UPDATE ON ISSDOTv2 METHOD FOR MEASURING BED-LOAD TRANSPORT WITH TIME SEQUENCED BATHYMETRIC DATA

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Introduction

The ISSDOTv2 (Integrated Section Surface Difference Over Time version 2) method to compute bed-load transport has been employed in the field for several years. This method utilizes difference plots of time-sequenced three-dimensional bathymetric data to calculate bed-load transport. Scour volumes determined from the difference plots are related to the average transport in a sand wave. The method is described in Abraham et al. (2011) and Shelley et al. (2013).

Purpose

The need to quantify bed-load sediments moving along the bottom of large sand bed rivers varies depending on agency perspective. Sands moving in the bed of a river are no longer viewed simply as a nuisance or problem related to dredging requirements, but as a ***resource***. River engineers and managers are now asked on a regular basis to allocate bed sediment resources to a variety of competing purposes and interests. Critical issues must be addressed such as land-building in the Louisiana Coastal Areas (LCA) and commercial sand mining in many locations throughout the country. With regards to environmental concerns related to the Endangered Species Act (ESA) and Environmental Impact Statements (EIS), managers must assess the availability of sand to maintain ecological habitat features of rivers such as islands and bars. These concerns must be addressed in addition to the requirements of maintaining adequate draft depths in the navigation channels and functionality of locks and dams. In order to adequately address the varied interests, river managers must have some idea of how much bed material is available, which is directly related to its rate of movement through a river system. If the mass transport rate can be determined and related to changes in river flow, a bed-load rating curve can be produced which provides a quantitative management tool for those tasked with allocating the river's sand resources.

With regards to dredging needs, dredging records have in the past provided an estimate of future dredging requirements. However, they are only applicable to that location. Dredging records also do not provide information about the rate at which the bed-load sediments are moving. If a bed-load rating curve is produced as mentioned above, a yearly average hydrograph can be used with the bed-load rating curve to produce a bed-load transport curve for the year. Integrating under this curve provides the total mass (or volume) of bed-load sediments that moved through a reach during that year.

Theoretical Basis

By way of review and for those who are reading about this method for the first time, a brief discussion of the theoretical basis is presented here. With the new bathymetric imaging and mapping techniques developed in the mid-1990's, the ability to accurately measure the bed surface of water bodies in three dimensions became a reality. The equipment and processing of the bathymetric data were of sufficient quality that the individual features of river bottoms such as dune fields could be adequately resolved to the sub-dune scale. For the duration of this paper the terms sand waves and dunes are used interchangeably and all bed-load transport values are reported in US tons per day (1 US ton/day = 0.907 metric tons/day). Figure 1 shows a swath of bed elevation data obtained from the Mississippi River at Red-Eye-Crossing, just south of Baton Rouge, Louisiana. The dune lengths varied from about 21 to 46 meters (~70 to 150 ft), with their direction of travel being from the top of the figure to the bottom. When the same area is surveyed a second time, the two sequential data sets can be subtracted to obtain a difference plot. In such a plot, the eroding portion of any dune will be noted by a decrease in surface elevation from time 1 to time 2, while the depositional side of the dune will show an increase in elevation. These differences can be plotted as positive and negative values using two colors to show areas of scour and deposition. Such a plot is shown in figure 2 where scour is plotted as red and deposition as blue. The lateral extent of the scour occurring on any dune as well as its depth of scour is available in the difference plot. Thus the volume of scoured bed material can be determined for any individual dune or for any selected group of dunes.

