Quantifying Bed-Load and Bed-Material-Load from Repeat Bathymetric Surveys:

Report to FISP Technical Committee on Work Completed

Brandon McElroy U.S. Geological Survey Columbia Environmental Research Center 4200 New Haven Rd Columbia, MO 65201 David Abraham U.S. Army Corps of Engineers Engineer Research and Development Center 3909 Halls Ferry Rd Vicksburg, MS 39180

October 21, 2011

### **Technical Summary**

Quantitative understanding of bed-load and bed-material-load fluxes in sandy rivers would afford greater understanding and prediction of channel form, channel evolution, and physical habitats of river corridor biota. Currently, practical difficulties and cost ineffectiveness often exclude direct bed-sediment measurements from studies and monitoring efforts aimed at estimating sediment loads in rivers. An alternative to direct measurement is through the measurement of evolution of bed topography constrained by sediment-mass conservation. As has been previously demonstrated, pure bed-load transport is responsible for the mean migration of trains of bed forms when no sediment is exchanged between individual bed forms. Extending that notion it has been proposed based on theory that the component of bed-material load flux that moves in suspension is responsible for the deformation of bed topography. With two data sets from the Mississippi River, USA, we test the hypothesis that the suspended bed-materialload flux equals the flux associated with bed deformation. The data sets each include repeat multibeam sonar surveys, acoustic Doppler current profile (ADCP) measurements, and pointintegrated suspended sediment samples. Sediment concentrations (as a function of grain-size) were assessed and are convolved with ADCP backscatter to determine total suspended bed material fluxes. Using the repeat bathymetry, deformation flux is calculated from the rates of topographic evolution in the beds mobile frame of reference. For both data sets these two fluxes match within a factor of 2/3. This result supports the hypothesis that deformation flux accounts for the bed material transported in suspension over an evolving sandy bed and indicates a need to test with more equivalent datasets.

#### Work Product Summary

In fulfillment of the terms laid out in our proposal, the following work was presented 3 times by McElroy: USGS Surface Water & Hydroacoustics meeting, Tampa, FL; Coherent Flow Structures conference, Simon Fraser University, BC; and Geological Society of America Meeting, Minneapolis MN. This report is the last product. This analysis will be included in a future journal manuscript with additional data to make are more substantial hypothesis test.

#### 1.0 Introduction

Accurately and consistently measuring and monitoring bed-load and bed-material-load in sandy rivers has always been a challenge. While it is clearly a difficult and potentially dangerous challenge to obtain direct, physical samples of bed-load transport in large, sandy rivers, Gaeuman and Jacobson (2007) provide evidence that fluxes calculated with physical sampling is poorly correlated with other internally consistent methods. They as well as Gray and others (2010) strongly suggest that surrogate methodologies will provide the best way forward in developing a practical and widely applicable technique for evaluating bed-material loads. One of the most widely used surrogate methods combines the evolution of bed forms and the conservation of sediment mass. This idea has been used to various ends for at least the last century, but was first made very explicit by Simons and other (1965) in a set of laboratory experiments that measured bed form migration and total sediment transport with a load cell in a sediment trap. They found that dune tracking successfully predicted sediment fluxes as long as bed material suspension was kept to near zero values.

More recently, with the proliferation of compact, high quality sonar, this method has been revisited by many (e.g. Gaeuman and Jacobson, 2005; Nittrouer et al., 2008, Abraham et al., 2010). Interestingly, each of these sets of investigators apply the general method with modifications to the details of calculations- indicative of the need for a resolution to the ambiguity in best applying the theory of Simons and others (1965). This is because bed sediment is regularly suspended is most natural systems must have an effect on bed evolution and its relation to bed material transport. McElroy and Mohrig (2009) attempt to address this issue by specifically relating the deformation of sandy bed topography to the interaction of suspended bed material and bed forms. They provide a theoretical framework to demonstrate how the conservation of sediment mass over a deforming bed is connected to the interactions of bed forms and suspended bed material, and they show how to use bed deformation to calculate the flux of sediment that is exchanged between bed forms.

