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Bed Material Sizes, Variability, and Trends in the Lower Mississippi River and Their Significance to Calculated Bed Material Loads

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Bed Material Sizes, Variability, and Trends in the Lower Mississippi River and Their Significance to Calculated Bed Material Loads

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Abstract

This report compiles and makes readily available data and supporting information contained in past U.S. Army Corps of Engineers reports on the sizes and size distributions of sediment forming the bed of the Lower Mississippi River. Based on these sources, the report establishes how particle size distributions and the widely used, statistically representative sizes (D50, D16, and D84) of the bed material vary with distance downstream and through time. Preliminary analyses are performed to identify downstream and time trends in bed material characteristics at a variety of scales, and establish the sensitivity of bed material transport rates and annual loads calculated using the Hydraulic Engineering Center-River Analysis System/Sediment Impact Analysis Method (HEC-RAS/SIAM), to local and short-term variability in bed sediment characteristics. The report closes by considering the overall conclusions and wider applications of its findings.

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Preface

The research documented in this report was conducted as part of the Mississippi River Geomorphology and Potamology (MRG&P) Program; Project 127672, “Bed Material Variability in the Lower Mississippi River.” The MRG&P is sponsored by Headquarters, U.S. Army Corps of Engineers (USACE), and is managed by the USACE Mississippi Valley Division (MVD) in Vicksburg, MS. The MRG&P Technical Director was Dr. Ty Wamsley. The MVD Commander was MG Richard G. Kaiser. The MVD Director of Programs was Mr. Jim Bodron.

The Mississippi River Commission provided Mississippi River engineering direction and policy advice. The Commission members were MG Richard G. Kaiser, USACE, President; the Honorable Sam E. Angel; the Honorable R. D. James; the Honorable Norma Jean Mattei, Ph.D.; RDML Shepard Smith, National Oceanic and Atmospheric Administration; BG Mark Toy, USACE-LRD; and COL Paul E. Owen, USACE-SWD.

Mr. Jeffrey R. Eckstein was the Deputy Director of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory, and Mr. José E. Sanchez was the Director.

COL Bryan S. Green was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters

1 Overview: MRG&P and Bed Material in the Lower Mississippi River (LMR)

1.1 Background

The Mississippi River Geomorphology and Potamology (MRG&P) program is sponsored by Headquarters, U.S. Army Corps of Engineers (USACE), and managed by Mississippi Valley Division. MRG&P studies are designed to provide a comprehensive analysis of physical forces that influence the flood conveyance capacity, navigability, and environmental quality of the Mississippi River. The purpose is to identify cause-effect and process-response relationships that result in short- and long-term changes in the hydrology, hydraulics, and morphology of the Mississippi River and to develop improved design approaches and criteria for construction of channel improvement actions that will result in flood damage reductions, enhanced navigation, and environmental sustainability.

Earlier Lower Mississippi River Division Potamology Programs, which ran from the 1940s through the 1980s, were initiated to address these concerns. A summary of the programs and detailed bibliography of works related to the LMR Potamology Programs can be found in Biedenharn et al. (2014), and historical potamology reports and studies can be accessed at the following website:

<http://www.mvd.usace.army.mil/Missions/MississippiRiverScienceTechnology/MSRiverGeomorphologyPotamology.aspx>.

1.2 Objectives

Within the context of the MRG&P program, the purposes of this report are the following:

- gather, review, and make readily available data and supporting information contained in past and recent USACE reports on the sizes and size distributions of sediment forming the bed of the LMR
- examine variability and downstream trends in sediment size distributions and how these have changed through time
- investigate the sensitivity to changes in sediment size distributions of bed material transport rates and annual loads calculated using the Hydraulic Engineering Center-River Analysis System/Sediment Impact Analysis Method (HEC-RAS/SIAM).

1.3 Approach

This report compiles data from five main sources. In chronological order, these are the following:

1. Waterways Experiment Station. 1935. *Studies of River Bed Materials and their Movement, with Special Reference to the Lower Mississippi River, Paper 17*. Vicksburg, MS: U.S. Army Corps of Engineers.
2. Robbins, L. G. 1977. *Suspended Sediment and Bed Material Studies on the Lower Mississippi River*. Potamology Investigation Report 300-1. U.S. Army Corps of Engineers, Vicksburg District.
3. Nordin, D. F., and B. S. Queen. 1992. Particle Size Distributions of Bed Sediments along the Thalweg of the Mississippi River, Cairo, Illinois, to Head of Passes, September 1989. Potamology Program (P-1), Report 7. Vicksburg, MS: U.S. Army Corps of Engineers, Lower Mississippi Valley Division.
4. Thorne, C. R., O. P. Harmar, C. C. Watson, N. J. Clifford, D. S. Biedenbarn, and R. Measures. 2008. *Current and Historical Sediment Loads in the Lower Mississippi River*. Final Report to the United States Army, European Research Office, London, England, under Contract Number 1106-EN-01. University Park Nottingham: School of Geography, University of Nottingham.
5. Gaines, R. A., and A. M. Priestas. 2016. *Particle Size Distributions of Bed Sediments along the Mississippi River, Grafton, Illinois, to Head of Passes, Louisiana, November 2013*. MRG&P Report No. 7. Vicksburg, MS: U.S. Army Corps of Engineers.

This report addresses bed material sizes, variability, and trends in Chapter 2, which is divided into four sections: Section 2.1 discusses the particle size distributions along the Middle and Lower courses of the Mississippi River in 1932, 1989, and 2013 as described by Gaines and Priestas (2016); Section 2.2 addresses the bed material trends in the Vicksburg District potamology reaches between 1966 and 1974; Section 2.3 discusses the bed material trends at the four permanent gaging stations on the LMR (Arkansas City, Vicksburg, Natchez, and Tarbert Landing); and Section 2.4 addresses the sensitivity of calculated sediment loads to bed material variability using the HEC RAS/SIAM model. In Chapter 3, the report concludes by considering its overall conclusions, the wider applications of its findings, and recommendations for further studies.

1.4 Points of contact

Please refer to the Appendix for points of contact.

2 Bed Material Size Distributions, Variability, and Trends

2.1 Gaines and Priestas (2016): *Particle Size Distributions of Bed Sediments along the Mississippi River, Grafton, Illinois, to Head of Passes, Louisiana, November 2013*

2.1.1 Overview

This section provides an overview of the recent Gaines and Priestas (2016) report in the MRG&P series, which is an important standalone document that adds new, original, field-based data for 2013 to bed material gradations for 1932 (WES 1935) and 1989 (Nordin and Queen 1992). It is recommended that people interested in bed material characteristics and their long-term trends read the Gaines and Priestas (2016) report in full. However, the report is summarized here so that their data and findings can be considered alongside those based on samples collected in the Vicksburg District (Robbins 1977) and at gaging stations (Thorne et al. 2008).

The decision to resample the bed in 2013 was triggered by the expectation that the river is continuing to respond to the impacts of multiple changes that occurred in the Mississippi River, its tributaries, and its catchment between 1932 and 1989, including (but not limited to) construction of dams on the Missouri River, shortening of the river by meander cutoffs and channel realignments, and construction of bank revetments and river training works. However, issues are also emerging concerning the morphology and sediment transport in the Middle Mississippi River (MMR), which is the reach of the Mississippi River between Cairo, IL, and the confluence of the Upper Mississippi River with the Missouri River (which is a predominant contributor of sediments to the LMR). For this reason, the 2013 sampling program was extended to include the Mississippi River upstream of its confluence with the Ohio River at Cairo, IL, as far as the confluence with the Illinois River at Grafton, IL.

The findings of the study are, consequently, based on 754 bed material samples, collected during November 2013 at 496 locations spaced at intervals of 2 to 3 miles along the Mississippi River between Grafton, IL, and Head of Passes, LA.

2.1.2 Field sampling sites and staff

To allow for direct comparison between the results of the 2013 sampling campaign and those obtained in 1932 and 1989, sample sites, equipment, and protocols were matched as closely as possible to those used in the previous studies. However, this was not straightforward because the delineation of river mileage was changed in 1962 (with river miles beginning with River Mile (RM) 0 at the Head of Passes, LA, and increasing upstream) such that Cairo is now at RM 954.6 whereas in 1932 sample locations were identified by river miles measured downstream of Cairo, IL. Also, and more significantly, the course of the river has changed markedly. For example, in 1932 the length of the channel between Cairo, IL, and the Head of Passes, LA, was 1,070 miles. Due mostly to the shortening effect of the cutoff program that was undertaken during the mid-twentieth century, at the time of the 2013 study this distance was just 955 miles.

The bed samples were collected by teams that included U.S. Army Engineer Research and Development Center (ERDC) researchers, a representative from the U.S. Geological Survey (USGS), and USACE District staff. Involvement of staff from the district within whose jurisdiction the sample site was located added valuable local knowledge to the operation and was essential to collecting data from the river reliably and repeatably. Note that Gaines and Priestas (2016) define sample locations used in 2013 not only in 1962 river miles ahead of passes (AHP) but also by their geographic coordinates. This should make it easy to relocate the sample points in any repeat survey, and it would be prudent to adopt this *belt and braces* approach to geolocating sample points in all future MRG&P studies.

2.1.3 Sampling device

The bed material sampler used in 2013 was of the same Waterways Experiment Station (WES) drag sampler design as that used in 1932 and 1989 (i.e., a 4-inch [in.] inside diameter steel pipe closed at one end and flared to 8 in. diameter at the other end) but with one modification. The 1932/1989 sampler had a length of 4 feet (ft) and was found difficult to handle using the boat and suspension equipment available in 2013. It was therefore shortened by 11 in. (Figure 1). Back-to-back check samples established that this made no difference to its performance in collecting bed material samples, but it did make the sampler much easier to manage.

Figure 1. WES drag samplers used in the 1932, 1989, and 2013 studies. Upper sampler is the original 4 ft long sampler used in 1932 and 1989. Lower sampler is that shortened by 11 in. for use in 2013 (Figure 2 from Gaines and Priestas [2016]).

2.1.4 Particle size analysis

Comparability of samples collected in 2013 to those from earlier studies also depends on consistency in the way the size distributions of the samples are established. This presented further challenges because laboratory techniques for particle size analysis (PSA) have changed radically since 1989. Also, there is no universally accepted methodology for constructing a single size distribution for a sample that includes particles ranging in size from gravels to clays. As a first step in ensuring repeatability and transparency in the PSA, an independent check of PSA performed at the ERDC laboratory was performed on 10% of samples by the USGS Kentucky Water Science Center Sediment Laboratory.

The 1932 and 1989 studies used the then conventional pipet technique for analysis of particles finer than 0.063 millimeter (mm) (i.e., silts and clays). Present practice is to use laser diffraction (LD) techniques that require significantly less analysis time. Gaines and Priestas (2016) used both techniques to establish how the two methods compare. For particles coarser than 0.063 mm (i.e., sands and gravels), the 2013 study used conventional sieving, in line with the 1932 and 1989 studies. To handle samples that ranged in size from sand to clay, a Matlab program was developed at the ERDC, Coastal and Hydraulics Laboratory, to merge the results of separate sieve and LD-based particle size analyses performed on the coarse and fine fractions in a consistent manner.

Investigation of differences between sieve-pipet and sieve-LD PSA techniques produced significant findings with implications beyond the scope of the present study, but to which interested readers are referred. In summary, the LD method produced coarser particle size distributions than the SP method in the very fine to medium sand size

classes (0.063–0.5 mm) and for medium silt (0.004–0.016 mm); conversely, the SP method significantly overestimated the clay fractions relative to LD (Figure 2).

Figure 2. Comparison of particle size analysis in terms of a cumulative distribution (A) and volume percent distribution using sieve-pipet (USGS) and LD (ERDC) methods (Figure 4 from Gaines and Priestas [2016]).

2.1.5 Results

Grain size distributions are customarily described using four statistical parameters: D_{16} , D_{50} , D_{84} , and a sediment sorting coefficient. D_{16} , D_{50} , D_{84} are, respectively, the grain sizes for which 16%, 50%, and 84% of the sample are finer. This is illustrated in Figure 3. As exactly half the sample is coarser than the D_{50} and half is finer, this parameter is the median grain size in the distribution.

Figure 3. Definition sketch for grain size distribution plotted on a linear scale (Figure 22 from Gaines and Priestas [2016]).

The sorting coefficient is defined as follows:

$$Sg = \frac{(D_{84}/D_{50} + D_{50}/D_{16})}{2}$$

and provides a measure of the diversity of grain sizes in a sample. A sample composed of grains all of the same size (i.e., a perfectly uniform sample) would have a sorting coefficient of unity. The wider the range of grain sizes present in a sample, the larger the sorting coefficient.

Engineers often refer to the sorting coefficient as the sample's *gradation* (Bunte and Abt 2001). Sediment specialists use a geometric sorting coefficient ($S_{g,sq} = \sqrt{D_{84}/D_{16}}$), which gives slightly different values to the equation above if the size distribution is skewed (as is usually the case).

The reach-averaged median (D_{50}) grain diameter in the MMR between Grafton, IL, and Cairo, IL, in 2013 was found to be 0.74 ± 0.70 mm. No downstream trend in median grain size was identified (Figure 4(a)).

In the LMR, between Cairo, IL, and Head of Passes, LA, in 2013, the median (D_{50}) grain size decreased downstream from approximately 0.6 mm to 0.18 mm (Figure 4 (b)).

Plotting grain size distributions averaged over 24 mile reaches as a function of River Mile AHP allows for direct, visual comparison of bed material data from 1932, 1989, and 2013 (Figure 5).

Figure 4. Downstream trends in median (D50) grain sizes measured in November 2013 in (a) the MMR between Grafton, IL, and Cairo, IL, (Figure 23 from Gaines and Priestas [2016] and (b) the LMR between Cairo, IL, and Head of Passes, LA [Figure 24 from Gaines and Priestas 2016]).

Comparison of the grain sizes measured in 2013, 1989, and 1932 shows that, overall, bed sediments are now generally finer and more uniform than they were in 1932 and 1989, though little change has occurred since 1989 (Table 1). For example, the reach-averaged median grain diameter (D_{50}) in 2013 was 0.40 ± 0.22 mm, compared to 0.96 ± 2.64 mm and 0.46 ± 1.29 mm in 1932 and 1989, respectively. Increased uniformity in the grain size distribution is evident from the fact that the reach-averaged sorting coefficient was 1.93 in 2013 while values in 1932 and 1989 were 2.40 and 1.67, respectively.

Figure 5. Downstream trends in bed material grain size distributions in the LMR in (a) 1932, (b) 1989, and (c) 2013 (Figures 26, 27, and 28 from Gaines and Priestas [2016]).

Table 1. Reach-averaged bed sediment statistics for the LMR between RM 950 and RM 0 (modified from Table 7 in Gaines and Priestas [2016]).

Year	D ₈₄ (mm)	D ₅₀ (mm)	D ₁₆ (mm)	Sorting Coefficient
2013	0.92	0.40	0.25	1.93
1989	0.98	0.46	0.27	1.67
1932	2.25	0.96	0.44	2.40

2.1.6 Interpretation of results

Gaines and Priestas (2016) attribute the bed material changes listed in Table 1 to the fact that since 1932, the relative fractions of gravel and very coarse sand have decreased in the upper reaches of the LMR (above RM 500) while the relative fractions of clay, silt, and very fine sand have decreased along the entire length of the river, but mostly downstream of Baton Rouge (RM 200). Both these size fractions have been replaced by increases in the relative fractions of fine, medium, and coarse sand. In essence, since 1932, bed materials have become more uniform through fining of the bed upstream of RM 500 and coarsening of the bed below RM 500.

