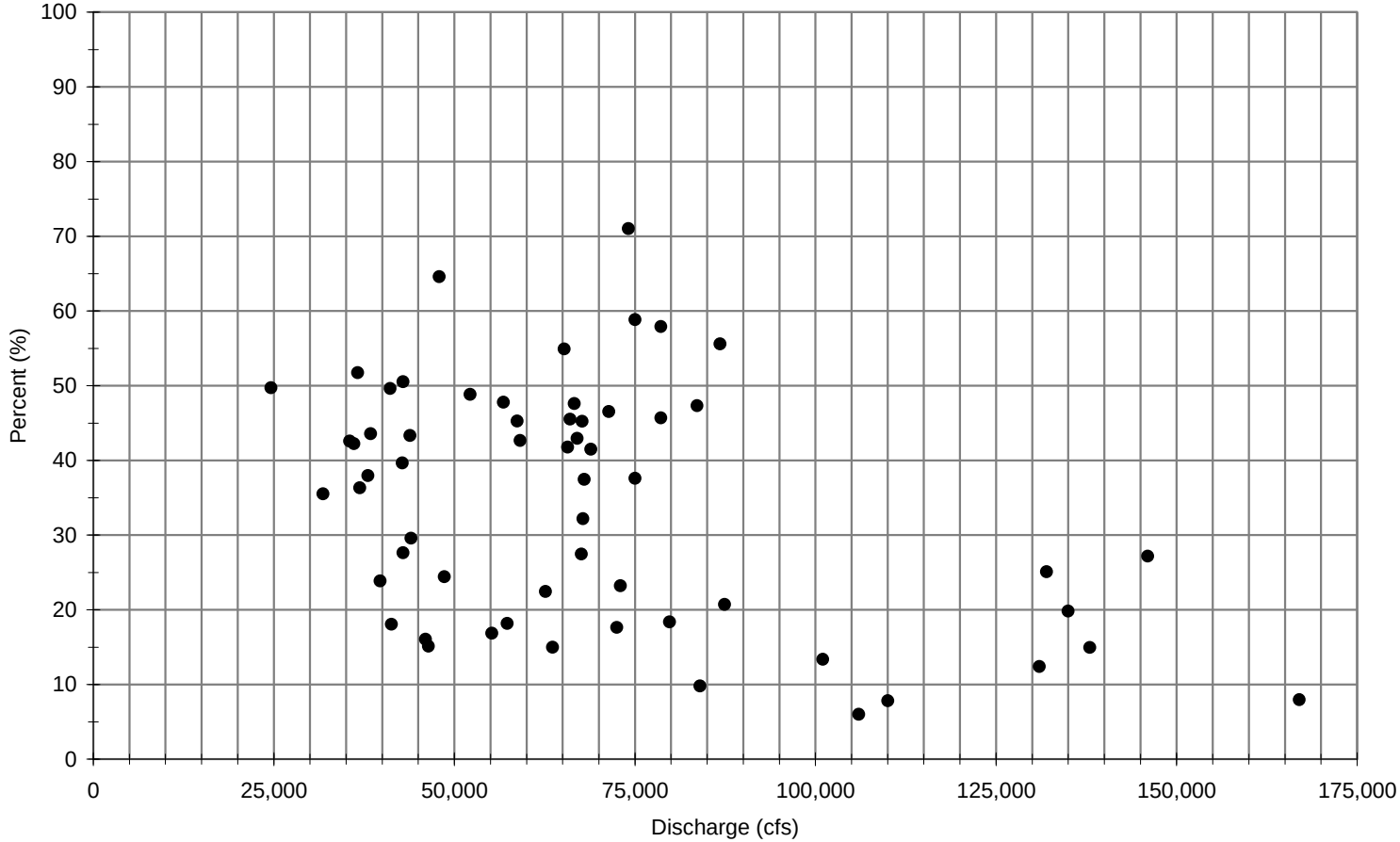

Figure A-14 USGS Total Suspended Sediment Percent Sand Content – Kansas City Gage #06893000 (1994–2002)

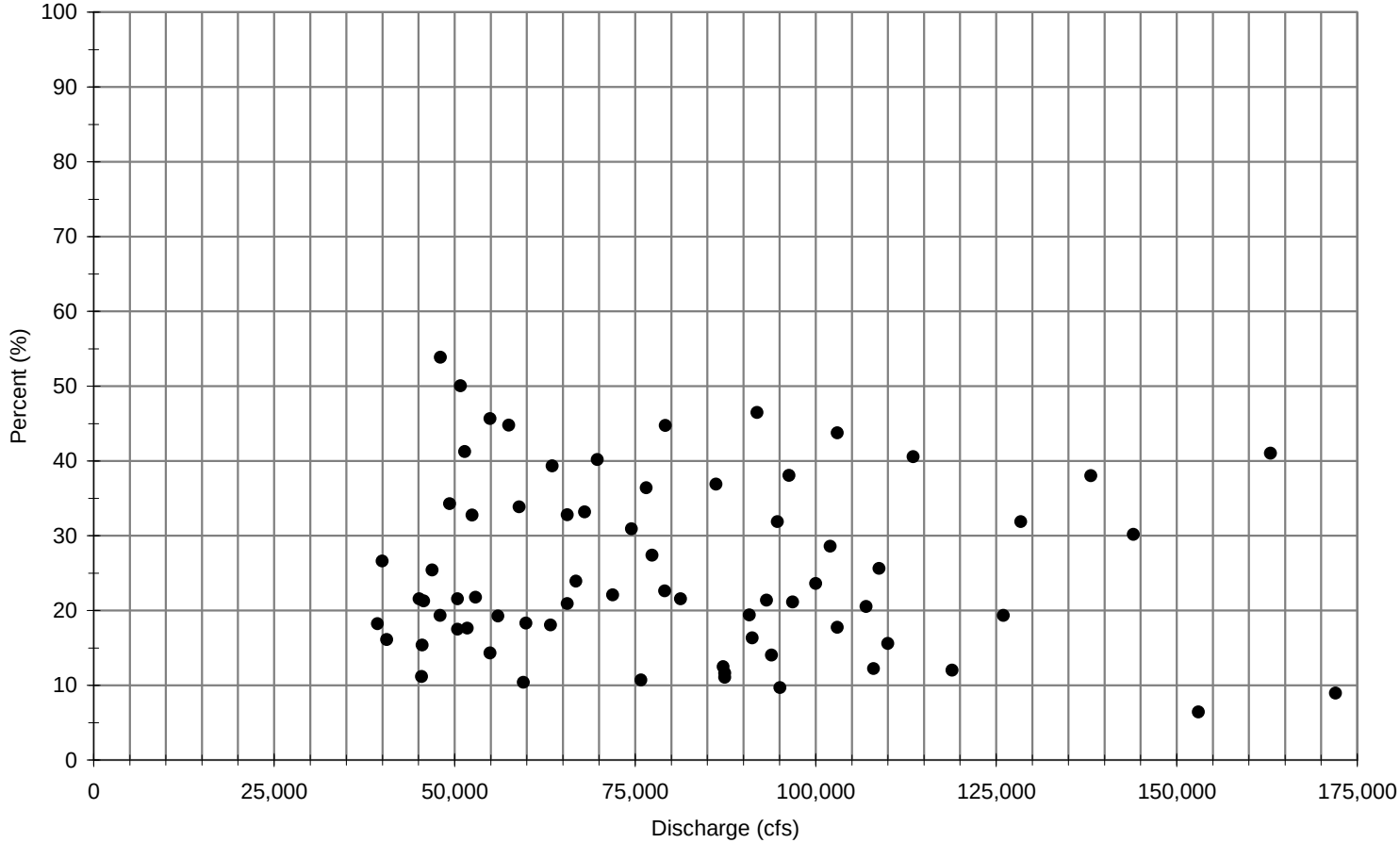

Figure A-15 USGS Total Suspended Sediment Percent Sand Content – Hermann Gage #06934500 (1994–2005)

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.

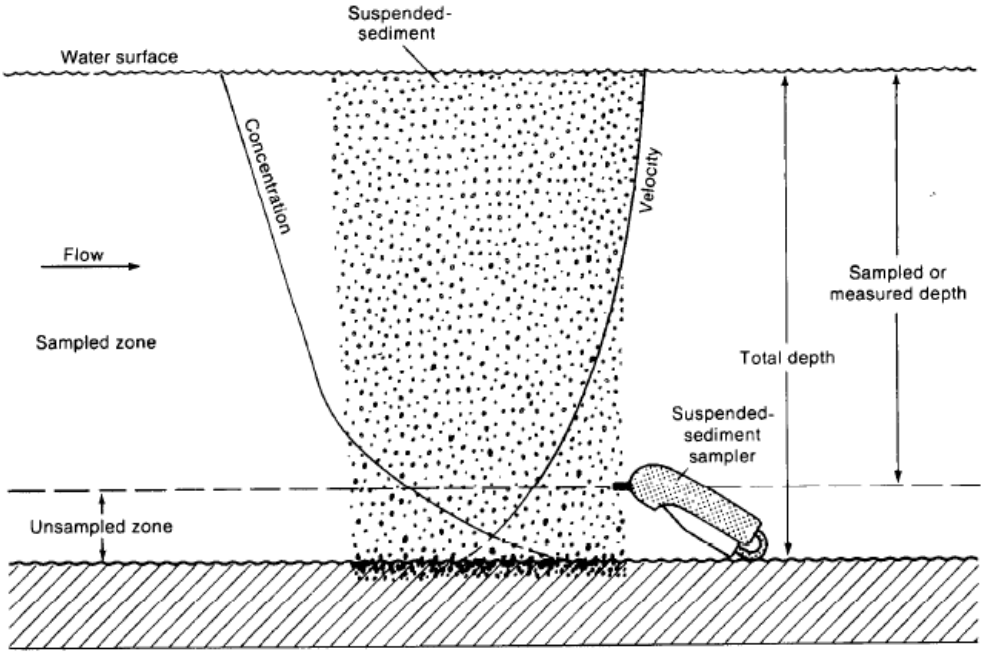

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Figure A-16 Measured and Unmeasured Suspended Sediment Sampling Zones

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.

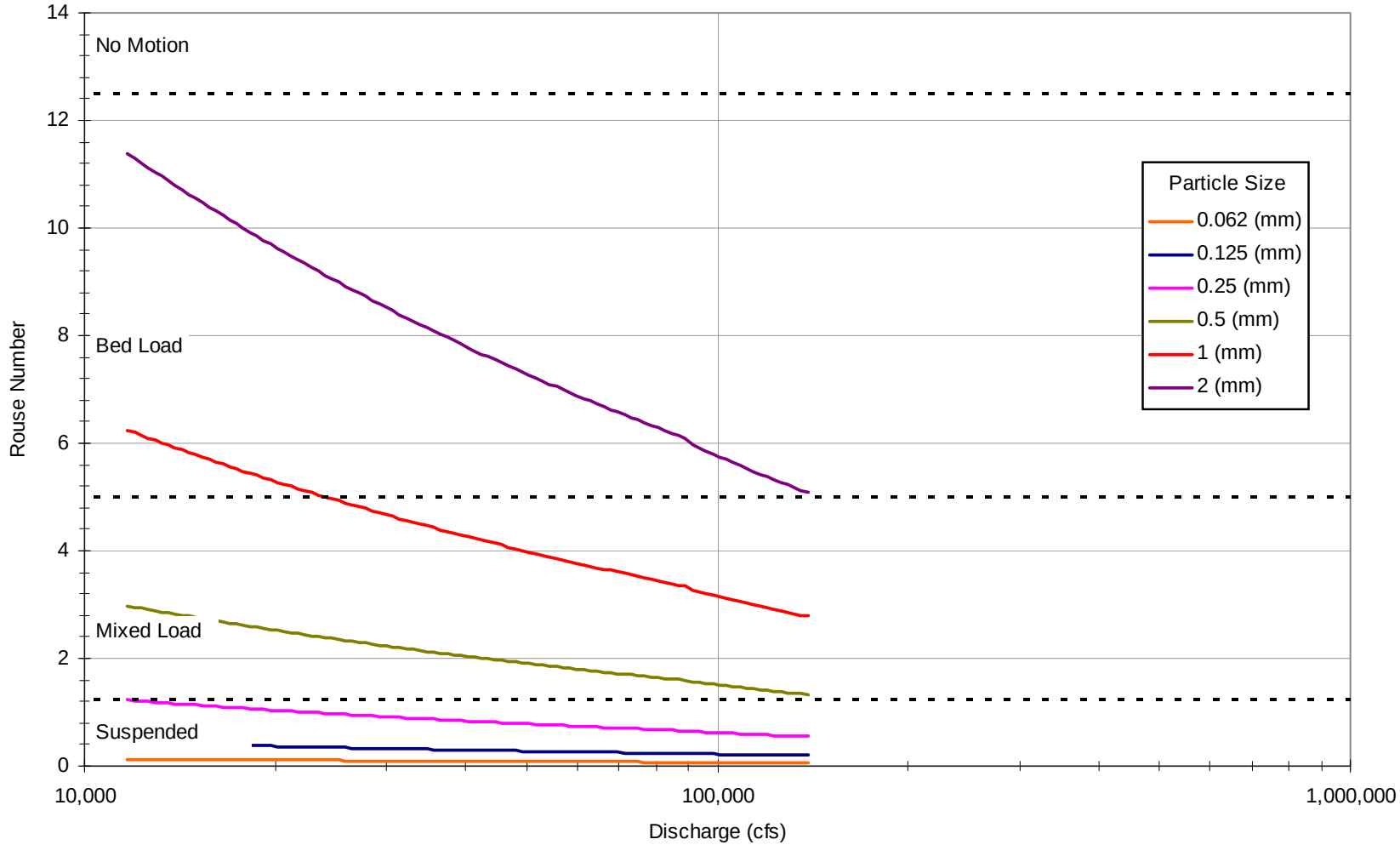

Figure A-17 Mode of Sediment Transport Predicted from Rouse Number Analysis at the Nebraska City Hydraulic Modeling Reach

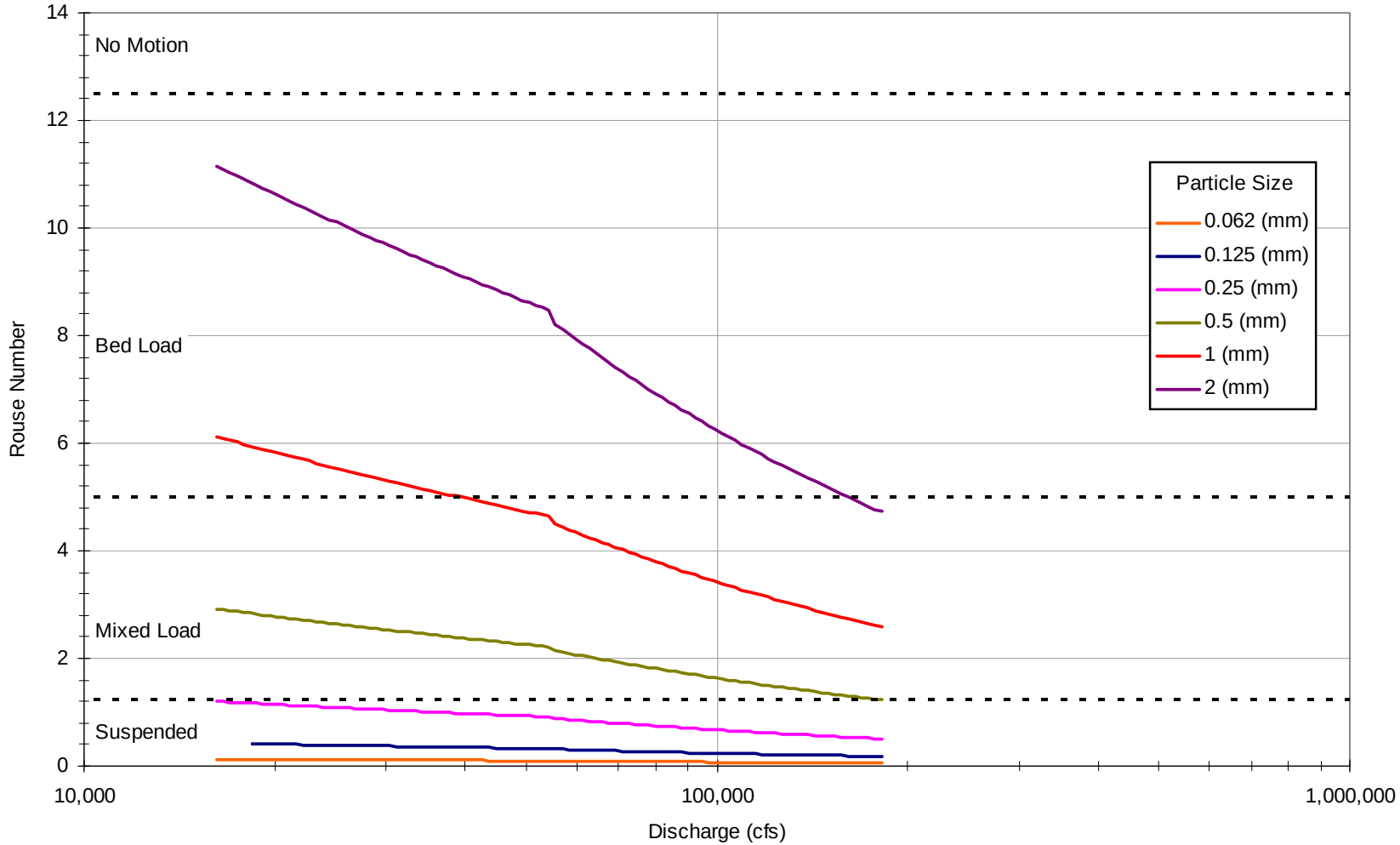

Figure A-18 Mode of Sediment Transport Predicted from Rouse Number Analysis at the St. Joseph Hydraulic Modeling Reach

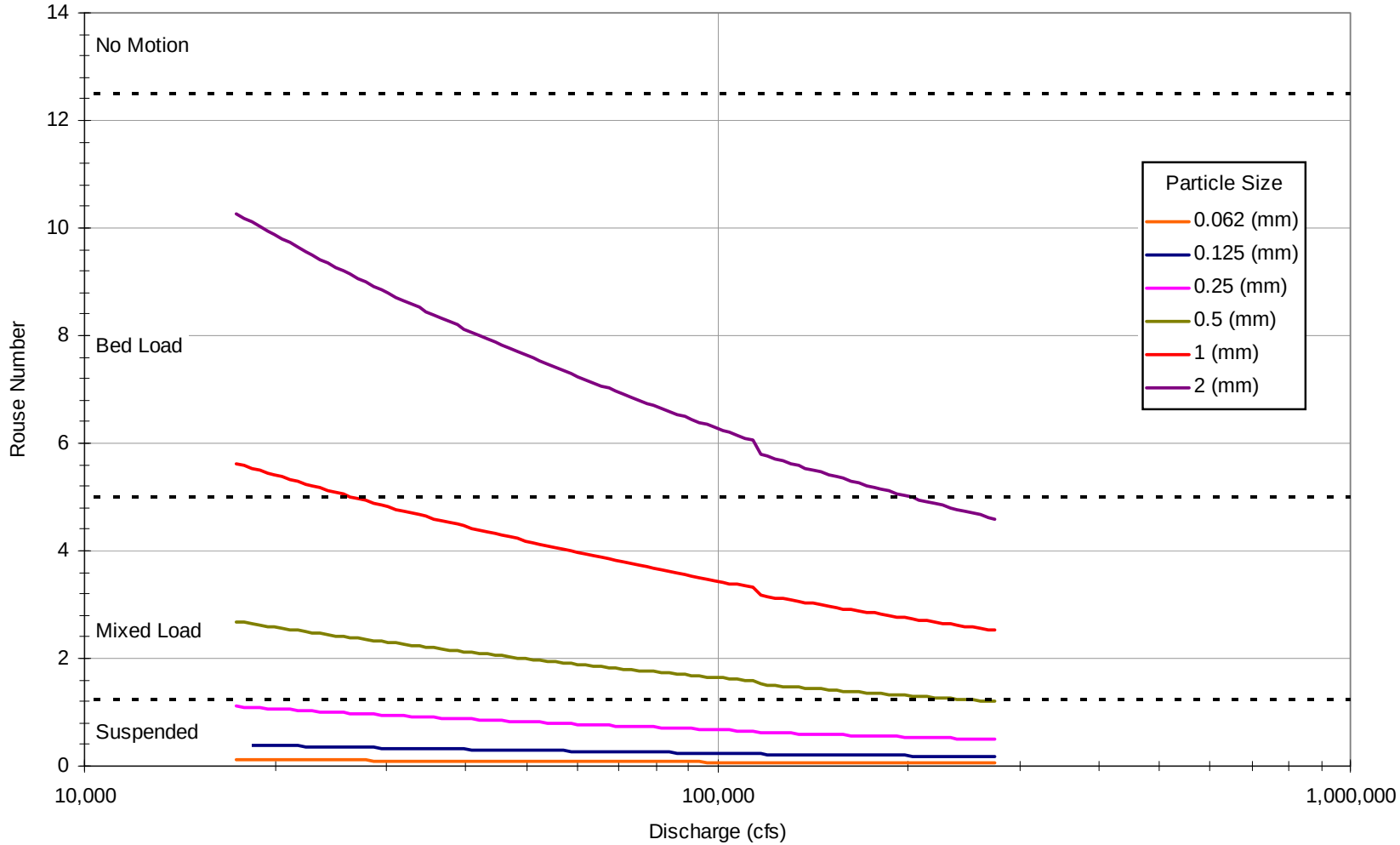

Figure A-19 Mode of Sediment Transport Predicted from Rouse Number Analysis at the Kansas City Hydraulic Modeling Reach

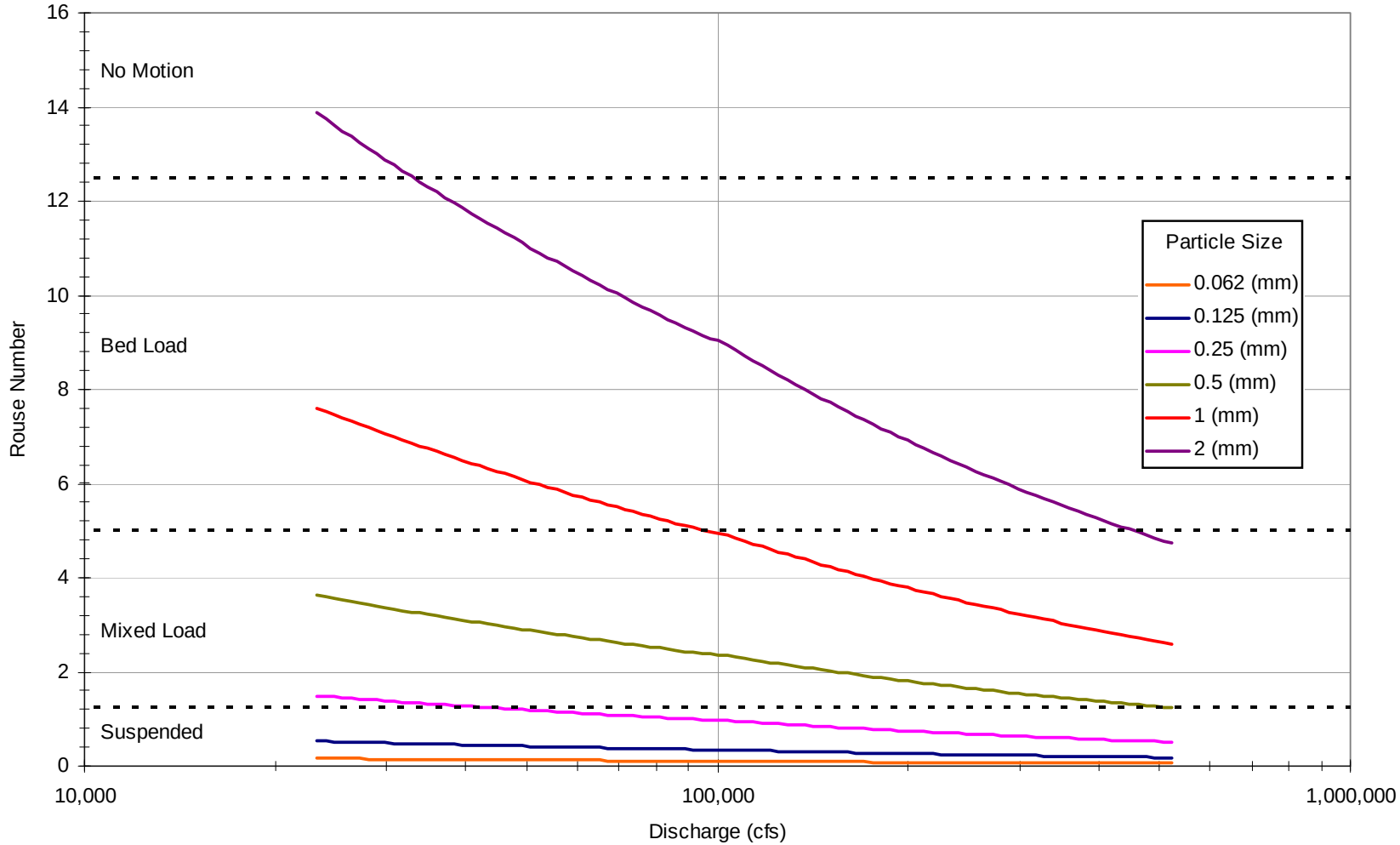

Figure A-20 Mode of Sediment Transport Predicted from Rouse Number Analysis at the Hermann Hydraulic Modeling Reach

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.