In this context McElroy and Abraham proposed for FY2011 to "perform some initial tests on the ability of a new method to compute total bed material load in large sand bed rivers". The general idea was to utilize existing USACE datasets that include repeat bed topography and suspended sediment samples to relate the methods of Abraham and others (2010) and McElroy and Mohrig

(2009). In this approach the directly sampled suspended bed material is the thread that connects bathymetric evolution to bed deformation, bed load, and the ISSDOTv2 method.

#### 1.1 Background Theory

In 1965 Simons and others used the longstanding intuition that the migration of sandy bed forms is well approximated by the translation of regular triangular forms, and they coupled it with the conservation of sediment mass to derive

(1) 
$$\langle q_s \rangle = \frac{1}{L} (1-p) V \left(\frac{HL}{2}\right) + q_{s0}$$

where  $q_s$  is the mean sediment flux, *L* is the length of the bed forms, *p* is the porosity, *V* is the migration rate of the bed forms, *H* is their height, and  $q_{s0}$  is a constant of integration that represents all the material that moves beyond a slip-face and past a trough (Fig. 1).



Figure 1. Schematic diagram illustrating the quantities in Eqn. 1.

McElroy and Mohrig (2009) argue that because  $q_{s0}$  is necessarily the material that is exchanged between bed forms, it must also be responsible for their changes in size, shape, and spacing, i.e. their deformation. They propose that the flux associated with deformation can be calculated as a function of all topographic changes measured within the frame of reference in which the bed forms remain stationary, i.e. a Lagrangian frame. The elevation changes of the bed in that reference frame are determined by

(2) 
$$\Pi(x) = \frac{|\eta(x+V\Delta t, t_2) - \eta(x, t_1)|}{\Delta t}$$

where  $\Pi$  is the rate of deformation,  $\eta$  is the bed elevation, x is the horizontal coordinate,  $t_i$  is the i<sup>th</sup> time-step, and  $\Delta t$  is the duration over which deformation is measured. The rate of deformation is an elevation change per unit time and represents a net exchange of sediment volume between the bed and the water column over a time-step. In essence this is a vertical movement of material and can be scaled to a horizontal movement of material with the ratio of the sediment horizontal velocity to fall velocity, and the result is the flux associated with bed deformation

(3) 
$$q_{sD} = (1-p) \frac{V_s}{W_s} \frac{\Delta x}{2N} \sum_x |\Pi|$$

where  $q_{sD}$  is the deformation flux,  $V_s$  is the horizontal sediment velocity,  $w_s$  is the sediment fall velocity,  $\Delta x$  is the measurement spacing along the bed profile, and N is the total number of positions over which the deformation rate is averaged.

Separately from the development for a theoretical framework of bed deformation, Abraham and others (2010) describe a method for calculating bed load also based on the work of Simons and others (1965). They demonstrate a methodology for differencing two bathymetric maps, termed Integrated Section Surface Difference Over Time (ISSDOTv2), and with data from a set of experiments conclude that it captures the flux of bed-load equivalently to Eqn 1. The utility of their method comes from precluding the need to define the quantities of bed form height, length, and migration rate. With this set of methods for measuring fluxes based on topographic evolution, we now evaluate their relation to the modes of movement of bed material.

#### 1.2 Hypothesis

Simons and others (1965) clearly show that the second term of Eqn. 1 is equal to bed load flux associated with migrating bed forms. Abraham and others (2010) mirror this with the ISSDOTv2 method. Clearly, the first term in Eqn. 1, the mean sediment flux, is the bed material flux. Because it is derived by integrating the topographic evolution of the bed, by definition it must include, and only include, the bed material load. Therefore, the remaining third term in Eqn. 1 would appear to be the suspended portion of the bed material load. Written out this is

Bed Material Load = Bed Load + Suspended Bed Material Load

### And equivalently

## Bed Material Flux = Translation Flux + Deformation Flux

These two word equations represent a hypothesis statement: deformation flux accounts for the bed material load transported in suspension over an evolving reach. Similarly, deformation flux is the difference between the magnitudes of the bed load flux (calculated as either the translation flux or with the ISSDOTv2 method) and bed material load in a given reach.