In their 1989 report, Nordin and Queen stated that their expectation was that dam construction, the cutoff program, and bank stabilization would have caused the bed to coarsen relative to that sampled in 1932. Their results showed just the opposite, with a decrease in D_{50} in 1989 compared to 1932 above RM 300 and no significant change below RM 300.

Gaines and Priestas also predicted that upstream reaches would have coarsened compared to 1989, although grain sizes would probably not have returned to those measured in 1932. This prediction was based on observations of extensive gravel bars between Cairo, IL, and Memphis, TN, evidence of continued channel degradation and downward revision of the Low Water Reference Plane (LWRP) in 2007. In fact, results for 2013 show that, with the exception of the reach between RM 700 to RM 475, there has been a further reduction in the relative fraction of gravel-sized sediment since 1989. Conversely, between 1989 and 2013 there was little or no change in bed material sizes downstream of RM 350.

Gaines and Priestas (2016) highlight that multiple factors affect the bed gradation of the LMR. For example, during the months and years preceding the sampling campaigns of 1932 and 1989, the LMR experienced no periods of sustained, high discharge. In contrast, the flood of 2011 (which preceded sampling in 2013) set new record high

discharges at locations upstream of Memphis, TN, and crested at near historic highs at Memphis and gaging stations farther downstream. Mobilization of the bed during this extreme event must have resulted in remixing of bed sediments in ways unrepresented in the samples collected in 1932 and 1989 both. However, the depth and lateral extent of such mixing is unknown. Nevertheless, it is reasonable to suppose that reworking of the river bed during the 2011 flood might at least partly explain why sediments were more uniform in 2013 than was the case in 1989.

Evidence of continued lowering of the LWRP (USACE 2007) suggests that response of the LMR to construction of dams, cutoffs, and revetments during the twentieth century is continuing in the twenty-first century. However, not only are responses intrinsically complex, they are also influenced by geologic controls that in places locally reduce the capacity of the alluvial river to adjust to changes in flow regime, sediment supply, planform, and bank characteristics.

The repeated bed material sampling along the entire length of the LMR in 1932, 1989, and 2013 reported by Gaines and Priestas (2016) provides invaluable insights into long-term response of the river at the system scale. However, close inspection of the mass of data provided by Gaines and Priestas (2016) also reveals alternating cycles of decrease and increase in grain size distributions along the length of LMR that indicate the existence of spatially and temporally nested cycles of feedback and complexity in the process-response mechanisms through which adjustments proceed and long-term change is achieved. Managing the river efficiently requires that these shorter-term and more localized process-response mechanisms are also understood and explained, and to this end Gaines and Priestas (2016) draw attention to the intensive sampling described in Robbins (1977), which is the subject of the next section in this document.

2.1.7 Summary conclusions based on Gaines and Priestas (2016)

The main conclusions that can be drawn from Gaines and Priestas (2016) are the following:

1. Bed material samples from 2013 are significantly finer than those collected in 1932. On average, the D_{50} grain size in 2013 (0.40 mm) is approximately half that measured in 1932 (0.96 mm). However, there has been little change in median grain size since 1989 (0.46 mm).

2. Grain sizes in the 2013 samples are more uniform than those measured in 1932 and close to those measured in 1989. The 2013, reach-averaged sorting coefficient is 1.93 compared to 1.67 in 1989 and 2.40 in 1932.
3. Since 1932, the percentages of gravel and very coarse sand have declined upstream of RM 500. In contrast, below RM 500 there have been marked declines in the percentages of clay, silt, and very fine sand. In both cases, these size fractions have been replaced by increases in the percentages of sand. Essentially, the bed of the LMR is becoming more uniform through fining upstream of RM 500 and coarsening downstream of RM 500.
4. The samples collected in 2013 contained less gravel than in either 1932 or 1989 except between RM 650 and RM 575.
5. It is difficult to make casual links between these changes in bed material characteristics and drivers of morphological adjustment (such as dams, cutoffs, and revetments) due to complicating factors such as the occurrence of major floods and existence of local geological controls that reduce the capacity of channel morphology to adjust to changes in the flow and sediment regimes.
6. While examination of changes in bed material characteristics over long time spans and at the system-scale provides invaluable insights, the global response of the river, the existence of spatially and temporally nested cycles of feedback, and complexity in the process-response mechanisms through which adjustments proceed mean that there is also much to be learned through examination of local changes in bed sediment characteristics that occur over shorter time spans, based on more intensive sampling like that described in Robbins (1977), which is the subject of the next section in this document.

2.2 Robbins (1977): *Suspended Sediment and Bed Material Studies on the Lower Mississippi River*

2.2.1 Background

Robbins (1977) was one of a series of potamology investigations conducted by the USACE, Vicksburg District, on the portion of the LMR within its jurisdiction. The general aim of these studies was to gain a better understanding of the fluvial processes of the river and to apply this knowledge toward effective and economical stabilization works for flood control and navigation. Within this context, the particular purpose of Robbins (1977) was to compile, present, and review data based on measurements of suspended and bed sediments in the LMR made within the Vicksburg District between 1929 and 1974, identifying any trends in the data that might have significance for flood control and navigation.

2.2.2 Field sampling sites

For the purposes of the potamology studies reported by Robbins, the LMR within the Vicksburg District (RM 320 and 606 AHP) was divided into 25 potamology study reaches (Figures 6 and 7), within which data could be aggregated to support reach-scale interpretation. Data collected in these reaches included hydrographic surveys, bed-form profiles, discharges and horizontal velocity distributions, bed-material and suspended sediment samples, and water-surface profiles. As the present report focuses on bed sediment, no further reference is made herein to the other measurements mentioned in Robbins (1977).

Between 1966 and 1972, bed sediment samples were collected at specially set up potamology sediment study ranges distributed along the LMR within the Vicksburg District. At each range, between 4 and 12 bed material samples were collected, depending on the width of the cross section. However, in 1972 the sampling protocol was changed, and in 1973 and 1974 bed material samples were collected only at the centerline of the flow. This change in sampling procedure must be considered when comparing samples and looking for time trends in the characteristics of bed sediments in the Vicksburg District.

Figure 6. Potamology study reaches along the LMR within the Vicksburg District (Plate 1 in Robbins [1977]).

Figure 7. Potamology study reaches along the LMR within the Vicksburg District (Plate 2 in Robbins [1977]).

In addition to bed samples collected specifically for the potamology studies, since 1967 bed material samples in the Vicksburg District have also been collected in conjunction with suspended sediment sampling at the discharge gaging ranges at Arkansas City, Vicksburg, and Natchez. These samples are taken at the same sampling verticals used for suspended sediment sampling, which are located at centroids of equal portions of flow. Bed material data for the Arkansas City, Vicksburg, and Natchez gages are considered in the next section of this report, together with, and in the context of, that for all the other gaging stations along the LMR. Hence, no further reference is made to the bed samples collected at gaging stations in this section.

2.2.3 Sampling device

Until 1967, bed material samples were collected in the Vicksburg District using a drag bucket similar to that used in the 1935 and 1989 bed material sampling campaigns, as described by Gaines and Priestas (2016) and illustrated in Figure 3 in the previous section. During 1967, the District switched to the BM-54 bed-material sampler designed and used routinely by the USGS, except for collection of bed samples on the left side of the Vicksburg discharge gaging range. Use of the drag bucket continued at that particular location because it is adjacent to a limestone

bluff, the base of which extends out into the bed of the river, and it was feared that contact with the rocky bed might risk damaging the BM-54 sampler. The advantages of switching to the BM-54 were that this ensured consistency with USGS sampling of bed materials and that the BM-54 was designed to retain fine material while being raised through the water column. The disadvantage of this switch was a possible inconsistency with previous samples collected using the drag bucket.

To establish whether samples collected using the BM-54 could be compared to those collected using the drag bucket, in 1967 the Vicksburg District collected 77 paired samples using the two samplers at the same location and time. The results for almost all paired samples showed no difference between the median grain sizes. However, the BM-54 did retain slightly more fine material while the drag bucket tended to collect a little more gravel (Table 2).

Table 2. Comparison of sample size statistics obtained using the drag bucket and BM-54 devices (from Robbins [1977], page 13).

	Average Size (mm)		
	D ₈₄	D ₅₀	D ₁₆
Drag Bucket	1.21	0.42	0.28
BM-54	1.14	0.42	0.26
Difference (%)	6	0	6

2.2.4 Particle size analysis

Particle size distributions for bed sediment samples collected between 1966 and 1974 were determined by sieving. However, the finest sieve size used was mesh 200, equivalent to a sieve opening of 0.074 mm. In the Vicksburg District bed sediment study, no further analysis was performed on material finer than 0.074 mm, which was classified as silt-clay.

2.2.5 Results

While each bed material sample was sieved individually, the results for each sediment range were averaged to give a single, representative particle size distribution for the cross section as a whole. Range-averaged particle size distributions were then further aggregated to yield reach-averaged bed sediment sizes for the 25 potamology study reaches of the LMR within the Vicksburg District between 1966 and 1974. However, not all ranges and potamology reaches were sampled in each year, so there are gaps in the coverage. Downstream trends in reach-averaged bed material grain size distributions are plotted for the years 1932 and

between 1966 and 1974 in Figure 8. In these graphics, the vertical distances between adjacent jagged lines represent the percentage of the bed material that falls into the range between the lines.

Robbins (1977) observes that the graphs presented in Figure 8 reveal that in the Vicksburg District, the percentage of sediment finer than 0.295 mm was generally higher between 1966 and 1974 than it was in 1932. Conversely, the percentage of material coarser than 0.589 mm decreased. The percentage of material sized between 0.295 and 0.589 mm was markedly greater in 1966 than it had been in 1932, but by 1974, the percentage of sediment sized between 0.295 and 0.589 mm had decreased to approximately what it was in 1932.

Figure 9 compares values and downstream trends in (D_{50}) in the Vicksburg District measured in 1932, 1968, 1971, and 1974. Reach-averaged values of the median bed material sizes (D_{50}) vary between 0.106 and 0.577 mm. There is a slight tendency for the median grain size to decrease with distance downstream. In general, the time trend is for D_{50} sizes to have decreased since 1932, which is contrary to what Robbins expected. D_{50} sizes in 1968 and 1971 are similar, but those measured in 1974 are noticeably finer. However, Robbins (1977) cautions against over-interpreting trends in the median grain size due to changes in sampling techniques and variation in the number of samples collected in each year and within each reach, all of which need to be considered when interpreting these data.

Robbins (1977) also calculated weighted average statistics representative of bed material sizes and size distributions in the Vicksburg District as a whole. In this calculation, the reach-averaged size distributions were weighted using the potamology study reach length as the weighting factor. Values of the grain sizes D_{50} , D_{84} , and D_{16} were then determined from the weighted average size distribution. The results for 1932 and for 1966–1974 in the reach between RM 422.8 and 606.0 AHP and for all available data are shown in Figure 10. Robbins (1977) does not include any results for the LMR downstream of RM 422.8 AHP. No explanation is provided for this, but presumably it is because for many years there were little to no data for the LMR between RM 320 and 422.4 AHP.

Figure 8. Downstream trends in bed material grain size distributions in the LMR in the Vicksburg District in 1932 and between 1966 and 1974 (modified from Figures 45 to 54 in Robbins [1977]).

Figure 9. Values and downstream trends in median size (D_{50}) of bed material in the Vicksburg District measured in 1932, 1968, 1971, and 1974 (modified from Figure 55 in Robbins [1977]).

Figure 10. Time trends in weighted average bed material statistics for the reach between RM 422.8 and 606.0 AHP and for all data available for the Vicksburg District as a whole (modified from Figure 56 in Robbins [1977]).

Between 1932 and 1966, D_{84} decreased markedly, median grain size (D_{50}) decreased somewhat, and D_{16} increased slightly. Between 1966 and 1974, a general downward trend is apparent in all size statistics. However, this trend is interrupted in 1967 and 1973. Robbins (1977) hypothesizes that the low values in 1966 may be due to the fact that samples were collected using the drag bucket rather than the BM-54 used in all other years while the temporary increase in bed material sizes measured in 1973 may be related to the extreme flood that occurred that year. The 1973 flood increased the river's capacity and competence to transport sediment, which probably resulted in temporary coarsening of the bed material. Overall, during the period of record, the weighted average D_{50} between RM 422.8 and 606.0 AHP decreased from 0.376 to 0.304 mm.

2.2.6 Interpretation of results

Robbins (1977) did not attempt to interpret variability and trends in bed material sizes and statistics in the context of the drivers of morphological change in the Vicksburg reach of the LMR. However, he

did comment at length on potential causes of a significant increase in the extent of exposed gravel on middle bars and islands between the upstream limit of the Vicksburg District (at RM 606 AHP) and Natchez Island (at RM 357 AHP), approximately 78 RM downstream from Vicksburg. He noted that the increase in exposed gravels had occurred even though there had been a general decrease in bed material sizes throughout the district.

Robbins (1977) attributed the increase in exposed gravels to the floods of 1973, 1974, and 1975 on the basis that these gravels were transported and deposited on top of islands and middle bars at elevations inundated by the very high water levels that are only attained during extreme floods. He postulated that during these high flows, the river is able to scour into ancient gravel layers, and it then transports the entrained bed material for a relatively short distance before depositing it at the head end of an island, middle bar, or point bar.

Field trips were made during the 1973–1975 low-water seasons to investigate the fresh gravel deposits and examine the sand waves left by the high flows at selected locations within the Vicksburg reach including the upstream end of a middle bar located in the left channel at Cottonwood Bar (RM 470 AHP), Togo Island Dike No. 2 (RM 416 AHP), the head of Middle Ground Island (RM 409 AHP), and the head of a middle bar at approximately RM 388 AHP.

These field studies led to a series of important observations concerning the nature of gravel-sized bed materials and the occurrence of sand waves in the LMR that add important, supplementary information to the particle size analyses that are the main outcome of Robbins (1977). These field-based observations and interpretations are therefore summarized here.

Gravel cover

1. In the Cottonwood Bar potamology reach, gravel formed an extensive, continuous sheet at the head of a middle bar in the left channel (RM 470 AHP) comprising particles with long axes typically to 80 to 120 mm (3 to 5 in.) in size (Figure 11).
2. At Togo Island Dike No. 2 (RM 416 AHP), river-transported gravel had filled the gaps between the quarry-run stone forming the dike 107 meters (m) (350 ft) out into the river. The river gravel ranged in size to approximately 60 mm (expressed as 2 in. in Robbins [1977]) when measured along the major axis (Figure 12). As the crest of the dike is 3

to 4.5 m (expressed as 10 to 15 ft in Robbins [1977]) above the river bed, the presence of gravel in the top of the dike indicates that gravel must have been carried in suspension, possibly due to very intense turbulence around the dike during high water. While this suggests that the LMR is capable of transporting coarse sediment in suspension during flood flows, Robbins (1977) noted that coarse sediment is excluded from suspended sediment samples because the nozzle of the P-61 suspended sediment load sampler is only 0.48 mm (3/16 in.) in diameter.