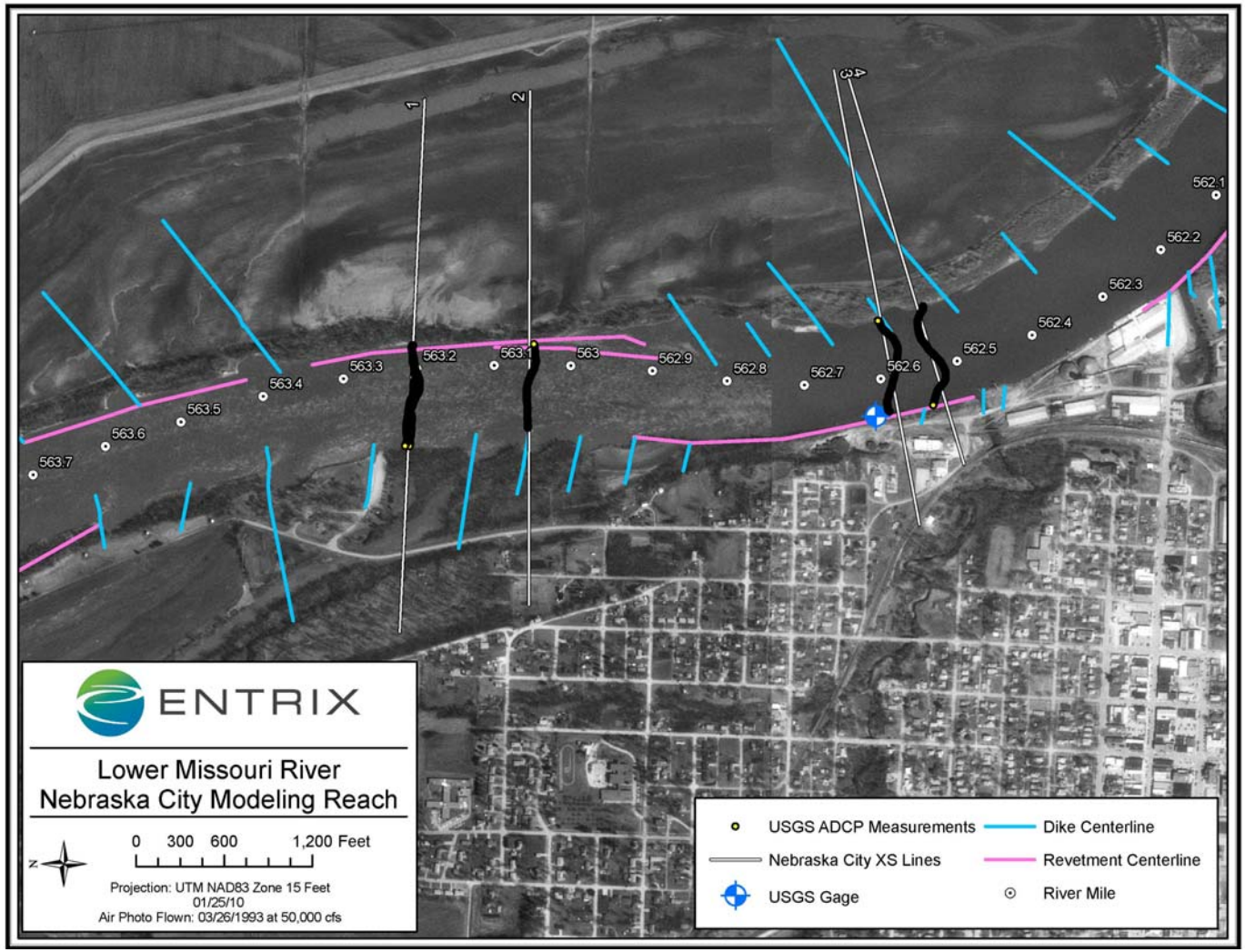

Figure A-21 Overview of the Nebraska City Hydraulic Modeling Reach

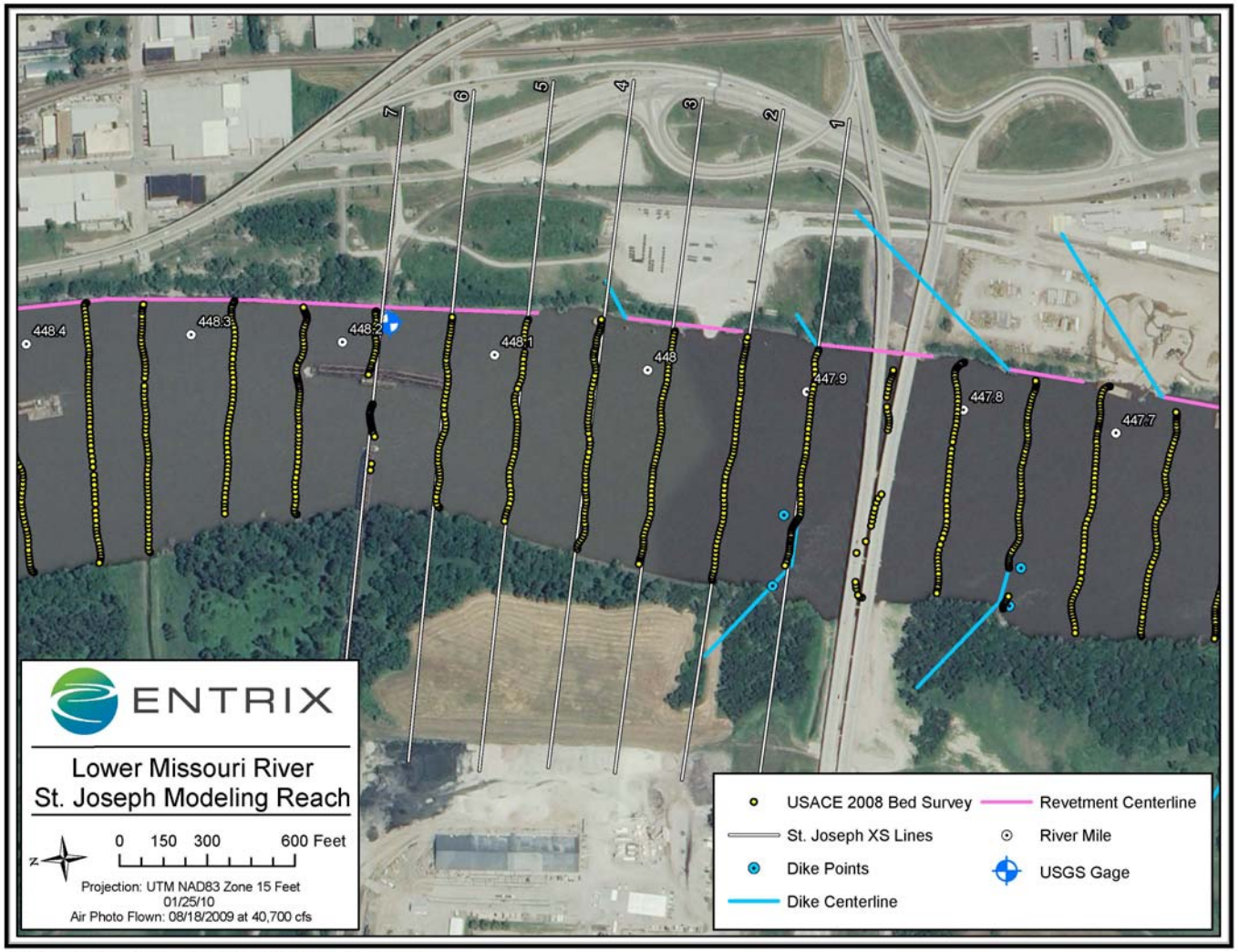

Figure A-22 Overview of the St. Joseph Hydraulic Modeling Reach

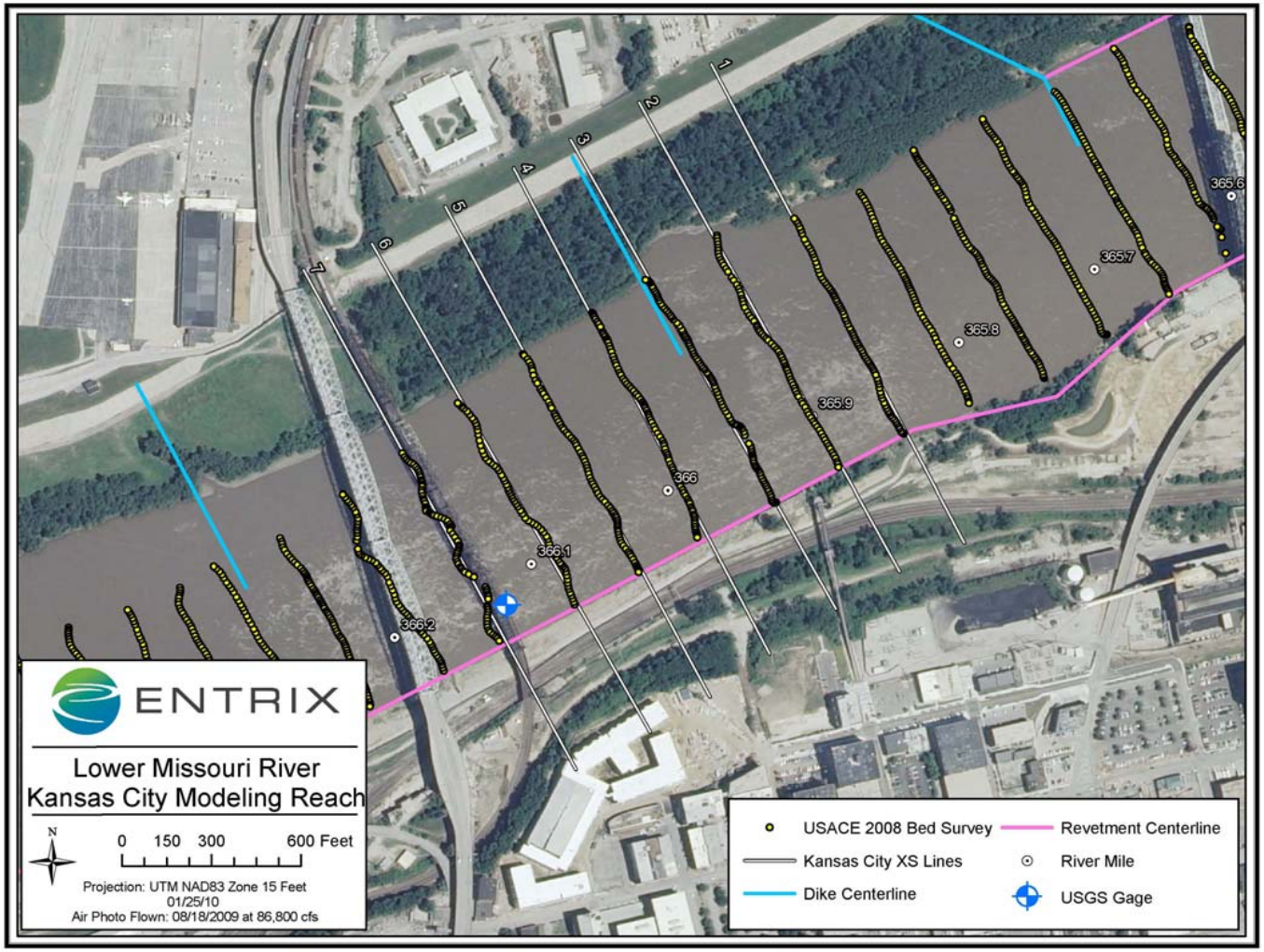

Figure A-23 Overview of the Kansas City Hydraulic Modeling Reach

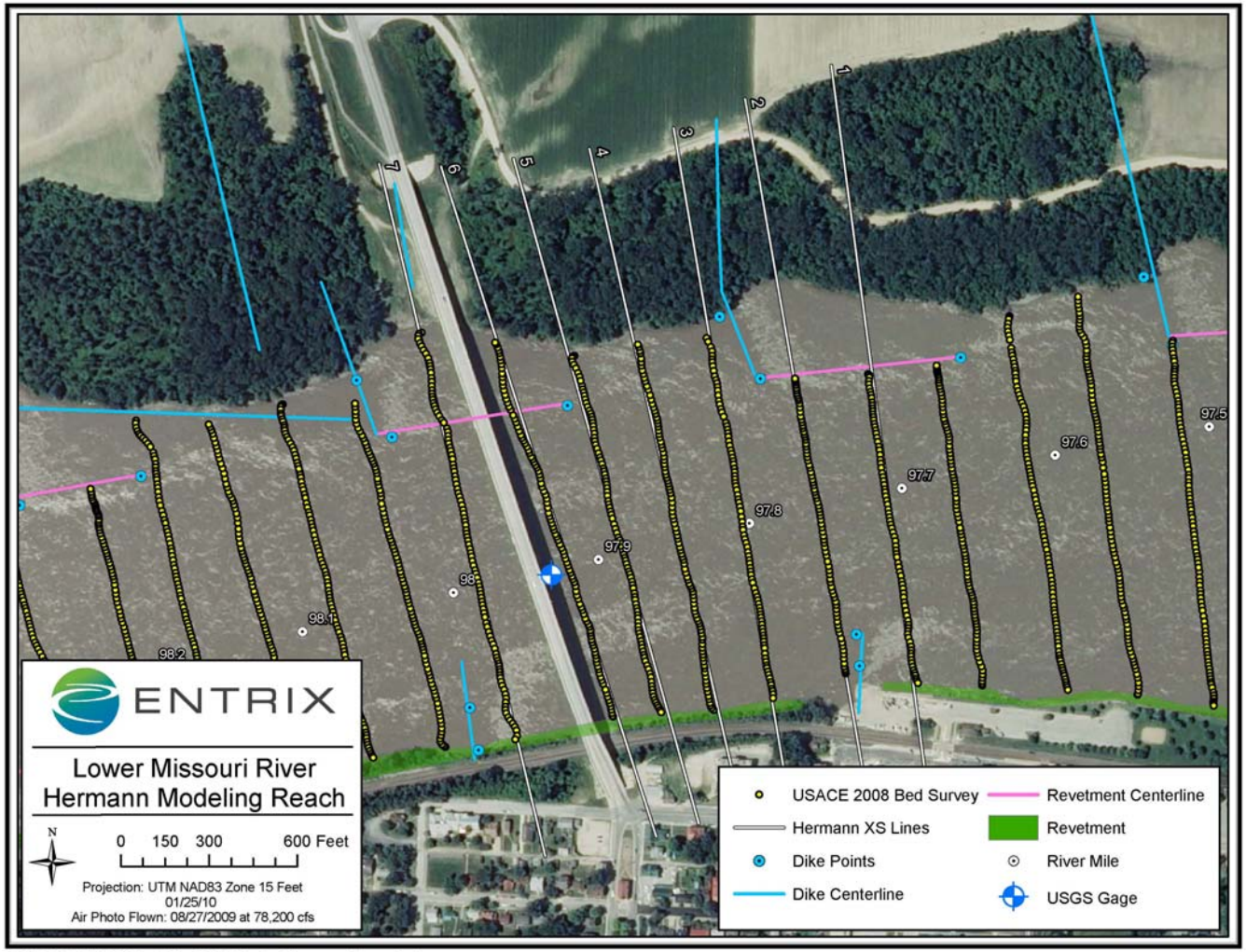

Figure A-24 Overview of the Hermann Hydraulic Modeling Reach

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.

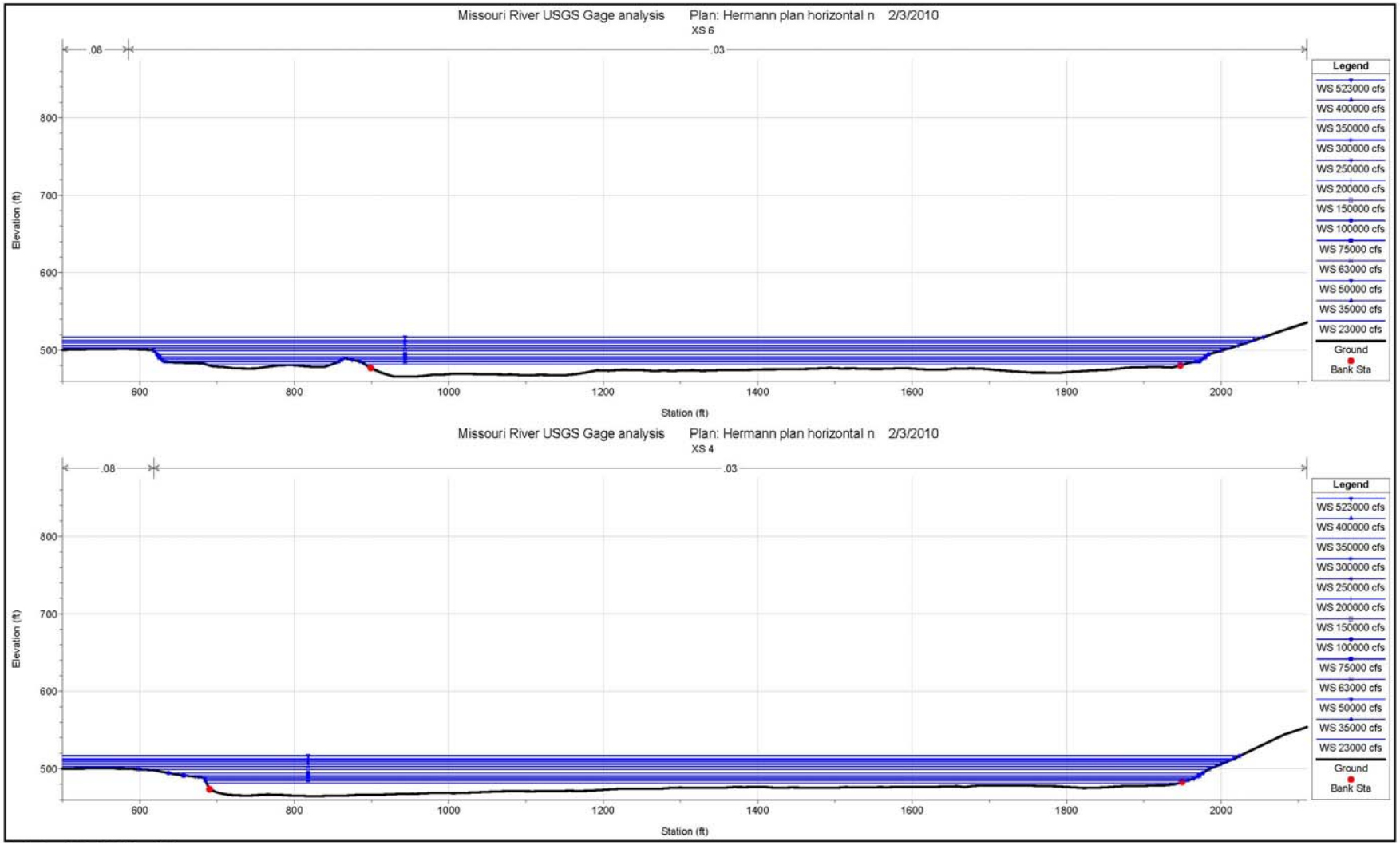

Figure A-25 Example HEC-RAS Cross Section Plots Showing Bed Material Transport Widths for a Cross Section with (XS 6 top) and without (XS 4 bottom) Missouri River Bank Stabilization and Navigation Project Revetments

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.

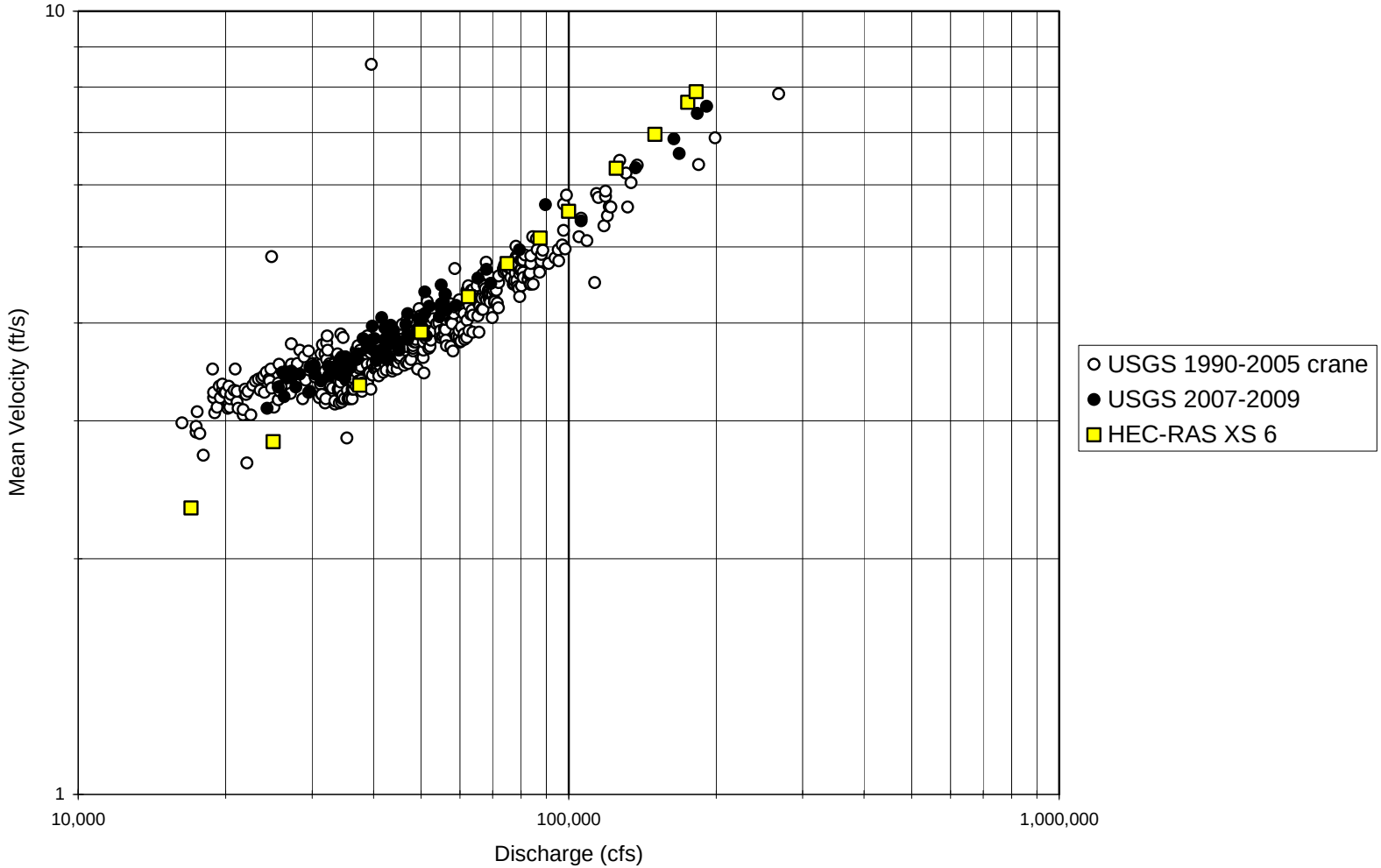

Figure A-26 Comparison of USGG Measured and HEC-RAS Modeled Mean Channel Velocities at the St. Joseph Gage

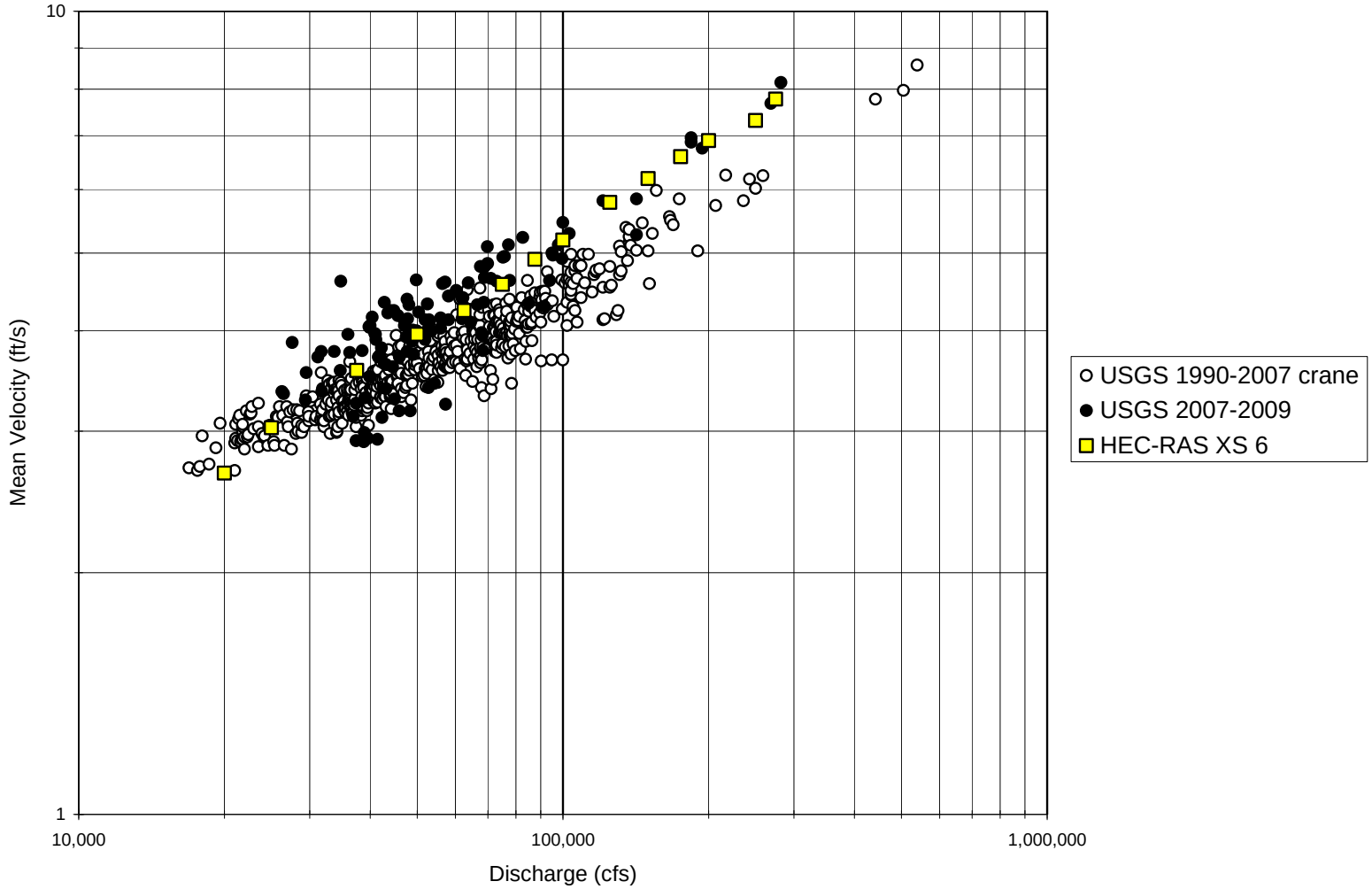

Figure A-27 Comparison of USGG Measured and HEC-RAS Modeled Mean Channel Velocities at the Kansas City Gage

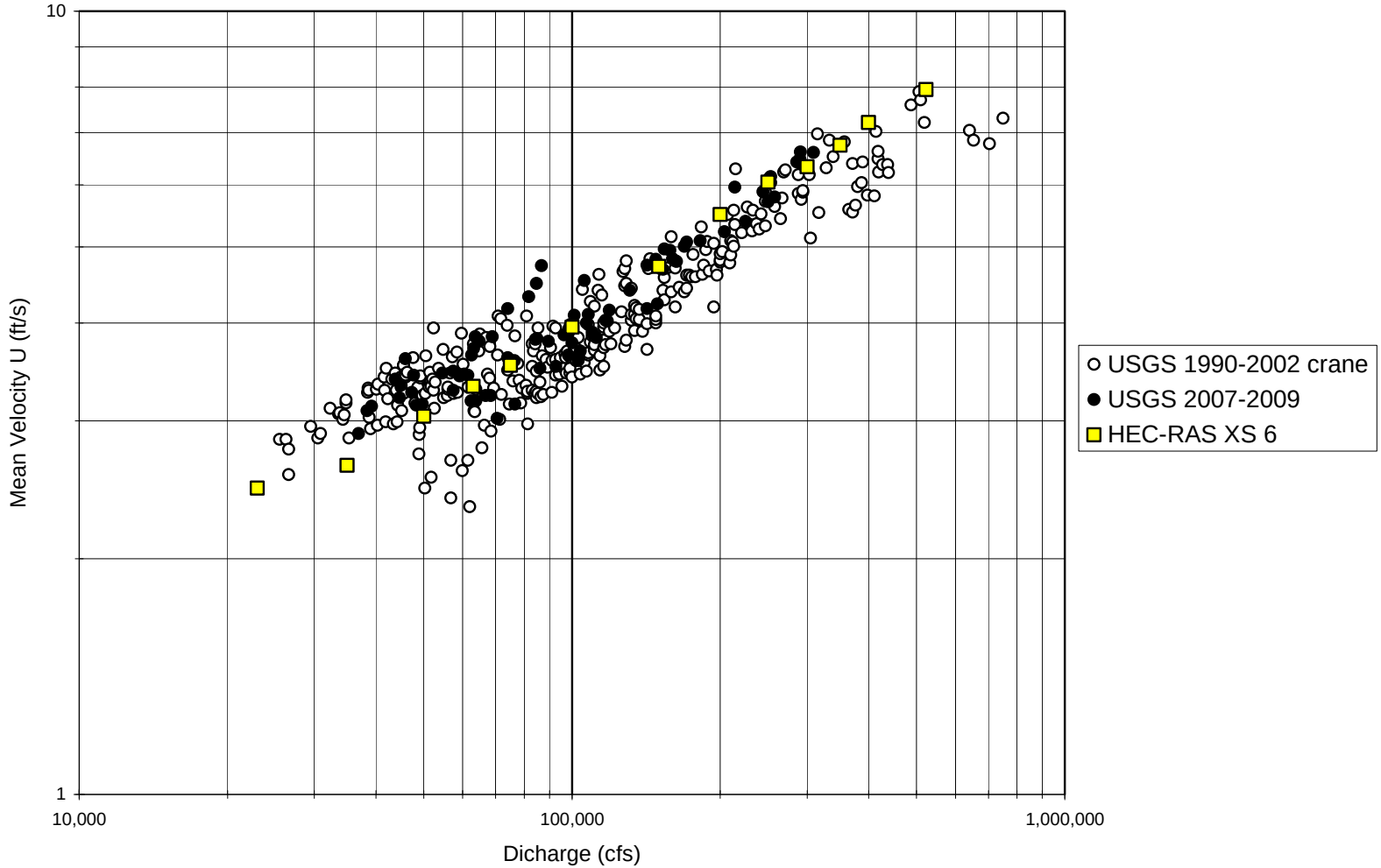

Figure A-28 Comparison of USGG Measured and HEC-RAS Modeled Mean Channel Velocities at the Hermann Gage

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

HEC-RAS Cross Section	Discharge (cubic feet per second)	Velocity (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

$$C_f = \frac{2(gR_h S_f)}{U^2}$$, 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]
$\tau_b = \rho g H S_f$, 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]
v_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

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

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

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

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

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

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]
$\tau_b = \rho g H S_f$, 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:

v_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.