# 2.0 Data

In order to test this hypothesis, we used existing datasets that independently measure evolution of bed topography and transport of bed material in suspension in a sandy river. Two separate datasets, one from July 12, 2010 and one from July 14, 2010, were identified from a collection of datasets obtained by the USACE. These two datasets were collected from fairly straight river reaches where a normal flow assumption could be valid (i.e. steady, uniform flow). Datasets from river reaches with curvature were excluded for violation of normal flow assumptions. Each dataset includes repeat bathymetric maps, acoustic cross-sections, and suspended sediment samples.

# 2.1 Collection Location and Conditions

Both datasets were collected near the Old River control structure on the Mississippi River, USA, approximately 505 kilometers upstream from the Head of passes at the bird's foot delta (Fig. 2).



Figure 2. Location of sites where data was collected with data types indicated.

Water stage elevation at the Knox Landing Gage remained essentially steady at 45.35 feet throughout data collection. Water discharge was about 750,000 ft<sup>3</sup>/s during this time which corresponds to a flow exceedence of about 15%. Although the surveyed segments are within the backwater zone of the lower Mississippi River at lower flows, at the surveyed discharge the water surface and bed slopes are sub-parallel at around  $2 \cdot 10^{-5}$  (Nittrouer et al., in press). This is the best evidence that a normal flow assumption is valid for these sites at this time.

### 2.2 Collection Methods

Three independent data types were collected at each survey site: multibeam sonar bathymetry, acoustic Doppler current profiles, and point-integrated suspended sediment samples. The bathymetric surveys were made using a boat equipped with an Inertial Motion Unit (IMU), Multibeam fathometer and a Real Time Kinematic (RTK) Global Positioning System (GPS). All of these components are integrated into a Hydrographic survey package. The multibeam systems used are 250 KHz and a 500 KHz Geoswath Plus interferometric Multibeam Sonars with an Applanix PosMV-IMU. Real-time GPS corrections are supplied by a Trimble R8 GNSS and broadcast to the PosMV for positioning and crucial time tagging of all instruments. The swath width provided by this system is up to 12 times the water depth per pass with a nominal ranging accuracy of 3.0 mm for the 250 KHz and 1.5mm for the 500 KHz. At each site data was collected in a series of six swaths across the channel, and each swath was reoccupied after a period of about 2 hours. The subsequent resurvey lines were run as close as possible along the exact previous survey lines, in the same direction and with the same boat speed. This creates two maps at each site representing snapshots of bathymetry used to calculate fluxes of bed sediments.

Acoustic Doppler current profile (ADCP) data were collected with an R.D.I. Workhorse 600 KHz. Two repeats were made at each cross section are made, subject to a 5% agreement between the two readings. If the 5% agreement condition was not met, additional measurements are made until the error is about 5%. Cross-section locations were selected based on proximity to the bathymetric surveys and on appearance that a location that would provide the best conditions for steady, uniform flow.

At five stations along the ADCP cross-section, point-integrated suspended sediment samples were collected using a Federal Interagency Sedimentation Project (FISP) P-61 point sampler. At each station 5 samples were obtained throughout the depth of the water column roughly spaced with a sample taken near the bed, near the water surface, and equally spaced throughout. The approximate vertical positions were at 10, 30, 50, 70, and 90 percent of water depth at the station. This strategy resulted in a total of 25 samples taken along each cross section. Each sample was around 700 ml of combined water and sediment. Because flow velocity varies throughout the sections, the sampling duration varied from point to point with shorter periods in higher flows and longer periods in slower flows.

### 2.3 Analysis Methods

A suite of analysis methods are required to turn the raw observations, suspended sediment samples, bathymetric sonar, and ADCP sections into a set of flux measurements used to investigate the stated hypothesis. In general the ADCP data is coupled with the suspended sediment data to determine loads of suspended bed material as well as total suspended load (i.e. including wash load). The bathymetric evolution is used in three separate ways: 1) ISSDOTv2 is applied to calculate bed load flux. 2) The method of Simons and others (1965) is used to calculate bed load flux. 3) The method of McElroy and Mohrig (2009) is used to calculate the deformation flux. These quantities are then compared and evaluated in the context of the hypothesis that the flux of material responsible for deforming bed topography is equal in magnitude to the suspended bed material flux. The remainder of this section describes the methods by which the raw observations are turned into sediment fluxes.