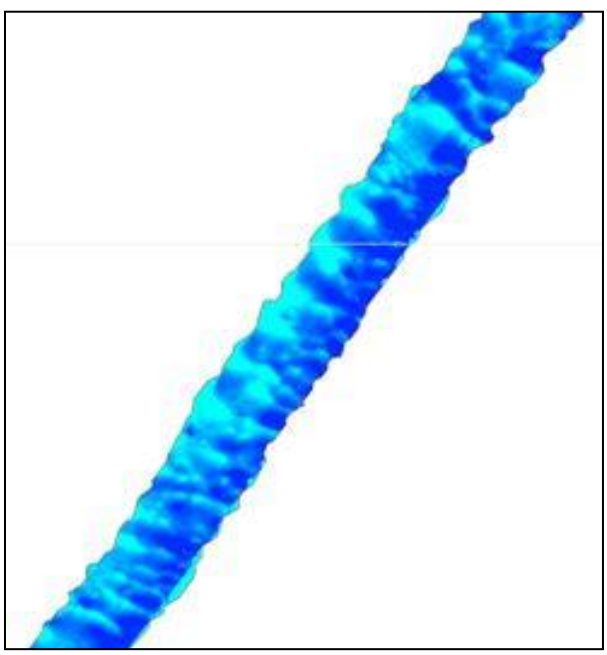

Figure 1 Plotted bathymetric data clearly delineating the individual dunes.

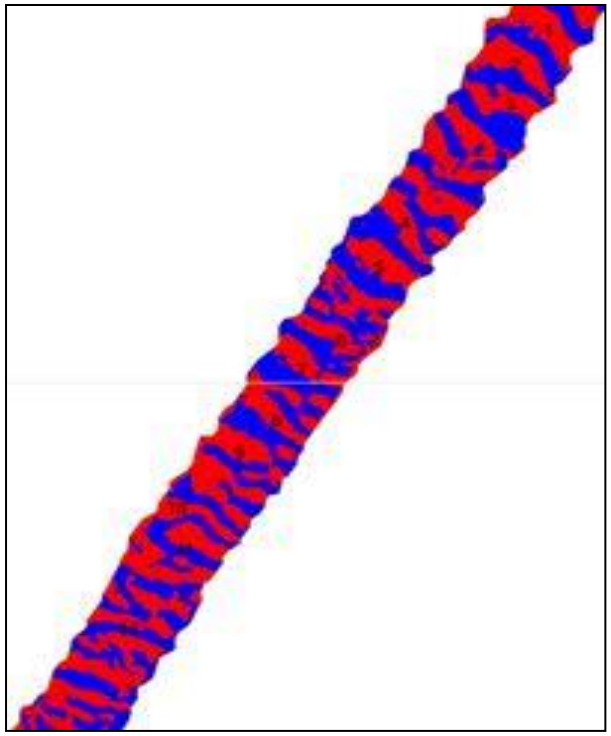

Figure 2 Bathymetric differences showing scour (red) and deposition (blue).

The relationship between the rate of scour on the eroding side of the dune and the average transport rate of the same dune is explained in Abraham et al (2011). The equation developed to quantify this relationship is shown in Equation 1

$$q_{sbi} = \frac{\rho(1-p)V}{2\Delta \mathrm{t}} \tag{1}$$

where q_{sbi} is the bed-material load moving in the sand wave computed by the ISSDOTv2 method, ρ is the density of the submerged sand, p is the porosity of the sand, Δt is the time difference between measurements, and V is the scoured volume during the time interval Δt. Equation 1 is mathematically equivalent and dimensionally homogenous to the equation developed by Simons and Richardson (1965), provided in Equation 2.

$$q_{sb} = \frac{\rho(1-p)c\eta}{2} \tag{2}$$

where q_{sb} is the bed-material load moving in the sand wave, ρ and p are as above, c is the dune speed, and η is the dune height.

Equation 1 for the ISSDOTv2, or scour volume method, was applied to flume data [56 data sets representing 6 different flow rates varying from 0.203 cms (7.17 cfs) to 0.426 cms (15.04 cfs)] for which actual transport values were measured in a clear water scour

condition. This implies the volume of eroded bed-material on the upstream side of the dune should be equal to the volume deposited on the downstream side of the same dune. The results are shown in figure 3, which is more completely described in Abraham et al (2011). Significant to note is that assumptions of uniform wave velocity and minimal wave deformation were made in analyzing these flume data. These are conditions associated with steady uniform flow maintained during these flume experiments. The comparisons in figure 3 illustrate both the validity of those assumptions and the ability of the equation to accurately measure bed-load transport.