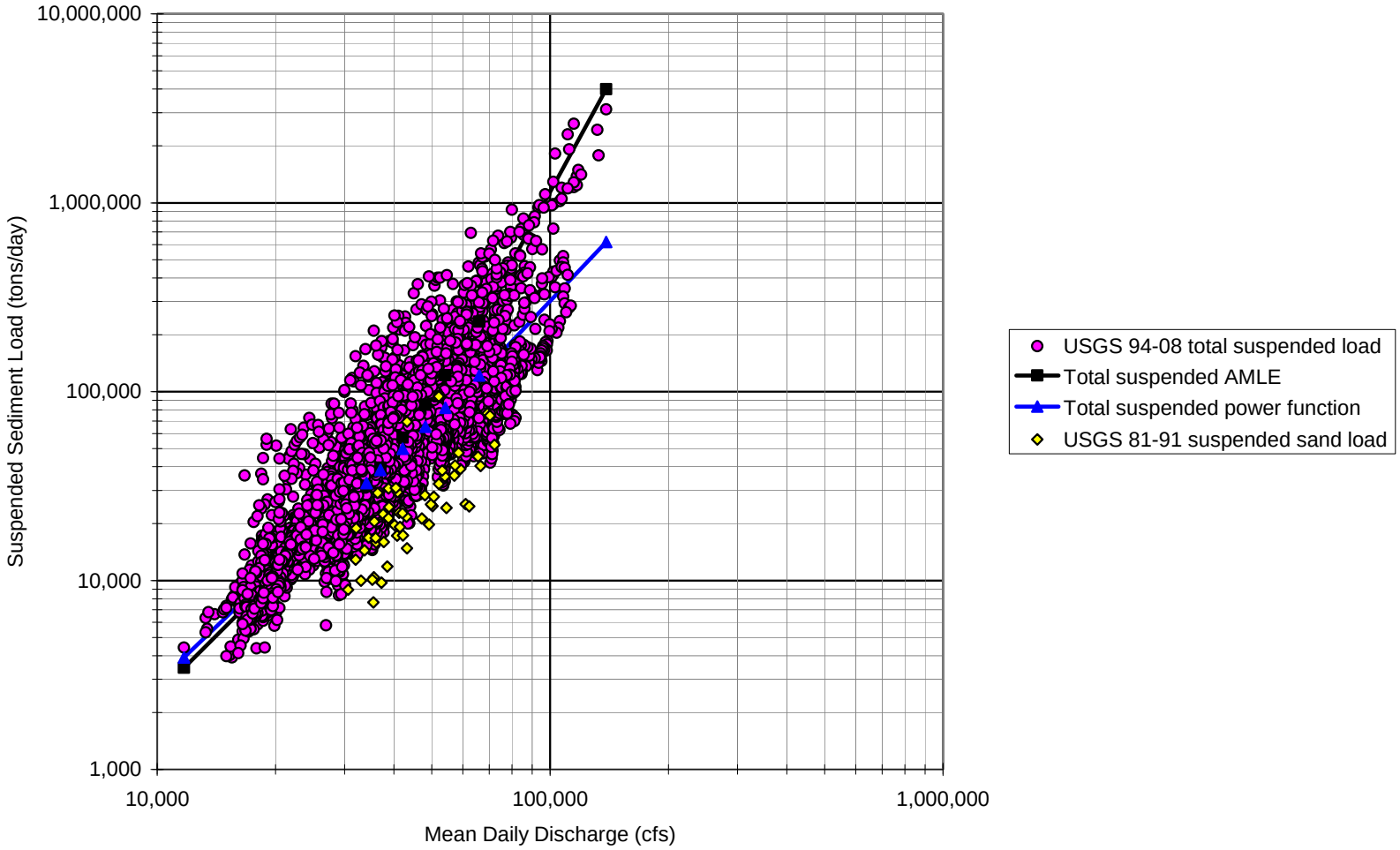

Figure A-29 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the Nebraska City Gage

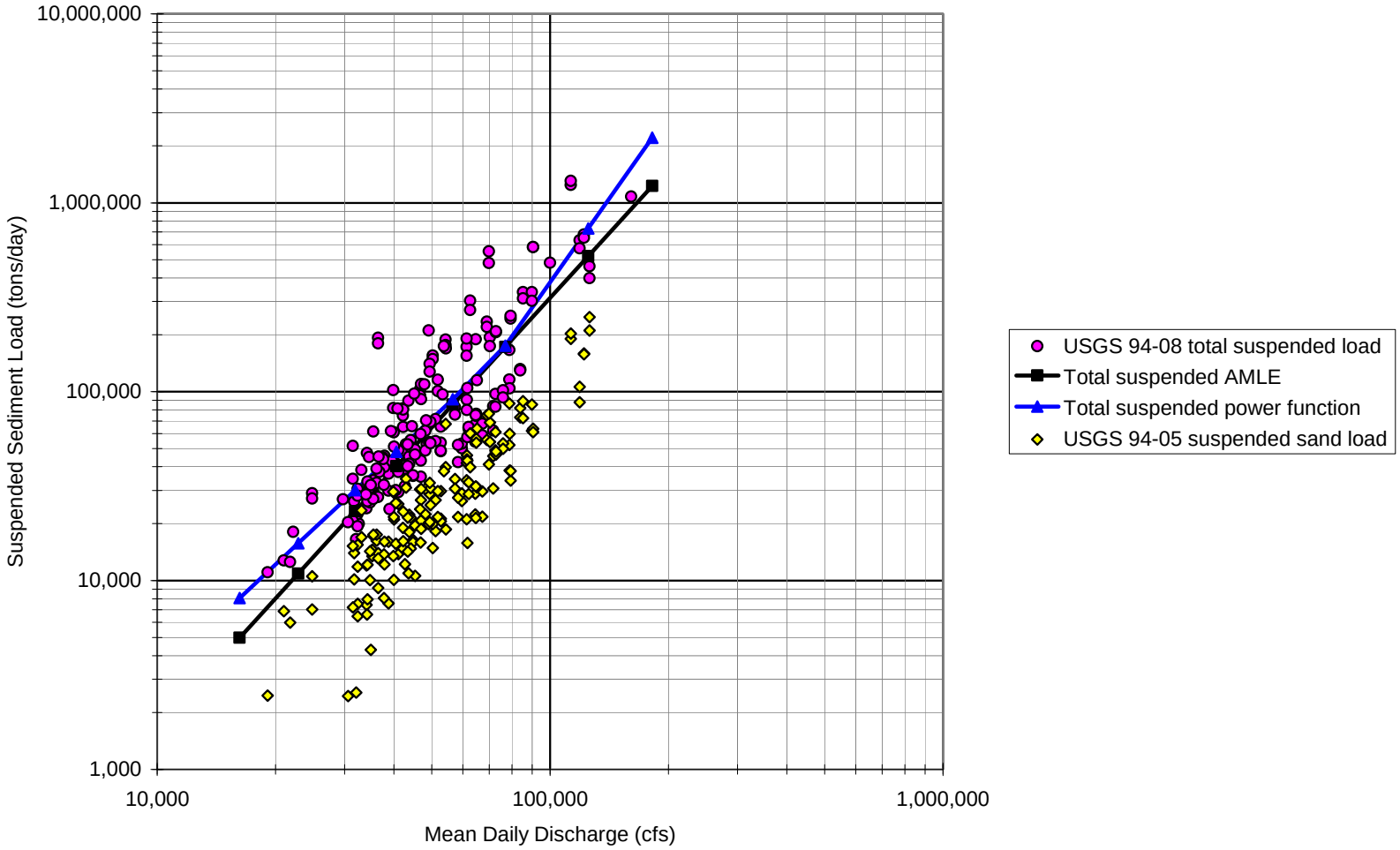

Figure A-30 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the St. Joseph Gage

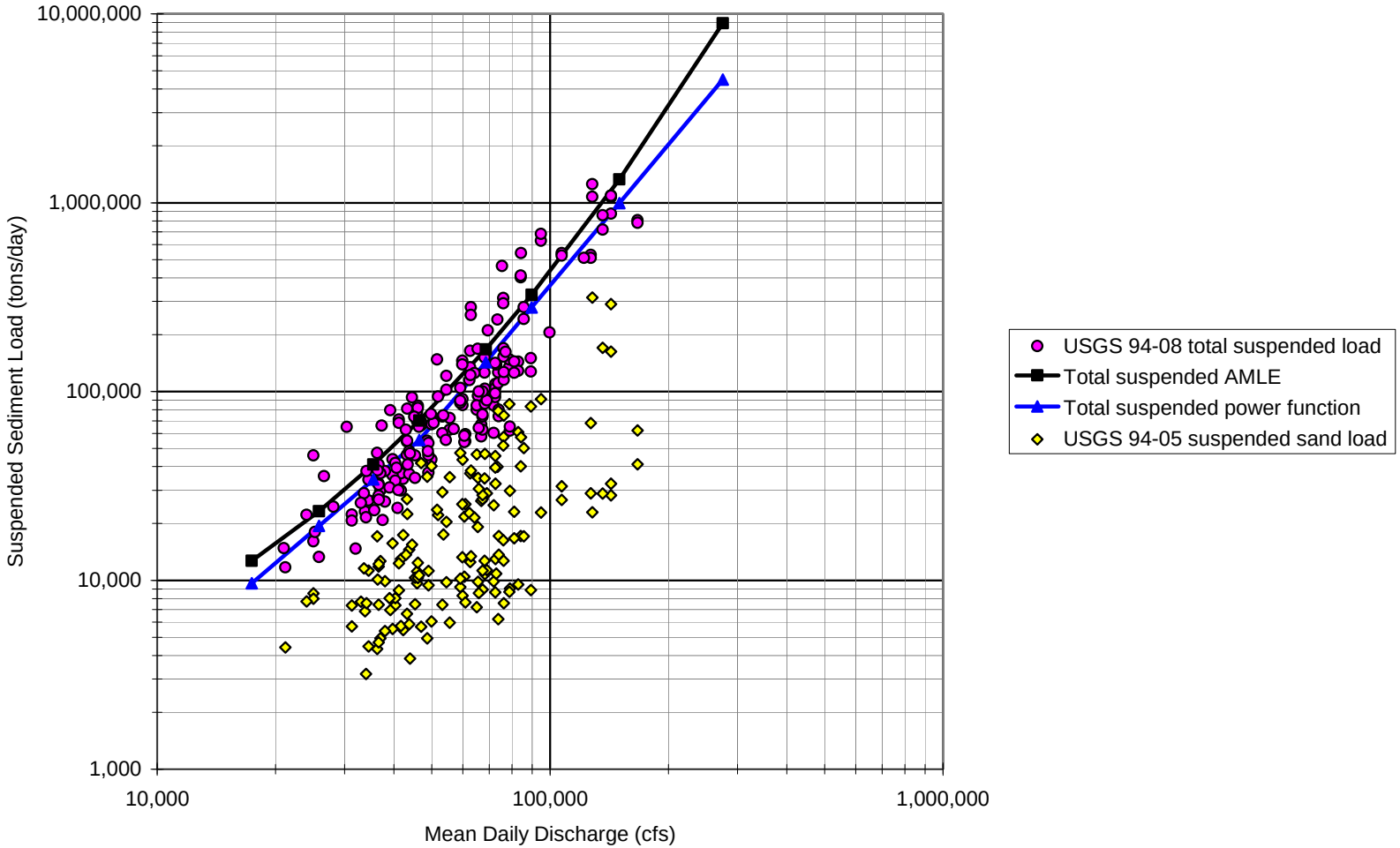

Figure A-31 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the Kansas City Gage

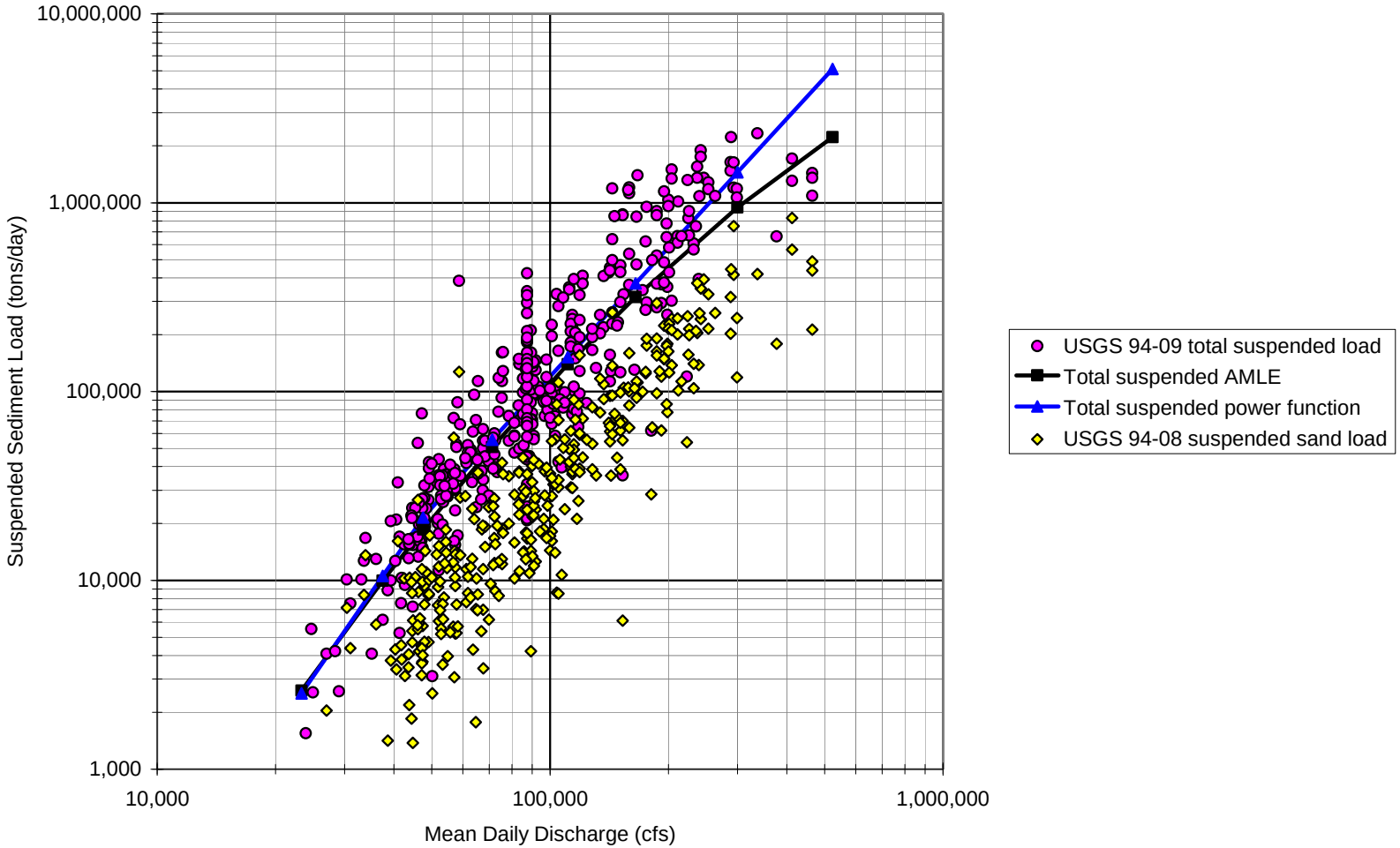

Figure A-32 USGS Measured Total Suspended Sediment and Suspended Sand Loads with Comparison of AMLE and Power Function Total Suspended Sediment Rating Curves at the Hermann Gage

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.

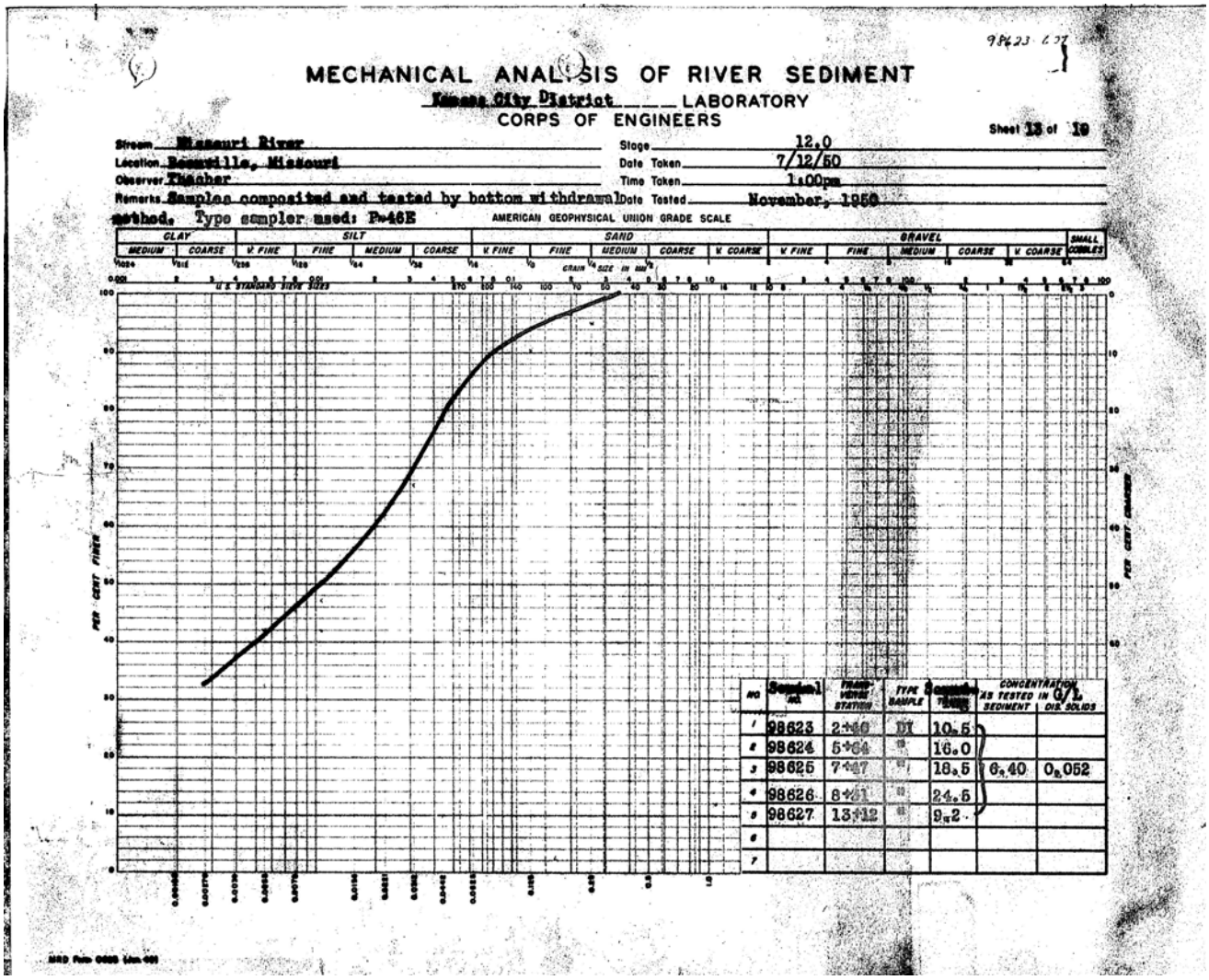

Figure A-33 Example of USACE Mechanical Analysis Curve That Includes Particle Size Analysis for the Clay and Silt Fraction of the Suspended Load

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.

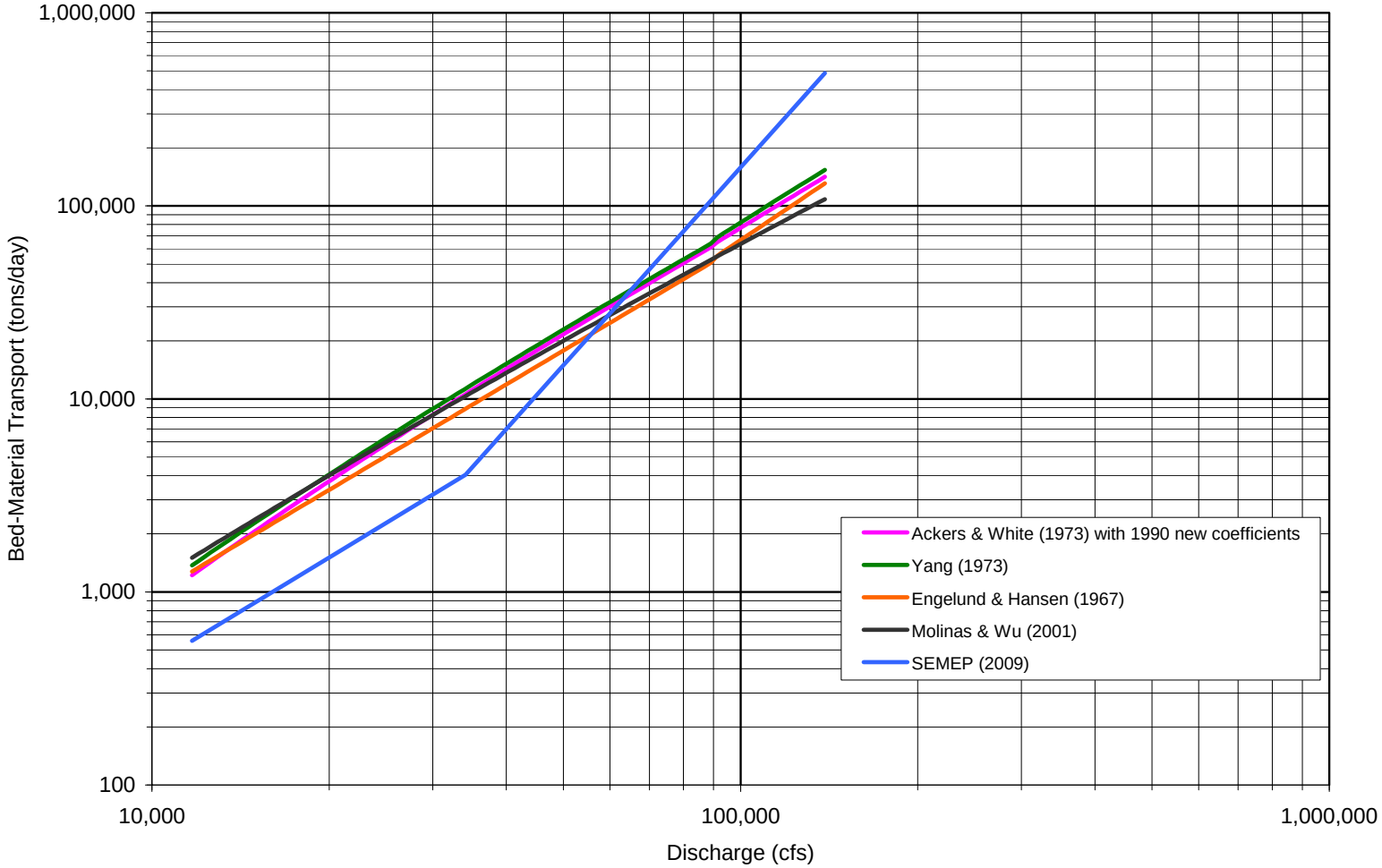

Figure A-34 Total Bed Material Rating Curves Produced by the Five Equations at the Nebraska City Hydraulic Modeling Reach

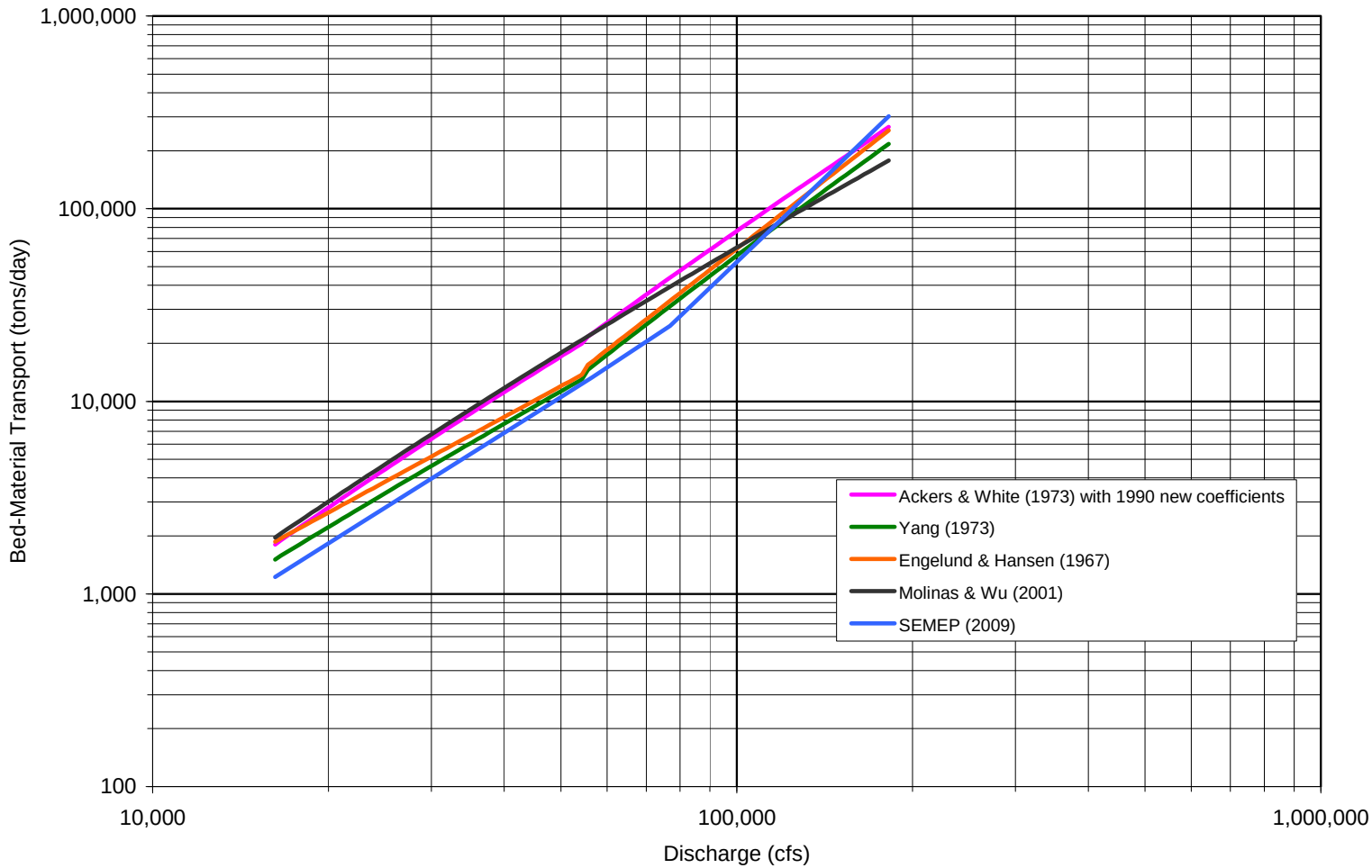

Figure A-35 Total Bed Material Rating Curves Produced by the Five Equations at the St. Joseph Hydraulic Modeling Reach

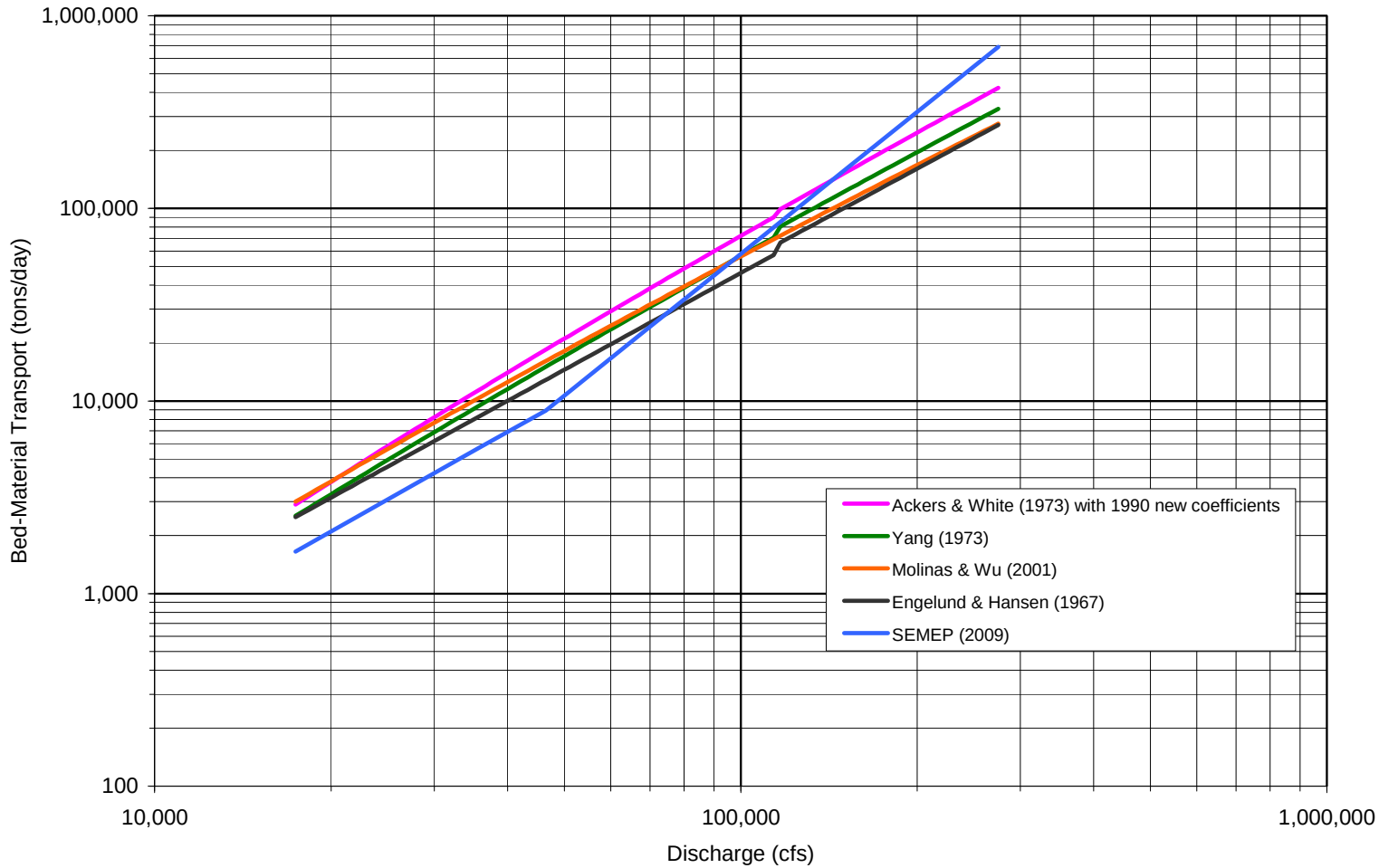

Figure A-36 Total Bed Material Rating Curves Produced by the Five Equations at the Kansas City Hydraulic Modeling Reach