#### 2.3.1 Multibeam Sonar

In order to turn the raw multibeam sonar into a gridded bathymetric map from which topographic evolution can be quantified, the multibeam data was processed using either Hypack software or the native software of the GeoSwath System, both packages produce the same results. This process was completed at the USACE for separate reasons prior to initiating the current work. The first step was to apply the Heave, Pitch, Roll and position data from the IMU to the raw sonar data. In the process of doing this the appropriate patch tests were run on the multibeam calibration data to insure the offsets and latency for the different signal streams were as accurate

as possible. The next step was to apply the data from the sound velocity probe casts to account for variations of the speed of sound as a function of depth. This data will affect the quality and width of the usable swath if it is not performed correctly. Generally speaking, neither site showed a significant gradient in the speed of sound, likely attributable to substantial turbulent mixing.

Once the lines were cleaned of bogus sonar returns and other outlying data, each individual line is processed as an individual data set. The ISSDOTv2 method analysis is performed on a line by line basis so the data is needed in that format. In contrast the deformation flux is computed using the entire bed at once, so the individual lines were combined into single maps at each site for that purpose. The output format from the processing software is a uniform rectilinear grid of XYZ elevation data for the bottom topography. The spacing of the grid is 5 ft. square (5 ft. in each direction-longitudinal and transverse to flow) with vertical resolution of tenths of a foot.

## 2.3.2 ADCP and Suspended Sediment Samples

From each suspended sediment sample, a suspended sediment concentration (SSC) was determined using the volume of sample collected and the mass of dry sediment in each sample. A grain size distribution was then determined from each sample. This allowed us to distinguish between bed material load in suspension and wash load within each sample, thus creating information about the distribution of sediment concentration throughout both cross-sections as a function of sediment caliber. In addition to the SSC from the water samples, ADCP flow velocity and backscatter data were collected. At points where the SSC samples were taken, the backscatter data were related to SSC with a logarithmic function. Backscatter values for the entire section were then transformed to SSC values for subsequent calculations. This work was all completed by the USACE prior to using the data for the present purposes.

### 2.3.3 Suspended Sediment Flux Calculations

The method by which suspended sediment fluxes were calculated utilizes the ADCP water velocity and the SSC converted from ADCP backscatter during the transect surveys. The velocity data for each cell or bin from an ensemble was multiplied by SSC values for each corresponding cell that was obtained through the calibration process. The product of the water flux with the concentration at each cell yields the sediment flux through that cell. This process is

done throughout the entire profile, and the values for each ensemble are summed for the entire cross section.

The next step toward calculating suspended bed material flux from suspended sediment concentrations is to distinguish the bed material load from the wash load. Because we do not have any data regarding the materials present on the bed when these data were collected we do not have certainty about the exact composition of the bed materials. In order to move forward, we assume that all sands participate in the evolution of the bed but that all sediment smaller than sand remain entirely in suspension throughout the reach. Further, because bathymetric evolution was surveyed over modest reach lengths, not all levels in the flow are capable of exchanging sediment with the bed. Ultimately, the portions of the water column from which sediment can reach the bed are determined by the length of sectioned surveyed scaled by the rate at which sediment advects relative to its fall rate. The maximum elevation above the bed at which sediment can be and still participate in bed evolution over a length,  $L_x$ , is termed the operational bed material height,  $z^*$  (Fig. 3). It is the level in the flow above which the bed sediment reservoir and suspended sediment reservoir are locally isolated.



Figure 3. Schematic diagram illustrating the concept of the operational bed material height. Any sediment above  $z^*$  will never be exchanged with sediment in the bed over the length  $L_x$ . The formula  $L_x$  ( $w_s/V_s$ ) sets the distance that a particle will drop as it advects the distance  $L_x$ .