3. Gravel cover was often extensive (Figure 13) at the head of Middle Ground Island (RM 409 AHP). However, excavation of a trench through the bar head showed the gravel to be an armor layer with a thickness approximately equal to the diameter of the larger particles that was underlain by sand that had gravel interspersed within it (Figure 14).
4. Gravel cover was observed at the heads of bars and islands as far downstream as RM 388.4 AHP, which is between Vicksburg and Natchez. As shown in Figure 15, the extent of gravel cover on the bar at RM 388.4 was still large, though the gravel was finer than that farther upstream, the long axes of the larger particles being 60 to 80 mm (2 to 3 in.).
5. While gravel deposits were found through a substantial proportion of the Vicksburg reach, the proportion of the bed of the LMR that was covered by gravel is tiny compared to that covered by sand. Nevertheless, the effect of a gravel armor layer at the head of a bar or islands is to tend to anchor the features in place, at least at low and intermediate flows and perhaps at all but the highest flows. Hence, the morphological influence and significance of the gravel armor may be considerable despite the relatively small area that it covers.
6. The extent and size of coarse bed sediment found at multiple locations within the Vicksburg District indicate that during high flows, the river transports particles far coarser than those collected during routine sampling. This indicates that while suspended load sampling records provide reliable estimates of the *capacity* of the LMR to transport sediment, they do not provide a reliable guide to the *competence* of the river because the largest sizes of material transported are evidently much larger than the orifice size of the samplers routinely used to measure the suspended sediment load.

Figure 11. Gravel layer at the head of Cottonwood Bar (RM 470 AHP) on 26 September 1975. Grid divisions = 20 mm (Photos. 1 and 2 in Robbins [1977]).

Figure 12. Togo Island Dike No.2 (RM 416 AHP) on 23 September 1975. Large angular material is quarry-run dike stone. Smaller, rounded particles are river transported gravels. Grid divisions = 20 mm (Photos. 3 and 4 in Robbins [1977]).

Figure 13. Gravel layer at the head of Middle Ground Island (RM 409 AHP) on 3 October 1973 and close up of gravel surface on 7 August 1974 with 6 in. ruler for scale (Photos 5 and 6 in Robbins [1977]).

Figure 14. Surface armor layer and underlying sand at head of Middle Ground Island (RM 409 AHP) on 7 August 1974 with 6 in. rule for scale (Photo 7 in Robbins [1977]).

Figure 15. Gravel cover at head of middle bar at RM 388.4 AHP on 22 September 1975. Grid divisions = 20 mm (Photos 8 and 9 in Robbins [1977]).

Sand waves

1. Field observations following high flows experienced during the mid-1970s established that huge quantities of sand are transported along the bed of the LMR in the form of large sand waves.
2. For example, during fieldwork in 1975, well-preserved sand waves from the 1975 high water season were observed at the lower end of the

middle bar in the left channel at Rodney (at approximately RM 387 AHP) (Figure 16). Sand waves ranged from 1.8 to 3.0 m (6 to 10 ft) in height at their crest.

3. These sand waves were found to be highly dynamic, adjusting radically to high and low flows. For example, longitudinal bed profiles made during 1973 (Figure 17) show that in the Ozark-Eutaw Potamology Reach at high flow (stage = 36 ft), sand waves approached 30 ft in amplitude and 400 to 600 ft in length (Figure 17, upper graphic) but were reduced to only 5 or 10 ft in amplitude and 300 to 500 ft in length at low flow (stage = 12 ft) (Figure 17, lower graphic).
4. These massive changes in sand wave geometry are driven by vigorous bed load transport in the LMR, which is demonstrated to be very large by the sheer magnitude of stage-related adjustments to bed topography that it drives.

Figure 16. Sand waves in the LMR around the lower end of the middle bar in left channel at Rodney (RM 387 AHP) on 22 September, 1975: (top) view upstream; (center) view cross stream; (bottom) view downstream. Wave heights = 1.8 to 3.0 m (6 to 10 ft) (Photos 10 to 12 in Robbins [1977]).

Figure 17. Longitudinal bed profiles made during 1973 in the Ozark-Eutaw Potamology Reach, above for location: (upper profile) at high flow (stage = 36 ft) sand waves approached 30 ft in amplitude and 400 to 600 ft in length; (lower) sand waves are only 5 or 10 ft in amplitude and 300 to 500 ft in length at low flow (stage = 12 ft).

2.2.7 Variability at the local space scale and decadal time scale

2.2.7.1 Study approach

The data included in Robbins (1977) provide the basis for additional analyses beyond those undertaken in the 1970s. These data are a particularly useful addition to the system-wide samples of bed material collected in 1932, 1989, and 2013 (collated by Gaines and Priestas and summarized in the previous section of this report). While those samples give invaluable synoptic indications of the composition of the bed at three widely spaced moments in time, the measurements made in 1932, 1989, and 2013 give no indication of how bed material in the Mississippi River varies locally and over short time spans. In contrast, the network of closely spaced sampling points and annual frequency of re-sampling in Robbins (1977) data provides the basis for investigating how bed material sizes vary at the local (reach) scale and the degree to which the composition of bed material of the LMR fluctuates in response to variations in the annual hydrograph. While Robbins (1977) data are based exclusively on sampling within the Vicksburg District, there is every reason to suppose that the degrees, types, and patterns of local scale and short-term variability established for that stretch of the river are replicated throughout the Mississippi River.

The Robbins (1977) data set is extensive and worthy of thorough investigation. In compiling this report, no attempt is made to perform an exhaustive analysis, though in due course that should be done as

part of ongoing MRG&P studies. Instead, indicative analyses have been undertaken to illustrate the potential utility of the Robbins data while also identifying and exploring some of its limitations. For these purposes, treatments are focused on base data from just seven potamology reaches that have been selected to be representative of the twenty-five used in Robbins (1977).

In the contemporary era, management of the LMR relies heavily on the application of physics-based and empirical modeling of sediment transport, primarily using the ERDC HEC-RAS. Recognizing this, a further additional analysis performed as part of the present study was to test the sensitivity of sediment transport rates calculated using HEC-RAS to variability typical of that experienced in the seven potamology reaches selected from those in Robbins (1977).

2.2.7.2 Base data

Base data cover the period 1966 to 1974 and are reach-averaged particle size distributions for the seven, selected potamology reaches listed in Table 3.

Table 3. Potamology reaches selected for initial evaluation in this study.

Potamology Reach	Extent (RM AHP)	Mid-Point (RM AHP)	Length (RM)	Period of Record
Ajax - Cottonwood	472 – 479.8	475.9	7.8	1968 - 74
Cottonwood Bar	467.8 - 472	469.9	5.8	1966 - 74
Cottonwood – Belle Island	461.4 – 467.8	464.4	6.4	1967 - 74
Belle Island - Milliken	451.8 – 461.4	456.6	9.6	1966 - 74
Milliken - Vicksburg	435 – 451.8	443.4	16.8	1968 - 74
Racetrack Towhead	422.8 - 435	428.9	12.2	1966, 1968 - 74
Point Pleasant	407 – 422.8	415.1	15.8	1966, 1970 - 74

The available bed material size distributions for these reaches are presented in Figure 18.

Figure 18. Particle size distributions for seven selected Potamology Reaches in the Vicksburg District (data taken from Robbins [1977]).

Examination of the base data indicates first that the majority of the bed material falls between 0.1 and 1 mm in size.

Spatial variability between reaches is limited, but while the overall shape of the size curves for all seven reaches are broadly similar, there are differences, especially in the coarse and fine tails of the distributions. For example, size variability in fines is much larger at Ajax–Cottonwood, Cottonwood–Belle Island, and Point Pleasant while variability in the coarse fraction is noticeably large at Cottonwood–Belle Island, and Belle Island–Milliken.

Generally, temporal variability between years is also limited, but there are prominent exceptions to this rule. At Ajax–Cottonwood, large percentages of fine sediment change the shape of the particle size curve radically in 1973 and 1974. This is also the case at Cottonwood–Belle Island in 1972 and Point Pleasant in 1973 and 1974. Conversely, in the coarse tail of the distribution, unexpectedly large percentages of coarse sand and gravel were sampled at Cottonwood–Belle Island in 1971, Belle Island–Milliken in 1973, and Racetrack Towhead in 1969.

Taking these observations together, the results indicate that the bed throughout the Vicksburg District is predominantly formed in sand, and the LMR is certainly best described as a sand-bed river. That said, the bed includes significant amounts of gravel at some locations, and this may, evidently, be exposed at the surface periodically.

The sediment load transported by the river is known to consist predominantly of fine sediment (silt, very fine sand, and fine sand) that is customarily regarded as *wash load*—which is defined as sediment finer than that found in significant quantities in the bed, which passes through a river but does not long reside there. The fine tails of the particle size distributions shown in Figure 18 confirm that silt, very fine sand, and fine sand seldom constitute more than approximately 5% of the bed material, which is consistent with treatment of these size fractions as wash load. Nevertheless, in some years, 30% to 40% of the bed material in the Ajax–Cottonwood, Cottonwood–Belle Island, and Point Pleasant reaches was composed of fines, indicating that under some conditions and in some locations significant quantities of wash load may be deposited and stored in the bed of the LMR.

2.2.7.3 *Impact of change in sampling protocol in 1973–1974*

As reported above, initial examination of the particle size distributions drew attention to differences between reach-averaged results obtained

in different years. In this context, results for 1973 and 1974 appeared to differ from those for earlier years in some reaches. As pointed out in the sub-section on “Field sampling sites,” between 1966 and 1972, between 4 and 12 bed material samples were collected at each sample site, depending on the width of the cross section while in 1973 and 1974 bed material samples were collected only at the centerline of the flow.

This change in the sampling protocol raised the concern that the change in sampling protocol might be responsible for differences between bed material size distributions for 1966–1972 and those for 1973–1974 rather than morphological and sediment adjustments actually occurring in the river.

To investigate this issue, in addition to particle size curves for the full period of record in each of the selected reaches, additional curves were plotted for data collected up to 1972 and for 1973–1974, in isolation. The results are displayed in Figure 19.

The decision to be made is whether to exclude data for 1973 and 1974 from the database used for further analyses on the basis that changing the sampling protocol has resulted in a systematic difference between particle size distributions based on multiple samples (between 4 and 12 in number) taken across the bed width at each sampling site and size distributions based on a single sample taken at the centerline of the flow.

On initial inspection, differences between the particle size distributions based on multiple and single samples are clearly apparent in several reaches. For example, at Ajax–Cottonwood, samples for 1973–1974 are much finer than those for 1966–1974. A difference is also apparent at Belle Island–Milliken, but in this case samples for 1973–1974 are coarser than those for 1966–1974. In Table 4, differences for all seven potamology reaches are classified on the basis of their sense.

Even though the pre-1973 samples were taken at several locations across the river, they were still predominately collected within the main channel and were only rarely located in perimeter backwater areas where major change bed material characteristics might be expected. Hence, there is no reason to expect a priori that the change in sampling protocol would systematically change the results. Also, the distribution in Table 4 provides no empirical evidence for concluding that there is a *systematic* difference between particle size distributions for 1966–1972 and 1973–1974 that can be attributed to the change in sampling protocols.

Figure 19. Particle size distributions for the selected potamology reaches indicated in the caption to each graph, sampled using different protocols in 1966–1972 and 1973–1974 (data taken from Robbins [1977]).

Table 4. Comparison of particle size distributions for 1966–1972 and 1973–1974.

Finer	No Difference	Coarser
3	1	3

This is unsurprising when the origin of the curves plotted in Figure 19 is considered: the curves in Figure 19 are not based on a single site; they are reach-averages derived by pooling data from multiple sampling sites within each potamology reach. Furthermore, they are time averages based on more than 1 year of observation. Considering this, while it would be preferable to have more rather than fewer samples, there is no reason to expect that size distributions based on multiple samples that have been averaged through both space and time should differ systematically depending on whether samples are taken at the centerline of the flow or distributed across the width of the main channel.

On the basis of this qualitative assessment, it was decided to include all the data available from Robbins (1977) in the database used to support further analysis of variability in the bed material properties of the LMR over short distance and time scales.

An additional reason for proposing that the characteristics of the bed of the LMR might have changed in the 1973–74 period as compared to 1966–1972 is that while 1966–1972 was a relatively flood-free period, 1973–1974 includes the flood of 1973, which was an extreme event. The peak discharge at Baton Rouge was approximately 1.4 million cfs, making this flood at the time of its occurrence the largest flood to occur since the Great Flood of 1927. On the basis that high-magnitude, rare flood events are known to have distinctive morphological impacts, it would be expected that the 1973 flood may have had lasting effects on bedforms, bar forms, and bed material characteristics in the LMR within the Vicksburg District.

Considering this, further inspection of the pre-flood (1966–1972) and post-flood (1973–1974) particle size distributions in Figure 19 does suggest that variability between the potamology reaches may have increased due to the impacts of the 1973 flood on bedforms, bar morphology, and bed material characteristics.

2.2.7.4 Variability in the median bed material grain size (D_{50}) through time and space

This section considers time and downstream trends in the median bed material size (D_{50}) and its variability through time, using all the data available for the 25 potamology reaches in the Vicksburg District derived from samples collected between 1966 and 1974. The base data used in the analysis are listed in Table 5. Initial inspection of Table 5 reveals that there are significant data gaps for some of the potamology reaches. That must be considered when the results are analyzed. In the next section, these data gaps are addressed by aggregating data for individual potamology reaches into four, longer sub-reaches for subsequent analysis.

Box and whisker plots were produced to display the data listed in Table 5. The bottom of the box (referred to as the lower hinge) represents the 25th percentile of the data and the top (upper hinge) represents the 75th percentile, with the band near the middle of the box representing the median particle size (D_{50}). Note that this is not the same as the mean particle size unless the scatter is normally distributed, which it usually is not for these samples. Fifty percent of the data are within the box (i.e., between 25th and 75th percentiles). The whiskers are related to the height of the box, which is referred to as the interquartile range (IQR). For this investigation, the extent of the whiskers was defined as the lowest data point within $1.5 \times$ IQR of the lower quartile and the highest data point within $1.5 \times$ IQR of the upper quartile. Data outside the whisker limits that are depicted as crosses are referred to as *outliers*.

To allow a preliminary evaluation of the hypothesis that the 1973 flood may have had impacts on the bed morphology and size characteristics of the LMR that would be evident in D_{50} sizes and variability (through space and time), data are plotted separately for all 25 potamology reaches including results for 1973–74 in Figure 20(a) and excluding 1973–1974 in Figure 20(b).

Table 5. Variation in bed material median grain size in the Vicksburg District (compiled from all data available in Robbins [1977]).