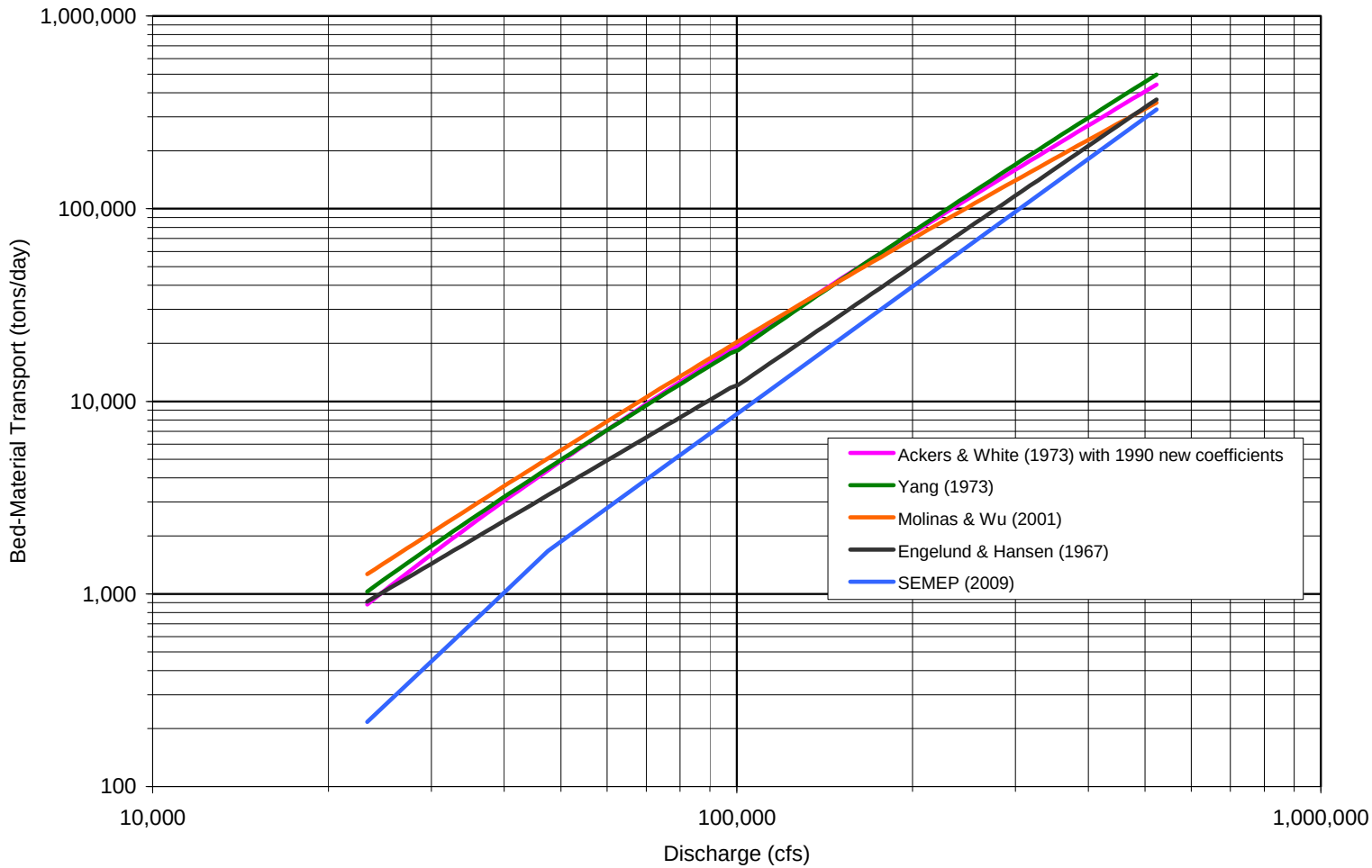

Figure A-37 Total Bed Material Rating Curves Produced by the Five Equations at the Hermann Hydraulic Modeling Reach

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)

		Location			
	Period	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,

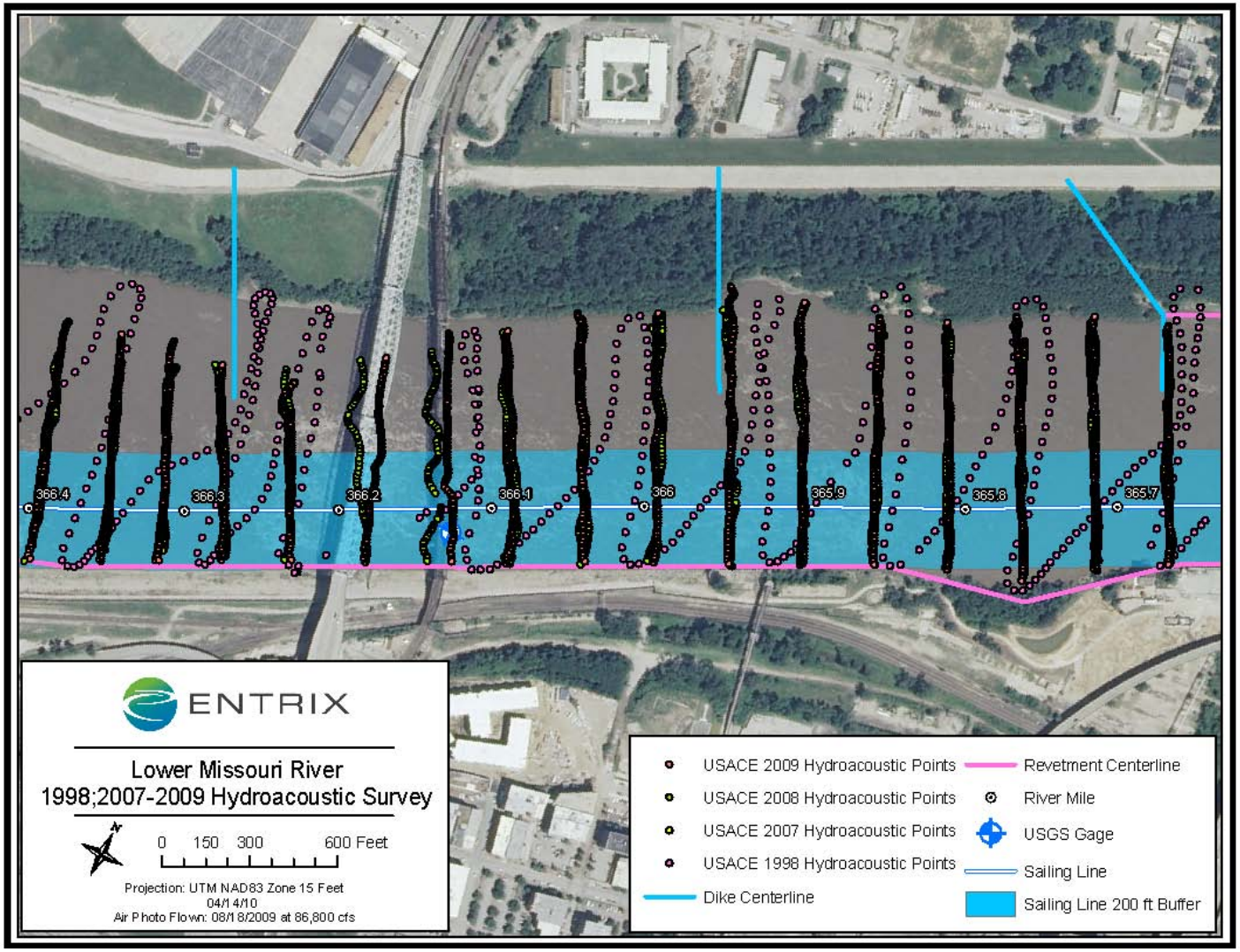

Figure A-38 Hydroacoustic Survey Points in the Kansas City Segment (RM 350 – RM 383) (1998 and 2007–2009)

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.

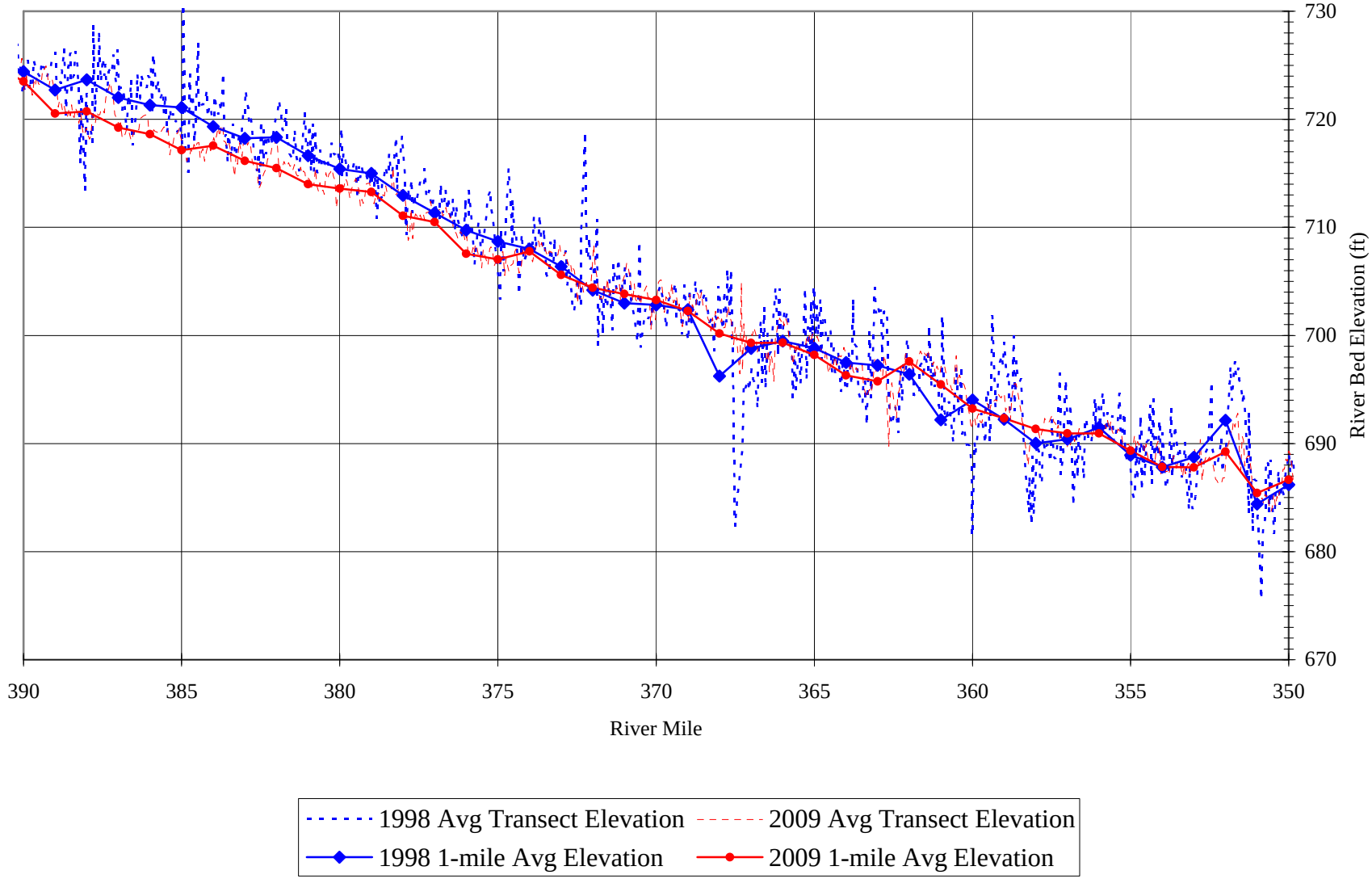

Figure A-39 Average Bed Elevation Points for the 1998 and 2009 Hydroacoustic Surveys Plotted against 1-Mile Average Elevations for the Kansas City Segment

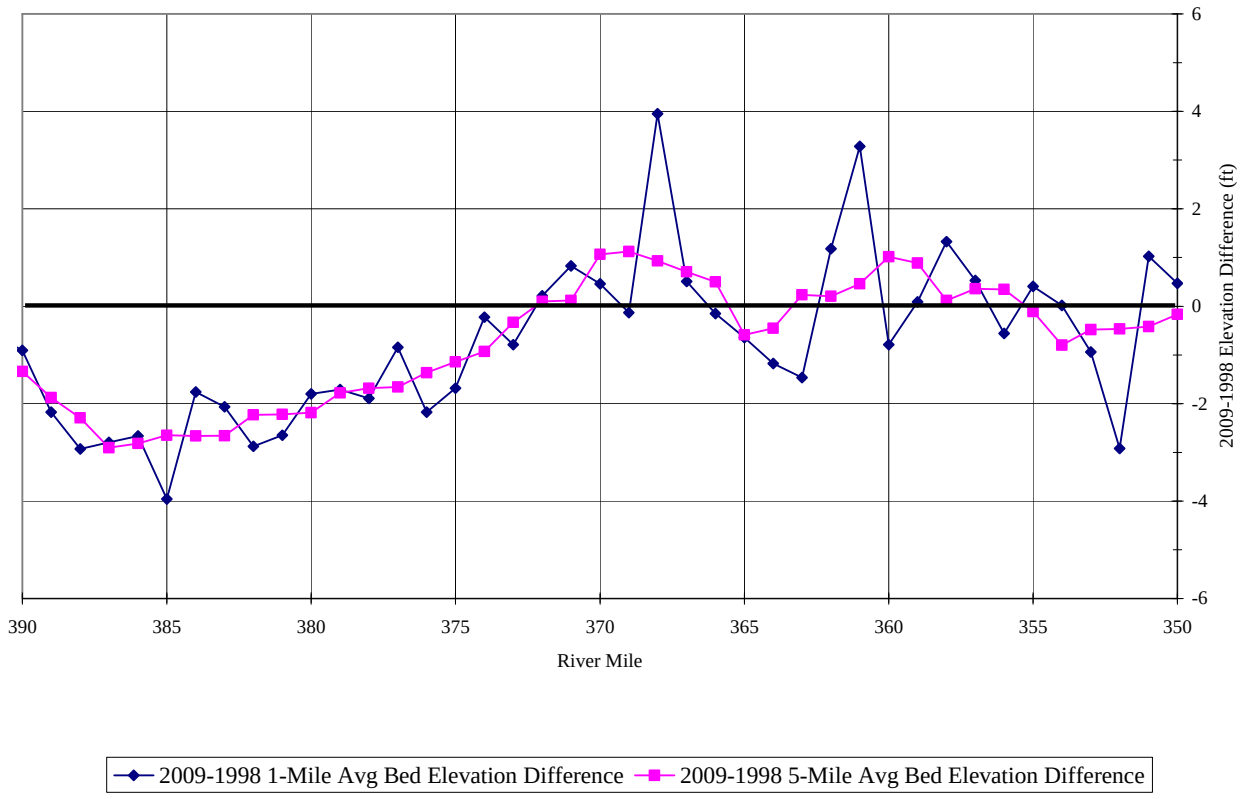

Figure A-40 1-Mile and 5-Mile Averaged Difference between 2009 and 1998 River Bed Elevation Averages for the Kansas City Segment

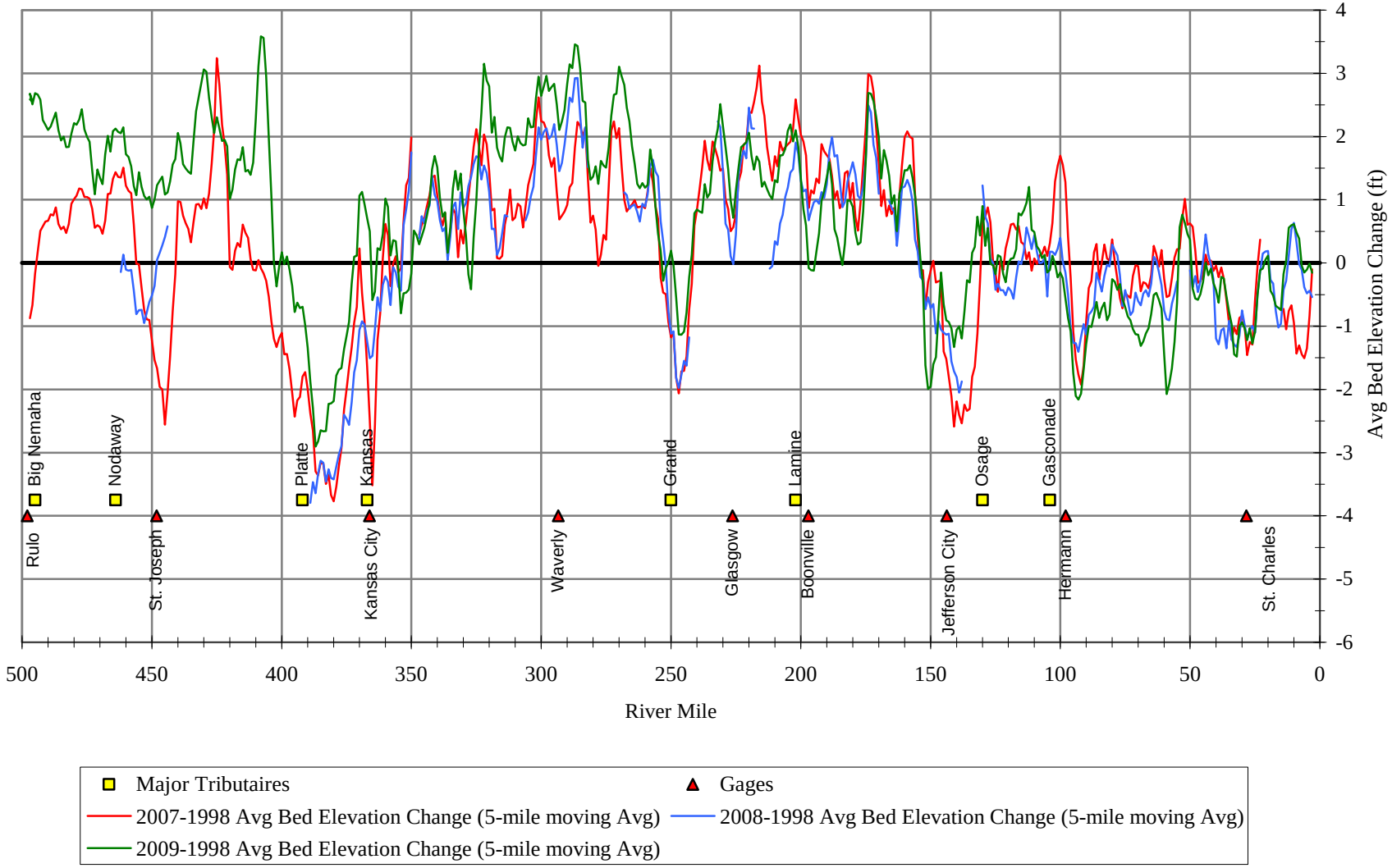

Figure A-41 Change in Average River Bed Elevation between 2007, 2008, and 2009 and 1998 Using 5-Mile Moving Average

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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UNITED STATES ARMY CORPS OF ENGINEERS

Missouri River Commercial Dredging Draft EIS

JULY 2010

Appendix B
Related Action – Development of New Sand Plants

PREPARED BY

ENTRIX, Inc.
200 First Avenue West, Suite 500
Seattle, WA 98119
T 206.269.0104 ▪ F 206.269.0098

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Abbreviations & Acronyms

CWA	Clean Water Act
EIS	environmental impact statement
LOMR	lower Missouri River
Master's	The Master's Dredging Company
MDNR	Missouri Department of Natural Resources
MoDOT	Missouri Department of Transportation
Rau	Edward N. Rau Contractor Company
RHA	Rivers and Harbors Act of 1899
RM	river mile
USACE	U.S. Army Corps of Engineers

A P P E N D I X B

Related Action – Development of New Sand Plants

B.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 a Draft Environmental Impact Statement (EIS). The Draft EIS examines the potential environmental impacts of the proposed dredging activities and any related actions. In addition to dredging, facilities for unloading, sorting, and temporarily storing dredged sand and gravel are required. These facilities, located on the shore at various locations along the LOMR are called sand plants.

Two of the applicants—The Master's Dredging Company (Master's) and Edward N. Rau Contractor Company (Rau)—do not presently own or operate sand plants that could serve their proposed dredging operations. If a permit is authorized for either of these applicants, they propose to build sand plants on sites that they presently own or control. While these facilities are not part of the proposed dredging activity, they are a related action as a means of offloading, processing, storing, and distributing commercial sand and gravel produced by the dredging operation as required. Sites have been secured and some preliminary steps have been taken to initiate development of these facilities. The locations of the existing and proposed sand plants are shown in Figure B-1 (Sheets 1–5).

The following sections include descriptions of the preliminary plans for development of sand plants to support dredging operations for Master's and Rau.

B.2 THE MASTER'S DREDGING COMPANY, INC.

Master's proposes to dredge in river reaches from approximately RM 383.1 to RM 390. Master's has control of a property near Waldron, Missouri. Master's plans to develop a sand plant at one of two sites on the Waldron property to support approved dredging operations.

The Master's dredging operation differs from that of all the other applicants in that the dredge slurry is not screened on the dredge and the selected material is not loaded onto a barge. Instead, Master's plans to string a pipeline from the dredge to its sand plant and pipe the dredged slurry to shore, where it would be separated, screened, and dewatered. The processed material then would be stacked for distribution. The site plan shows each of these components (Figure B-2). After the dredged material has been sorted and stacked, the remainder of the operation would be similar to operations at the sand plants of the other Dredgers.

The Master's property at Waldron is located on Morris Ferry Road, as described below. Two separate sites are being considered for the proposed sand plant on the Morris Road property. These sites are shown as Plant Site 1 and Plant Site 2 in Figure B-2. The configuration and permitting requirements for the sites are described below.

Location: 39 deg. 14.25' north, 94 deg. 49.366' west, approximately RM 388.

Size: 20 – 60 acres would be developed depending on the amount of dredging approved.

Site Plan: The site would be developed to include a sand plant configured as shown in Figure B-3. The sand plant would be connected to the dredging operation via a slurry pipeline that carries the dredged material. The slurry pipeline would require an easement over the shoreline and to the sand plant site. At the sand plant, the slurry would be delignified (coal would be removed from the sand and gravel) and dewatered, and then the material would be classified by size and transported via a conveyor/stacker to a storage pile. Depending on the dredging amounts allowed in any approved dredging permit, one of two storage piles would be established with a storage volume of 500,000 tons per pile. The pile could be up to 100 feet high. Although not shown, the site plan would likely include an office/maintenance building and truck scale. Access to the sand plant would be from Morris Road.