### 2.3.4 Deformation Flux

The first step in determining flux associated with bed deformation is to perform a crosscorrelation of two bathymetry maps to find the mean distance of the collection of bed forms. Once this is done, the migration rate is found as the ratio of the migration distance to the elapsed time between the two maps. The migration rate, V, is part of both Eqn. 1 and Eqn. 2. Equation 2 is applied to calculate the topographic deformation rate,  $\Pi$ , over the entire bed survey, and then deformation flux can be calculated.

(4) 
$$q_{sD} = M(1-p)\rho D \frac{V_s}{W_s} \frac{\Delta x^2}{2N} \sum |\Pi|$$

This is similar to the profile case but includes a second dimension of space (i.e. flow-transverse) and must be normalized to the total number of grid cells in the entire domain. In order to calculate mass flux, the density term is added. The variable M represents the number of grid cells spanning the width of the channel and is required to transform the result from per unit area flux into total flux. Fall velocity for the bed material is calculated using a weighted average (with grain size frequency as the weighting function) of fall velocities determined with the Dietrich (1982) formulation for fall velocity as a function of physical grain properties. Horizontal sediment advection velocities are those of the sediment while in suspension. It is therefore assumed that the particle velocity,  $V_s$ , is equal to the velocity of the water in the vicinity of the particle while in motion. This is calculated as the mean water velocity in the lower portions of the flow (i.e. those below the operational bed-material height).

## 2.3.5 Bed Load Flux

Bed Load flux was calculated using two independent methods- ISSDOTv2 (Abraham et al., 2010) and bed form translation (Simons et al., 1965). The ISSDOTv2 method computes a total difference between the two bed surveys. Then the regions of erosion and deposition are defined on each bed form present. These regions represent the mass that has left from one portion of the bed an arrived at another portion of the bed. Dividing by the time of bed evolution, a sediment flux is estimated. The second method is given exactly in Eqn. 1. To apply this equation, values for height, H, length, L, and porosity, p must be estimated. Height and length were determined using the roughness function described by Nikora and others (1997) and modified by McElroy and others (2008). Porosity was assumed at 0.35; a value commonly used and based on similar conditions (Bear and Weyl, 1973).

## 3.0 Results

Overall results of all calculations are located in Table 1. These show all quantities as determined for each site. Site specific characteristics are described in the following.

3.1 Site A

Multibeam sonar bathymetry collected at site A covers 474 m (flow-normal)  $\times$  393 m (flowparallel), spans up to 18 m deep, and took 30 minutes to collect. Two surveys collected 127 minutes apart were used to quantify bed evolution. The mean bed migration length determined by the correlation method described in McElroy and Mohrig (2009) was 4.6 m, and bed deformation rate is constrained between  $\pm 10^{-2}$  cm/s in the evolved bed topography.

With the median size of bed material of 0.24 mm and a fall velocity of 2.9 cm/s, the operational bed material height is determined to be 6.3 m. With a mean water velocity of 140 cm/s below that height, the ratio of horizontal sediment velocity to settling velocity is ~48. Combining this with the mean deformation rate, size of the survey area, and bulk bed porosity results in a deformation flux of 540 kg/s. The mean bed form height is found to be 3.0 m and with a bed velocity (based on mean bed migration) of 0.013 cm/s, the bed load flux is 160 kg/s from the translation method. The ISSDOTv2 method is calculated to be 167 kg/s.

Integrating SSC estimates for the cross-section results in a total suspended load flux of 4080 kg/s including wash load. This value is useful for gaining a context in which to interpret the magnitude of the various fluxes of bed sediments. Applying the operational bed material height to the SSC proxy data and integrating the concentrations of only those sediments that are sand sized, the suspended bed material flux is found to be 330 kg/s.