Potamology Reach	RM Mid-Point	Reach Length (miles)	D ₅₀ (mm)								
			1966	1967	1968	1969	1970	1971	1972	1973	1974
Cessions-Henrico	611	10	0.41						0.34	0.38	0.27
Smith Pt-Terrene	600.1	11.8	0.42		0.37	0.37	0.38	0.33	0.30	0.33	0.22
Terrene-Ozark	587.6	13.2	0.37	0.38	0.35	0.35	0.34	0.30	0.27	0.30	0.32
Ozark-Eutaw	573.45	15.1	0.36	0.37	0.36	0.36	0.36	0.34	0.34	0.35	0.30
Choctaw Bar	558.15	15.5	0.39	0.35	0.38	0.35	0.35	0.36	0.37	0.34	0.29
Greenville	540.8	19.2	0.33	0.37	0.35	0.34	0.34	0.37	0.40	0.34	0.26
Lakeport	527.7	7		0.35	0.36	0.32	0.33	0.36	0.31	0.29	0.30
Kentucky Bend	519.5	9.4	0.36	0.39	0.35	0.36	0.39	0.38	0.36	0.33	0.33
Cracraft Carolina	510.7	8.2	0.34	0.38	0.36	0.32	0.30	0.33	0.31	0.34	0.25
Carolina Baleshed	501.1	11		0.54	0.40	0.39	0.32	0.29	0.39	0.31	0.32
Baleshed Landing	490.6	10	0.39	0.34	0.35	0.35	0.35	0.31	0.33	0.33	0.38
Ajax Bar	482.7	5.8	0.34	0.36	0.32	0.29	0.31	0.30	0.27	0.30	0.32
Ajax Cottonwood	475.9	7.8			0.35	0.32	0.33	0.34	0.26	0.14	0.11
Cottonwood Bar	469.9	4.2	0.43	0.36	0.31	0.33	0.27	0.33	0.21	0.28	0.35
Cottonwood - Belle Is.	464.6	6.4		0.27	0.34	0.28	0.37	0.36	0.22	0.35	0.38
Belle Island - Milliken	456.6	9.6	0.36	0.38	0.37	0.37	0.36	0.36	0.41	0.55	0.40
Milliken - Vicksburg	443.4	16.8			0.35	0.38	0.40	0.40	0.41	0.50	0.42
Racetrack - Towhead	428.9	12.2	0.29		0.33	0.41	0.33	0.35	0.29	0.25	0.25
Pt. Pleasant	415.1	15.4	0.36				0.36	0.31	0.25	0.21	0.31
Grand Gulf	401.3	12.2					0.30	0.29	0.33	0.34	0.31
Rodney	388.3	13.8	0.26		0.31	0.33	0.35	0.30	0.29	0.31	0.23
Waterproof	374.8	13.2	0.33				0.26	0.28	0.28	0.26	0.27
Natchez	361.7	13					0.32	0.31	0.34	0.40	0.40
St. Catherine	346.9	16.6						0.25	0.26	0.28	0.16
Bougere	329.5	18.2							0.32	0.31	0.31

Figure 20. Box and whisker plot for median grain size (D_{50}) in the Vicksburg District for (a) 1966–1974 and (b) 1966–1972 (compiled from all data available in Robbins [1977]).

Initial comments on the impacts of the 1973 flood as represented in the data plotted in Figure 20 must be tempered by consideration of the limitations inherent to the base data. For example, the pre-1973 data records for Cessions–Henrico (RM 611), Grand Gulf (RM 401.3), Natchez (RM 361.7), St. Catherine (RM 346.9), and Bougere (RM 329.5) are particularly sparse, reducing the significance of comparisons between the 1966–1972 and 1973–1974 periods. Even ignoring these data sparse reaches, comparison of Figure 20(a) and (b) does suggest that time variability in median grain size is increased when data for the post-flood period are included in the records. Table 6 lists the trends of change for reaches that have fairly complete records.

Temporally, the main impacts of adding the 1973–1974 data (which include the 1973 flood) on median bed material grain sizes in the Vicksburg District are to reduce the D_{50} somewhat and increase variability considerably compared to values recorded the previous, flood-free period (1966–1972). In most reaches, variability increases primarily on the fine side of the distribution of D_{50} values; however, the nature of changes does appear to change as a function of downstream distance. In potamology reaches upstream of Cottonwood Bar, the predominant impact of including the 1973–1974 data is to increase variability on the fine side of the distribution while reducing the time-averaged D_{50} . There is no change in D_{50} or its variability in the Cottonwood Bar reach. Between the Cottonwood–Belle Island and Milliken–Vicksburg reaches, the predominant impact of including the 1973–1974 data is to increase variability on the coarse side of the distribution while increasing the time-averaged D_{50} . Downstream of Milliken–Vicksburg, the predominant impact of including the 1973–1974 data is to increase variability on both sides of the distribution while reducing the time-averaged D_{50} .

Table 6. Indicative changes in D_{50} when data for 1973–1974 are added to the record for 1966–1972.

Potamology Reach	Mid-Point (RM AHP)	Increased Variability (fine side)	Decreased Average D_{50}	Increased Variability (coarse side)	Increased Average D_{50}
Cessions-Henrico	611	Insufficient data pre-1973			
Smith Pt-Terrane	600.1				
Terrane-Ozark	587.6				
Ozark-Eutaw	573.45				
Choctaw Bar	558.15				
Greenville	540.8				

Potamology Reach	Mid-Point (RM AHP)	Increased Variability (fine side)	Decreased Average D ₅₀	Increased Variability (coarse side)	Increased Average D ₅₀
Lakeport	527.7				
Kentucky Bend	519.5				
Cracraft-Carolina	510.7				
Carolina-Baleshed	501.1				
Baleshed Landing	490.6				
Ajax Bar	482.7				
Ajax-Cottonwood	475.9				
Cottonwood Bar	469.9				
Cottonwood-Belle Is.	464.6				
Belle Is.-Milliken	456.6				
Milliken-Vicksburg	443.4				
Racetrack-Towhead	428.9				
Pt. Pleasant	415.1				
Grand Gulf	401.3	Insufficient data pre-1973			
Rodney	388.3				
Waterproof	374.8				
Natchez	361.7	Insufficient data pre-1973			
St. Catherine	346.9	Insufficient data pre-1973			
Bougere	329.5	Insufficient data pre-1973			

Key:

	Marked change
	Change
	Slight change
	No change

Spatially, the plots in Figure 20 indicate that while the median grain size is medium sand throughout the Vicksburg District, there are reach-scale fluctuations in D₅₀ that at least hint at there being a cyclical downstream pattern within the Vicksburg District as a whole. There is, however, little or no evidence of a downstream, decreasing trend in D₅₀, except perhaps downstream of the Milliken–Vicksburg reach (RM 443.4 AHP).

2.2.7.5 *Variability in D₁₆ through time and space*

This section considers time and downstream trends in the sixteenth percentile bed material size (D_{16}) and its variability through time, using data available for the Vicksburg District. The significance of D_{16} (the grain size for which 16% of the sample is smaller) is that it represents the finer fraction of the bed material size distribution. In a normally distributed sample, the sixteenth percentile is one standard deviation smaller than the mean. D_{16} is also a significant because, together with the D_{84} , it defines the sediment sorting coefficient. The data used in the analysis is listed in Table 7. The significant data gaps for some of the potamology reaches noted for D_{50} data reported in the previous section are also present for D_{16} , and this must be considered when interpreting the results listed in Table 7.

Box and whisker plots were produced to display the data listed in Table 7. To allow a preliminary evaluation of the hypothesis that the 1973 flood may have had impacts on the bed morphology and size characteristics of the LMR that would be evident in D_{16} sizes and variability (through space and time), data are plotted separately for all 25 potamology reaches including results for 1973–1974 in Figure 21(a) and excluding 1973–1974 in Figure 21(b).

Even ignoring the data-sparse reaches, comparison of Figure 21(a) and (b) does suggest that time variability in the D_{16} grain size is increased when data for the post-flood period are included in the records. Table 8 lists the trends of change for reaches that have fairly complete records.

Temporally, the main impacts of including the 1973–1974 data (which incorporate the 1973 flood) on D_{16} bed material grain sizes in the Vicksburg District are to reduce the D_{16} and increase variability compared to values recorded the previous, flood-free period (1966–1972). Variability increased on both the fine and coarse sides of the distribution of D_{16} values, and the nature of changes shows a weak pattern with downstream distance. In potamology reaches upstream of Cottonwood Bar, the predominant impact of including the 1973–1974 data is to increase variability on the fine side of the distribution while reducing the time-averaged D_{16} .

Table 7. Variation in bed material D₁₆ grain size in the Vicksburg District (compiled from all data available in Robbins [1977]).

Potamology Reach	RM Mid-Point	Reach Length (miles)	D ₁₆ (mm)								
			1966	1967	1968	1969	1970	1971	1972	1973	1974
Cessions-Henrico	611	10	0.25						0.21	0.23	0.15
Smith Pt-Terrene	600.1	11.8	0.26		0.21	0.21	0.21	0.20	0.09	0.07	0.07
Terrene-Ozark	587.6	13.2	0.24	0.25	0.21	0.22	0.18	0.17	0.12	0.16	0.07
Ozark-Eutaw	573.45	15.1	0.23	0.24	0.23	0.21	0.24	0.23	0.23	0.23	0.21
Choctaw Bar	558.15	15.5	0.25	0.22	0.25	0.22	0.22	0.22	0.23	0.23	0.17
Greenville	540.8	19.2	0.19	0.24	0.19	0.20	0.19	0.25	0.25	0.22	0.16
Lakeport	527.7	7	0.29	0.23	0.23	0.15	0.18	0.24	0.22	0.21	0.19
Kentucky Bend	519.5	9.4	0.24	0.27	0.20	0.23	0.24	0.25	0.24	0.23	0.22
Cracraft Carolina	510.7	8.2	0.19	0.23	0.21	0.21	0.21	0.20	0.22	0.22	0.07
Carolina Baleshed	501.1	11		0.27	0.26	0.26	0.20	0.18	0.24	0.20	0.17
Baleshed Landing	490.6	10	0.23	0.22	0.23	0.22	0.22	0.16	0.21	0.21	0.24
Ajax Bar	482.7	5.8	0.22	0.23	0.22	0.15	0.17	0.18	0.15	0.19	0.19
Ajax Cottonwood	475.9	7.8			0.24	0.19	0.17	0.17	0.19	0.07	0.07
Cottonwood Bar	469.9	4.2	0.25	0.22	0.19	0.21	0.16	0.11	0.14	0.18	0.23
Cottonwood - Belle Is.	464.6	6.4		0.17	0.20	0.19	0.20	0.23	0.07	0.22	0.20
Belle Island - Milliken	456.6	9.6	0.23	0.26	0.23	0.22	0.18	0.23	0.22	0.31	0.24
Milliken - Vicksburg	443.4	16.8			0.20	0.23	0.25	0.24	0.27	0.33	0.26
Racetrack - Towhead	428.9	12.2	0.18		0.23	0.29	0.22	0.20	0.21	0.15	0.16
Pt. Pleasant	415.1	15.4	0.24				0.20	0.18	0.15	0.07	0.09
Grand Gulf	401.3	12.2					0.19	0.15	0.16	0.22	0.22
Rodney	388.3	13.8	0.19		0.21	0.21	0.21	0.18	0.17	0.18	0.07
Waterproof	374.8	13.2	0.22				0.16	0.18	0.18	0.17	0.18
Natchez	361.7	13					0.21	0.17	0.22	0.28	0.25
St. Catherine	346.9	16.6						0.16	0.16	0.17	0.07
Bougere	329.5	18.2							0.19	0.18	0.21

Figure 21. Box and whisker plot for D_{16} grain size in the Vicksburg District for (a) 1966–1974 and (b) 1966–1972 (compiled from all data available in Robbins [1977]).

Table 8. Indicative changes in D₁₆ when data for 1973–1974 are added to the record for 1966–1972.

Potamology Reach	Mid-Point (RM AHP)	Increased variability (fine side)	Decreased Average D ₁₆	Increased Variability (coarse side)	Increased Average D ₁₆
Cessions-Henrico	611	Insufficient data pre-1973			
Smith Pt-Terrane	600.1				
Terrane-Ozark	587.6				
Ozark-Eutaw	573.45				
Choctaw Bar	558.15				
Greenville	540.8				
Lakeport	527.7				
Kentucky Bend	519.5				
Cracraft-Carolina	510.7				
Carolina-Baleshed	501.1				
Baleshed Landing	490.6				
Ajax Bar	482.7				
Ajax-Cottonwood	475.9				
Cottonwood Bar	469.9				
Cottonwood-Belle Is.	464.6				
Belle Is.-Milliken	456.6				
Milliken-Vicksburg	443.4				
Racetrack-Towhead	428.9				
Pt. Pleasant	415.1				
Grand Gulf	401.3	Insufficient data pre-1973			
Rodney	388.3				
Waterproof	374.8				
Natchez	361.7	Insufficient data pre-1973			
St. Catherine	346.9	Insufficient data pre-1973			
Bougere	329.5	Insufficient data pre-1973			

Key:

	Marked change
	Change
	Slight change
	No change

Between the Cottonwood Bar and Milliken–Vicksburg reaches, the predominant impact of including the 1973–1974 data is to increase variability on the coarse side of the distribution while slightly increasing the time-averaged D_{16} . Downstream of Milliken–Vicksburg, the predominant impact of including the 1973–1974 data is to increase variability on both sides of the distribution while reducing the time-averaged D_{16} .

Spatially, the plots in Figure 21 indicate that while the D_{16} grain size is fine sand throughout the Vicksburg District, there are reach-scale fluctuations in D_{16} that appear to show a cyclical downstream pattern in the amount of fine sediment in the bed. There is, however, no evidence of a downstream, decreasing trend in D_{16} .

2.2.7.6 Variability in D_{84} through time and space

This section considers downstream trends in the eighty-fourth percentile bed material size (D_{84}) and its variability through time, using data available for the Vicksburg District. The significance of D_{84} (the grain size for which 84% of the sample is smaller) is that it represents the coarser fraction of the bed material size distribution. In a normally distributed sample, the eighty-fourth percentile is one standard deviation larger than the mean. D_{84} is also a significant because together with the D_{16} , it defines the sediment sorting coefficient. The data used in the analysis are listed in Table 9. The significant data gaps for some of the potamology reaches noted for D_{50} and D_{16} data reported in the previous sections are also present for D_{84} , and this must be considered when interpreting the results listed in Table 9.

Table 9. Variation in bed material D_{84} grain size in the Vicksburg District (compiled from all data available in Robbins [1977]).