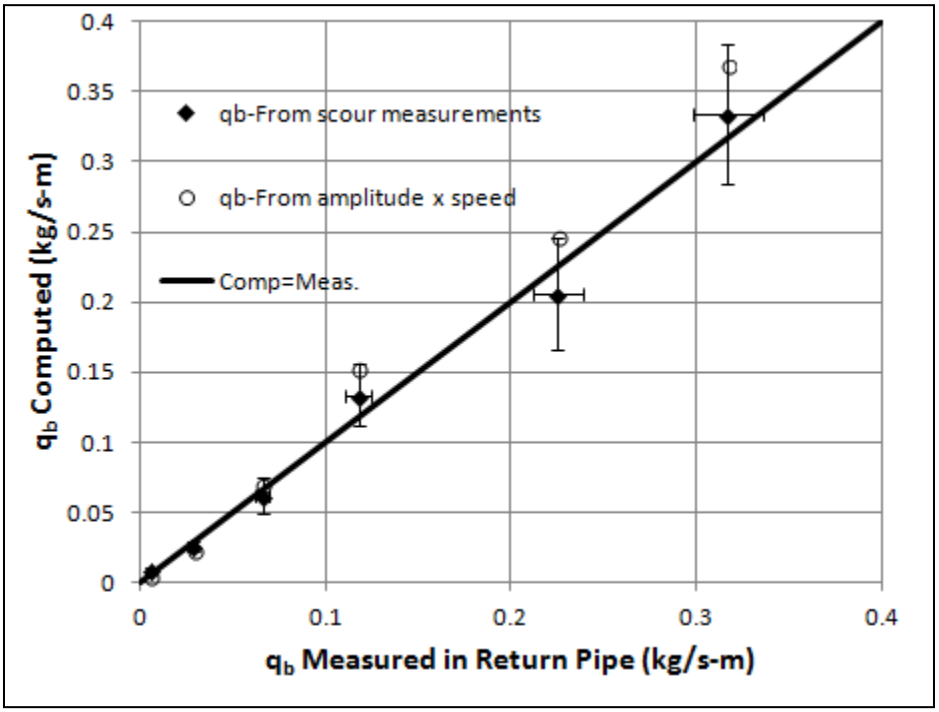

Figure 3 ISSDOTv2 computed versus measured bed-load transport in a flume study (Figure from Abraham et al. 2011).

The aforementioned discussion and results were presented in order to show that the method is founded on a sound theoretical basis that was substantiated with a large quantity of measured flume data. However, in river field applications, such ideal conditions rarely exist and present additional challenges for applying the scour volume method.

Practical Application of the Method

The high shear stresses and turbulent nature of natural channels result in a sizeable amount of the bed-material load moving in suspension. The unsteady nature of gradually varied flow also means that the rate of suspension or deposition can change significantly with time over a given river reach. In the aforementioned flume experiments, there were no suspended sediments, and therefore the assumption of the scoured volume moving to the depositional side of the same wave was a valid assumption. In a natural meandering

channel one cannot expect scoured volume to be equal to depositional volume. Some of the scoured bed-material does go into suspension and can travel far enough that it is not deposited on the dune from which it originated, thus adding depositional volume to other dune(s). The result is that for a given dune, and/or for a large dune field, the assumption of scour volume being equal to deposition volume is violated. It was noticed early on that this is often the case in natural rivers. How does this affect the computations? If, for example, 30% of the scoured volume went into suspension and was carried to some other dune, then that same 30% volume was not deposited on the same dune and thus did not participate in the dune movement. Thus the computed value of bed load transport could be in error by calculating 30% more transport in the dune than actually occurred. Based on these considerations, comparing the scour-deposition ratio should be a way to avoid data sets in which the river was excessively erosional or depositional. Such events could be caused by a rising or falling limb of a hydrograph. For ISSDOTv2 computations, scour-deposition ratios are computed for all difference plots. Those with values from 0.8 to 1.2 are retained while plots with values outside this range are deemed unsuitable for this method.