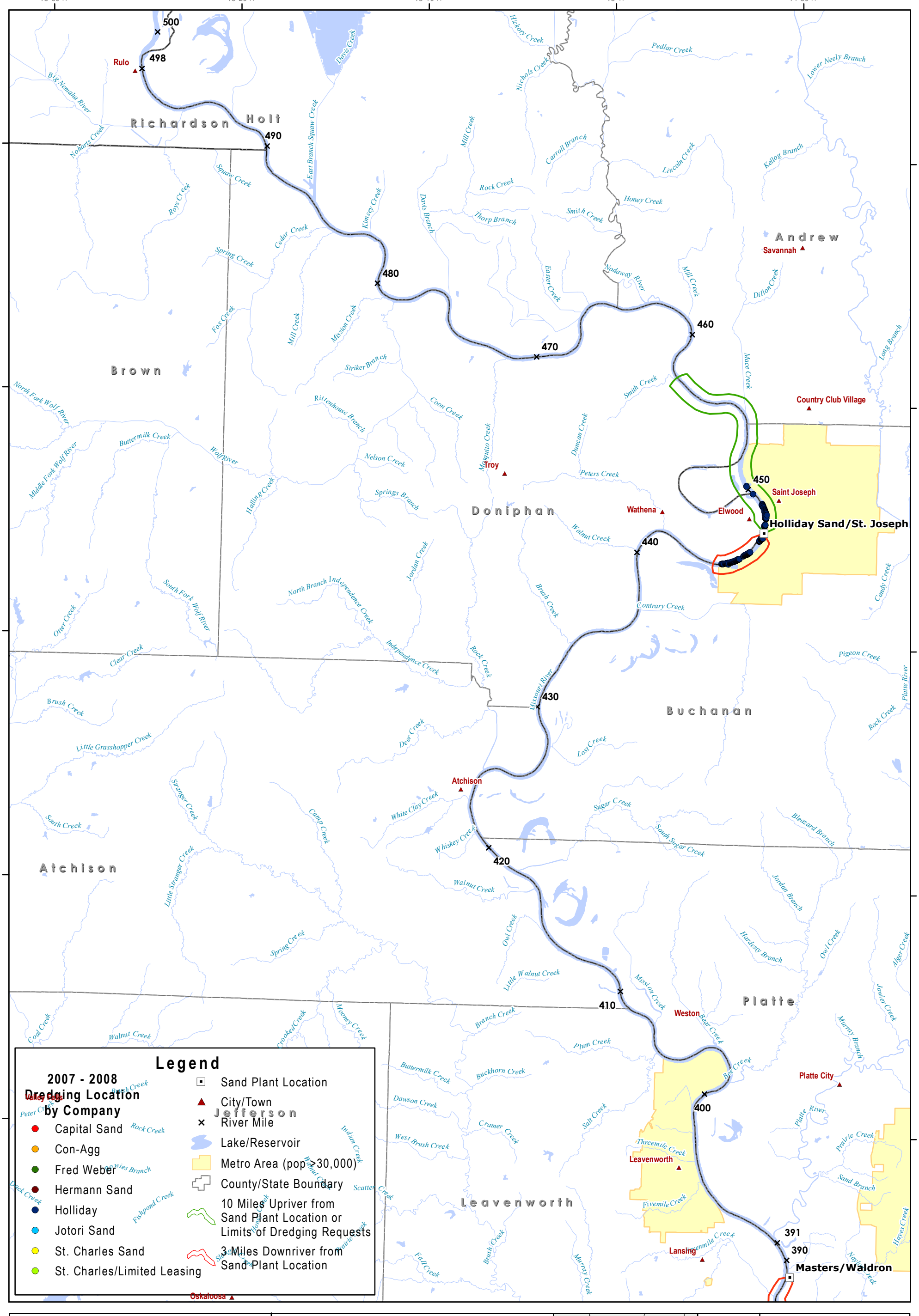
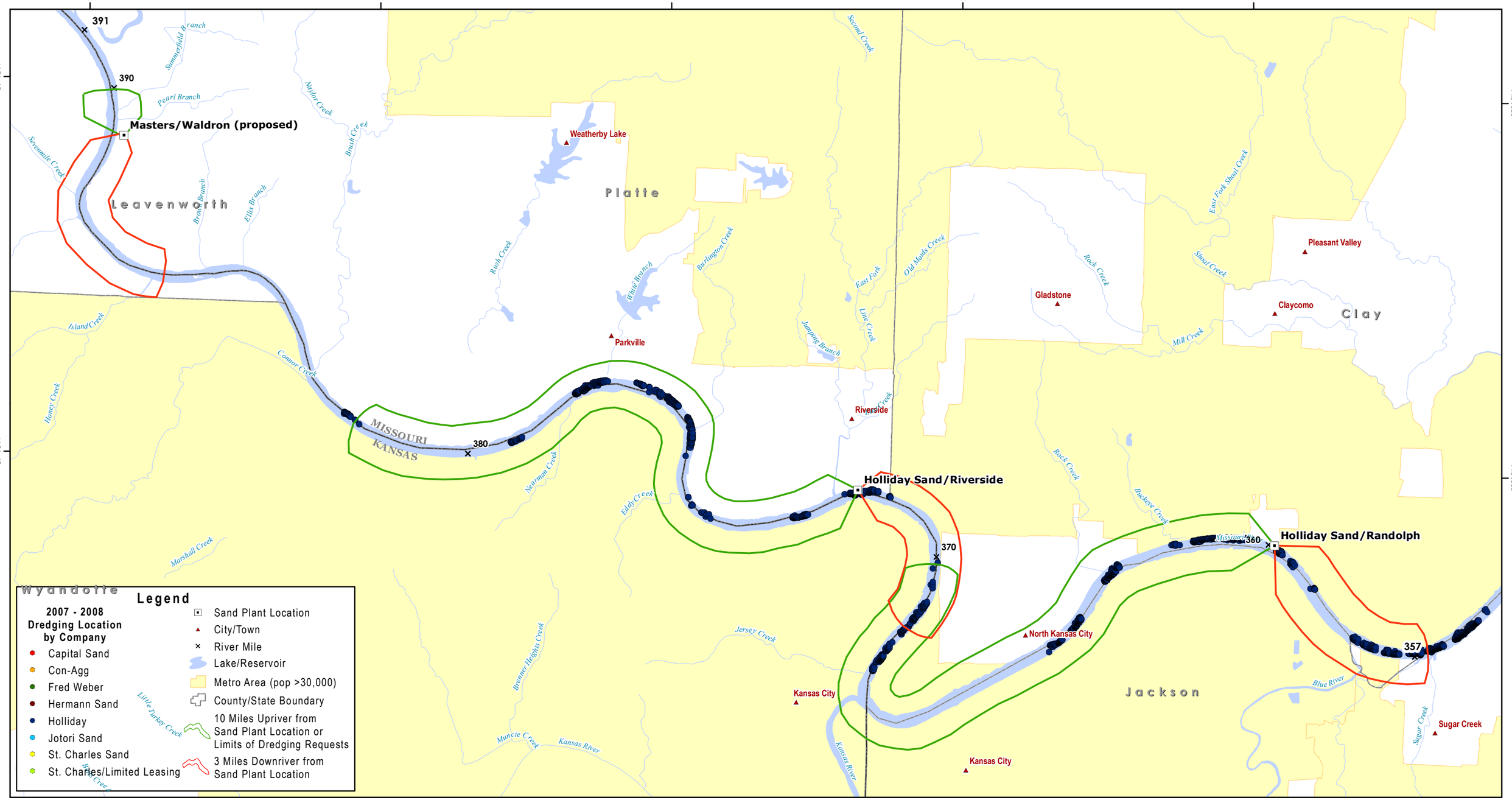


Figure B-1
Dredging Sand Plant Locations
Sheet 1 - St. Joseph Segment
Missouri River Commercial Dredging EIS



0 2.5 5 Miles

0 2.5 5 Kilometers

Figure B-1
Dredging Sand Plant Locations
Sheet 2 - Kansas City Segment

Missouri River Commercial Dredging EIS

July 2010

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Map Projection: NAD83 UTM Zone15 North

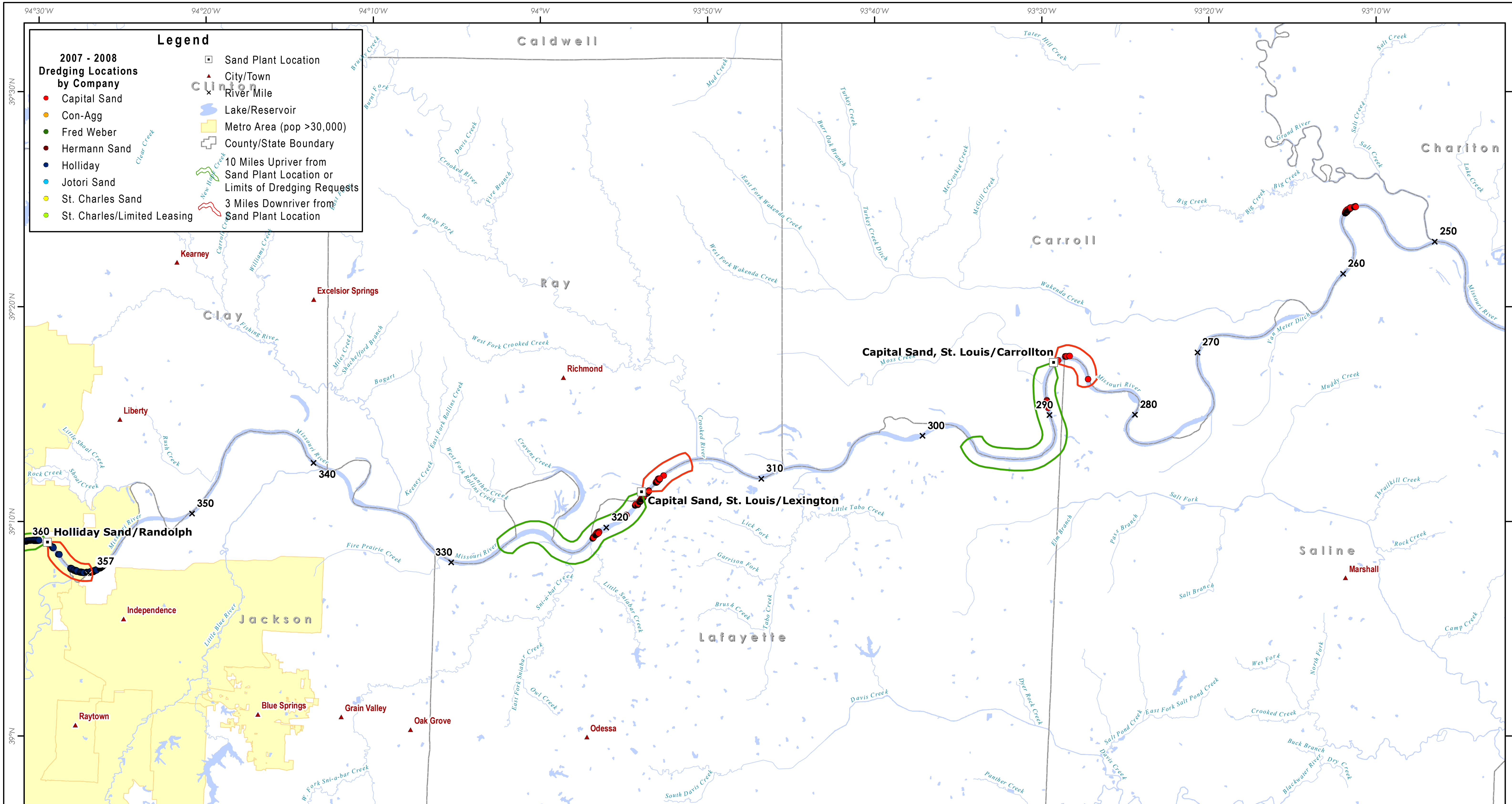

Figure B-1
Dredging Sand Plant Locations
Sheet 3 - Waverly Segment

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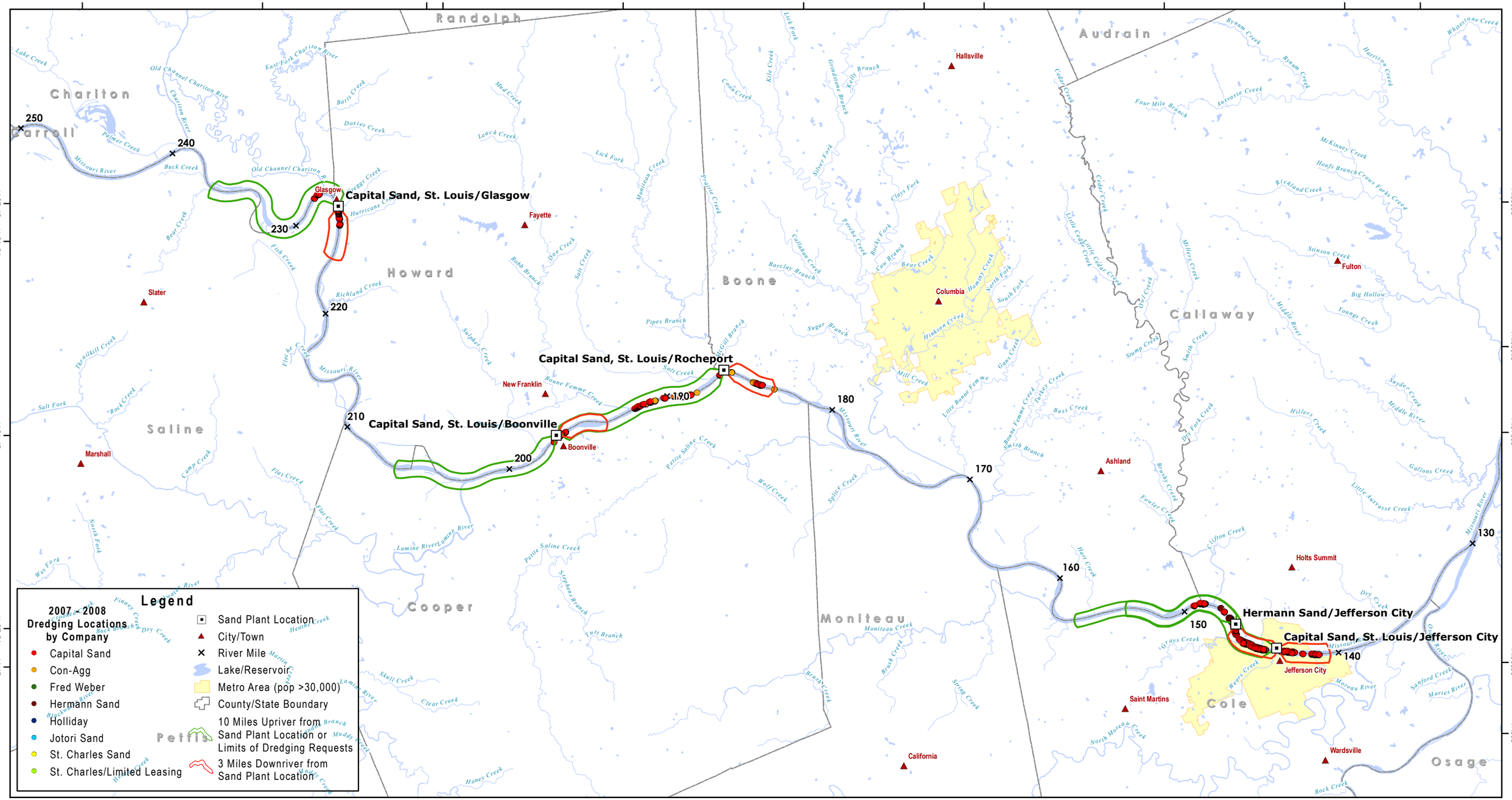

Figure B-1
Dredging Sand Plant Locations
Sheet 4 - Jefferson City Segment

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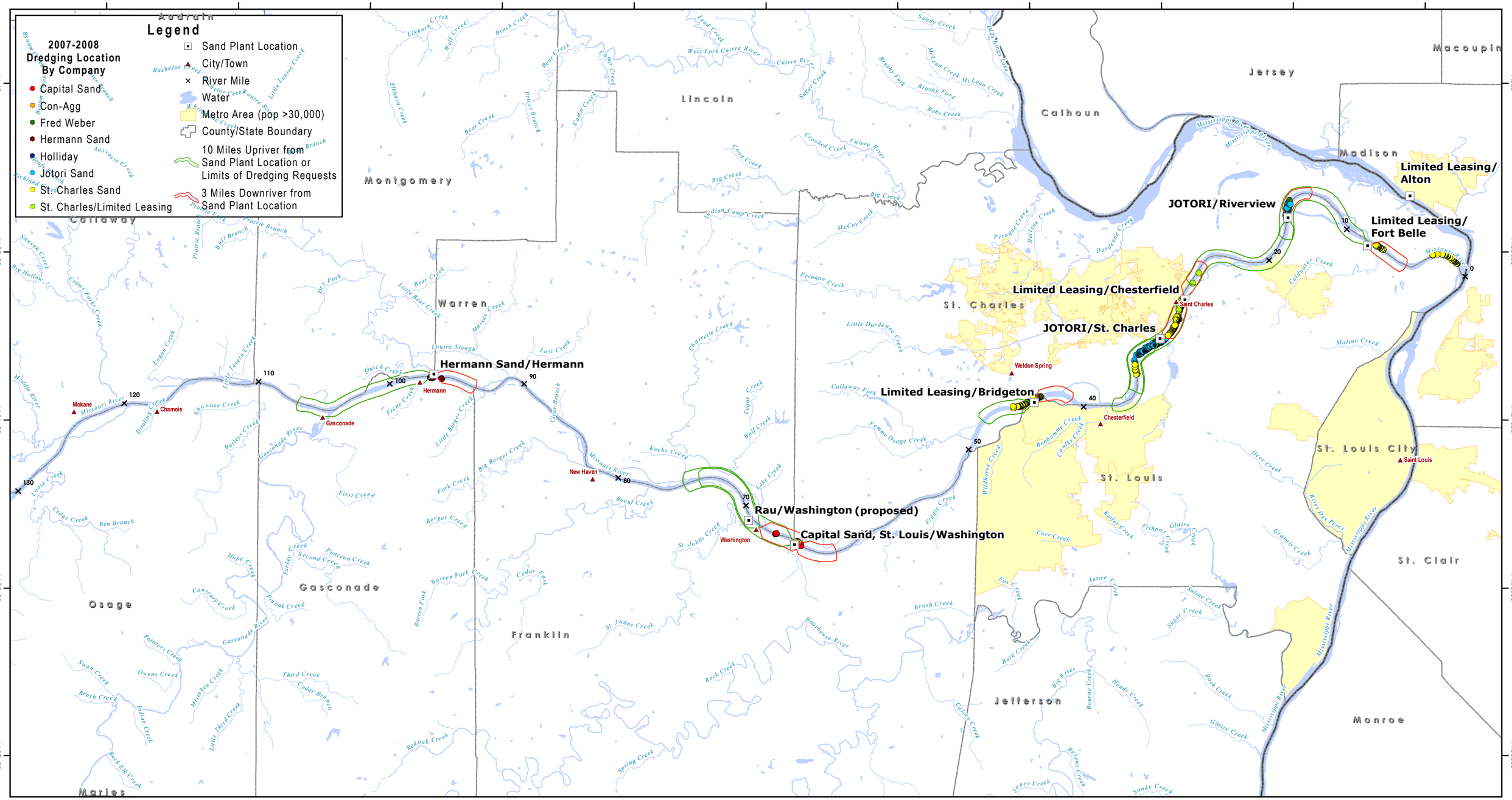

0 5 10 15 20 25 30 Miles

0 5 10 15 20 25 30 Kilometers

Figure B-1
Dredging Sand Plant Locations
Sheet 5 - St. Charles Segment

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Figure B-2 Master's Waldron Optional Sand Plant Sites

Source: GoogleEarth.

Site 1 – Site 1 is located on the river side of federal flood control levee L-400**,** maintained by the Waldron Levee District. Master's has indicated that, if they constructed on this site, they would include a boat ramp for marshalling dredging equipment.

Site 2 – Site 2 is located on the upland side of federal flood control levee L-400 and would require a pipeline crossing of the levee.

Adjacent Land Use: Agricultural

Capacity: Operating capacity would range from 1,000 to 3,000 tons/hour depending on the dredge used. Sand storage would range from 0.3 to 1.0 million tons depending on the size of development.

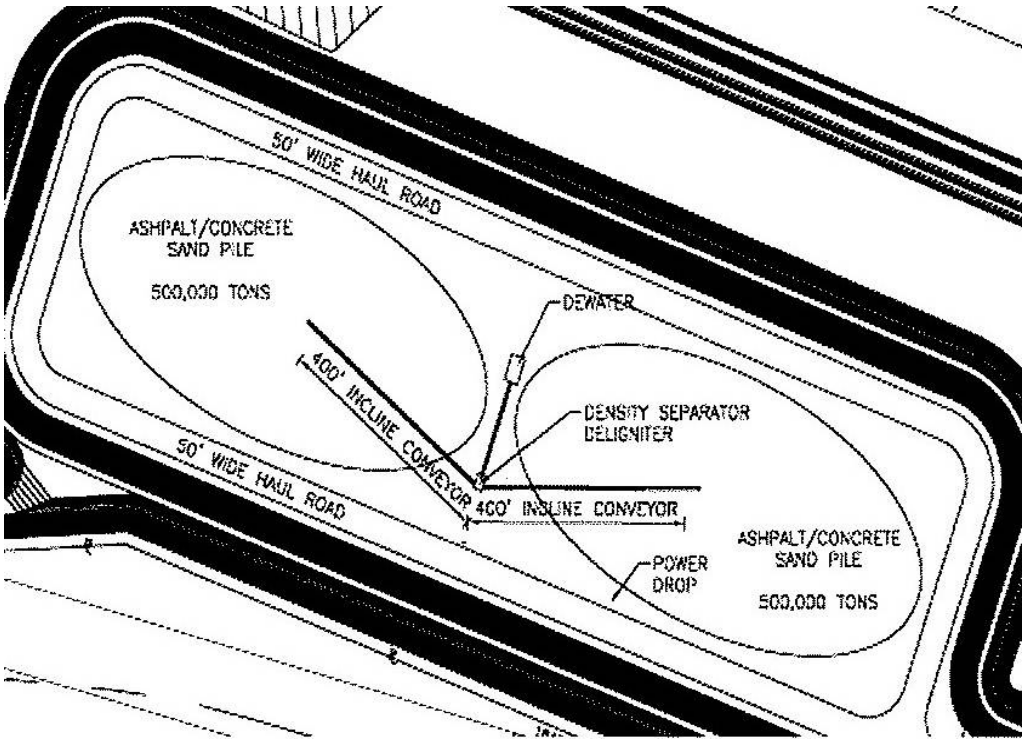

Figure B-3 Master's Waldron Sand Plant – General Site Plan

Site Development Permits, Approvals and Consultations: Federal, state, and local permits, approvals, and consultations that may be required for development of the Waldron facility include:

- County – Conditional Use Permit (zoning);
- Missouri Department of Transportation (MoDOT) – highway access;
- Missouri Department of Natural Resources (MDNR) – air permit, water quality (wastewater discharge) permit;
- USACE– consultation with levee district for construction adjacent to a levee;
- Section 10 of the Rivers and Harbors Act of 1899 (RHA) – permit for construction of facilities below the high water mark;
- Section 404 of the Clean Water Act (CWA) – permit for dredge and fill in the river or fill in wetlands;
- Land owner easements – for pipeline access from the river to the sand plant site; and
- Electric utility – installation of electrical distribution line.

B.3 EDWARD N. RAU CONTRACTOR COMPANY

Rau plans to construct a sand plant on the shore of the Missouri River at Washington, Missouri. If the USACE issues a dredging permit, Rau would contract with an independent dredging contractor for extraction and delivery of commercial sand and gravel to a Rau-owned and -operated sand plant. The proposed site is shown in Figure B-4. The configuration and permitting requirements for the site are described below.

Location: 38 deg. 34.04' north, 91 deg. 1.273' west, approximately RM 67.

Size: 25.6 acres.

Adjacent Land Use: Commercial, industrial, institutional.

Operation: Rau would contract with a dredging company to dredge under Rau permits. The dredging contractor would be responsible for offloading material to conveyors that would handle material during sorting and stacking operations. Because offloaded sand and gravel would have been graded during dredging, minimal processing would occur. The primary activity would be stacking and then loading material onto trucks for distribution.

Onsite facilities are expected to include:

- Delignifier/washer;
- Classifier;
- Stockpile storage area – 100,000 tons;
- Conveyors/stackers;
- Truck scale;
- Portable scale house/office;
- Generator;
- Rubber-tired front-end loader for truck loading; and
- Graveled roadways.

Figure B-4 Rau Washington Sand Plant Site

Source: GoogleEarth.

Potential Site Development Permitting Requirements: Federal, state, and local permits, approvals, and consultations that may be required for development of the Washington facility include:

- City of Washington zoning conformance permit (the site is zoned M-2 Industrial);
- MoDOT – highway access;
- MDNR – air permit, water quality (wastewater discharge) permit;
- USACE– Section 10 of the RHA – permit for construction of facilities below the high water mark; and
- Section 404 of the CWA – permit for dredge and fill in the river or fill of wetlands.

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JULY 2010

Appendix C
Noise Ordinances

PREPARED BY

ENTRIX, Inc.
200 First Avenue West, Suite 500
Seattle, WA 98119
T 206.269.0104 ▪ F 206.269.0098

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Abbreviations & Acronyms

dB	decibel
dBA	A-weighted decibel
Hz	hertz
L_{eq}	equivalent A-weighted sound level

A P P E N D I X C

Noise Ordinances

C.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.

As part of the environmental analysis, the effects of the Proposed Action and alternatives on environmental noise were examined. Local jurisdictions adjacent to the LOMR have promulgated standards for noise emissions from industrial activities such as dredging.

This appendix describes noise ordinances that have been considered in the evaluation of noise emissions. It is included in the EIS in support of Section 3.13 in Chapter 3 Affected Environment that describes existing noise conditions and the analysis of noise impacts found in Chapter 4 Environmental Consequences (Section 4.11).

C.2 MISSOURI COUNTIES

In Missouri, Buchanan and Platte Counties have Zoning Orders that reference noise, and St. Louis County has a noise ordinance. Andrew, Atchison, Boone, Callaway, Carroll, Chariton, Clay, Cole, Cooper, Franklin, Gasconade, Hold, Howard, Jackson, Lafayette, Moniteau, Montgomery, Osage, Ray, St. Charles, Saline, and Warrant Counties do not have noise ordinances or regulations.

C.2.1 Buchanan County Zoning Order

Buchanan County does not have a noise ordinance, but the Buchanan County Zoning Order does have noise performance standards for various land uses, as follows:

Business districts: No land use shall emit or provide vibration, concussion, or noise that is detectable from the outside of the building.

Industrial districts: No land use shall be permitted or operated that produces a noise level greater than that level produced by the average traffic of the area discernible at the property and road boundary.

The Buchanan County Zoning Commission may approve a conditional use permit provided the property owner establishes that the requirements listed below have been met or shall be met (Buchanan County n.d.):

- Conformity to plans and drawings submitted with the application;
- Special yards, open spaces, buffer strips, walls, fences, hedges, and landscaping;
- Performance standards relative to emission of noise, vibration, or other potentially dangerous or objectionable elements;
- Limits on time of day for conducting specified activities;
- A period in which the use shall be exercised or the approval shall lapse; and
- Guarantees as to compliance with the terms of approval.

C.2.2 Platte County Zoning Order

Performance standards for all land uses in Platte County are the following:

> No land or building in any district shall be used or occupied in any manner so as to create any dangerous, injurious, noxious or otherwise objectionable fire, explosive or other hazards, including possible potential hazards; noise or vibration; smoke, dust, odor or other form of air pollution; heat, cold, dampness, electrical or other substance, condition or element (referred to herein as "dangerous or objectionable elements") in such a manner or in such amount as to adversely affect the surrounding area or adjoining premises.

In addition, the following performance standards apply to Planned Industrial Districts:

> a. Sound levels shall be measured with a sound level meter and associated octave band filter manufactured according to standards prescribed by the United States Standards Institute. Impulsive type noises shall be subject to the performance standards hereinafter prescribed provided that such noise shall be capable of being accurately measured with such equipment. Noises capable of being so measured, for the purpose of this Order, shall be those noises which cause rapid fluctuations of the needle of the sound level meter with a variation of no more than plus or minus two (2) decibels. Noises capable of being so measured shall be so muffled or otherwise controlled, as not to become objectionable, due to intermittence, beat frequency, impulsive character (such as hammering), periodic character (humming and screeching,) or shrillness. Sirens, whistles, and bells, which are maintained and utilized solely to serve a public purpose (such

as fire, ambulance, Police and air raid warning sirens) shall be excluded from the above regulations.

Table C-1 Platte County Noise Levels

Octave Band (Preferred Center Frequency)	Sound Level in Decibels (RE .0002 Microbar)	
	8:01 a.m. to 9:59 p.m.	10:00 p.m. to 8:00 a.m.
31.5	79	73
63	74	68
125	68	62
250	60	54
500	55	49
1000	50	44
2000	46	40
4000	41	35
8000	36	32

Source: Platte County n.d.

b. No industrial activity shall be responsible for the transmission of noise across any residential or business zoning district boundary line in excess of the levels established above [Table C-1].

The octave band sound levels in Table C-1 correspond to 54 dBA during the daytime hours and 59 dBA during nighttime hours.

C.2.3 St. Louis County Noise Ordinance

Noise within St. Louis County is regulated under the County Code Chapter 625 Noise Control Code. The county noise ordinance sets forth numerical limits for allowable noise levels. Table C-2 lists allowable noise levels for residential land uses, Table C-3 identifies allowable noise levels for commercial land uses, Table C-4 specifies allowable noise levels for industrial land uses, and Table C-5 delineates allowable noise levels for heavy industrial land uses.

Table C-2 St. Louis County Noise Levels – Residential Land Use Category

Tn[a]	(dBA)[b]
Daytime Hours	
60	55 or less
30	56–58
15	59–61
8	62–64
4	65–67
2	68–70
0	71 or greater
Nighttime Hours	
60	50 or less
30	51–53
15	54–56
8	57–59
4	60–62
2	63–65
0	66 or greater

Note: dBA = A-weighted decibel.

[a] Total duration of time noise to be emitted from noise source during period of measurement (minutes).

[b] A-weighted sound pressure level.

Table C-3 St. Louis County Noise Levels – Commercial Land Use Category

Tn[a]	(dBA)[b]
Daytime Hours	
60	65 or less
30	66–68
15	69–71
8	72–74
4	75–77
2	78–80
0	81 or greater
Nighttime Hours	
60	60 or less
30	61–63
15	64–66
8	67–69
4	70–72
2	73–75
0	76 or greater

Note: dBA = A-weighted decibel.

[a] Total duration of time noise to be emitted from noise source during period of measurement (minutes).

[b] A-weighted sound pressure level.

Table C-4 St. Louis County Noise Levels –Industrial Land Use Category

Tn[a]	(dBA)[b]
60	70 or less
30	71–73
15	74–76
8	77–79
4	80–82
2	83–85
0	86 or greater

Note: dBA = A-weighted decibel.

[a] Total duration of time noise to be emitted from noise source during period of measurement (minutes).

[b] A-weighted sound pressure level.

Table C-5 St. Louis County Noise Levels – Heavy Industrial Land Use Category

Tn[a]	(dBA)[b]
60	80 or less
30	81–83
15	84–86
8	87–89
4	90–92
2	93–95
0	96 or greater

Note: dBA = A-weighted decibel.

[a] Total duration of time noise to be emitted from noise source during period of measurement (minutes).

[b] A-weighted sound pressure level.

C.3 KANSAS COUNTIES

In Kansas, Atchison, Doniphan, and Leavenworth Counties do not have noise ordinances or regulations.

C.4 MISSOURI CITIES

Kansas City, Boonville, Jefferson City, St. Charles, Maryland Heights, Florissant, and St. Louis have noise ordinances. Missouri City, St. Joseph, Sibley, Napoleon, Wellington, Lexington, Waverly, Miami, Glasgow, Arrow Rock, Rocheport, Huntsdale, Lupus, Chamois, Gasconade, Hermann, New Haven, and Washington do not have noise ordinances or regulations.

C.4.1.1 Kansas City Noise Ordinance

Noise within Kansas City is regulated under the City Code Chapter 46 Noise Control. The City noise ordinance sets forth numerical limits for allowable noise levels.