3.2 Site B

Multibeam sonar bathymetry collected at site A covers 584 m (flow-normal)  $\times$  381 m (flowparallel), spans up to 5.8 m deep, and took 30 minutes to collect (Fig. 4A). Two surveys collected 130 minutes apart were used to quantify bed evolution. The mean bed migration length

|   | Site A | Site B |
|---|--------|--------|
| Bed Material, D <sub>50</sub> [mm]            | 0.24   | 0.24   |
| Settling Velocity, w <sub>s</sub> [cm/s]      | 2.9    | 2.9    |
| Horizontal Velocity, Vs [cm/s]                | 140    | 160    |
| Operational Bed Material<br>Height, z* [m]    | 6.3    | 6.9    |
| Mean Dune Height, H [m]                       | 3.0    | 1.4    |
| Bed Velocity, V [cm/s]                        | 0.013  | 0.032  |
| Suspended Load Flux [kg/s]                    | 4080   | 3680   |
| Bed Load Flux<br>(ISSDOTv2) [kg/s]            | 167    | 259    |
| Bed Load Flux<br>(Bed FormTranslation) [kg/s] | 160    | 230    |
| Deformation Flux [kg/s]                       | 540    | 440    |
| Suspended Bed Material<br>Flux [kg/s]         | 330    | 650    |

Table 1. Results and quantities of calculations at both Sites A & B.

determined by the correlation method described in McElroy and Mohrig (2009) was 9.1 m, and bed deformation rate is constrained between  $\pm 10$ -2 cm/s in the evolved bed topography (Fig 4B). With the median size of bed material of 0.24 mm and a fall velocity of 2.9 cm/s, the operational bed material height is determined to be 6.9 m. With a mean water velocity of 160 cm/s below that height, the ratio of horizontal sediment velocity to settling velocity is ~55. Combining this with the mean deformation rate, size of the survey area, and bulk bed porosity results in a deformation flux of 440 kg/s. The mean bed form height is found to be 1.4 m and with a bed



Figure 4. Two maps of Site B survey showing A) Multibeam bathymetry processed, gridded and merged from raw swath data and B) Deformation rate calculated as the rate of topographic change within the bed migrating frame of reference (Eqn. 2).

velocity (based on mean bed migration) of 0.032 cm/s, the bed load flux is 230 kg/s from the translation method. The ISSDOTv2 method is calculated to be 259 kg/s.

ADCP data indicate velocities between 0.5 and 3.5 m/s with an average of 1.6 m/s in the lower portions of the flow (Fig. 5A). ADCP backscatter used in conjunction with point-integrated suspended sediment samples to make estimates of SSC for the entire cross-section (Fig 5B) results in a total suspended load flux of 3860 kg/s including wash load. Applying the operational bed material height to the SSC proxy data and integrating the concentrations of only those sediments that are sand sized, the suspended bed material flux is found to be 650 kg/s.



Figure 5. Cross-section at Site B survey showing A) ADCP flow velocities and depths and B) ADCP backscatter. Black dots represent point-integrated suspended sediment sample locations. Backscatter was transformed into SSC across the entire section using the relation between them developed at the black points.

## 4.0 Discussion and Conclusions

Our originally proposed goal was to close the loop in comparing independent portions of sediment flux as contribute to the total bed material flux: bed load from ISSDOTv2, deformation flux, and suspended bed load from direct physical sampling. Our scope has slightly expanded to include comparing bed load flux from bed from migration with the other three methods of flux measurements.

First, there are two distinct methods used here to estimate the bed load flux: ISSDOTv2 (Abraham et al., 2010) and bed form translation (Eqn.1; Simons et al, 1965). At Site A the values for these two flux estimates are 167 kg/s and 160 kg/s respectively. At Site B the values for these two flux estimates are 259 kg/s and 230 kg/s, respectively. Without appropriate characterizations for error propagation from the observational data all the way through the analysis to the final estimates, these values can be regarded as essentially equal. While those at Site are truly indistinguishable, those at Site B are within a factor of about 1/10. In agreement with the laboratory results of Abraham and others (2010), these two methods to quantify bed load flux are equivalent, at least under the surveyed conditions.