Another necessary correction occurs as a systematic bias inherent in the methodology. Figure 4 shows a translating wave form. The volumes of triangles C and D do not show up in the difference plots. These values get increasingly large as Δt gets larger and thus the 'missed' volumes result in smaller and smaller computed values of transport. So when Δt is very small, this systematic error is small, and when Δt is large, the corresponding error is large. This error was kept small in the flume study by using small time differences. In field conditions, however, this is seldom possible when surveying multiple swaths at a given river section. The later surveys could be hours apart. Shelley at al. (2013) details a procedure to correct for this systemic bias, which allows the longer time differences to still be used to obtain an accurate estimation of the true dune transport value.

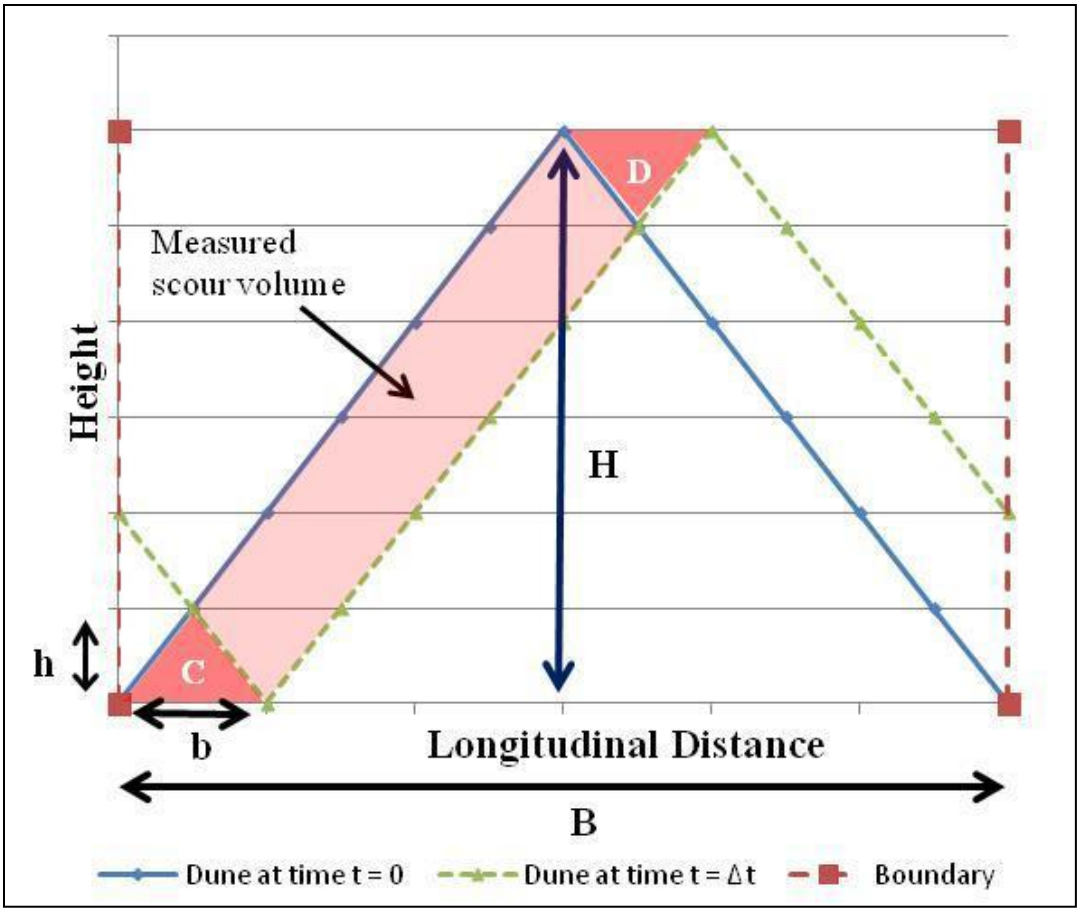

Figure 4 Schematic showing a systematic error due to lost volumes.

Example

When the two quality control procedures mentioned above are applied to the ISSDOTv2 computational method for a single bathymetric swath location, for which several repetitions were made, (temporally sequential), a transport value can be computed for that portion of the river. When multiple swaths cover a river from bank to bank, the values for each swath can be summed to provide the total bed-load transport at a river section. Figure 5 shows an example of such computations on the Ohio River near Mound City, IL. Additional information on the particular project methods and procedures are available in Abraham, Clifton and Vessels (2014).