According to the Kansas City Noise Ordinance, no person shall operate or cause to be operated on private property any source of sound in such a manner as to create a sound level that exceeds the equivalent A-weighted sound level (L_{eq}) limits set forth in Table C-6 when measured at or within the property boundary of the receiving residential district. A measurement period shall not be less than 2 minutes.

Table C-6 Maximum Permissible Sound Levels in Kansas City by Receiving Residential Districts

Receiving Land Use Category	Time	Equivalent A-Weighted Sound Level Limit (L_{eq})
Any residential district	7:00 a.m. – 10:00 p.m. 10:00 p.m. – 7:00 a.m.	60 dBA 55 dBA

Notes:

dBA = A-weighted decibel.
L_{eq} = Equivalent sound level.

Source: Kansas City 2009.

In addition, no person shall operate or cause to be operated on private property within a commercial/light industrial district any source of sound in such a manner as to create a sound level that exceeds the L_{eq} limits set forth in Table C-7 when measured at a distance of 25 feet from the structure

wherein the source of sound is located, or at the real property boundary of the property whereon the sound is generated, whichever is greatest. A measurement period shall not be less than 10 minutes (Kansas City 2009).

Table C-7 Maximum Permissible Sound Levels in Kansas City by Receiving Commercial/Light Industrial Districts

Receiving Land Use Category	Time	Equivalent A-Weighted Sound Level Limit (L_{eq})
Any commercial/industrial district	80 dBA	Any commercial/industrial district

Notes:

dBA = A-weighted decibel.
L_{eq} = Equivalent sound level.

Source: Kansas City 2009.

C.4.1.2 Boonville Noise Ordinance

According to the Boonville Noise Ordinance, any uses permitted in Districts C-1, C-2, C-P, and M-1, and all City zoning districts except residential and agricultural, shall be subject to such controls as may be imposed by the City Council if such uses are or become noxious or offensive by reason of vibration, noise, odor, dust, smoke, gas, glare or heat, perceptible at the property lines, if such uses generate an amount of traffic so as to cause traffic congestion in the streets, or if covered by Subsection 2.95(b)(3)a., b., or c. With the exception of District M-1, inoperative vehicles may not be stored or repaired, other than in closed garages on the premises.

C.4.1.3 Jefferson City Code

The Jefferson City Code, Chapter 21 Nuisances states:

> …It shall be unlawful for any person to make, continue, or cause to be made or continued any excessive, unnecessary, raucous, or unusually loud noise which terms shall mean any sound which, because of its volume level, duration and character, annoys, disturbs, injures or endangers the comfort, health, peace or safety of reasonable persons of ordinary sensibilities within the limits of the city. The term includes the kinds of noise generated by the activities enumerated in Section 3 of the code. The terms shall be limited to noise heard upon the public streets, in any public park, in any school or public building or upon the grounds thereof while in use, in any church or hospital or upon the grounds thereof while in use, upon any parking lot open to members of the public as invitees or licensees, or in any occupied residential unit which is not the source of the noise or upon the grounds thereof, and in any event from a location not less than 50 feet from

the source of the noise, measured in a straight line from the radio, loudspeaker, motor, horn or other noise source.

C.4.1.4 St. Charles Noise Ordinance

Noise within the city of St. Charles is regulated under the Noise Ordinance, Chapter 97 Noise Control. The city noise ordinance sets forth numerical limits for allowable noise levels.

As stated in the St. Charles Noise Ordinance, in I-1 Light Industrial zoning districts, at no point on the boundary of a residence, business, or commercial district shall the sound pressure level of any individual operation or plant, or the combined operations of any person, firm or corporation, exceed the decibel levels in the designated octave bands shown in Table C-8 for the zoning districts indicated—as measured using test equipment per ANSI Standards S1.1 1960, S1.4 1961, S1.11 1966, and S1.12 1967, and SAE J 184, and with reference to sections 10-141 and 20-142.

Table C-8 Maximum Sound Pressure Levels for Light Industrial Districts in St. Charles

Octave Band Center(dB) along District Boundaries		
Frequency (Hz)	Residence	Business-Commercial
31.5	72	79
63	71	78
125	65	72
250	57	64
500	51	58
1000	45	52
2000	39	46
4000	34	41
8000	32	39

Notes:

dB = Decibel.
Hz = Hertz.

In M-2 Heavy Industrial zoning districts, at no point either on the boundary of a residence, business or commercial district, or at 125 feet from the nearest property line of a plant or operation, whichever distance is greater, shall the sound pressure level of any individual operation or plant, or the combined operations of any person, firm or corporation, exceed the decibel levels in the designated octave bands shown in Table C-9 for the zoning districts included—as measured using test equipment per ANSI

Standards S1.1 1960, S1.4 1961, S1.11 1966, and S1.12 1967, and SAE J 184, and with reference to Sections 97.06 and 97.07.

Table C-9 Maximum Sound Pressure Levels for Heavy Industrial Districts in St. Charles

Octave Band Center(dB) along District Boundaries		
Frequency (Hz)	Residence	Business-Commercial
31.5	75	80
63	74	79
125	69	74
250	64	69
500	58	63
1000	52	57
2000	47	52
4000	43	48
8000	40	45

Notes:

dB = Decibel.
Hz = Hertz.

C.4.1.5 Maryland Heights Noise Ordinance

The Maryland Heights Noise Ordinance states that every use shall be so operated that the pressure level of sound or noise generated does not exceed the limitations of the county revised ordinances governing noise control. (See Tables C-2 through C-5 for the St. Louis County revised ordinances.)

C.4.1.6 Hazelwood Noise Ordinance

Article XV of the Hazelwood City Code presents environmental performance standards. It states that noise that is objectionable due to volume, frequency, or heat shall be muffled or otherwise controlled so that there is no production of sound discernible at lot lines in excess of the average intensity of street and traffic noise at the lot lines. Every use shall be so operated that the pressure level of sound or noise generated does not exceed the limitations of the Noise Control Code, Chapter 625, St. Louis County Revised Ordinance. Emergency warning sirens and related apparatus used solely for public purposes shall be exempt from this requirement. (Ord. No. 3674 §§1–3, 8-17-05) (See Tables C-2 through C-5 for the St. Louis County revised ordinances.)

C.4.1.7 St Louis Noise Ordinance

Noise within the city of St. Louis is regulated under the Noise Ordinance, Chapter 97 Noise Control. The City noise ordinance sets forth numerical limits for allowable noise levels, which are the same as those presented above in Tables C-8 and C-9 of the St. Charles Noise Ordinance.

C.5 KANSAS CITIES

The cities of Elwood and Leavenworth have noise ordinances. The cities of White Cloud, Atchison, and Kansas City do not have noise ordinances or regulations.

C.5.1.1 Elwood Noise Ordinance

The city of Elwood's noise ordinance states that noises such as stereos and loud music should not be heard from 75 feet away. The ordinance does not limit noise from construction or heavy equipment.

C.5.1.2 Leavenworth Noise Ordinance

Noise within the city of Leavenworth is regulated under the Noise Ordinance, in Sections 46-76 through 46-88. Section 46-83 (Pile drivers and hammers) states that operation between the hours of 10:00 p.m. and 7:00 a.m. of any pile driver, steam shovel, pneumatic hammer, derrick, steam or electric hoist, or other appliance, the use of which is attended by loud or unusual noise, shall be deemed a violation of this article.

C.6 REFERENCES

Buchanan County. No Date. Zoning Order, as amended. Website (http://vivid.phpwebhosting.com/~buchcomo/offices/planning_zoning/zoning.pdf) accessed on December 16, 2009.

Kansas City. 2009. Code of Ordinances, City of Kansas City, Codified through Ordinance No. 091074, enacted Dec. 17, 2009. (Supp. No. 76.) Website (http://library3.municode.com/default-test/home.htm?infobase=10156&doc_action=whatsnew) accessed on December 17, 2009.

Platte County. No Date. Chapter 400: Zoning Regulations. Website (http://www.co.platte.mo.us/docs/planning_zoning/zoning_order.pdf) accessed on December 16, 2009.

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Appendix D Air Quality and Climate Change Technical Information

PREPARED BY

ENTRIX, Inc.
200 First Avenue West, Suite 500
Seattle, WA 98119
T 206.269.0104 ▪ F 206.269.0098

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List of Acronyms

Capital Sand	Capital Sand Company, Inc.
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_{2s}	carbon dioxide equivalent
Con-Agg	Con-Agg of MO, L.L.C
EIS	environmental impact statement
g	gram(s)
GHG	greenhouse gas
Hermann Sand	Hermann Sand & Gravel, Inc.
Holliday Sand	Holliday Sand & Gravel Company, L.L.C.
HP	horsepower
J.T.R.	Jotori, Inc.
kW	kilowatt(s)
l/CD	cylinder displacement
Limited Leasing	Limited Leasing Company
LOMR	lower Missouri River
Master's	The Master's Dredging Company, Inc.
MDNR	Missouri Department of Natural Resources
N_20	nitrous oxide

NO_x	oxides of nitroxen
PM	particulate matter
Rau	Edward N. Rau Contractor Company
RIA	U.S. Environmental Protection Agency Regulatory Impact Analysis
RM	river mile
ROG	reactive organic gas
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
VOC	volatile organic compound

A P P E N D I X D

Air Quality and Climate Change Technical Information

D.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.

As part of the environmental analysis, the potential effects of the Proposed Action and alternatives on air quality and climate change were examined. This appendix provides technical information in support of Section 3.16 in the Affected Environment chapter of the EIS, which describes existing air quality conditions, and Section 4.14, the analysis of air quality impacts and effects on climate change in the Environmental Consequences chapter of the EIS.

This technical appendix describes the methodology used to estimate criteria pollutant and greenhouse gas (GHG) emissions generated under the Proposed Action and alternatives, based on information received from the permit applicants. In addition, emissions factors and methodologies were obtained from the following previous studies: *Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories* (ICF International 2009), the *Puget Sound Maritime Air Emissions Inventory* (Starcrest Consulting 2007), and the *2007 Good Movement Air Emissions Inventory at the Port of Houston* (Starcrest Consulting 2009).

As discussed in Section 4.14 in the EIS, the following three activities were considered:

- Dredging (removal of sand and gravel from the river bed and the transport of that material onshore),
- Onshore materials handling (use of earth-moving equipment to transport and process the dredged material) and sand plants, and
- Transportation of sand and gravel to local market areas.

This appendix describes the data and methods used to estimate emissions from these three activities and the procedures for estimating emissions from construction of new facilities. It also discusses why potential emissions generated by facility operations (e.g., fugitive dust from processed materials and air pollutants from the upkeep of offices and employee commute trips) were not quantified and were excluded from the impact analysis.

The following companies were assumed to operate under existing conditions: Capital Sand Company, Inc. (Capital Sand), Con-Agg of MO, L.L.C (Con-Agg), Hermann Sand & Gravel, Inc. (Hermann Sand), Holliday Sand & Gravel Company, L.L.C. (Holliday Sand), Jotori, Inc. (J.T.R.), and Limited Leasing Company (Limited Leasing). These companies, as well as two new applicants (The Master's Dredging Company, Inc. [Master's] and Edward N. Rau Contractor Company [Rau]), were assumed to operate under the Proposed Action and alternatives.

D.2 DREDGING

Primary emissions resulting from dredges and tug boats include reactive organic gases/volatile organic compounds (ROG/VOC), carbon monoxide (CO), oxides of nitrogen ($NO_{X)}$, particulate matter (PM), and GHGs emitted as engine exhaust. Information on engine horsepower, load factor, and hours of operation were provided by the majority of permit applicants. When companies did not supply complete information, assumptions were made using the most conservative scenarios so that potential emissions would not be underestimated. Tables D-1 and D-2 summarize the equipment used in the emissions modeling. The tables indicate where assumptions were made and how they were developed. Note that the operating information (e.g., hours of operation) presented below represents existing conditions unless otherwise noted.

Emission factors summarized in previous studies were used to quantify emissions from the dredge and tug boat engines identified in Tables D-1 through D-3 (ICF International 2009, Starcrest Consulting 2009). The use of a specific emissions factor is dependent upon engine power, model, year, and cylinder displacement (l/Cd). The U.S. Environmental Protection Agency (USEPA) has identified three categories of marine engines (Starcrest 2007):

- Category 1: 1–5 liters per l/Cd;
- Category 2: 5–30 liters per l/Cd; and
- Category 3: over 30 liters per l/Cd.

Marine engine standards are also broken down by engine year, where Tier 0 standards apply to engines 1999 and older, Tier 1 standards apply to engines constructed from 2000 to 2003, and Tier 2 standards apply to engines constructed from 2004 and 2007 (ICF International 2009). New Tier 3 and 4 standards will be required for engines constructed from 2009 to 2013 and after 2014, respectively (USEPA 2008). The emissions factors used in this analysis are organized by engine category and tier, as presented in Table D-4.

Table D-1 Dredge Equipment Assumptions for Existing Companies

Company	Dredge Name	Engine(s)	Engine HP	Engine Year	Load Factor (%)	Hours of Operation[a]
Capital Sand[b]	*Kathy Lee*	Caterpillar 3512[c]	1,150	1996	80	1,920
	Sandy K	Caterpillar C18	450	1987	60	
		Caterpillar 3412	450	1987	80	
	Rae Marie	Caterpillar 3412	450	2004	50	
		Caterpillar 3412	600	2004	65	
		Caterpillar 3406	450	2004	65	
Hermann Sand[d]	*Arl-501*	Cummins	335	2004	50	2,165
Holliday Sand	*Randolph*	EMD 16-645-E6[c]	1,200	2008	30	2,880
	Riverside	EMD 12-645E2	950	2004	38	2,720
	St. Joseph	John Deere 6125AFM	392	2006	30	1,520
J.T.R.	*Queenfish*	Cummins 1710	425	1986	100	974
	Mark V	Caterpillar 3408	455	1986	100	
	JTR	Caterpillar 3408	455	2002	100	
Limited Leasing	*St Charles*	Caterpillar 3406	365	1993	80[e]	2,165
	Traveler	Caterpillar 3406	365	1968	80[e]	
	Chesterfield	Caterpillar 3406	365	1971	80[e]	

Note: HP = Horsepower.

[a] Hours of operation were assumed to represent existing conditions. If permit applicants provided a range of operational hours, engine activity was based on the maximum number of operational hours to ensure that emissions were not underestimated.

[b] Capital Sand is contracted by Con-Agg to perform dredging operations. Capital Sand's fleet therefore was assumed to dredge the amounts requested by Con-Agg under the Proposed Action and alternatives.

[c] Engine horsepower greater than 1,000; Category 2 emissions factors were assumed (refer to Table D-3).

[d] Hermann Sand would be contracted by Rau to perform dredging operations. Hermann Sand's fleet therefore was assumed to dredge the amounts requested by Rau under the Proposed Action and alternatives.

[e] No information was provided. Default load factor was assumed (Starcrest 2009).

Source: Based on interviews with the companies conducted by the USACE for permitting purposes.

Table D-2 Dredge Equipment Assumptions for New Applicants

Company	Dredge Name	Engine(s)	Engine HP	Engine Year	Load Factor (%)	Hours of Operation[a]
Master's	Penny	Caterpillar D 398 TA	825	1990	50	4,209[b]
	Oklahoma	Caterpillar 3516 TA[c]	2,450	2005	50	4,676[b]
Rau[d]	--	--	--	--	--	--

Note: HP = Horsepower.

[a] Master's does not operate under existing conditions. Hours of operation therefore were assumed to represent conditions under the Proposed Action. Refer to Section D.2-1 for a discussion of operating conditions under the Proposed Action and alternatives.

[b] Master's does not operate under existing conditions. Hours of operation therefore were assumed to represent conditions under the Proposed Action. Refer to Section D.2-1 for a discussion of operating conditions under the alternatives.

[c] Engine horsepower greater than 1,000; Category 2 emissions factors were assumed.

[d] Rau does not operate dredging equipment.

Source: Based on interviews with the companies conducted by the USACE for permitting purposes.

Information on the distribution of Category 1 and 2 engines was not provided by the permit applicants. The Puget Sound Air Emissions Inventory indicates that 90 percent of all harbor craft engines are Category 1, and 10 percent are Category 2 (Starcrest 2007). Similarly, the 2007 Goods Movement Inventory conducted for the Port of Houston indicates that 89 percent of all engines are Category 1, and 9 percent are Category 2 (Starcrest 2009). Finally, the USEPA 2008 Regulatory Impact Analysis (RIA), which surveyed a higher number of inland tugs, found that 25 percent of vessels are Category 2 (ICF International 2009). Based on the equipment summarized in these documents and expected under the Proposed Action and alternatives, engines exceeding 1,000 horsepower (HP) were identified as Category 2. Under this assumption, 16 percent of the dredge engines and 22 percent of the tug engines were modeled using Category 2 emissions factors.

Table D-3 Tug Boat Equipment Assumptions

					Activity								
					Upstream Empty		Upstream Full		Downstream Empty		Downstream Full		
Company	Tug Name	Engine(s)	Engine HP	Engine Year	Load Factor (%)	Hours per Year[b]	Load Factor (%)	Hours per Year[b]	Load Factor (%)	Hours per Year[b]	Load Factor(%)	Hours per Year[b]	Trips per Day
Capital Sand[c]	*Marge 1*	(2) Caterpillar 3412	600	2004/2006	55	373[d]	60	496[d]	40	216[d]	60	280[d]	7
	Allison Marie	(3) Caterpillar 3412	600	2001/2002	50	373[d]	60	435[d]	40	216[d]	60	250[d]	
	Tarkio	(2) Caterpillar 3412	600	2006/2007	55	373[d]	60	559[d]	40	216[d]	60	280[d]	
Hermann Sand[e]	*Kathryn*	(2) Cummins N-14	880	2005	50	540	31[f]	573[g]	31[f]	264[g]	25	270	5
	Mel Sue	(2) NH 220 Cummins	400	1954	50	540	31[f]	573[g]	31[ef]	264[g]	25	270	
Holliday Sand	*Chouteau*	(2) Caterpillar C12	680	2006	55	581	70	756	20	423	35	454	14[j]
	Sibley	(2) Caterpillar 3406E	950	2006	55	581	70	756	20	423	35	454	
	Dakota	(2) Caterpillar 3412C[h]	1,040	N/A[i]	60	581	75	756	25	423	40	454	
	Fairfax	(2) Caterpillar 3412C[h]	1,300	2004	60	581	75	756	25	423	40	454	
	Edward Perry	(2) Caterpillar 3406	730	2009	83	816	100	907	45	454	63	242	
J.T.R.	*Barbara Sue*	(2) GM 8V-71	470	2000	100	367	100	918	80	154	50	261	5
	Shelby J	(2) 12V-71	680	2005		305		459	75	140	75	165	
	William Powell	(2) Cummins KTA19[h]	1,200	2001		206		367	75	121	50	140	

Table D-3 Tug Boat Equipment Assumptions

					Activity								
					Upstream Empty		Upstream Full		Downstream Empty		Downstream Full		
Company	Tug Name	Engine(s)	Engine HP	Engine Year	Load Factor (%)	Hours per Year[b]	Load Factor (%)	Hours per Year[b]	Load Factor (%)	Hours per Year[b]	Load Factor(%)	Hours per Year[b]	Trips per Day
Limited Leasing	*Atlas*	(3) Luggar L6140[g]	1,500	1962	31[f]	275	31[f]	367	31[f]	184	31[f]	275	10[k]
	Janet	(2) Detroit 8V71	460	1979		367		551		275		367	
	Joanne	(2) Detroit 8V71	460	1982		367		551		275		367	
	Leona	(2) Detroit 12V71	660	1956		275		367		184		275	
	Patricia	(2) Detroit 12V71	660	1959		275		367		184		275	
	Piasa	(2) Detroit 12V71	660	1959		275		367		184		275	

Note: HP = Horsepower.

[a] Master's does not use tugs to transport dredged materials to shore.

[b] Hours were assumed to represent existing conditions and were calculated according to the following formula: (hours per day) X (days per year) X (number of trips per tug) where the hours per day were provided by the permit applicants, days per year were assumed to be 216 (unless otherwise noted), and number of trips per tug were assumed to equal the number of trips per day divided by the number of tugs. The annual number of operating days (216) is based on dredging occurring 5 days per week from March to December (see Chapter 2).

[c] Capital Sand's fleet was assumed to dredge amounts requested by Con-Agg.

[d] Number of operational days per year was assumed to be 160 per information supplied by Capital Sand.

[e] Hermann Sand's fleet was assumed to dredge amounts requested by Rau under the Proposed Action and alternatives.

[f] Default load factor (Starcrest 2009).

[g] Information was not supplied by the permit applicant. Hours represent an average of the information provided by all applicants listed in the table.

[h] Engine horsepower greater than 1,000; Category 2 emissions factors were assumed (see Table D-3).

[i] Not available; no information received.

[j] Based on seven barges being unloaded per shift, with two shifts per day.

[k] Based on 10 barges being unloaded per day, assuming that one barge requires one tug trip.

Source: Based on interviews with the companies conducted by the USACE for permitting purposes.

Table D-4 Emissions Factors for Dredge and Tug Boat Engines (grams/kilowatt-hour [g/kW-hr])

Engine Power (kW)	VOC	NO_X	CO	PM	SO_2[a]	CO_2	N_2O	CH_4
Tier 0 Engines								
37	0.27	11	2	0.9	0.21	690	0.02	0.09
75	0.27	10	1.7	0.4	0.21	690	0.02	0.09
130	0.27	10	1.5	0.4	0.21	690	0.02	0.09
225	0.27	10	1.5	0.3	0.21	690	0.02	0.09
450	0.27	10	1.5	0.3	0.21	690	0.02	0.09
560	0.27	10	1.5	0.3	0.21	690	0.02	0.09
1,000	0.27	13	2.5	0.3	0.21	690	0.02	0.09
Category 2	0.5	13.2	1.1	0.72	0.21	690	0.02	0.09
Tier 1 Engines								
37	0.27	9.8	2	0.9	0.21	690	0.02	0.09
75	0.27	9.8	1.7	0.4	0.21	690	0.02	0.09
130	0.27	9.8	1.5	0.4	0.21	690	0.02	0.09
225	0.27	9.8	1.5	0.3	0.21	690	0.02	0.09
450	0.27	9.8	1.5	0.3	0.21	690	0.02	0.09
560	0.27	9.8	1.5	0.3	0.21	690	0.02	0.09
1,000	0.27	9.8	2.5	0.3	0.21	690	0.02	0.09
Category 2	0.5	9.8	1.1	0.72	0.21	690	0.02	0.09
Tier 2 Engines								
37	0.27	6.8	5	0.4	0.21	690	0.02	0.09
75	0.27	6.8	5	0.3	0.21	690	0.02	0.09
130	0.27	6.8	5	0.3	0.21	690	0.02	0.09
225	0.27	6.8	5	0.3	0.21	690	0.02	0.09
450	0.27	6.8	5	0.3	0.21	690	0.02	0.09
560	0.27	6.8	5	0.3	0.21	690	0.02	0.09
1,000	0.27	6.8	5	0.3	0.21	690	0.02	0.09
Category 2	0.5	9.8	5	0.72	0.21	690	0.02	0.09

Notes:

CH4 = Methane.
N_2O = Nitrous oxide.
VOC = Volatile organic compounds.
CO = Carbon monoxide.
NO_X = Oxides of nitrogen.
CO_2 = Carbon dioxide.
PM = Particulate matter.
kW = Kilowatt.
SO_2 = Sulfur dioxide.

[a] Based on U.S. Environmental Protection Agency emission standard of 500 parts per million sulfur content of marine diesel fuel. Calculated using the following equation: (500 grams S/1,000,000 grams fuel) X (210 grams fuel/kW-hour) X (2 grams SO_2/grams S).

Sources: ICF International 2009, Clean Air Task Force n.d.

The following equation was used to calculate emissions from each of the engines identified in Tables D-1 through D-3 (ICF International 2009, Starcrest 2009). Because the emissions factors summarized in Table D-4 are in grams/kilowatt-hour (g/kW-hour), the engine HP ratings provided by the permit applicants were converted to kilowatts, assuming that one HP is equal to 0.746 kilowatt. It was assumed that all engines would use off-road diesel fuel.

$$E = (kW) \times (Activity) \times (EF) \times (LF) \times (\# ENG)$$

Where:

E	=	Emissions, grams per year
kW	=	Kilowatts (one HP is equal to 0.746 kilowatt)
Activity	=	Activity, hours per year
EF	=	Engine emissions factor (see Tables D-1 through D-3)
LF	=	Engine load factor
# ENG	=	Number of vessel engines (see Tables D-1 through D-3)

The calculated emissions (in grams per year) were converted to tons per year by dividing emissions by the conversion factor, which is 907,184 grams/ton. Emissions for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were converted to metric tons, assuming that 1 ton is equal to 0.907 metric ton.

D.2.1 Dredging Scaling Factors

Emissions from dredging activities are highly dependent on the number, type, and age of the dredging equipment, as well as the intensity (e.g., the hours of activity and distance of tug trips) of the dredging operation. Because this information is not available for each alternative, the rate at which emissions are affected by changing dredging amounts is currently unknown. For the purposes of this analysis, emissions generated by dredging activities were assumed to be proportional to permitted sand and gravel amounts, on a ton-for-ton basis. In other words, a 50-percent increase in dredging amounts, relative to existing conditions, was assumed to correspond to a 50-percent increase in dredging emissions.

The following sections describe the methodology used to estimate dredging emissions under the Proposed Action and alternatives. The reader is directed to Tables D-1 through D-3 for information on the dredger and tug boat equipment assumed in the analysis. Note that this information is presented by company, rather than by river segment. Consequently, emissions were calculated for each

company and then apportioned by river segment for use in the impact analysis. Figure D-1 illustrates the steps taken to estimate dredging emissions.

D.2.1.1 Emissions Calculations for Existing Companies

Existing emissions generated by Capital Sand, Con-Agg, Hermann Sand, Holliday Sand, J.T.R., and Limited Leasing were calculated using the information summarized in Section D.2. To determine emissions generated by these companies under the Proposed Action and alternatives, existing emissions were multiplied by the percent change in sand and gravel amounts between existing conditions and the alternative in question (see Table D-5). For example, under the Proposed Action, permitted tonnage would increase by 74 percent in the Jefferson City segment. Existing dredging emissions generated by companies operating in the Jefferson City segment were multiplied by 1.74 to obtain dredging emissions for the Proposed Action.

D.2.1.2 Emissions Calculations for Master's and Rau

Master's and Rau are the only companies not part of existing conditions that would be permitted under the Proposed Action and alternatives. The methodology used for Table D-5 was not used to estimate emissions for these companies because it is based on existing dredging amounts by river segment. Separate scaling factors therefore were used to estimate emissions generated by the two proposed companies.

The emissions calculated for Master's and Rau using the information listed in Tables D-1 through D-3 were assumed to represent conditions under the Proposed Action because these companies do not operate under existing conditions. The estimated dredging emissions calculated for Master's and Rau were used as a basis for estimating dredging emissions under Alternatives A, B, and C. More specifically, calculated emissions under the Proposed Action were scaled by the percent change in dredging amounts between the Proposed Action and each of the alternatives in order to determine emissions associated with these companies for each alternative (see Tables D-5 and D-6). As for existing companies, this approach assumes that emissions generated by dredging activities would be proportional to permitted sand and gravel amounts.

Table D-5 Scaling Factors for Emissions Generated by Existing Companies

Segment	Existing Dredging[a]	Proposed Action		No Action Alternative		Alternative A		Alternative B		Alternative C	
		Dredging [b]	% Change	Dredging [b]	% Change	Dredging [b]	% Change	Dredging [b]	% Change	Dredging [b]	% Change
St. Joseph	326,928	1,150,000	251.76	0	-100.00	350,000	7.06	860,000	163.05	330,000	0.94
Kansas City	2,658,831	4,060,000	52.70	0	-100.00	540,000	-79.96	1,230,000	-53.74	2,660,000	0.04
Waverly	677,987	1,005,600	48.32	0	-100.00	500,000	-26.25	1,140,000	68.14	680,000	0.30
Jefferson City	1,578,858	2,750,000	74.18	0	-100.00	430,000	-72.77	980,000	-37.93	1,580,000	0.07
St. Charles	1,649,326	4,384,400	165.81	0	-100.00	370,000	-77.57	840,000	-49.07	1,650,000	0.04
Total[b]	6,891,930	13,350,000	93.70	0	-100.00	2,190,000	-68.22	5,050,000	-26.73	6,900,000	0.12

[a] Represents average annual dredging for the last 5 years (2004–2008). See Table 2.4-1 in the main volume.

[b] Values represent sand and gravel amounts requested by the existing companies under the Proposed Action and alternatives. In other words, amounts requested by Masters and Rau, the two new dredgers (see Table 2.2-1 in Chapter 2), have been removed from the segment totals.