Second, the deformation flux is compared to the flux of suspended bed material. Our hypothesis is based on the intuition that the sum of topographic changes to the bed, exclusive of mean translation, is the effect bed material that moves in suspension. The exchange of sediment between the bed and the suspended load results in deformation and the flux of this sediment, deformation flux, is calculated to be 540 kg/s and 440 kg/s at Sites A and B, respectively. In comparison, the suspended bed material load fluxes estimated as the portion of bed material in suspension from combined physical and acoustic sampling are 330 kg/s and 650 kg/s at the two sites, respectively. The flux magnitudes at both sites are within a factor of 2/3. While this is not as small of a margin as the bed load flux estimates, it is very promising in the general context of sediment flux estimates which are often accompanied by orders of magnitude in their variations about predicted values.

The total suspended load at each site provides a baseline for interpreting the magnitudes of the bed sediment fluxes. At Sites A and B the suspended sediment load fluxes are 4080 kg/s and 3860 kg/s, respectively. The suspended bed material fluxes account for 10% to 15% of the suspended load, and the bed material load accounts for 15% to 20% of the total load. This is an important part of the overall sediment load and is a justification for the work being done to quantify these loads and their effects on the bed.

These results are promising and clearly represent both the best of current technology for estimating and comparing fluxes of bed sediments and the remaining levels of uncertainty associated with the relation of bed topographic evolution to environmental conditions. Although we have not performed a rigorous hypothesis test, we have shown that bed evolution can be a very good indicator of all bed material flux even in a field setting. Because the methods used to obtain the bathymetric observations are becoming more widely available, continued development of these analytical methodologies will have large effects on the utility of those data. One important step in that direction could be to remove the uncontrollable variables from the system and make an initial hypothesis test in an experimental system similar to those made by Abraham and others (2010). These should include the ability to compare fluxes associate with deformation to the suspended bed material fluxes. We believe that this will ultimately lead to a method of calculating bed material load using only topographic evolution under appropriate conditions. This effort has been a very useful proof of concept analysis toward that end.

# Acknowledgement

The data collection and original processing was done at the USACE under the guidance of Thad Pratt. His cooperation in allowing us to use the data and consult on the details of its collection is greatly appreciated. Tate McAlpin and David Perkey are also greatly thanks for their help.

# References Cited

Abraham D., Kuhnle, R. Odgaard, A. J., (2011), 'Validation of Bed Load Transport Measurements with Time Sequenced Bathymetric Data'', ASCE Journal of Hydraulic Engineering, vol. 137, p. 723-728.

Beard, D., P. Weyl, 1973. Influence of texture on porosity and permeability of unconsolidated sand, American Association of Petroleum Geologists Bulletin, vol. 57, p. 349-369.

Dietrich, W., 1982. Settling velocity of natural particles, Water Resources Research, vol. 18, p. 1615-1626.

Gaueman, D., Jacobson, R., 2007. Field assessment of alternative bed-load transport estimators, Journal of Hydraulic Engineering, vol. 133, p. 1319-1328.

Gray, J.R., Laronne, J.B., Marr, J.D.G., 2010, Bedload-surrogate monitoring technologies: U.S. Geological Survey Scientific Investigations Report 2010–5091, 37 p.

McElroy, B., and Mohrig, D., (2009). "Nature of deformation of sandy bed forms." Journal of Geophysical Research, vol. 114, F00A04, doi:10.1029/2008JF001220.

McElroy, B., Mohrig, D., Blom, A., 2008. Determining characteristic scales for the dynamics and geometry of sandy bedforms. MARID, Leeds, U.K.

Nikora, V., A. Sukhodolov, P. Rowinski, 1997. Statistical sand wave dynamics in onedirectional water flows, Journal of Fluid Mechanics, vol. 351, p. 17-39.

Nittrouer, J., M. Allison, D. Mohrig, R. Campanella, 2008. Bedform transport rates for the lowermost Mississippi River, Journal of Geophysical Research, vol. 113, F03004.

Nittrouer, J., Mohrig, D., Allison, M., *in press*. Punctuated sand transport in the lowermost Mississippi River, Journal of Geophysical Research.

Simons, D., E. Richardson, C. Nordin, 1965. Bedload equation for ripples and dunes, United States Geological Survey Professional Paper, 462-H.