Potamology Reach	RM Mid-Point	Reach Length (miles)	D_{84} (mm)								
			1966	1967	1968	1969	1970	1971	1972	1973	1974
Cessions-Henrico	611	10	0.74						0.54	0.57	0.41
Smith Pt-Terrene	600.1	11.8	0.61		0.71	0.59	0.70	0.56	0.54	0.61	0.56
Terrene-Ozark	587.6	13.2	0.57	0.75	0.56	0.54	0.54	0.54	0.45	0.49	0.55
Ozark-Eutaw	573.45	15.1	0.55	0.72	0.70	0.62	0.57	0.52	0.51	0.55	0.58
Choctaw Bar	558.15	15.5	0.74	0.68	0.71	0.57	0.57	0.54	0.57	0.54	0.46
Greenville	540.8	19.2	0.52	0.60	0.55	0.54	0.55	0.57	0.58	0.59	0.43

Potamology Reach	RM Mid-Point	Reach Length (miles)	D ₈₄ (mm)								
			1966	1967	1968	1969	1970	1971	1972	1973	1974
Lakeport	527.7	7	0.74	0.56	0.56	0.56	0.56	0.54	0.55	0.47	0.44
Kentucky Bend	519.5	9.4	0.53	0.61	0.57	0.56	0.72	0.67	0.56	0.50	0.54
Cracraft Carolina	510.7	8.2	0.55	0.68	0.64	0.54	0.44	0.53	0.41	0.59	0.39
Carolina Baleshed	501.1	11		2.32	0.79	0.69	0.53	0.49	0.81	0.52	0.61
Baleshed Landing	490.6	10	0.65	0.58	0.56	0.54	0.56	0.54	0.52	0.52	0.58
Ajax Bar	482.7	5.8	0.54	0.63	0.51	0.43	0.47	0.50	0.50	0.54	0.56
Ajax Cottonwood	475.9	7.8			0.51	0.54	0.53	0.70	0.39	0.52	0.50
Cottonwood Bar	469.9	4.2	0.67	0.74	0.56	0.53	0.55	0.51	0.41	0.51	0.53
Cottonwood - Belle Is.	464.6	6.4		0.56	0.70	0.41	0.97	2.20	0.49	0.58	0.73
Belle Island - Milliken	456.6	9.6	0.59	0.56	0.58	0.58	0.55	0.56	1.04	22.18	0.66
Milliken - Vicksburg	443.4	16.8			0.55	0.62	0.84	0.67	0.71	1.13	0.75
Racetrack - Towhead	428.9	12.2	0.47		0.55	2.19	0.57	0.60	0.48	0.41	0.39
Pt. Pleasant	415.1	15.4	0.54				0.67	0.54	0.51	0.45	0.56
Grand Gulf	401.3	12.2					0.48	0.52	0.53	0.56	0.80
Rodney	388.3	13.8	0.38		0.53	0.56	0.63	0.55	0.51	0.51	0.39
Waterproof	374.8	13.2	0.42				0.41	0.41	0.41	0.41	0.40
Natchez	361.7	13					0.51	0.52	0.54	0.58	0.65
St. Catherine	346.9	16.6						0.40	0.41	0.53	0.36
Bougere	329.5	18.2							0.55	0.55	0.50

Box and whisker plots were produced to display the data listed in Table 9. To allow a preliminary evaluation of the hypothesis that the 1973 flood may have had impacts on the bed morphology and size characteristics of the LMR that would be evident in D₈₄ sizes and variability (through space and time), data are plotted separately for all 25 potamology reaches including results for 1973–1974 in Figure 22(a) and excluding 1973–1974 in Figure 22(b). Note that due to the widely fluctuating grain sizes in this plot, the *y*-axis in Figure 22 uses a logarithmic scale. If this is not realized

by the reader, it gives the false impression that variability in D_{84} is lower than that in D_{50} or D_{16} when the opposite is, in fact, the case.

Figure 22. Box and whisker plot for D_{84} grain size in the Vicksburg District for (a) 1966–1974 and (b) 1966–1972. Note that due to the widely fluctuating grain sizes in this plot, the μ -axis uses a logarithmic scale (compiled from all data available in Robbins [1977]).

Even ignoring the data sparse reaches, comparison of Figure 22(a) and (b) does suggest that time variability in the D_{84} grain size is increased when data for the post-flood period are included in the records. Table 10 lists the trends of change for reaches that have fairly complete records.

Temporally, the main impacts of including the 1973–1974 data (which incorporate the 1973 flood) on D_{84} bed material grain sizes in the Vicksburg District are to reduce the D_{84} and increase variability compared to values recorded the previous, flood-free period (1966–1972). However, these impacts are perhaps not as marked because during the flood-free period (1966–1972), variability in D_{84} was higher than it was in either D_{50} or D_{16} .

In addition to increasing variability on the fine side of the distribution of D_{84} values, adding the 1973–1974 data also increases variability on the coarse side in some potamology reaches, and the nature of changes shows a weak pattern with downstream distance.

In potamology reaches upstream of Belle Island–Milliken, the predominant impact of including the 1973–1974 data is to increase variability on the fine side of the distribution while reducing the time-averaged D_{84} . In the Belle Island–Milliken and Milliken–Vicksburg reaches, the predominant impact of including the 1973–1974 data is to increase variability on the coarse side of the distribution while markedly increasing the time-averaged D_{84} . Downstream of Milliken–Vicksburg, the predominant impact of including the 1973–1974 data is to increase variability on both sides of the distribution while reducing the time-averaged D_{84} .

Spatially, the plots in Figure 22 indicate that while the D_{84} grain size is coarse sand throughout the Vicksburg District, samples for some reaches and years include sufficient quantities of sediment coarser than 2 mm to move the D_{84} up to very coarse sand and even into the gravel size class. There are reach-scale fluctuations in D_{84} that at least hint at there being a cyclical downstream pattern, but there is no evidence of a downstream, decreasing trend in D_{84} .

Table 10. Indicative changes in D₈₄ when data for 1973–1974 are added to the record for 1966–1972.

Potamology Reach	Mid-Point (RM AHP)	Increased Variability (fine side)	Decreased Average D ₈₄	Increased Variability (coarse side)	Increased Average D ₈₄
Cessions-Henrico	611	Insufficient data pre-1973			
Smith Pt-Terrane	600.1				
Terrane-Ozark	587.6				
Ozark-Eutaw	573.45				
Choctaw Bar	558.15				
Greenville	540.8				
Lakeport	527.7				
Kentucky Bend	519.5				
Cracraft-Carolina	510.7				
Carolina-Baleshed	501.1				
Baleshed Landing	490.6				
Ajax Bar	482.7				
Ajax-Cottonwood	475.9				
Cottonwood Bar	469.9				
Cottonwood-Belle Is.	464.6				
Belle Is.-Milliken	456.6				
Milliken-Vicksburg	443.4				
Racetrack-Towhead	428.9				
Pt. Pleasant	415.1				
Grand Gulf	401.3	Insufficient data pre-1973			
Rodney	388.3				
Waterproof	374.8				
Natchez	361.7	Insufficient data pre-1973			
St. Catherine	346.9	Insufficient data pre-1973			
Bougere	329.5	Insufficient data pre-1973			

Key:

	Marked change
	Change
	Slight change
	No change

2.2.7.7 *Broader-scale variability through time and space*

To avoid the gaps in sampling records for some of the potamology reaches in Robbins (1977), data were aggregated into four, longer reaches.

Combining the data for the potamology reaches in this way provides more complete data for each of the larger reaches, making the statistics more reliable in representing variability in the data through time and space. The potamology reaches included in each of the four longer sub-reaches of the LMR in the Vicksburg District are listed in Table 11.

Box and whisker plots for reach-averaged values of D_{50} , D_{16} and D_{84} for each of the four broad-scale reaches are shown in Figure 23.

The grouped data for median grain size establish that D_{50} fluctuates between approximately 0.2 and 0.4 mm: that is it is usually within the medium sand size class. D_{16} fluctuates within the fine sand size class while D_{84} is usually at the lower end of the coarse sand size class. That said, the presence of very coarse particles in the bed of the LMR in the Vicksburg District results in very high variability in D_{84} that is manifest as outliers in the distributions graphed in Figure 22(c). Time variability in all three parameters appears to be high in Sub-reach 3 relative to that in the other three sub-reaches.

Spatially, the only evidence of a downstream, decreasing trend in bed material size is between Sub-reaches 3 and 4, in that D_{50} , D_{16} , and D_{84} all appear to be somewhat smaller in Sub-reach 4 than in the Sub-reaches upstream.

In the final sub-section of Chapter 2 of this report, the results obtained for Sub-reach 3 in the Vicksburg District are used to test the sensitivity of bed material transport calculations to variability and uncertainty in the composition of the bed material.

Table 11. Summary list of potamology reaches combined to aggregate data for four, longer sub-reaches of the LMR in the Vicksburg District (compiled from all data available in Robbins [1977]).

Broad-Scale Reaches	Potamology Reach	RM Mid-Point	Reach Length (miles)
Reach 1	Cessions-Henrico	611	10
	Smith Pt-Terrene	600.1	11.8
	Terrene-Ozark	587.6	13.2
	Ozark-Eutaw	573.45	15.1
	Choctaw Bar	558.15	15.5
Reach 2	Greenville	540.8	19.2
	Lakeport	527.7	7
	Kentucky Bend	519.5	9.4
	Cracraft Carolina	510.7	8.2
	Carolina Baleshed	501.1	11
	Baleshed Landing	490.6	10
	Ajax Bar	482.7	5.8
Reach 3	Ajax Cottonwood	475.9	7.8
	Cottonwood Bar	469.9	4.2
	Cottonwood - Belle Is.	464.6	6.4
	Belle Island - Milliken	456.6	9.6
	Milliken - Vicksburg	443.4	16.8
	Racetrack - Towhead	428.9	12.2
	Pt. Pleasant	415.1	15.4
Reach 4	Grand Gulf	401.3	12.2
	Rodney	388.3	13.8
	Waterproof	374.8	13.2
	Natchez	361.7	13
	St. Catherine	346.9	16.6
	Bougere	329.5	18.2

Figure 23. Box and whisker plot for (a) D₅₀, (b) D₁₆, and (c) D₈₄ grain sizes in the Vicksburg District based on aggregated data for the four sub-reaches listed in Table 11 (compiled from data available in Robbins [1977]). Note that the scale of the y-axis for D₈₄ is logarithmic.

2.3 Analysis of bed material trends at permanent gaging stations (Thorne et al. [2008] data set)

2.3.1 Variability and trends at permanent gaging stations through time and space

The report prepared by Thorne et al. (2008) presents the results of a 1-year study performed by Nottingham University, Halcrow, and the Biedenharn Group in collaboration with ERDC that was aimed at assembling available data on sediment loads in the Mississippi River, assessing its reliability and temporal variability, and exploring the implications for sediment diversions. Although the report is primarily concerned with compilation and preliminary analysis of suspended sediment measurements from gaging stations along the LMR, it also includes recorded discharges and bed material gradations at those stations.

In this study, bed material size data available for four key stations on the LMR are reviewed. These stations are Arkansas City, Vicksburg, Natchez, and Tarbet Landing. The bed material data from these supplement those available in the reports by Gaines and Priestas (2016) and Robbins (1977) in that they are based on more frequent sampling of the bed at a single sampling range (cross section). The periods of record at the stations are comparable to those in the Robbins report, although they are relatively short compared to the times scales relevant to the data reported by Gaines and Priestas (2016).

The graphics on the next four pages present summary statistics for Arkansas City (Figure 24), Vicksburg (Figure 25), Natchez (Figure 26) and Tarbert Landing (Figure 27).

While the median grain size at Arkansas City varies somewhat through time, it is almost always in the medium sand size category (Figure 24(a)). Similarly, the D_{16} does not vary very much and is usually fine sand. Until approximately 1990, the D_{84} oscillated widely between coarse sand and 10 to 20 mm gravel. However, the gravel component of the coarse fraction of the bed material disappears very abruptly at the end of the 1980s. Disappearance of the gravel and the resulting drop in the D_{84} is interesting. It may be real or an artifact of some undocumented change(s) in sampling/laboratory procedures. In any case, this warrants further investigation.

No sustained time trend can be detected in D_{50} , D_{16} , or D_{84} at Arkansas City. The high variability and bimodal nature of D_{84} apparent in the time series (at least to approximately 1990) is also evident in the box and whisker plot in Figure 24(b).

Data for Vicksburg are broadly similar in that D_{50} and D_{16} are consistently in the medium and fine sand classes, respectively, while D_{84} is distinctly bimodal in first half of the period of record (Figure 25(a)). However, at Vicksburg the gravel fraction does not disappear entirely until 1992, a little later than at Arkansas City. No sustained time trend can be detected in D_{50} , D_{16} , or D_{84} at Vicksburg.

The box and whisker plot for Vicksburg (Figure 25(b)) highlights multiple, outlying values for D_{84} that are associated with a gravel component in the coarse tail of the distribution of measured values. However, it also illustrates that measured values of D_{16} occasionally slip into the very fine sand size class, indicating that periodically, the fine fraction at Vicksburg makes up a greater proportion of the bed material than is usually the case.

Figure 24. (a) Time trends in D₅₀, D₁₆, and D₈₄ and (b) box and whisker plot for Arkansas City.

Figure 25. (a) Time trends in D₅₀, D₁₆, and D₈₄ and (b) box and whisker plot for Vicksburg.

Figure 26. (a) Time trends in D₅₀, D₁₆, and D₈₄ and (b) box and whisker plot for Natchez.

Figure 27. (a) Time trends in D_{50} , D_{16} , and D_{84} and (b) box and whisker plot for Tarbert Landing.

At Natchez, variability in D_{50} and D_{16} is small for most of the period of record, except during the years between 1998 and 2001 when the bed appears to have been invaded by finer sediment than is usual (Figure 26(a)). That said, variability in D_{50} and D_{16} is low during most of the period of record, and this is reflected in very small inter-quartile ranges in Figure 26(b) that are supplemented by outliers on both sides of the distribution, but mainly in the fine tail. D_{84} values are weakly bi-modal up to 1988 when the gravel disappears, but even the coarse tail of bed material particle size distribution seems to have been affected by the ingress of fine sediment between 1998 and 2001, with D_{84} values slipping down to the border between medium and fine sand during 1999. No sustained time trend can be detected in D_{50} , D_{16} , or D_{84} at Natchez. The occurrence of both unusually coarse and fine values of D_{84} is clearly evident in the box and whisker plot in Figure 26(b) in the form of multiple outliers on both sides of the inter-quartile range.

Variability in D_{50} and D_{16} at Tarbert Landing is small, and these parameters usually fall within the medium and fine sand classes, respectively (Figure 27(a)). The distribution of D_{84} values is again bimodal, but at Tarbert Landing, while coarse sand predominates, values in the gravel size class persist throughout the period of record, albeit becoming less frequent later in the time series. No sustained time trend can be detected in D_{50} , D_{16} , or D_{84} at Tarbert Landing. Box and whisker plots for this station (Figure 27(b)) are asymmetrical, featuring multiple outliers that extend the coarse tails of the distributions of D_{50} , D_{16} , and especially D_{84} .

2.3.2 Downstream trends

To investigate whether statistics for samples collected at these four gaging stations provide evidence of a downstream trend in bed material properties, box and whisker plots for all four locations were prepared, and these are shown in Figure 28.

Inspection of the box and whisker plots indicates that the degrees of spatial variation in D_{50} , D_{16} , and D_{84} values derived for the four stations all fall within the inter-quartile ranges for at-a-station variability. Consequently, it may be concluded a priori that these plots cannot provide evidence that differences between stations are significant or that there are any systematic downstream trends in these parameters of bed material size distribution.

Figure 28. Box and whisker plot for D_{16} , D_{50} , and D_{84} at the four gaging stations. Note Arkansas City is farthest upstream, and Tarbert Landing is farthest downstream on the LMR.

Notwithstanding this, the box and whisker plots in Figure 28 do at least hint at the possibility of a downstream trend for grain sizes to decrease between Vicksburg and Tarbert Landing. For example, the median grain size (D_{50}) decreases from 0.41 mm at Vicksburg to 0.36 mm at Natchez and 0.32 mm at Tarbert Landing. Similar trends are apparent for D_{16} (0.29 mm to 0.25 mm to 0.21 mm) and D_{84} (0.69 mm to 0.56 mm to 0.49 mm).

The other salient point made clear by the distributions and extents of the boxes, whiskers, and outliers in Figure 28 concerns time variability in D_{84} , which is highly asymmetrical and which dwarfs that in either D_{50} or D_{16} .