Table D-6 Scaling Factors for Emissions Generated by New Companies

Company/Segment	Proposed Dredging Amount	No Action Alternative		Alternative A		Alternative B		Alternative C	
		Dredging Amount	% Change	Dredging Amount	% Change	Dredging Amount	% Change	Dredging Amount	% Change
Master's/Kansas City	1,000,000	0.00	-100.00	133,005	-86.70	302,956	-69.70	731,527	-26.85
Rau/St. Charles	100,000	0.00	-100.00	8,439	-91.56	19,159	-80.84	37,633	-62.37

D.2.1.3 Dredging Percentages by River Segment

Three companies—Capital Sand, Hermann Sand, and Holliday Sand—would operate in more than one segment (see Table 2.2-1 in the EIS). Emissions generated by these four applicants were apportioned by segment using the breakdown of annual dredging amounts by river segment summarized in Table 2.2-5 in the EIS because emissions were calculated for a company's entire fleet and information on the operational location of individual dredges and tugs is not available. Emissions calculated for these companies were multiplied by the percentage of each company's total requested permit amounts expected to occur in each segment. For example, Hermann Sand has requested a permit for 1,000,000 tons per year. One-half of this amount is expected to be dredged in the Jefferson City segment, and the remaining one-half in the St. Charles segment. It was assumed therefore that one-half of the emissions calculated for Hermann Sand would occur in the Jefferson City segment and the remaining one-half would occur in the St. Charles segment.

D.2.1.4 Calculation of Tonnage Ratios

A breakdown of company dredging amounts by river segment under Alternatives A, B, and C is currently not available. Consequently, the ratio of dredged materials between companies in each river segment under the Proposed Action (as presented in Table 2.2-5 in the EIS) was used to determine tonnage estimates by company and river segment for the alternatives. This approach assumes that the breakdown of company dredging amounts will remain constant between the Proposed Action and alternatives. For example, the ratio of dredging amounts between Holliday Sand and Master's in the Kansas City segment is 3,060,000 to 1,000,000 for the Proposed Action (see Table 2.2-5 in the EIS). It therefore was assumed that Holliday Sand would dredge approximately 75 percent of the permitted tonnage in the St. Joseph segment under Alternatives A, B, and C.

D.2.1.5 Total Emissions by Company by River Segment

Once tonnage amounts by company and river segment were estimated for the Proposed Action and alternatives, total dredging emissions by river segment were calculated. This step was completed by multiplying the total emissions estimated for each company under the Proposed Action and alternatives by the percentage of each company's permitted dredging amount expected to occur in the river segments. For example, because 45.46 percent of all activities within the Jefferson City segment under the Proposed Action were associated with Herman Sand, emissions calculated for Hermann Sand under the Proposed Action were multiplied by 45.46 percent (see Table D-7) to determine the company's contribution to emissions in the Jefferson City Segment.

Table D-7 summarizes the dredging amounts under the Proposed Action requested by the companies in their permit applications, as well as the tonnage breakdown calculated for Alternatives A, B, and C (refer to Section D.2.1.4). Segment percentages used in this analysis are also presented.

D.2.1.6 Total Emissions by River Segment

When company emissions had been quantified, scaled, and appropriated among segments, total emissions generated by river segment were calculated for the Proposed Action and the alternatives. This was completed by summing the emissions produced by each company operating in each segment.

Figure D-1 illustrates the steps taken to estimate dredging emissions.

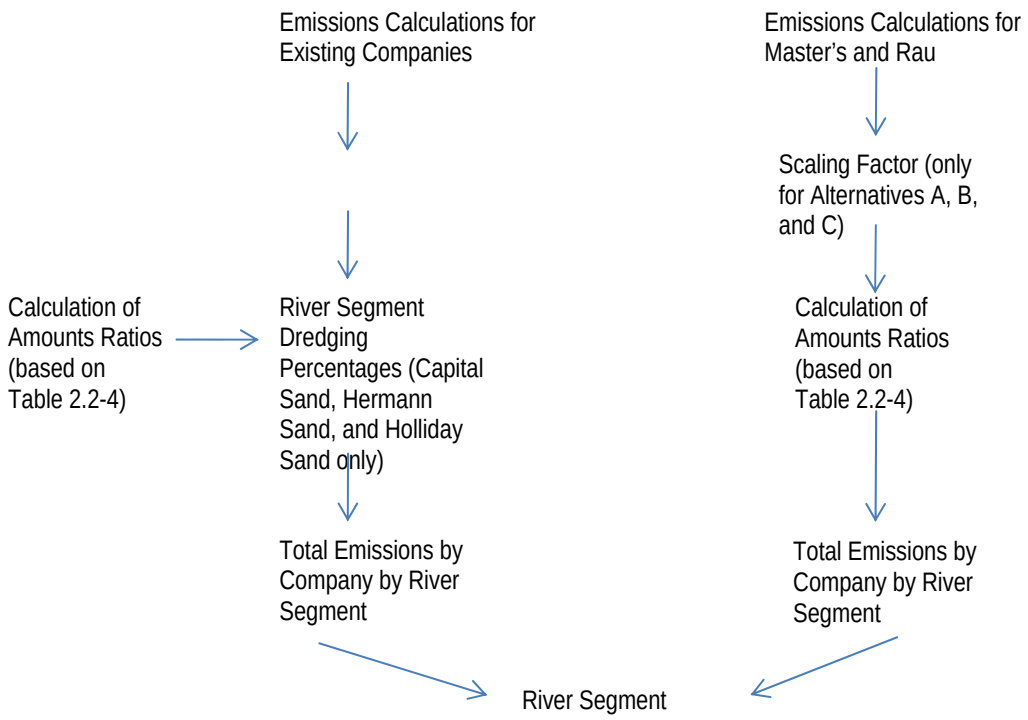

Figure D-1 Dredging Emissions Methodology

Table D-7 Dredging Breakdown by River Segment and Company Contribution Percentages

	Capital Sand[a]		Hermann Sand[b]		Holliday Sand	
Segment	Amount Requested (tons/year)	Percent of Company Total	Amount Requested (tons/year)	Percent of Company Total	Amount Requested (tons/year)	Percent of Company Total
Proposed Action[c]						
St. Joseph	--	--	--	--	1,150,000	25.28
Kansas City	--	--	--	--	3,060,000	67.26
Waverly	665,600	16.85	--	--	340,000	7.47
Jefferson City	2,250,000	56.96	500,000	45.46	--	--
St. Charles	1,034,400	26.19	600,000	54.55	--	--
Alternative A[d]						
St. Joseph	--	--	--	--	350,000	37.80
Kansas City	--	--	--	--	406,995	43.95
Waverly	330,947	42.98	--	--	169,053	18.26
Jefferson City	351,818	45.69	78,182	60.69	--	--
St. Charles	87,293	11.34	50,634	39.31	--	--
Alternative B[d]						
St. Joseph	--	--	--	--	860,000	39.59
Kansas City	--	--	--	--	927,044	42.67
Waverly	754,559	43.01	--	--	385,442	17.74
Jefferson City	801,818	45.70	178,182	60.79	--	--
St. Charles	198,179	11.30	114,953	39.22	-	-
Alternative C[d]						
St. Joseph	--	--	--	--	330,000	11.79
Kansas City	--	--	--	--	2,238,473	79.99
Waverly	450,088	21.11	--	--	229,912	8.22
Jefferson City	1,292,727	60.63	287,273	55.99	--	--
St. Charles	389,280	18.26	225,801	44.01	--	--

[a] Amounts include tonnage requested by Con-Agg.

[b] Amounts include tonnage requested by Rau.

[c] Breakdown is based on Table 2.2-4 in the EIS. Values are based on the ratio of dredging amounts between companies in each segment.

[d] Values for J.T.R., Limited Leasing, and Master's Dredging are not shown as these companies operate in only one segment. Consequently, 100 percent of the emissions calculated for these companies were assumed to occur in their segment of operation.

D.3 MATERIALS HANDLING

The USEPA NONROAD2008 model was used to estimate emissions from materials-handling equipment operating at each of the onshore facilities identified in Figure 2.2-1 in the EIS. NONROAD is

a USEPA-approved emissions model that calculates emission inventories (i.e., tons of pollutants) for user-specified off-road equipment in a given geographic area rather than emissions associated with specific equipment associated with a specific activity. For example, the model generates an emissions inventory for Missouri associated with certain equipment pieces that can be used to calculate equipment-specific emissions factors; the emissions inventory can then be used to generate emissions associated with this Project.

A detailed description of the type and amount of equipment was not provided by the permit applicants. Equipment estimates therefore were based on conversations with the Missouri Department of Natural Resources (MDNR) (Zeaman pers. comm.). For this analysis, one crane (399 HP), one dozer (357 HP), one crusher (300 HP), and four loaders (108 HP) were assumed to operate at each onshore facility.[1,2]

Emissions inventories for these four pieces of equipment were generated using NONROAD based on the following inputs: (1) geographic location: Missouri; (2) year: 2011; and (3) time period: typical weekday. Based on the inventories (i.e., the total emissions for each piece of equipment in Missouri) produced by NONROAD, emissions factors were calculated for each piece of equipment using the following equation.

$$EF = (Tons/Day) \times (1/Activity) \times (1/HP) \times LF$$

Where:

EF	=	Emissions factor, tons per horsepower-hour
Tons/Day	=	NONROAD emissions inventory for each pollutant
Activity	=	NONROAD output for activity (i.e. equipment use)
HP	=	NONROAD default for equipment horsepower
LF	=	Load factor (model default: crane 0.43, loader 0.21, dozer 0.59)

Table D-8 summarizes the calculated emissions factors. The emissions factors summarized in Table D-8 were multiplied by the company hours of operation and maximum horsepower of each piece of equipment in order to estimate emissions. Operating assumptions were based on information supplied by the permit applicants (see Table D-9). As a worst-case scenario, each piece of equipment was

[1] While conveyors are common pieces of equipment, the MDNR indicated that most are electric powered and therefore do not produce direct emissions (Zeaman pers. comm.). Although operation of these conveyors would generate indirect GHG emissions through electricity usage, given the speculative nature of the amount of electricity consumed by individual conveyors, GHG emissions associated with these pieces of equipment were not quantified.

[2] No equipment would operate at the Waldron (Master's) or Washington (Rau) facilities under existing conditions because they do not exist under existing conditions.

assumed to operate during the entire operating period. Note that the assumptions summarized in Table D-9 represent existing conditions, unless otherwise noted.

Table D-8 Emissions Factors for Materials-Handling Equipment (tons/horsepower-hour)

Equipment	VOC	NO_X	CO	PM_{10}[a]	CO_2[b]
Crane	3.17E-07	4.41E-06	9.38E-07	2.25E-07	6.30E-04
Crusher	3.16E-07	4.41E-06	9.34E-07	2.24E-07	6.17E-04
Dozer	3.81E-07	4.87E-06	1.68E-06	3.63E-07	8.19E-04
Loader	1.00E-06	4.44E-06	5.48E-06	8.36E-07	5.06E-04

Notes:

CH4 = Methane.
CO = Carbon monoxide.
CO_2 = Carbon dioxide.
NO_X = Oxides of nitrogen.
N_2O = Nitrous oxide.
$PM_{2.5}$ = Particulate matter less than 2.5 microns.
PM_{10} = Particulate matter less than 10 microns.
SO_2 = Sulfur dioxide.
VOC = Volatile organic compounds.

[a] NONROAD does not provide emission outputs for $PM_{2.5}$. An emissions factor therefore was not calculated. Instead, $PM_{2.5}$ emissions were assumed to equal 92 percent of PM_{10} emissions (SCAQMD 2006).

[b] NONROAD does not provide emission outputs for CH_4 and N_2O. An emissions factor therefore was not calculated. Instead, emissions were determined by scaling calculated CO_2 emissions by the ratio of CH_4/CO_2 and N_2O/CO_2 emissions expected per gallon of diesel fuel according to the Climate Action Registry (California Climate Action Registry 2009).

D.3.1 Materials-Handling Scaling Factors

Limited information is currently available on how implementation of the Proposed Action and alternatives would affect the operation and number of materials-handling equipment. As discussed above, the assumptions summarized in Table D-9 represent existing conditions, except in the case of Master's and Rau, where they represent conditions under the Proposed Action. emissions calculated for materials-handling equipment were scaled by the factors presented in Tables D-5 and D-6 because this analysis assumes that emissions are proportional to the amount of sand and gravel permitted, and the use of onshore equipment is required to process any sand and gravel removed from the river.

Unlike the locations of dredges and tugs, the locations of onshore facilities and associated materials-handling equipment are fixed and known. Therefore, emissions produced by companies permitted in more than one river segment did not require further calculations. Once the appropriate scaling factors were applied, total emissions estimates for each river segment were obtained by adding the emissions calculated for equipment operating at each onshore facility within the segment.

Table D-9 Materials-Handling Operating Assumptions

Company	Hours per year
Capital Sand	1,600[a]
Hermann Sand	2,160[b]
Holliday Sand	2,160[b]
J.T.R.	2,052[c]
Limited Leasing	2,160[b]
Master's	2,160[b, d]
Rau	2,160[d, e]

Notes:

[a] Based on a 10-hour work day and 160 work days per year. Assumed to represent existing conditions.

[b] Based on a 10-hour work day and 216 work days per year. Assumed to represent existing conditions, unless otherwise stated.

[c] Based on a 9.5-hour work day and 216 work days per year. Assumed to represent existing conditions.

[d] Hours assumed to represent conditions under the Proposed Action.

[e] No information was provided. The maximum number of hours provided by any one applicant was assumed as a worst-case scenario. Hours were assumed to represent conditions under the Proposed Action.

Source: Based on interviews with the companies conducted by the USACE for permitting purposes.

D.4 TRANSPORTATION OF SAND AND GRAVEL

Transportation of sand and gravel produces emissions of ROG/VOC, CO, NO_X, PM, and GHGs as vehicle exhaust. Emissions of these pollutants were estimated using emissions factors generated by the USEPA MOVES2010 model and information summarized in Sections 3.13 and 4.11 (Noise) and Section 3.12 (Economics and Demographics) in the EIS.

MOVES2010 calculates emissions factors for on-road vehicles based on user-specified vehicle types, time periods, geographical areas, and operating characteristics. All vehicles were assumed to be single-unit short-haul diesel trucks operating in the State of Missouri. Table D-10 summarizes the emissions factors used in this analysis.

Haul truck characteristics, such as number of trips and distance traveled, were based on information presented in Sections 3.12, 3.13, and 4.11 in the EIS. Table 3.13-6 and Tables 4.11-5 through 4.11-8 in the EIS summarize the estimated number of truck trips under existing conditions, the Proposed Action, and the alternatives. As discussed in Section 3.12, the market area served by sand plants

along the Missouri River is within a 25-mile radius of the sand plant. It therefore was assumed that each of the trips summarized in Table 3.13-6 and Tables 4.11-5 through 4.11-8 were 25 miles.[3]

Table D-10 Emissions Factors for Vehicles Hauling Sand and Gravel (grams per kilometer for one single-unit short-haul diesel truck)

VOC	NO_X	CO	PM_{10}[a]	$PM_{2.5}$[a]	CO_2e
0.2018	2.5918	0.7546	0.1364	0.1221	0.2348

Notes:

CO = Carbon monoxide.
CO_2e = Carbon dioxide equivalent.
NO_X = Oxides of nitrogen.
$PM_{2.5}$ = Particulate matter less than 2.5 microns.
PM_{10} = Particulate matter less than 10 microns.
VOC = Volatile organic compounds.

Emissions factors include emissions from brakeware, tireware, and exhaust.

Emissions factors based on MOVES2010. The U.S. Environmental Protection Agency model MOVES2010 calculates emissions factors for on-road vehicles based on user-specified vehicle types, time periods, geographical areas, and operating characteristics. All vehicles were assumed to be single-unit short-haul diesel trucks operating in the State of Missouri.

The following equation was used to calculate emissions from sand and gravel hauling operations.

$$E = (\#\ of\ trips)\ X\ (trip\ distance)\ X\ (EF)\ X\ (CON)$$

Where:

E = Emissions, tons per year

# of trips = Estimated truck deliveries per year (based on Table 3.13-6 and Tables 4.11-5 through 4.11-8 in the EIS)

Trip distance = 25 miles (40.23 kilometers)

EF = Emissions factor, grams/kilometer (see Table D-10)

CON = Conversion from grams to tons (907,184 grams is equal to 1 ton)

D.4.1 Materials-Handling Scaling Factors

As discussed above, haul truck characteristics for existing conditions, the Proposed Action, and the alternatives are provided in Section 3.13 in the EIS. Consequently, emissions generated by sand and gravel hauling operations were not scaled, as emissions could be independently calculated for each alternative.

[3] The 25-mile figure represents an approximation of the primary market area for construction material extracted from the Missouri River. Note that the market area, and thus haul trips, extends beyond 25-miles. However, this distance was assumed to represent the upper bound for shipping distance.

D.5 CONSTRUCTION EMISSIONS

Construction activities, which can generate fugitive dust and exhaust emissions, can result in substantial temporary impacts on local air quality (i.e., exceed state air quality standards for ozone, CO, PM_{10}, and $PM_{2.5}$). Such emissions result from earthmoving and use of heavy-duty equipment. Emissions can vary substantially from day to day, depending on the level of activity, the specific operations, and the prevailing weather.

Under the Proposed Action and Alternatives A, B, and C, Rau and Master's would construct a new sand plant. Rau's facility would be approximately 25.6 acres and would be located in Franklin County. Master's facility would be 20–60 acres and would be located in Platte County. In addition to these facilities, increased demand on alternate sources of sand and gravel may require construction of new or expanded facilities at alternate source locations. The size and number of these facilities are currently unknown.

Limited information is available on the schedule and types of equipment that would be used to construct the new facilities. This analysis therefore relies heavily on professional judgment and air quality model default values. Actual emissions may vary depending upon specific construction information.

The URBEMIS2007 (Version 9.2.4) and NONROAD2008 emissions models were used to estimate emissions from construction activities. URBEMIS2007 is an emissions model that analyzes construction-, area-, and mobile-source emissions from land use development projects. Based on a specific type of land use, URBEMIS can estimate construction exhaust and fugitive dust emissions based on default assumptions regarding construction types and numbers of construction equipment, equipment activity data (i.e., number of hours per day and the load factor), and earth disturbance. URBEMIS was developed for use in California because it takes into account fuel regulations and vehicle characteristics specific to the state. Emissions estimates generated by URBEMIS for construction equipment therefore were not used for this analysis because fuel regulations and emission control technologies are more stringent in California than in other parts of the United States. Instead, URBEMIS was used to estimate fugitive dust emissions and to develop an equipment inventory for construction activities. NONROAD2008 emissions factors then were used to calculate emissions from each of the equipment pieces identified by URBEMIS.

Table D-11 lists the assumptions used in the URBEMIS modeling for construction activities and the basis for those assumptions.

The assumptions in Table D-11 were input into the URBEMIS model, the result of which was the equipment inventory, which is listed in Table D-12. Construction of Master's and Rau's facilities would require use of the equipment identified in Table D-12 for each facility.

Table D-11 URBEMIS Modeling Assumptions for Construction Activities

	Assumption	Rationale
Property size (number of acres graded)	Master's: 60	Permit applicant
	Rau: 25.6	Permit applicant
Number of acres disturbed per day	25 percent of total property area	Model default
Building construction	1,000-square-foot general office building	GoogleEarth aerials of existing facilities and photographs supplied by permit applicants
Construction schedule[a]	Master's: site grading (3/1/2011 – 7/30/2011); building construction (7/15/2011 – 7/30/2011)	Professional judgment
	Rau: site grading (3/1/2011 – 5/15/2011); building construction (5/1/2011 – 5/15/2011)	Professional judgment

[a] Construction activities were assumed to take place 5 days per week.

Emission factors for the equipment inventory in Table D-12 were calculated from the NONROAD model using the equation identified in Section D-3. Table D-13 summarizes the calculated emissions factors. These factors were multiplied by the maximum horsepower of each piece of equipment and the total number of hours operating for the entire construction period (see Table D-11). Calculated emissions for construction equipment were then combined with fugitive dust emissions generated by URBEMIS to obtain a total emissions estimate for construction of each of the facilities.

D.6 FACILITY OPERATIONS

The primary emissions generated by sand and gravel facilities are fugitive dust from processed materials and air pollutants from the upkeep of offices, and employee commute trips. Dust emissions can occur during materials processing. Generally, these materials are wetted or moistened for handling, which suppresses dust emissions. All commercial dredging operations must also abide by MDNR Regulation 10 CSR 10.6.170 (see Table 3.16-9 in the EIS), which restricts fugitive dust emissions beyond the premises of origin. Consequently, implementation of the Proposed Action or alternatives is anticipated to result in negligible fugitive dust emissions. No further analysis is required.

Table D-12 URBEMIS Modeling Assumptions for Construction Equipment

Phase	Equipment	Number	Horsepower	Hours/Day
Site grading	Grader	1	174	8
	Dozer	1	357	8
	Tractor	2	108	7
	Water Truck	1	189	8
Building construction	Crane	1	399	4
	Forklift	2	145	6
	Tractor	1	108	8

Table D-13 Emissions Factors for Construction Equipment (tons/horsepower-hour)

Equipment	VOC	NO_X	CO	PM[a]	CO_2[b]
Grader	4.56E-07	5.57E-06	2.31E-06	1.05E-06	8.62E-04
Dozer	1.73E-05	2.21E-04	7.63E-05	1.65E-05	3.72E-02
Tractor	1.00E-06	4.44E-06	5.48E-06	8.36E-07	5.06E-04
Water truck	7.24E-07	9.09E-06	4.53E-06	1.13E-06	1.68E-03
Crane	3.17E-07	4.41E-06	9.38E-07	2.25E-07	6.30E-04
Forklift	3.22E-07	4.01E-06	1.57E-06	3.45E-07	5.31E-04

Notes:

CO = Carbon monoxide. CO_2 = Carbon dioxide. NO_X = Oxides of nitrogen.
PM = Particulate matter. VOC = Volatile organic compounds.

[a] NONROAD does not provide emissions outputs for $PM_{2.5}$. An emissions factor therefore was not calculated. Instead, $PM_{2.5}$ emissions were assumed to equal 92 percent of PM_{10} emissions (SCAQMD 2006.

[b] NONROAD does not provide emissions outputs for CH_4 and N_2O. An emissions factor therefore was not calculated. Instead, emissions were determined by scaling calculated CO_2 emissions by the ratio of CH_4/CO_2 and N_2O/CO_2 emissions expected per gallon of diesel fuel according to the Climate Action Registry (California Climate Action Registry 2009).

Upkeep of the commercial offices and natural gas combustion for heating are sources of additional air pollutants from onshore facilities. In addition, GHG emissions would be generated through electricity usage, water consumption, and wastewater production. Employee travel to and from the property also would generate criteria pollutants and GHG emissions through vehicle exhaust. These emissions would be minimal compared to those produced by other dredging activities. Moreover, in response to data requests posed by the USACE, several permit applicants indicated that operational changes would be minimal with implementation of the Proposed Action. It is therefore unlikely that changes in the level of permitted sand and gravel volumes would result in a substantial increase or decrease in operational

activities. Consequently, office operations under the Proposed Action and alternatives would result in a negligible impact on air quality and climate change. No further analysis is required.

D.7 REFERENCES

D.7.1 Printed Literature

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D.7.2 Personal Communication

Zeaman, Bill. Chief, Non-Coal Unit. Missouri Department of Natural Resources, Jefferson City, Missouri. Email message to Laura Smith, ICF International. February 9, 2010.

UNITED STATES ARMY CORPS OF ENGINEERS

Missouri River Commercial Dredging Draft EIS

JULY 2010

Appendix E Distribution List for the Draft EIS

PREPARED BY

ENTRIX, Inc.
200 First Avenue West, Suite 500
Seattle, WA 98119
T 206.269.0104 ▪ F 206.269.0098

A P P E N D I X E

Distribution List for the Draft EIS

The U.S. Army Corps of Engineers (USACE) has distributed this Draft Environmental Impact Statement (EIS) to the contacts listed in the table that follows.

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Amanda	Shaw	Finney County Natural Resources Conservation Service	2106 East Spruce	Garden City	KS	67846	amanda.shaw@ks.usda.gov
Andy	Austin	Missouri Department of Conservation					andy.austin@mdc.mo.gov
Andy	Phelps	Russell County Natural Resources Conservation Service	125 E. 7th	Russell City	KS	67665	andy.phelps@ks.nrcs.usda.gov
Tonya	Cochran	Aqua-Terra Constructing & Engineering Systems, Inc.	P.O. Box 10260	Gulfport	MS	39505-0260	aquatera@bellsouth.net
William	Beacom						bbeacom@pionet.net
Brian	Lensing	Lensing Earthworks, Inc.	P.O. Box 376	Rhineland	MO	65069	bclensing@ktis.net
Bill	Brouk	Benton County Natural Resources Conservation Service	Route 1, Box 338-D	Lincoln	MO	65338	bill.brouk@mo.usda.gov
Bob	Hagedorn	Boone County Natural Resources Conservation Service	1715 West Worley Street #C	Columbia	MO	65203	bob.hagedorn@mo.usda.gov
Bob	Legler	Missouri Department of Conservation	P.O. Box 138	West Plains	MO	65775	bob.legler@mdc.mo.gov
Brian	Schulze	Natural Resources Conservation Service	112 N. Bell	Beloit	KS	67420	brian.schulze@ks.usda.gov
Bruce	Yonke	Jackson County Natural Resources Conservation Service	307 Montana	Holton	KS	66436	bruce.yonke@ks.usda.gov
Robert	Sholl	Burns and McDonnell, Inc	9400 Ward Parkway	Kansas City	MO	64114	bsholl@burnsmcd.com
Buck	Brooks	Missouri Department of Transportation					buck.brooks@modot.mo.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
		California Democrat	319 South High Street	California	MO	65018	caldem1@yahoo.com
Judith	Deel	Missouri Department of Natural Resources	PO Box 176	Jefferson City	MO	65102	judith.deel@dnr.mo.gov
Chad	Remley	USDA/NRCS	760 South Broadway	Salina	KS	67401-4642	chad.remley@ks.usda.gov
Chris	Hoskinson	Harper County Natural Resources Conservation Service	803 Fanning Drive	Anthony	KS	67003	chris.hoskinson@ks.usda.gov
Chris	Vitello	Missouri Department of Conservation	2630 North Mayfair	Springfield	MO	65803	chris.vitello@mdc.mo.gov
Christopher	White	U.S. Army Corps of Engineers		PM-PR			christopher.m.white@usace.army.mil
		Cherokee County Engineer	Courthouse	Columbus	KS	66725	ckeng@columbus-ks.com
		Finney County Commission	PO Box M	Garden City	KS	67846	clerk@finneycounty.org
		Grant County Commission	108 South Glenn	Ulysses	KS	67880	clerk@pld.com
		Boone County Commission	801 East Walnut Street, #245	Columbia	MO	65201	commission@boonecountymo.org
		Chautauqua County Road & Bridge	215 North Chautauqua	Sedan	KS	67361	cqrb2000@yahoo.com
Craig	Fuller	Missouri Department of Conservation	2350 South Jefferson	Lebanon	MO	65536	craig.fuller@mdc.mo.gov
Laura	Calwell		5610 West 61st Terrace	Shawnee Mission	KS	66202	creativechoice@yahoo.com
		Chase County Commission	Courthouse	Cottonwood	KS	66845	cs_county_clerk@wan.kdor.state.ks.us
		Tonganoxie Mirror	P.O. Box 920	Tonganoxie	KS	66086	ctrowbridge@tonganoxie.com
Curtis	Gooch	St. Clair County Natural Resources Conservation Service	3835 NE Highway 13	Osceola	MO	64776-9500	curtis.gooch@mo.usda.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Dale	Cornelius	Missouri Department of Conservation	Route 2, Box 247	Camdenton	MO	65020	dale.cornelius@mdc.mo.gov
Jason	Daniels	Environmental Protection Agency	901 North 5th	Kansas City	KS	66101	daniels.jason@epa.gov
Arch	Naramore	Kansas Key Press	900 New Jersey	Lawrence	KS	66044	datamail@kansaskeypress.com
Dave	Johnson	Carroll County Natural Resources Conservation Service	Route 1, Box 211C	Carrollton	MO	64633	dave.johnson@mo.usda.gov
David	Clyman	Vernon County Natural Resources Conservation Service	100 West Allison	Nevada	MO	64772	david.clyman@mo.usda.gov
David	Grossman	LG Barcus and Sons	1430 State Avenue	Kansas City	KS	66102	david.grossman@barcus.com
David	Wright	Natural Resources Conservation Service	Route 2, Box 2800	Hermitage	MO	65668	david.wright@mo.usda.gov
Douglas	Gaines	Gaines Soil Consulting	8611 Wieseman Road	Worden	IL	62097	dbgaines@madisontelco.com
Dee	Vanderburg	Randolph County Natural Resources Conservation Service	Rural Route 3	Moberly	MO	65270	dee.vanderburg@mo.usda.gov
DeEtte	Huffman	Arkansas River Coalition					deettehuffman@sbcglobal.net
Dick	Elliott	Bartlett & Company	4800 Main	Kansas City	MO	64112	delliott@bartlett-grain.com
Dennis	Brinkman	Shawnee County Natural Resources Conservation Service	3231 SW Van Buren	Topeka	KS	66611-2291	dennis.brinkman@ks.usda.gov
		Douglas County - County Engineer	1242 Massachusetts	Lawrence	KS	66044	dgcopubw@douglas-county.com
		Clay Center Dispatch	Box 519, 805 5th Street	Clay Center	KS	67432	dispatch@claycenter.com
		Butler County, Kansas - County Engineer	205 W. Central, Room 105	El Dorado	KS	67042	dlutz@bucoks.com