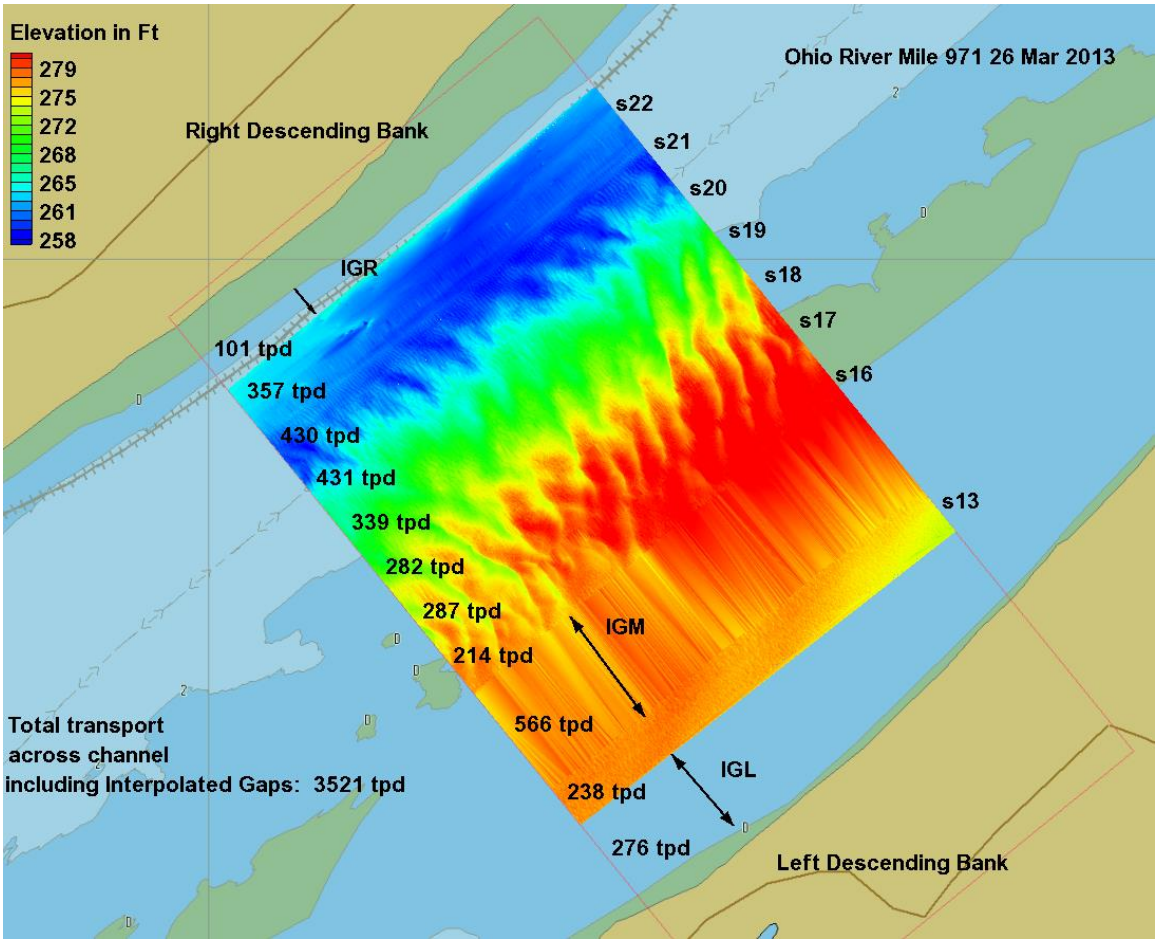

Figure 5 Multiple swaths and computed transport across a river section.

A MATLAB code has been created to calculate the transport for each swath. For this location each swath was divided into 1.524 m (5 ft) wide sections with the transport being calculated in each section using Equation 3

$$transport(tons/day) = \frac{43.2 * \rho(1-\mathrm{p}) * \mathrm{V}(ft^3)}{1.82 * \Delta t(\sec) * (\#\,waves)} \tag{3}$$

where 43.2 is a conversion from kg/s to tons/day and 1.82 is a parameter that accounts for the non-triangular shape of the dunes. The total transport for a given swath is then determined by integrating across the width of the swath. After determining the transport for various difference data sets (and different time steps), the previously discussed systematic bias was removed to obtain an accurate bed load transport value for each swath.