The presence of quantities of gravel-sized particles in the bed of the Mississippi River is primarily responsible for the highly variable nature of D_{84} . Even though gravel constitutes relatively small percentages of the bed material size distribution (especially since approximately 1990), it is likely that gravel sheets and armor layers play disproportionately significant roles in controlling the stability and mobility of bars and islands. In this context, processes responsible for the marked reductions in the occurrence of D_{84} outliers since approximately 1990 in samples collected at the Arkansas City, Vicksburg, and Natchez gaging stations are worthy of further investigation.

2.4 Application of the Hydraulic Engineering Center-River Analysis System/Sediment Impact Analysis Method (HEC-RAS/SIAM) to estimate annual bed material loads in the LMR

2.4.1 Introduction

One of the most widespread and important uses of bed material sizes and particle size distributions is as input data for the calculation of sediment transport rates and annual bed material loads. The resulting sediment transport rates and loads are used for a wide variety of purposes in modeling and managing the LMR.

The accuracy and reliability of calculated bed material loads depend to a large degree on the reliability and accuracy of the input data. Consequently, the findings of the bed sediment study were used to investigate the sensitivity of calculated bed loads to variability in the size distribution of the bed material. For this purpose, data used from Robbins (1977) gathered in the seven potamology reaches that make up Sub-reach 3 of the Vicksburg District (between RM 406 and 479 AHP), as listed in Table 11 above.

2.4.2 Sediment transport modeling

The modeling platform used to test the sensitivity of calculated annual bed material loads in the LMR to variability in bed material size distributions was HEC-RAS/SIAM (Biedenharn et al. 2006; Gibson and Little 2006; Thorne et al. 2011). The SIAM is a sediment accounting tool that integrates a bed material sediment transport function (i.e., bed material load as a function of the transport capacity at selected discharges) over the annual hydrograph to estimate the annual bed material load in tons per year. The

model works on the principle that the annual bed material load is limited by the capacity of the flow to transport sediment with sizes that are present in the bed of the river *in significant quantities*. Hence, SIAM does not estimate the wash load of the river—which is made up of sediment finer than the great majority of that present in the bed material. The wash load in a river is limited by how much is supplied from sources other than the channel bed rather than by the capacity of the flow to transport it.

Selection of the upper size limit for wash load is an important step in setting up a SIAM model. The selection of the wash load size class can have a significant impact on the calculated annual bed material loads. Plausible arguments may be made to set the wash load limit as low as 0.074 mm to possibly as high as 0.2 mm. However, the objectives of this study were not to evaluate the effects of the wash load selection on SIAM results, but rather to test the sensitivity of the bed material gradations on the calculations. A selection of 0.074 mm as the wash load limit was used for the sensitivity analysis performed here. Therefore, only sediment in the clay, the silt, and the finer half of the very fine sand size classes was treated as wash load and excluded from the bed material load calculations performed using HEC-RAS/SIAM. As a test, the model runs were repeated with the upper bound wash load sediment size set to 0.147 mm. As anticipated, using a larger washload-bed material load split did result in different estimates for the bed material loads, but the trends were similar to the runs with the wash load size set at 0.074 mm.

SIAM extracts most of the data it needs from the HEC-RAS hydraulic and sediment transport routines. It uses that data to estimate annual bed material loads carried within a series of user-specified sediment reaches. In the present study, the sediment reaches used in the SIAM model correspond to the seven potamology reaches within Sub-reach 3 of the Vicksburg District.

Channel geometry was specified using bathymetry performed in 1973–1975 that was complemented with lidar data to extend HEC-RAS cross sections as necessary to cover overbank areas inundated at high flows. The HEC-RAS hydraulic model was calibrated based on stage-discharge curves at (a) Lake Providence (upstream end of model), (b) Vicksburg (mid-reach in the model), and (c) St. Joseph (downstream end of model).

The sediment transport routine in HEC-RAS includes a number of alternative sediment transport functions. There is no theory upon which to select the appropriate function—this decision must be made by the user based on experience, sound engineering judgement, and consideration of the plausibility/utility of results generated using alternative functions. In this study, the candidate sediment transport functions available in HEC-RAS considered to be potentially applicable to the LMR in Sub-reach 3 were those developed by Ackers and White (1973), Yang (1972), and Toffaleti (1969). Based on consideration of initial test-run results (as explained below), the equation developed by Toffaleti (1969) was selected for use in the sensitivity analysis.

SIAM estimates annual bed material load by integrating sediment transport rates for selected discharges over the annual hydrograph. For this purpose, a representative flow duration curve was developed for Sub-reach 3 of the LMR, using daily discharge data for the period 1965–1980 collected at the Vicksburg gaging station, which is located in the middle of the sub-reach.

2.4.3 Input parameter variability

SIAM was run nine times: once for each year of record in the Robbins (1977) data set (i.e., 1966 to 1974). In each year, the bed material size distributions for that year (averaged for each potamology reach) were used to estimate the annual bed material load carried in each sediment (potamology) reach. In potamology reaches that were not sampled every year, the bed grain size distribution from the potamology reach upstream was used to fill these data gaps. However, in potamology reaches with incomplete sampling records, only results for years in which bed material was actually sampled were included in the sensitivity analysis.

All the other input parameters (channel bathymetry, flow hydraulics, flow duration) remained constant for all runs: that is, only the bed material size distribution varies between the SIAM model runs for each potamology reach.

Consequently, differences between the annual bed material loads calculated for each year in the period of record result exclusively from variability in the reach-averaged bed material grain size distribution.

2.4.4 Selection of the sediment transport function

To determine which of the three candidate sediment transport functions was best suited for application to the sensitivity analysis, HEC-RAS/SIAM was run for the Cottonwood Bar and Belle Island–Milliken potamology reaches, using the Ackers and White (1973), Yang (1972), and Toffaleti (1969) sediment load equations. The results are shown in Figure 29.

Figure 29. Annual bed material sediment loads in the Cottonwood Bar and Belle Island–Milliken reaches calculated using HEC-RAS/SIAM using three candidate sediment transport functions and reach-averaged bed material size distributions for 1966–1974.

Sediment loads calculated using the Toffaleti (1969) and Ackers and White (1973) equations were consistently similar while Yang predicted much smaller loads that are both unexpectedly low and highly insensitive to changes in bed material gradation. No reason for this is immediately apparent, and the contrast between the outputs from Yang's equation and those from the other two equations merit further investigation.

While either the Toffaleti (1969) or Ackers and White (1973) equation appeared suitable for use in the sensitivity analysis, it was decided to use Toffaleti's equation as this was developed specifically for sand-bed rivers like the LMR (Toffaleti 1969) while the Ackers and White (1973) equation is ideally suited for use in channels with mixed sand and gravel beds.

2.4.5 Sensitivity of the calculated annual bed material load to variability in the bed material size distribution

Table 12 lists the annual bed material loads (tons/year) calculated using the Toffaleti equation in SIAM, with the boundary wash load grain size set at 0.074 mm. Results are missing from some cells because

- in either 1966, 1967, or both, no bed material samples were collected in the Ajax–Cottonwood, Cottonwood–Belle Island, Milliken–Vicksburg and Racetrack–Towhead reaches
- as the Pt. Pleasant reach is the farthest downstream, its results may be influenced by model adjustment issues and end effects.

Table 13 lists percentage differences in calculated bed material loads between consecutive years. A positive value represents an increase in annual bed material load relative to that of the previous year.

Table 12. Annual bed material loads in potamology reaches in Sub-reach 3 of the Vicksburg District calculated using HEC-RAS/SIAM.

Reach	Annual Sediment Transport Capacity (million tons per year)								
	1966	1967	1968	1969	1970	1971	1972	1973	1974
Ajax-Cottonwood			54.1	99.7	47.9	110.0	119.0	308.0	95.0
Cottonwood Bar	34.1	28.4	46.0	36.5	66.2	44.9	102.0	49.0	25.5
Cottonwood-Belle Island		90.8	60.2	63.5	58.9	38.7	87.7	46.0	32.3
Belle Island-Milliken	60.4	39.3	67.4	60.6	56.0	58.6	65.7	23.9	85.5
Milliken-Vicksburg			64.4	70.4	48.9	71.9	43.8	34.6	43.5
Racetrack-Towhead	165.0		94.0	56.0	104.0	122.0	136.0	206.0	202.0
Point Pleasant									

Note: The only input data to vary between years is the bed material size distribution. Channel morphology (1973–75 bathymetry data), hydrology (1965–80 flow duration curve), and hydraulics and are all unchanged.

Table 13. Differences in annual bed material loads in potamology reaches between consecutive years in Sub-reach 3 of the Vicksburg District.

Reach	Percent Change in Annual Sediment Transport Capacity Relative to Previous Year							
	1966	1967	1968	1969	1970	1971	1972	1973
	- 1967	- 1968	- 1969	- 1970	- 1971	- 1972	- 1973	- 1974
Ajax-Cottonwood			84%	-52%	130%	8%	159%	-69%
Cottonwood Bar	-17%	62%	-21%	81%	-32%	127%	-52%	-48%
Cottonwood-Belle Island		-34%	5%	-7%	-34%	127%	-48%	-30%
Belle Island-Milliken	-35%	72%	-10%	-8%	5%	12%	-64%	258%
Milliken-Vicksburg			9%	-31%	47%	-39%	-21%	26%
Racetrack-Towhead			-40%	86%	17%	11%	51%	-2%
Point Pleasant								

Note: The only input data to vary between years is the bed material size distribution. Channel morphology (1973–75 bathymetry data), hydrology (1965–80 flow duration curve), and hydraulics and are all unchanged.

Initial inspection of the results listed in Table 13 demonstrates that annual bed material loads in the LMR calculated using HEC-RAS/SIAM are extremely sensitive to variations in the bed material grain size distribution. The records for the Cottonwood Bar and Belle Island–Milliken reaches are the most complete and may be used to illustrate the range of response in calculated annual bed material loads generated by changes in bed material size distributions.

For example, at Cottonwood Bar, inter-annual changes in bed material load in response to variability in the bed material gradation range from an increase of 127% (between 1971 and 1972) to a decrease of 52% (between 1972 and 1973). Notable also are increases of 62% and 81%, in 1967–1968 and 1969–1970, respectively, and decreases of 32% and 48% in 1970–1971 and 1973–1974, respectively. Similarly, at Belle Island–Milliken, the calculated bed material load decreased by 35% in response to variation in the bed material gradation at the beginning of the period of record (1966–1967) and increased by 257% between 1973 and 1974, at the end of the period of record.

2.4.6 Relationships between variability in bed material gradation and changes in calculated annual bed material load

Bed material size distributions for the Cottonwood Bar reach were used to explore the relationship between changes in bed gradation curves and responses in calculated annual bed material loads, which is not simple. For example, Figure 30 shows the grain size distribution curves for Cottonwood Bar in 1966, 1967, and 1968, together with median grain sizes, calculated annual bed material loads (tons/year) and the percent changes in annual load between those years.

Figure 30. Bed grain size distribution curves for Cottonwood Bar in 1966, 1967, and 1968 together with the calculated annual bed material loads and percent changes between years.

The median (D_{50}) is customarily used to represent the mobility of the bed material in a river. A priori, it would be expected that, for the same flow and channel morphology, the bed material load would increase in response to a decrease in median grain size. In fact, the calculated annual sediment load decreases by 17% between 1966 and 1967 in response to the reduction in D_{50} recorded between these years. D_{16} also decreases between 1966 and 1967, so the response in bed material load is also inconsistent with the direction of change in that parameter. Although D_{84} did increase slightly between 1966 and 1967, the change is much too small to explain the decrease in annual bed material load.

Comparison of bed material parameters in 1967 and 1968 reveals further decreases in D_{50} and D_{16} , as well as marked reduction in D_{84} . However, in contrast to the change between 1966 and 1967, the response of the annual bed material load to reductions in the standard parameters of bed material size was to increase by 62%.

The apparent paradox in the response of calculated bed material loads is explained by the fact that bed material transport in the LMR is dominated by movement of sediment in the smaller size fractions, where the river's transport capacities is very high. This is illustrated by breaking down the bed material loads calculated for the Cottonwood Bar reach in 1966 and 1967 according to grain size class (Table 14). Table 14 also lists the percentages of the sampled bed material in each size class in 1966 and 1967. The key data from Table 14 are plotted in Figure 31.

Table 14. Break down by size class of calculated bed material loads and percentage of sample in each size class for the Cottonwood Bar reach.

Year	Class Size (mm)*													
	Total	1	2	3	4	5	6	7	8	9	10	11	12	13
Annual Sediment Transport Capacity by Grain Size (million tons/year)**														
1966	34.1	12.2	9.9	3.5	4.2	2.1	1.6	0.5	0.1	**	**	**	**	**
1967	28.4	1.5	5.2	8.2	10.1	2.0	0.8	0.4	0.1	**	**	**	**	**
Percentage of Bed Material in Each Size Class														
1966	100	2.0	2.9	4.8	10.0	25.2	34.7	10.7	3.5	1.6	0.7	0.5	0.7	1.2
1967	100	0.2	1.5	11.1	24.3	23.9	18.0	9.3	3.3	2.3	1.0	1.4	2.4	1.3

*Class Sizes

0.074mm – 0.104mm 2- 0.104mm – 0.147mm 3- 0.147mm – 0.208mm

4- 0.208mm – 0.295mm 5- 0.295mm – 0.417mm 6- 0.417mm – 0.589mm

7- 0.589mm – 0.833mm 8- 0.833mm – 1.17mm 9- 1.17mm – 2.36mm

10- 2.36mm – 4.7mm 11- 4.7mm – 9.5mm 12- 9.5mm – 19.05mm

13- 19.05mm – 38.1mm

** Annual sediment transport is less than 50,000 tons/year.

Figure 31. Bed grain size distribution curves for Cottonwood Bar in 1966 and 1967 together with the calculated annual bed material loads, broken down by grain size class. Size classes and boundaries are marked on the particle size distribution curves illustrate how the contributions made to the total bed material load by different size classes vary across the range of grain sizes present in the bed material.

First, the key point to note in Figure 31 is that particle size curves for 1966 and 1967 cross at approximately 0.2 mm (approximately D_{12}): this in the tail below the D_{16} . This explains why D_{16} (which is customarily used to represent the finer fraction of the bed material) fails to reflect the decrease in the relative abundance of fine sediment that occurred in the bed between 1966 and 1967. The curves cross again at approximately 0.6 mm (approximately D_{80}), a change which is reflected in the change in D_{84} between 1966 and 1967.

Examination of the data listed in the lower part of Table 14 reveals that in 1966, 2% of the bed was in the 0.074–0.104 mm size but that this decreased to only 0.24% in 1967. This decrease resulted in a substantial reduction of the annual load for this size fraction, from approximately 12 metric tons/year (mt/year) in 1966 to just 1.5 mt/year in 1967. Similarly, while nearly 3% of the bed material was in the 0.104–0.147 mm size class in 1966, this halved to just 1.5% in 1967. Again, this resulted in a substantial reduction in the contribution made by transport in this size class to the annual bed material load; from 9.8 mt/yr in 1966 to just 5.2 mt/yr in 1967.

In the range covered by the next two sizes classes (0.147–0.208 mm and 0.208–0.295 mm), the curve for 1967 is much steeper than that for 1966, reflecting the fact that percentages of bed material in these classes increased between 1966 and 1967—from 4.7% to 11% and 10% to 24%, respectively (Table 14). This resulted in increases in the contributions these size classes made to the total bed material load in 1967 compared to 1966 (from 3.5 and 4.2 mt/yr in 1966 to 8.2 and 10.2 mt/yr in 1966, respectively).