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Roger	Korenstra	Better Way Products, Inc.	70891 CR 23	New Paris	IN	46553	dockbox@npcc.net
Matt	Stevenson	Dock Hardware and Marine Fabrication	60 Napco Drive	Terryville	CT		dockshardware1@optonline.net
		Advertiser-Courier	PO Box 350	Hermann	MO	65401	donac@ktis.net
Doug	Peterson	Harrison County Natural Resources Conservation Service	1400 North 41st	Bethany	MO 67876	64402	doug.peterson@mo.usda.gov
Doyle	Brown	Missouri Department of Conservation					doyle.brown@mdc.mo.gov
Dan	Trout	Office of Surface Mining					dtrout@osmre.gov
Daniel	VanPetten	HNTB	PO Box 419299	Kansas City	MO	64141	dvanpetten@hntb.com
David	Mesker						dwmesker@gmail.com
Manuel	Barnes	Environmental and GIS Consulting, Inc	314 South Main	Bentonville	AR	72712	egis@egis-env.com
Edwin	Harvey	Thompson Coburn	One Mercantile Center	St. Louis	MO	63101	eharvey@thompsoncoburn.com
Ed	Heisel						eheisel@moenviron.org
C.	Giessel	Kansas Chapter, Sierra Club	11705 W. 101st Terrace	Overland Park	KS	66214	elaine.giessel@kansas.sierraclub.org
FirstName	LastName	Company	Address	City	State	ZIP Code	EmailAddress
Mike	Farley		175 Quindaro	Florissant	MO	63034	farley_mike@email.msm.com
Frances	Klahr	Missouri Department of Natural Resources		Waste Pr	rfund Section	frances.klahr@dnr.mo.gov	
Gary	Bruner	Natural Resources Conservation Service	100 North Angela	Paola	KS	66071	gary.bruner@ks.usda.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Gary	Schuler	Marion County Natural Resources Conservation Service	303 Eisenhower Drive	Marion	KS	66361	gary.schuler@ks.usda.gov
Gayle	Unruh	Missouri Department of Transportation	PO Box 270	Jefferson City	MO	65102	gayle.unruh@modot.mo.gov
George	Kromrey	Missouri Department of Conservation	P.O. Box 248	Sullivan	MO	63080	george.kromrey@mdc.mo.gov
George	Taylor	Livingston County Natural Resources Conservation Service	1100 Morton Parkway	Chillicothe	MO	64601	george.taylor@mo.usda.gov
Norman	Nelson	Upper Republican Basin Advisory Committee	505 Sunset Drive	Norton	KS	67654	gn728@hotmail.com
		Gove County	PO Box 128	Gove	KS	67636	go_county_clerk@wan.kdor.state.ks.us
Grant	Butler	Jefferson County Natural Resources Conservation Service	10820 Highway 21, G-57	Hillsboro	MO	63050	grant.butler@mo.usda.gov
		Greenwood County Commission	311 North Main	Eureka	KS	67045	greenwoodcountyclerk@yahoo.com
Manuel	Gross	Shafer, Kline & Warren, Inc.	11100 West 91st Street	Overland Park	KS	66214-3216	gross@skw-inc.com
Greg	Wingfield	Nature Conservancy, The	700 SW Jackson, Suite 804	Topeka	KS	66603	gwingfield@tnc.org
Harold	Kerns	Missouri Department of Conservation	701 NE College Drive	St. Joseph	MO	64507	harold.kerns@mdc.mo.gov
Richard	Chinn	Richard Chinn Environmental Training	804 Cottage Hill Way	Brandon	FL	33511-8098	info@richardchinn.com
Cheryl	Hammond	Today Data					info@todaydata.com
Jake	Allman	Missouri Department of Conservation					jake.allman@mdc.mo.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
James	Krueger	Dickinson County Natural Resources Conservation Service	326 NE 14th	Abilene	KS	67410	james.krueger@ks.usda.gov
James	Maberry	Livingston County Natural Resources Conservation Service	1100 Morton Parkway	Chillicothe	MO	64601	james.maberry@mo.usda.gov
		B & F Engineering, Inc.	928 Airport Road	Hot Springs	AR	71913	jamesm@bnfeng.com
Jan	Skouby	Missouri Department of Transportation					jan.skouby@modot.mo.gov
David	Thorne	Missouri Department of Conservation					david.thorne@mdc.mo.gov
John	Barnes		P.O. Box 21346	Wichita	KS	67208	jbarnes37@cox.net
Jerry	Bassett						jbassett1@msn.com
Joseph	Gibbs, P.E.	Engineering Services	1115 Club Meadows Drive	Columbia	MO	65203	jbg6267@aol.com
		Kansas Department of Agriculture	109 SW 9th Street	Topeka	KS	66612	jdarrah@kda.state.ks.us
		J.D. Fields & Company, Inc.	313 Plainfield/Naperville Road	Plainfield	IL	60544	jdfieldsmidwest@aol.com
James	Dutt	Shannon & Wilson, Inc.	2043 Westport Center Drive	St. Louis	MO	63146	jdutt@shanwil.com
James	VanBlaricon	Terracon Companies, Inc.	2111 W. Harry	Wichita	KS	67213	jivanblaricon@terracon.com
Jim	Mason	Arkansas River Coalition	3302 Hood Street	Wichita	KS		jmason15@cox.net
Joel	Grant	Linn County Natural Resources Conservation Service	121 Pershing	Brookfield	MO	64628	joel.grant@mo.usda.gov
Joseph	Hecht	Morris County Natural Resources Conservation Service	209 Hockaday	Council Grove	KS	66846	joseph.hecht@ks.usda.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
James	Triplett	Neosho Basin Advisory Committee	1701 South Broadway	Pittsburg	KS	66726-5889	jtriplet@pittstate.edu
		Riley County - County Engineer	110 Court House Plaza	Manhattan	KS	66502-0012	jward@co.riley.ks.us
		Sedgwick County	1144 South Seneca	Wichita	KS	67213	jweber@sedgwick.gov
Kathy	Zuehlke	Midwest Electric Products, Inc.	P.O. Box 910	Mankato	MN	56001	kathy.zuehlke@indsys.ge.com
		Kearny County Engineer	Box 129	Lakin	KS	67860	kcrb@pld.com
Keith	Kisner	Rawlins County Natural Resources Conservation Service	East Highway 36	Atwood	KS	67730-0195	keith.kisner@ks.usda.gov
Ken	Berry	Knox County Natural Resources Conservation Service	Route 1	Edina	MO	63537	ken.berry@mo.usda.gov
Ken	Urban	Natural Resources Conservation Service	2715 Canterbury Drive	Hays	KS	67601	ken.urban@ks.usda.gov
Kenda	Flores	Missouri Department of Conservation					kenda.flores@mdc.mo.gov
Kevin	Nelson	Greeley County Natural Resources Conservation Service	Box 400	Tribune	KS	67879	kevin.nelson@ks.usda.gov
Carol	Kunh	K&K Environmental	700 North Walnut	Olathe	KS	66061	kuhnc@prodigy.net
Lance	Burr		16 East 13th Street	Lawrence	KS	66044	lancewburr@sunflower.com
		Kansas Department of Agriculture	425 Main	Stockton	KS	67669	lbristow@kda.state.ks.us
		Logan County Commission	710 W. 2nd	Oakley	KS	67748	lg_county_clerk@wan.kdor.state.ks.us
		Lincoln County Highway Department	216 East Lincoln	Lincoln	KS	67445	lincolnhwydept@lincolncoks.org

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
L.D.	Shannon	City of Topeka, Water Production	3245 Waterworks Drive	Topeka	KS	66606	lshannon@topeka.org
Stephanie	Green	ETC, Inc.	No. 39 Wolf Pen Hollow	Camdenton	MO	65020-0891	madamstephanie@aol.com
		Cedar County Republican	PO Box C	Stockton	MO	65785	marilyne@cpimo.com
Gary	Sheide	Marina Ventures. Ltd.	2501 Boston Street	Baltimore	MD	21224	marinaventures@erols.com
Mark	Frazier	U.S. Army Corps of Engineers					mark.d.frazier@usace.army.mil
Mary	Jungk	Andrew County Natural Resources Conservation Service	105 Highway West	Savannah	MO	64485	mary.jungk@mo.usda.gov
		Sumner County Natural Resources Conservation Service	320 North Jefferson	Wellington	KS	67152	matt.markley@ks.usda.gov
		Hayes Daily News	PO Box 857	Hays	KS	67601	mcorn@dailynews.net
		Merco Marine	60 Merco Road	Wellsburg	WV	26070	merco@mercomarine.com
Mike	Geisel	City of Chesterfield	16052 Swingley Ridge Road	Chesterfield	MO	63017	mgeisel@chesterfield.mo.us
Michael	Gregory	City of Shawnee, Kansas	11110 Johnson Drive	Shawnee	KS	66203	mgregory@cityofshawnee.org
		Harrington & Cortelyou, Inc	127 West 10th	Kansas City	MO	64105	mhuck@hcbridges.com
Mike	Grogan	Trego County Natural Resources Conservation Service	519 Russell	Wakeeney	KS	67672	mike.grogan@ks.usda.gov
Mike	Smith	Missouri Department of Conservation					mike.smith@mdc.mo.gov
		Rushing Marine Corporation	P.O. Box 440	Jackson	MO	63755-0440	miker@rushingmarine.com
Murray	Meierhoff	Shannon & Wilson, Inc.	11500 Olive Boulevard&#31;&#31;Suite 276	St. Louis	MO	63141-7126	mlm@shanwil.com

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Marlene	Nagel	Mid America Regional Council	600 Broadway	Kansas City	MO	64105	mnagel@marc.org
Monty	Breneman	Lincoln County Natural Resources Conservation Service	PO Box 156	Lincoln	NE	67455	monty.breneman@ks.usda.gov
		List-Clark Construction	6811 West 63rd	Overland Park	KS	66202	mvbeggs@list-clark.com
		Natoma Publishing	P.O. Box 160	Natoma	KS	67651	natomanews@ruraltel.net
Natha	McAllister	Tri-County Weekly	105 S. Broadway	Jamesport	MO	64648	nert@grm.net
Norman	Bowers	Johnson County, Kansas	1800 W. 56 Highway	Olathe	KS	66061	norman.bowers@jocoks.com
		Kansas Department of Health and Environment	Building 283, Forbes Field	Topeka	KS	66620	nps@kdhe.state.ks.us
Nancy	Riley	Jackson County Public Works	103 North Main	Independence	MO	64050	nriley@gw.co.jackson.mo.us
		Osborne County Farmer	210 West Main	Osborne	KS	67473	ospubco@ruraltel.net
Pam	Lanigan	Missouri Department of Conservation					pam.lanigan@mdc.mo.gov
Pat	Conger	Missouri Department of Natural Resources	P.O. Box 176	Jefferson City	MO	65102-0176	patricia.conger@dnr.mo.gov
Philip	Chegwidden	Ellsworth County Natural Resources Conservation Service	402 West Old 40 Highway #1	Ellsworth	KS	67439	philip.chegwidden@ks.usda.gov
Bruce	Perkins	Platte Land Trust	10150 Ambassador Drive, Suite 100	Kansas City	MO	64153	plattelandtrust@yahoo.com
Paul	Reitz	Reitz & Jens, Inc.	1055 Corporate Square Drive	St. Louis	MO	63132	preitz@reitzjens.com
		Republican Clipper	P.O. Box 351	Bethany	MO	64424	rclipper@grm.net
		Moniteau County Natural Resources Conservation Service	410 West Buchanan	California	MO	65018	ric.heckman@mo.usda.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Rob	Pulliam	Missouri Department of Conservation					rob.pulliam@mdc.mo.gov
Bob	Kessler	Knowledge Communications Technologies	9809 Mercier	Kansas City	MO	64114	robtkessler@earthlink.net
		Rooks County Highway Department	303 South Walnut	Stockton	KS	67669-2150	rocordbr@ruraltel.net
Rodney	Saunders	Andrew County Natural Resources Conservation Service	105 Highway West	Savannah	MO	64485	rodney.saunders@mo.usda.gov
		U.S. Coast Guard					RReid@grpumr.uscg.mil
Robert	Russell	Jefferson County	3709 Quail Creek Court	Lawrence	KS	66047	rrussell@sunflower.com
		Commander - Eight Coast Guard District	1222 Spruce Street	St. Louis	MO	63103	rwiebusch@cgstl.uscg.mil
Xavier	Mallet	Techno Marine Manufacturing					xmallet@technomarine.ca
John	Walker		P.O. Box 559	Camdenton	MO	65020	scotchjw@aol.com
Scott	Hamilton	Missouri Department of Conservation					scott.hamilton@mdc.mo.gov
Scott	Voney	Missouri Department of Conservation	1907 Hillcrest Drive	Columbia	MO	65201	scott.voney@mdc.mo.gov
Debbie	Hays						scouthays@sbcglobal.net
		Water District No. 1 of Johnson County	7601 Holliday Drive	Kansas City	KS	66101	spaterson@waterone.org
Scott	Satterwaite	Kansas Department of Health and Environment					ssattert@kdhe.state.ks.us
		St. Mary's Star	P.O. Box 190	St. Marys	KS	66536-0190	star@oct.net
Steve	Mauzey	Howard County Natural Resources Conservation Service	745 State Road DD	Fayette	MO	65248	steve.mauzey@mo.usda.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Steve	Wooden	WilsonCounty Natural Resources Conservation Service	704 North Miami	Marshall	MO	65340	steve.wooden@mo.usda.gov
Stuart	Lawson	Sullivan County Natural Resources Conservation Service	Route 1, Box 1B	Milan	MO	63556	stuart.lawson@mo.usda.gov
Stuart	Miller	Missouri Department of Conservation	PO Box 180	Jefferson City	MO	65102-0180	stuart.miller@mdc.mo.gov
Susan	Blackford	U.S. Fish and Wildlife Service	315 Houston, Suite E	Manhattan	KS	66502	susan_blackford@fws.gov
Ted	Houser	Wallace County Natural Resources Conservation Service	P.O. Box 608	Sharon Springs	KS	67758-0608	ted.houser@ks.usda.gov
Ted	Utz	Andrew County Natural Resources Conservation Service	105 Highway West	Savannah	MO	64485	ted.utz@mo.usda.gov
Terri	Bruner	Schuyler County Natural Resources Conservation Service	P.O. Box 249	Lancaster	MO	63548-0249	terri.bruner@mo.usda.gov
Terry	Alstatt	Republic County Natural Resources Conservation	1319 23rd Street	Belleville	KS	66935-2533	terry.alstatt@ks.usda.gov
Tom	Flowers	Meade County Natural Resources Conservation Service	PO Box D	Meade	KS	67864	thomas.flowers@ks.usda.gov
Timothy	Coy	Lewis County Natural Resources Conservation Service	502 South Washington	Monticello	MO	63457	tim.coy@mo.usda.gov
		Tipton Times		Tipton	MO		times@vernonpublishing.com
Tim	Gogolski	Osage County Natural Resources Conservation Service	115 West 17th	Lyndon	KS	66451	timothy.gogolski@ks.usda.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Todd	Gemeinhardt	Missouri Department of Conservation	3424 NW Duncan Road	Blue Springs	MO	64015	todd.gemeinhardt@mdc.mo.gov
Tonya	Bittiker	Lafayette/Johnson County Natural Resources Conservation Service	120 West 19th	Higginsville	MO	64037	tony.bittiker@mo.usda.gov
Tracy	Freeman	Wabaunsee County Natural Resources Conservation Service	Rural Route 2, Box 1	Alma	KS	66401	tracy.freeman@ks.usda.gov
Tracy	Smith	Daviess County Natural Resources Conservation Service	209 Ash Street	Gallatin	MO	64640	tracy.smith@mo.usda.gov
Vicki	Richmond						vic@kc.rr.com
Fred	Ward	Randolph County Commission	110 South Main	Huntsville	MO	65259	ward@mcmsys.com
		Osborne County Commissioners and Road Supervisor	423 West Main	Osborne	KS	67473	william@imaima.com
		Kansas Department of Wildlife and Parks- Wilson State Park	Rural Route 1,Box 181	Sylvan Grove	KS	67481	wilsonsp@wp.state.ks.us
W.	Praderio	Massman Construction Company	P.O. Box 8458	Kansas City	MO	64114	wpraderio@massman.net
							cindyesi@aol.com
Don	Shelhammer						texascocom@hotmail.com
Eric	Morris						eric.morris@swcd.mo.gov
Fred	Rogge	Kansas River Water Assurance District No. 1					krwad@att.net
Jeff	Green						wgreen@ameren.com
John	Baker						john.l.baker@mo.usda.gov
Kirby	Ross						kross@phillipscountyreview.com

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Larry	Watson						larry.d.watson@mvm02.usace.army.mil
Layton	Billips						layton.billips@ks.usda.gov
							malldritt@cyberlodge.com
Mark	Jordan	Amerenue					mjordan@ameren.com
Peggy	McGaugh	Carroll County, Missouri					countyclerk@carrollcomo.org
S	McAlister						smcalister@kc.rr.com
		Smith County, Kansas					smcopworks@ruraltel.net
Tom	Jacobs	MARC					tjacobs@marc.org
Brenda	Kinion	US Army Corps of Engineers, Tulsa District					brenda.kinion@usace.army.mil
							perkinslimnolab@earthlink.net
Scott	Crain						scottc@merriam.org
		Adair County Road and Bridge					adaircountyrandb@cableone.net
Alice	Alexander						aliceischaui@yahoo.com
		Atlantic-Meeco					sales@atlantic-meeco.com
Bill	Jackson	Agri Services of Brunswick, LLC					bill@agriservices.com
Deanne	Bahr	Sac and Fox Nation of Missouri in Kansas and Nebraska					deannbahr@yahoo.com
Dave	Flemming						cnroad@hotmail.com
Denise	Wolf						gcrd@ruraltel.net
Frank	Austenfeld						austenfeldlaw@kc.rr.com
Gale	Cantu						gcantu@co.platte.mo.us

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Gary	Luttrull						gary.luttrull@mo.usda.gov
Gordon	Gorton						ggkansas@yahoo.com
Jeffrey	Schmidt						jeffrey.schmidt@ks.usda.gov
Jim	Peterson	Kansas Department of Transportation					jimp@ksdot.org
Mary Ann	Little	Cherokee County, Kansas					maryann.commissioner@cherokeecounty-ks.gov
Matt	Woodruff						matt.woodruff@kirbycorp.com
		Missouri Department of Natural Resources					wpsc401cert@dnr.mo.gov
		National Park Service					MWRO_recplanner@nps.gov
Doreen	McDowell	Natural Resources Conservation Service					doreen.mcdowell@ks.usda.gov
Penny	Evans	Miami County, Kansas					pevans@miamicountyks.org
		Polk County, Missuori					commissioners@polkcountymo.org
Randy	Asbury	Coalition to Protect the Missouri River	4849 Highway B	Higbee	MO	65257	moriver@howardelectricwb.com
Richard	Harrison						richard.n.harrison@uscg.mil
Ron	Temaat	Natural Resources Conservation Service					ron.temaat@ks.usda.gov
Stephanie	Royer						stephanie.royer@ks.nacdnet.net
		Sun News					sunnews@socket.net
Tanya	Gerstberger	Natural Resources Conservation Service					tanya.gerstberger@ks.usda.gov
Tony	Eller						anthony.e.eller@usps.gov

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
		Republic County Highway					rpcohwy@sbcglobal.net
		Savannah Reporter - Andrew County					publisher@stjoelive.com
		Trego County, Kansas					clerk@ruraltel.net
		U.S. Army Engineer District, Tulsa					ceswt-ro@swt03.usace.army.mil
		Woodson County Road and Bridge Department					roadnbridge@woodsoncounty.net
Gary	Robinette	Ponca Tribe					garyr@poncatribe-ne.org
Paul	Davis	Interstate Marine Terminals, Inc					imt795@hotmail.com
Kathleen	Kullberg						kathleendkullberg@eaton.com
John	Taylor	The Mirror, Lansing Current and Basehor Sentinel					jtaylor@theworldco.info
Tim	Weston	Kansas State Historical Society					tweston@kshs.org
Stacy	Wilson						wilst8c@aol.com
Arch	Naramore						arch@sunflower.com
Norm	Bowers						bowers@kansascounties.org
Kevin	Maxwell	Tetra Tech EM, Inc.					kevin.maxwell@ttemi.com
Susan	Sickman	Missouri State Water Patrol					susan.sickman@mswp.dps.mo.gov
Harold	Draper	Burns and McDonnell					hdraper@burnsmcd.com
Tom	Waters	Missouri Levee & Drainage District	36257 Highway Z	Orrick	MO	64077	waters4@ix.netcom.com
Karin	Jacoby						karin_jacoby@att.net

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Karin	Jacoby	MOARK	5009 Walnut	Kansas City	MO	64112	karin_jacoby@kcmo.org
Morris	Kay	MOARK	PO Box 1773	Lawrence	KS	66044	morrisakay@cs.com
Kristin	Perry	Missouri Clean Water Commission	PO Box 418, 15241 Pike 138	Bowling Green	MO	63334	alot@onemain.com
William	Easley	Missouri Clean Water Commission	PO Box 126	Cassville	MO	65625	billdoris@mo-net.com
Ron	Hardecke	Missouri Clean Water Commission	3944 Blocks Branch Road	Owensville	MO	65066	haradecke@fidmail.com
Frank	Shorney	Missouri Clean Water Commission	4609 Northeast Dick Howser Circle	Lee's Summit	MO	64064	sshorney7@aol.com
Jason	Rode						jrode@emerysapp.com
Darin	Banks	Kickapoo Tribe in Kansas					darin.banks@gmail.com
Kirby	Robidoux	Sac and Fox Nation of Missouri					krobidoux@sacandfoxcasino.com
Doris	Sherrick						bjdjsher@casstel.net
Shari	Laroussa						slaroussa@yahoo.com
Kim	Knowles	Missouri Coalition for the Environment	6267 Delmar Blvd, 2E	St. Louis	MO	63130	kimjoon1@sbcglobal.net
Brian	Pietig	Johnson County Infrastructure and Public Works	1800 West 56 Highway	Olathe	KS	66061	brian.pietig@jocogov.org
Wally	Corey	Natural Resources Conservation Service	1911 Boggs Creek Road	Jefferson City	MO	65101	wally.corey@mo.usda.gov
Kelly	Cox	Missouri Department of Transportation					kelly.cox@modot.mo.gov
Stephen	Prockish	US Army Corps of Engineers, Tuttle Creek					stephen.e.prockish@usace.army.mil
J.	Sutterfield	Miami Tribe of Oklahoma					jsutterfield@miamination.com

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Lisa	French	Cheney Lake Watershed					lisa.french@ks.nacdnet.net
Carole	Jontra						carole.jontra@washburn.edu
Nate	Muenks	Missouri Department of Transportation	601 West Main Street	Jefferson City	MO	65102	nathan.muenks@modot.mo.gov
Clif	Baumer	Natural Resources Conservation Service	601 Business Loop 70 West, Suite 250	Columbia	MO	65201	clif.baumer@mo.usda.gov
Frank	Dean						frank@primelandco.com
Pam	Fortun	City of Overland Park, - Engineering Services Division					pam.fortun@opkansas.org
Stephanie	Duncan						mzsduncan@aol.com
Jane	Scaro	Aquila					janescaro@yahoo.com
John	Knowles	Federal Highway Administration					john.knowles@fhwa.dot.gov
Dennis	Takade	US Army Central Regional Environmental Office					dennis.takade@us.army.mil
Ernie	Longoria	City of Overland Park - Engineering Services Division		Overland Park	KS		ernie.longoria@opkansas,org
Cate	Holston	Environmental Protection Agency					holston.catherine@epa.gov
Troy	Gordon	Friends of Big Muddy					friends@friendsofbigmuddy.org
Mary	Litvan	Missouri Department of Conservation	2630 North Mayfair	Springfield	MO	65803	mary.litvan@mdc.mo.gov
Denise	Nelson	National Park Service	601 Riverfront Drive	Omaha	NE	68102	denise_nelson@nps.gov
Larry	O'Donnell	Little Blue River Watershed Coalition					turttle5@aol.com
Andrea	Hunter	Osage Tribe (Tribal Historic Preservation Officer)	627 Grandview, PO Box 779	Pawhuska	OK	70456	ahunter@osagetribe.org

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Jill	DeWitt	Burroughs Audubon Society	21509 SW Woods Chapel Road	Blue Springs	MO	64015	jdewitt@audubon.org
Larry	Shepard	Environmental Protection Agency		Kansas City	KS		shepard.larry@epa.gv
Joseph	Hale, Jr.	Prairie Band Potawatomie Indian Nation					chagoh@pbpnation.org
Jenny	Frazier	Missouri Attorney General Office	PO Box 899	Jefferson City	MO	65102	jenny.frazier@ago.mo.gov
Patrick	Robinson	Allen Group					probinson@allengroup.com
Jeffrey	Bunch	SES, Inc.	6750 Antioch Road, Suite 305	Merriam	KS	66204	jbunch@ses-corp.com
Ana	Smith	Techno Marine Manufacturing	598 Leclerc	Repentigny	CN		asmith@technomarine.ca
Patrick	Kline	US Army Corps of Engineers, ATTN: ED-GS		Kansas City	MO		patrick.f.kline@usace.army.mil
Rita Gail	Fulks	Douglas County Public Works Department	1242 Massachusetts Street	Lawrence	KS	66044	rfulks@douglas-county.com
Cindy	Kemper	Johnson County Environmental Department	11811 S. Sunset Drive, Suite 2700	Olathe	KS	66061	cindy.kemper@jocogov.org
Carl	Johnson	Missouri River Watershed					ceclj1@gmail.com
Todd	Trotter	George Butler Associates					ttrotter@gbateam.com
Martha	Clark		13724 County Road 249	Helena	MO	64459	clark@bbwi.net
Herb	Graves						sakwwatersheds@sbcglobal.net
Stacia	Bax	Missouri Department of Natural Resources		Jefferson City	MO		stacia.bax@dnr.mo.gov
James	Morrissey	Kansas Department of Transportation		Topeka	KS		jamesmo@ksdot.org

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First Name	Last Name	Organization	Address	City	State	Zip Code	Email
Victoria	Colangelo	National Mitigation Banking Association	PO Box 547881	Orlando	FL	32854	info@mitigationbanking.org
Doug	Phelps	Trout Headwaters, Inc. - Experience EcoBlu	5079 Old Yellowstone Trail North	Livingston	MT	59047	doug@troutheadwaters.com
Robert	Spagnuolo	Congresswoman Lynn Jenkins' Office		Topeka	KS		robert.spagnuolo@mail.house.gov
Francis	Morris	Pawnee Nation					pawneeodyssey@yahoo.com
Cindy	Allison	ESI Contracting Corporation	3001 East 83rd Street	Kansas City	MO	64132	aewesi@esicontractingcorp.com
Scott	Coder	US Coast Guard		St. Louis	MO		justin.s.coder@uscg.mil
Rick	Lincoln						avianman@comcast.net
David	Urban	Ecosystem Partners					david@ecosystempartners.com
Melanie	Ashby						melanie@marina-builder.com
Lori	Carpenter	7Q10, Inc (formerly Huffman & Carpenter, Inc.)					lcarpenter@7q10.com
Maxine	Lipeles	Washington University School of Law	One Brookings Drive	St. Louis	MO	63130	milipele@wustl.edu