The capacity of the LMR to transport sediment decreases as the size of the sediment increases. As a result, the contributions to the annual bed material load made by sediment transport in the larger size classes is relatively small. For example, in 1966, the 0.295–0.417 mm and 0.417–0.589 mm size classes contributed only 2.1 and 1.6 mt/yr, respectively. Consequently, while reductions in the bed material loads for these classes did result from the decreases in the percentages of bed material in them in 1967, the impact on the overall annual load was small.

The overall message to emerge from in-depth analysis of bed material load responses to changes in the bed material gradations for 1966 and 1967 is that it is impossible to predict the significance or even the direction of change in bed material load based on the change in median grain size or any of the other statistical parameters used to represent the grain size distribution of the bed material.

Rather, it is necessary to examine the grain size distribution curves, identifying crossing points, assessing changes in the shape and steepness (and therefore, the distribution of percentages between classes), and focusing on the smaller classes, for which transport capacity is the greatest.

2.4.7 Understanding variability and reducing uncertainty in bed material size distributions

This preliminary investigation of the sensitivity of bed material loads to changes in bed material properties is restricted to examining changes in the composition of the bed in a single potamology reach (Cottonwood Bar) between consecutive years (1966 and 1967). The graphs in Figure 32 illustrate that the changes studied are typical of inter-annual variability in grain size distributions sampled in the reach, which is one where bed material characteristics show no evidence of any persistent trend of change during the 9-year period of record.

Figure 32. Inter-annual variability in reach-averaged bed material size distributions in the Cottonwood Bar reach for three periods between 1968 and 1974, together with the calculated annual bed material loads and percent changes between years.

The sensitivity of calculated annual bed material loads to such variability is sufficiently high that it cannot be ignored. Neither is the relationship between changes in the shape and steepness of the curves simple to understand or straightforward to explain.

It is therefore concluded that further investigation of the Robbins (1977) data set should be performed to establish characteristic types, trends, and degrees of bed material load response to variability in bed material properties. It is also recommended that monitoring of bed material properties be resumed so that uncertainty in the particle size distributions used to characterize the bed material for bed load transport calculations can be established and in due course, reduced.

3 Conclusions, Wider Applications, and Recommendations

3.1 Sources of historical and recent bed material size data

The sources of data defining past and recent bed material gradations in the Mississippi River accessed in this report are those by the following:

1. Gaines and Priestas (2016), which adds new, original, field-based data based on 754 bed material samples collected during November 2013 at 496 locations spaced at intervals of 2 to 3 miles along the Mississippi River between Grafton, IL, and Head of Passes, LA, 2013. Data come from approximately the same locations sampled in 1932 (WES 1935) and 1989 (Nordin and Queen 1992), supporting identification of long-term (decadal) variability and trends, at the system-scale
2. Robbins (1977), which uses repeated sampling in 25 potamology reaches within the Vicksburg District between 1966 and 1974 to establish short-term (inter-annual) variabilities, trends, and responses to extreme events (such as 1973 flood) at the reach-scale
3. Thorne et al. (2008), which compiles bed material data routinely collected at gaging stations to examine short- to medium-term variability in bed material properties and downstream trends in sediment characteristics based on repeat data for specific points (gaging ranges) that are widely spaced along the length of the river.

The initial analyses performed in the present study demonstrate that the insights provided by these reports are all extremely valuable, but they are also different. Their utility to an end-user depends on the purpose for which that data will be used. For example, in terms of long-term planning, the databases compiled and consolidated by Gaines and Priestas (2016) are unique because the sampling period extends over 7 decades. However, there are just three sample dates (1932, 1989, and 2013), each representing a *snapshot* of the bed at that moment in time. This makes it difficult to assess the significance of changes observed over the long-term in relation to short-term (e.g., seasonal, inter-annual annual, and flood-related) variability in bed material properties.

Conversely, the Robbins (1977) data do provide the basis for analysis of short-term, local-scale variability and trends, which is of great utility to the designers of hydraulic structures, but sampling is confined to the

Vicksburg District over a 9-year period of record. Similarly, routine sampling at the Arkansas City, Vicksburg, Natchez, and Tarbert Landing gages provides repeat data collected at precisely the same locations, but the period of record included in the Thorne et al. (2008) report is limited to 1985 to 2004.

The conclusion drawn from this assessment of the available data sets is that while each is useful in its own right, there is also value in contextualizing the results of each study using the insights gained and analytical outcomes produced by the other studies. The understanding gained by developing a thorough understanding of how short-term, local adjustments in bed material sizes and gradations integrate up to drive longer-term, system-wide trends would be of considerable utility to river managers.

The wider implication of this finding is that in striving to understand, explain, and model bed sediment and its interactions with water flows and channel morphology in the LMR, a multi-scale approach is essential. This requires consideration of bed material properties and changes at space scales ranging from the section and reach to the entire LMR system and trends through time that persist over annual, decadal, and multi-decadal time scales.

While short-term local studies may be appropriate for some applications and long-term, broad-scale studies be useful for others, it is recommended that sediment studies should always be contextualized by reference to variability, changes, and trends at space and time scales other than that of direct relevance to a particular investigation.

3.2 Long-term changes and trends

Over the long term, and at the scale of the entire LMR, comparison of the grain sizes measured in 2013, 1989, and 1932 establishes that bed sediments are now generally finer and more uniform than they were in 1932 and 1989, though little change has occurred since 1989 (Table 15).

The average median grain diameter of bed material in the LMR (D_{50}) in 2013 was 0.40 ± 0.22 mm, compared to 0.96 ± 2.64 mm and 0.46 ± 1.29 mm in 1932 and 1989, respectively. The reach-averaged sorting coefficient was 1.93 in 2013, while values in 1932 and 1989 were 2.40 and 1.67, respectively.

Table 15. Reach-averaged bed sediment statistics for the LMR between RM 950 and RM 0 (modified from Table 7 in Gaines and Priestas [2016]).

Year	D ₈₄ (mm)	D ₅₀ (mm)	D ₁₆ (mm)	Sorting Coefficient
2013	0.92	0.40	0.25	1.93
1989	0.98	0.46	0.27	1.67
1932	2.25	0.96	0.44	2.40

The conclusion drawn from this finding is that through time, the bed sediment of the LMR is becoming increasingly uniform. However, this conclusion must be qualified by recognizing that bed sediment sizes and sorting are subject to local, short-term and flow event-related variabilities that are not represented in the three snapshots of bed material properties included in the report by Gaines and Priestas (2016).

Gaines and Priestas (2016) attribute these bed material changes to the fact that since 1932, the relative fractions of gravel and very coarse sand have decreased in the upper reaches of the LMR (above RM 500 AHP) while the relative fractions of clay, silt, and very fine sand have decreased along the entire length of the river, but mostly downstream of Baton Rouge (RM 200 AHP). Both these size fractions have been replaced by increases in the relative fractions of fine, medium, and coarse sand.

The overall conclusion is that since 1932, bed materials in the LMR have become more uniform through fining of the bed upstream of RM 500 AHP and coarsening of the bed below RM 500 AHP.

However, Gaines and Priestas (2016) went on to conclude that it is difficult to make casual links between these changes in bed material characteristics and anthropomorphic drivers of morphological adjustment (such as the construction of dams, meander cutoffs, and revetments) due to complicating natural factors such as the occurrence of major floods and existence of local geological controls that locally reduce the capacity of channel morphology to adjust to changes in the flow and sediment regimes.

In this context, close inspection of the mass of data provided by Gaines and Priestas (2016) reveals alternating cycles of decrease and increase in grain size distributions along the length of LMR that indicate not only the existence of local geologic controls but also spatially and temporally nested cycles of feedback and complexity in the process-response mechanisms

through which adjustments proceed and long-term change is achieved. Managing the river efficiently requires that these shorter-term and more localized process-response mechanisms are also understood and explained, and to this end Gaines and Priestas (2016) draw attention to the intensive sampling described in the Robbins (1977) report.

The wider implication of these conclusions is that at the system-scale and over decadal time periods, bed material properties in the LMR have been changing, though the rate of change may have slowed since the 1980s, that the changes are complex, and that they are sufficiently large to impact the river's navigation, flood control, and environmental functions.

It is recommended that further MRG&P analyses be performed, based on combining the results of individual studies of the anthropogenic drivers of change (including regulation of upstream flows and sediment trapping), engineering interventions (especially cutoffs, bank stabilization, and low dike construction), and natural factors (geology, flood events) on bed sediments, sediment loads, hydraulic geometry, channel morphology, and river environment with the aim of identifying causal links between historical sediment and morphological changes in the LMR and MMR and the natural and anthropomorphic drivers responsible for those changes.

3.3 Extending Sediment Sampling to the Middle Mississippi River (MMR)

While historical sampling efforts have focused on the LMR, enhanced bed sediment data for the MMR are also needed. This is reflected in the decision to extend sampling in the 2013 campaign reported by Gaines and Priestas (2016) to include the MMR.

The conclusion drawn from this is that increased interest in the morphology and dynamics of the MMR, taken together with the fact that the MMR transfers a significant proportion of the sediment input from the Missouri River that is subsequently transported by the LMR, makes it essential that reliable bed material data are available for that reach of the river.

The wider significance of this conclusion is that in the medium- and longer-term, changes in bed material and bed material loads in the MMR influence, and to an extent presage, changes farther downstream in the fluvial system. Also, resolution of issues concerning morphological

evolution of MMR would benefit from enhanced knowledge of bed material properties and variability.

For these reasons, it is recommended that the scope of future bed material sampling in the LMR be extended to include the MMR between the confluences of the Missouri and Ohio Rivers.

3.4 Reach-scale variability and trends

The general aim of Robbins (1977) was to gain a better understanding of the fluvial processes of the river and to apply that knowledge toward effective and economical stabilization works for flood control and navigation. To this end, the LMR within the Vicksburg District (RM 320 to 606 AHP) was divided into 25 potamology study reaches within which data were aggregated to support reach-scale interpretation. Data collected included hydrographic surveys, bed-form profiles, discharges and horizontal velocity distributions, bed-material and suspended sediment samples, and water-surface profiles.

In 1966, bed material samples were collected using a drag bucket, but during 1967, the Vicksburg District switched to the BM-54 bed-material sampler designed and used routinely by the USGS to ensure consistency with USGS sampling of bed materials. Paired samples collected to test whether this equipment switch significantly affected the results showed no difference between the median grains sizes, though the BM-54 retained slightly more fine material while the drag bucket tended to collect a little more gravel.

Up to 1972, multiple bed material samples were collected across the width of the main channel, but in 1973 and 1974, the bed material samples were collected only at the centerline of the flow. No evidence was found that this change in sampling procedure affected the reach-averaged results.

While each bed material sample was sieved individually, the results were expressed as reach-averaged bed sediment sizes for the 25 potamology study reaches, between 1966 and 1974. However, not all ranges and potamology reaches were sampled in each year, so there are gaps in the coverage.

Results in Robbins (1977) establish that in the Vicksburg District the percentage of sediment finer than 0.295 mm was generally higher between

1966 and 1974 than it had been in 1932. Conversely, the percentage of material coarser than 0.589 mm decreased. The percentage of material sized between 0.295 and 0.589 mm was markedly greater in 1966 than it had been in 1932, but by 1974 it had decreased to approximately what it was in 1932.

Between 1932 and 1966, D_{84} decreased markedly, median grain size (D_{50}) decreased somewhat, and D_{16} increased slightly. Taking these findings together, it may be concluded that the bed in the Vicksburg District in 1966 was finer than it had been in 1932.

Between 1966 and 1974, potamology reach-averaged values of median bed material (D_{50}) varied between 0.106 and 0.577 mm. There was a slight tendency for the median grain size to decrease with distance downstream. In terms of time trend, D_{50} sizes in 1968 and 1971 were similar, but those measured in 1974 were noticeably finer.

Between 1966 and 1974, a general downward trend was apparent in all size statistics. However, this trend was interrupted in 1967 and 1973. Robbins (1977) hypothesized that low values in 1966 might be due to the fact that samples were collected using the drag bucket rather than the BM-54 used in all other years while the temporary increase in 1973 could have been related to the extreme flood that occurred that year. Overall, during the period of record, the weighted average D_{50} between river miles 422.8 and 606.0 AHP in the Vicksburg District decreased from 0.376 to 0.304 mm.

Robbins (1977) did not attempt to interpret variability and trends in bed material sizes and statistics in the context of the drivers of morphological change in the Vicksburg reach of the LMR. However, he did comment at length on potential causes of a significant increase in the extent of exposed gravel on middle bars and islands between the upstream limit of the Vicksburg District (at RM 606 AHP) and Natchez Island (at RM 357 AHP), approximately 78 RM downstream from Vicksburg. Robbins (1977) noted that the increase in exposed gravels had occurred even though there had been a general *decrease* in bed material sizes throughout the District, and he noted the stabilizing effects of gravel sheets at the heads of some bars and islands. He attributed the increase in exposed gravels to the floods of 1973, 1974, and 1975 on the basis that these gravels were transported and deposited on top of islands and middle bars at elevations inundated by the very high water levels that are only attained during extreme floods. This

led him to the conclusion that during these events, the river transports particles far coarser than those collected during routine sampling.

Robbins (1977) also concluded that while suspended load sampling records provide reliable estimates of the *capacity* of the LMR to transport sediment, they do not provide a reliable guide to the *competence* of the river because the largest sizes of material transported are evidently much larger than the orifice size of the samplers routinely used to measure the suspended sediment load.

Drawing attention to the existence of highly dynamic sand waves that adjusted radically to high and low flows, Robbins (1977) also concluded that the sheer magnitude of stage-related adjustments to bed topography and massive changes in sand wave geometry must be driven by vigorous bed load transport in the LMR. Despite this, it is still the case that comparatively little is known about bed load fluxes in the LMR.

Further, indicative analyses were undertaken as part of this study to illustrate the potential utility of the Robbins (1977) data while identifying and exploring some of its limitations. For these purposes, treatment was focused on base data from seven potamology reaches selected to be representative of the twenty-five used in Robbins (1977). The results demonstrate that the bed throughout the Vicksburg District is predominantly formed in medium sand, and the LMR is certainly best described as a sand-bed river. That said, the bed includes significant amounts of gravel and fines.

Comparison of pre-flood (1966–1972) and post-flood (1973–1974) particle size distributions suggests that (with some local exceptions) the bed generally became finer as a result of the 1973 flood and that variability in bed material properties within and between the potamology reaches increased due to the impacts of this extreme event on bedforms, bar morphology, and bed material gradations.

To avoid the gaps in sampling records for some of the potamology reaches in Robbins (1977), data were aggregated into four, longer reaches. The grouped data for median grain size establish that D_{50} fluctuates between approximately 0.2 and 0.4 mm: that is, it is usually within the medium sand size class. D_{16} varies within the fine sand size class while D_{84} is usually at the lower end of the coarse sand size class. That said, the

presence of very coarse particles in the bed of the LMR in the Vicksburg District results in very high variability in D_{84} that is manifest as outliers in the distributions graphed in Figure 22(b). Time variability in all three parameters appears to be high in Sub-reach 3 relative to that in the other three sub-reaches.

Spatially, the only evidence of a downstream, decreasing trend in bed material size is below Vicksburg in that D_{50} , D_{16} , and D_{84} all appear to be somewhat smaller in the lowest sub-reach of the Vicksburg District than in the sub-reaches upstream.

The data in Robbins (1977) provide the basis for additional analyses beyond those undertaken in the 1970s. It is concluded that these data are a particularly useful addition to the system-wide samples of bed material collected in 1932, 1989, and 2013 collated by Gaines and Priestas (2016).

The wider implications of the conclusions drawn in Robbins (1977) are the following:

1. Both the size distribution and the topography of the bed of the LMR are responsive to high-magnitude flood events capable of transporting larger volumes of bed material and mobilizing much larger grains than is the case during normal flows.
2. Gravel may, periodically, be exposed at the surface, especially at the heads of bars and islands, while major floods may deposit large amounts of fine and very fine sand. Consequently, bed material composition varies both in time and space, mostly due to changes in the coarse and fine tails of reach-averaged particle size distributions.
3. Although the proportion of gravel sampled in the river is very small, gravel sheets may play a disproportionately important role in governing the mobility of bed sediments and the dynamics of bars and islands.
4. While Robbins (1977) data are based exclusively on sampling within the Vicksburg District, there is every reason to suppose that the degrees, types, and patterns of localized, short-term variability established for that stretch of the river also occur throughout the Mississippi River.

The Robbins (1977) data set is extensive and worthy of thorough investigation. In compiling the data presented in this report, no attempt has been made to perform an exhaustive analysis of the Robbins (1977)

data, and it is recommended that this should be done as part of ongoing MRG&P studies.

3.5 Variability and trends at river gages

The report prepared by Thorne et al. (2008) presents the results of a 1-year study that assembled available data on sediment loads in the Mississippi River, which also includes discharges and bed material gradations recorded at those stations. In this study, bed material size data available for the Arkansas City, Vicksburg, Natchez, and Tarbert Landing gages were reviewed. The bed material data from these gages supplement that included in the reports by Gaines and Priestas (2016) and Robbins (1977) in that it is based on repeated sampling of the bed at a single sampling range (cross section). The period of record (1985–2004) is longer than that in Robbins (1977), although much shorter than that for the data reported by Gaines and Priestas (2016).

At Arkansas City, D_{50} varies somewhat through time but is almost always in the medium sand size category. Similarly, D_{16} does not vary very much and is usually fine sand. However, until approximately 1990, D_{84} oscillated between coarse sand and 10 to 20 mm gravel. The gravel component of the coarse fraction of the bed material disappears very abruptly at the end of the 1980s.

Data for Vicksburg are broadly similar in that D_{50} and D_{16} are, respectively, in the medium and fine sand classes while D_{84} is distinctly bimodal in first half of the period of record. However, at Vicksburg the gravel fraction does not disappear entirely until 1992, a little later than at Arkansas City.

At Natchez, variability in D_{50} and D_{16} is small for most of the period of record, except between 1998 and 2001 when the bed appears to have been invaded by finer sediment than usual. D_{84} values are weakly bimodal up to 1988 when the gravel disappears, but even the coarse tail of bed material particle size distribution seems to have been affected by the ingress of fine sediment between 1998 and 2001, with D_{84} values slipping down to the border between medium and fine sand during 1999.

Variability in D_{50} and D_{16} at Tarbert Landing is small, and these parameters usually fall within the medium and fine sand classes, respectively. The distribution of D_{84} values is again bimodal, but while coarse sand predominates, values in the gravel size class persist

throughout the period of record, albeit becoming less frequent later in the time series.

The apparent disappearance of gravel (and the resulting drop in the D_{84}) at Arkansas City, Vicksburg, and Natchez is interesting. It may be real or an artifact of some undocumented change(s) in sampling/laboratory procedures. In any case, this warrants further investigation, and it is recommended that this be undertaken as part of ongoing MRG&P investigations.

The conclusion is that no sustained time trend in D_{50} , D_{16} , or D_{84} can be detected at any of the gage stations.

Spatial variability in D_{50} , D_{16} , and D_{84} values between the four gages all fall within the inter-quartile ranges for variability at each of the gages. Consequently, it was concluded a priori that the data cannot provide evidence that differences between stations are significant or that there are any systematic downstream trends in these parameters of bed material size distribution.

Notwithstanding this, the results hint at the possibility of a downstream trend for grain sizes to decrease between Vicksburg and Tarbert Landing. For example, the median grain size (D_{50}) decreases from 0.41 mm at Vicksburg to 0.36 mm at Natchez and 0.32 mm at Tarbert Landing. Similar trends are apparent for D_{16} (0.29 mm to 0.25 mm to 0.21 mm) and D_{84} (0.69 mm to 0.56 mm to 0.49 mm).

Another salient point to emerge from the gage site data is that time variability in D_{84} is highly asymmetrical and dwarfs that in both D_{50} and D_{16} . The presence of quantities of gravel-sized particles in the bed of the LMR at these locations is primarily responsible for the highly variable nature of D_{84} .

Taking this finding together with the insights provided by Gaines and Priestas (2016) and Robbins (1977), the wider implication is that even though gravel constitutes relatively small percentages of the bed material size distribution (especially since approximately 1990), it is likely that gravel sheets and armor layers play disproportionately significant roles in controlling the stability and mobility of bed sediments, especially around the heads of bars and islands.

In this context, processes responsible for the apparent reductions in the occurrence of D_{84} outliers since approximately 1990 in samples collected at the Arkansas City, Vicksburg, and Natchez gaging stations are worthy of further investigation, and it is recommended that this proceeds accordingly.

3.6 Sensitivity of calculated annual bed material loads to variability in bed material size distributions

One of the most widespread and important uses of bed material sizes and grain size distributions is as input data for the calculation of annual bed material loads. The resulting transport rates and loads are used extensively and for a wide variety of purposes in modeling, engineering, and managing the LMR. The accuracy and reliability of calculated loads depend to a large degree on the reliability and accuracy of the input data. Consequently, the findings of the bed sediment study were used to investigate the sensitivity of calculated bed material loads to variability in bed material size distributions. Data from Robbins (1977) gathered in the seven potamology reaches that make up Sub-reach 3 of the Vicksburg District (between RM 406 and 479 AHP) were used for this purpose.

In this element of the study, HEC-RAS/SIAM was run nine times: once for each year of record in the Robbins (1977) data set (1966 to 1974). In each year, the bed material size distributions for that year (averaged for each potamology reach) were used to estimate the annual bed material load carried in each sediment (potamology) reach. Sampling records were not available for all years for some potamology reaches, and only results for years in which bed material was actually sampled were included in the sensitivity analysis.

All the other input parameters (channel bathymetry, flow hydraulics, flow duration) remained constant for all runs: that is, only the bed material size distribution varies between the SIAM model runs for each potamology reach so that differences between the annual bed material loads calculated for each year in the period of record result exclusively from inter-annual variability in the reach-averaged bed material grain size distribution.

Based on the results of the sensitivity analysis, it is concluded that annual bed material loads in the LMR calculated using HEC-RAS/SIAM are extremely sensitive to variations in the bed material grain size distribution. For example, at Cottonwood Bar, inter-annual changes in bed

material load in response to variability in the bed material gradation range from an increase of 127% (between 1971 and 1972) to a decrease of 52% (between 1972 and 1973). Notable also are increases of 62% and 81%, in 1967–1968 and 1969–1970, respectively, and decreases of 32% and 48% in 1970–1971 and 1973–1974, respectively. Similarly, at Belle Island–Milliken, the calculated bed material load decreased by 35% in response to variation in the bed material gradation at the beginning of the period of record (1966–1967) and increased by 257% between 1973 and 1974, at the end of the period of record.

The median grain size (D_{50}) is customarily used to represent the mobility of widely-graded bed material in a river. It would be expected a priori that for the same flow and channel morphology, the bed material load would increase in response to a decrease in median grain size. The results of the sensitivity analysis indicate that this is not necessarily the case in practice. For example, for the Cottonwood Bar potamology reach, the calculated annual sediment load decreases by 17% between 1966 and 1967 in response to the *reduction* in D_{50} recorded between these years. Comparison of bed material parameters in 1967 and 1968 reveals a further decrease in D_{50} , but in contrast to the change between 1966 and 1967, response of the annual bed material load was to *increase* by 62%.

The apparent paradox in the response of calculated bed material loads is explained by the fact that bed material transport in the LMR is dominated by movement of sediment in the smaller size fractions, for which the river's transport capacities are very high. The analysis demonstrates that that responses in the annual sediment load are driven primarily by variability in the percentages of fine and medium sand, and this variability is not always reflected in changes in the median grain size.

The conclusion to emerge from this analysis of bed material load responses to changes in the bed material gradations for 1966 and 1967 is that it is impossible to predict the significance or even the direction of response in bed material load based on changes in median grain size or any of the other statistical parameters used to represent the grain size distribution of the bed material.

The wider implication of this finding is that to account for the effects of grain size variability on calculated bed material load, it is necessary to examine the grain size distribution curves, identifying crossing points,

assessing changes in the shape and steepness (and therefore, the distribution of percentages between classes), and focusing on the smaller classes, for which transport capacity is the greatest.

It is therefore recommended that further investigations be performed to develop a reliable and repeatable method of accounting for the uncertainty introduced to calculated sediment transport rates and annual bed material loads by local variability in the bed material grain size distribution.

3.7 Meeting the needs of engineers, river scientists, and geomorphologists for reliable bed sediment data

This report has gathered and made readily available data and supporting information contained in a series of past and recent USACE reports on the sizes and size distributions of sediment forming the bed of the LMR. In so doing it has created a valuable resource for engineers, river scientists, and geomorphologists seeking to understand, manage, and develop the river for a purposes including navigation, flood control, and environmental quality.

The significance of this resource to managing the river and the variability in bed material grain sizes and grain size distributions it characterizes is comparable to equivalent databases for water flow in the LMR. This is the case because changes in the composition of the bed sediments, together with the annual bed material load derived from their transport, have profound impacts on river morphology, bed and bar stability, navigation, flood conveyance capacity, hydraulic geometry, and both instream and channel-marginal habitats.

Recognizing this, the final conclusion of this report is that current abilities to characterize, understand, explain, and model bed material and its movement in the LMR are severely limited by lack of the data necessary to distinguish between natural variability and trends in bed material size distributions and characteristic parameters such as D_{50} , D_{16} , and D_{84} .

While the recent and historical measurements compiled here are a rich resource, the quantity of reliable data they provide is tiny compared to the records that exist for river discharge and water quality. Additionally, variability in the data is sufficiently large to introduce significant uncertainties into results derived from it.

The wider implication of this conclusion is that shortage of measured bed sediment data is a problem that affects all aspects of management. This problem can only be solved through a carefully designed, systematic sampling program that makes use of modern equipment and remote sensing to make it fit to purpose while being time-efficient, affordable, and over the long-term, sustainable.

Based on the wider implications of the lack of data, the following is recommended:

1. Any current protocols and programs for bed material sampling in the LMR should be reviewed and revised so that they fully meet the needs of river engineers, river scientists, and geomorphologists engaged in managing and restoring the river and its delta.
2. High priority should be given to performing the deep analyses required to unravel the complex relationships that link natural variability to local adjustments and long-term trends in bed material properties. These analyses will necessarily require both assessments based on the understanding of dynamic process-response mechanisms in the fluvial system and advanced time-series analyses of the records compiled and made available in this report.

References

- Ackers, P., and W. R. White. 1973. "Sediment Transport: New Approach and Analysis." *Journal of Hydraulics Division, American Society of Civil Engineers* 99(HY11): 2040–2060.
- Biedenharn, D. S., W. A. Stroupe, and J. H. Brooks. 2014. *A Review of the Lower Mississippi River Potamology Program*. MRG&P Report No. 1. Vicksburg, MS: U.S. Army Corps of Engineers.
- Biedenharn, D. S., L. C. Hubbard, C. R. Thorne, and C. C. Watson. 2006. *Understanding Sediment Sources, Pathways and Sinks in Regional Sediment Management: Wash Load and Bed-Material Load Concept*. ERDC-TN-SWWRP-06-3. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Bunte, K., and S. R. Abt. 2001. *Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel and Cobble Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring*. USDA General Technical Report RMRS-GTR-74.
- Gaines, R. A., and A. M. Priestas. 2016. *Particle Size Distributions of Bed Sediments along the Mississippi River, Grafton, Illinois, to Head of Passes, Louisiana, November 2013*. MRG&P Report No. 7. Vicksburg, MS: U.S. Army Corps of Engineers.
- Gibson, S. A., and C. D. Little, Jr. 2006. "Implementation of the Sediment Impact Assessment Model (SIAM) in HEC-RAS." In *Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, NV, April 2006*.
- Nordin, D. F., and B. S. Queen. 1992. *Particle Size Distributions of Bed Sediments along the Thalweg of the Mississippi River, Cairo, Illinois, to Head of Passes, September 1989*. Potamology Program (P-1), Report 7. Vicksburg, MS: U.S. Army Corps of Engineers, Lower Mississippi Valley Division.
- Robbins, L. G. 1977. *Suspended Sediment and Bed Material Studies on the Lower Mississippi River*. Potamology Investigation Report 300-1. Vicksburg, MS: U.S. Army Corps of Engineers, Vicksburg District.
- Syvitski, J. P. M., K. W. G. LeBlanc, and K. W. Asprey. 1991. "Interlaboratory, Interinstrument Calibration Experiment." In *Principles, Methods, and Application of Particle Size Analysis*. Edited by J. P. M. Syvitski, 174–193. New York: Cambridge University Press.
- Thorne, C. R., O. P. Harmar, C. C. Watson, N. J. Clifford, D. S. Biedenharn, and R. Measures. 2008. *Current and Historical Sediment Loads in the Lower Mississippi River*. Final Report to the United States Army, European Research Office, London, England, under Contract Number 1106-EN-01. University Park Nottingham: School of Geography, University of Nottingham.

- Thorne, C. R., N. P. Wallerstein, P. J. Soar, A. Brookes, D. Wishart, D. S. Biedenharn, S. A. Gibson, C. D. Little, D. M. Mooney, C. C. Watson, A. P. E. Green, T. J. Coulthard, and M. J. van de Weil. 2011. "Accounting for Sediment in Flood Risk Management." In *Flood Risk Science and Management*, edited by G. Pender and H. Faulkner, 87–113. Chichester: Wiley-Blackwell.
- Toffaletti, F. B. 1968. *Technical Report No. 5. A Procedure for Computation of Total River Sand Discharge and Detailed Distribution, Bed to Surface*. Committee on Channel Stabilization. U.S. Army Corps of Engineers.
- Toffaletti, F. B. 1969. "Definitive Computation of Sand Discharge in Rivers." *Journal of the Hydraulics Division* 95(1): 225–248.
- U.S. Army Corps of Engineers (USACE). 2007. Low water reference plane update. Internal report to Mississippi Valley Division, Memphis District. Memphis, TN: U.S. Army Corps of Engineers, Memphis District.
- Waterways Experiment Station. 1935. *Studies of River Bed Materials and Their Movement: With Special Reference to the Lower Mississippi River, Issue 17*. Vicksburg, MS: U.S. Army Corps of Engineers.
- Yang, C. T. 1972. "Unit Stream Power and Sediment Transport." *Journal of Hydraulics Division, American Society of Civil Engineers* 98(HY10): 1805–1826.

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