In figure 5, flow is from top to bottom. Swath numbers are at the top of each swath, and the computed bed load is at the bottom. The entire section was not covered, so linear interpolation was used for the gaps identified in the figure as IGR, IGM and IGL (values

of 0 were assumed for the bed-load transport at the left and right banks). They stand for Interpolated Gap Right, Interpolated Gap Middle and Interpolated Gap Left respectively. The total transport across the channel section was computed as 3,521 US tons per day including the interpolated gaps.

Field-data results from other large sand-bed rivers (Mississippi, Missouri, and Snake) have also been taken from 2011 to 2014. The measurements include bed-load transport values for various flow rates and river locations as well as suspended sediment concentrations and bed gradations. These data allow for the separation of wash load from bed-material load and also to compare total bed-material load (suspended bed material + bed load) to the ISSDOTv2 calculated bed load. In figure 6, data are plotted for a site on the Mississippi River just downstream of the Old River Control Complex (ORCC). The red square data points are the computed bed-load values (the sand moving in the dunes). As expected this value increases with increasing flow, and does so in a linear fashion as seen at this site and in most others that have been measured with three or more different flow rates. The blue diamond data points represent the bed load as a percentage of the total bed-material load. This is not a constant value and at this site varies from a low of about 10 % to a high value of over 45%.

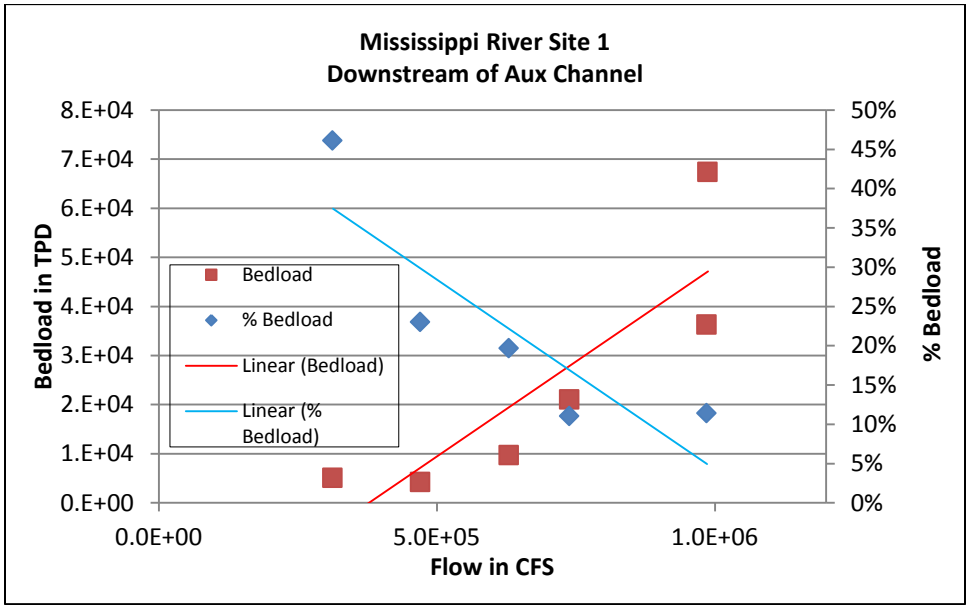

Figure 6 Bed load and % Bed load vs Flow rate on the Mississippi River.

In addition to Site 1 near the ORCC, whose data are plotted in figure 6, three other sites were measured during the same time periods, all of which were on the main channel of the Mississippi River. The bed-load computed values from all four sites (in total 22 independent data points) are plotted in figure 7. They show the same linear trend over a range of flows varying from 8,496 cms (300,000 cfs) to about 48,145 cms (1,700,000 cfs). By visual observation of the graph one can still make the case (similar to site 1) for a linear relationship between flow and bed load, with the R-squared value of 0.82 lending mathematical support to that conclusion.

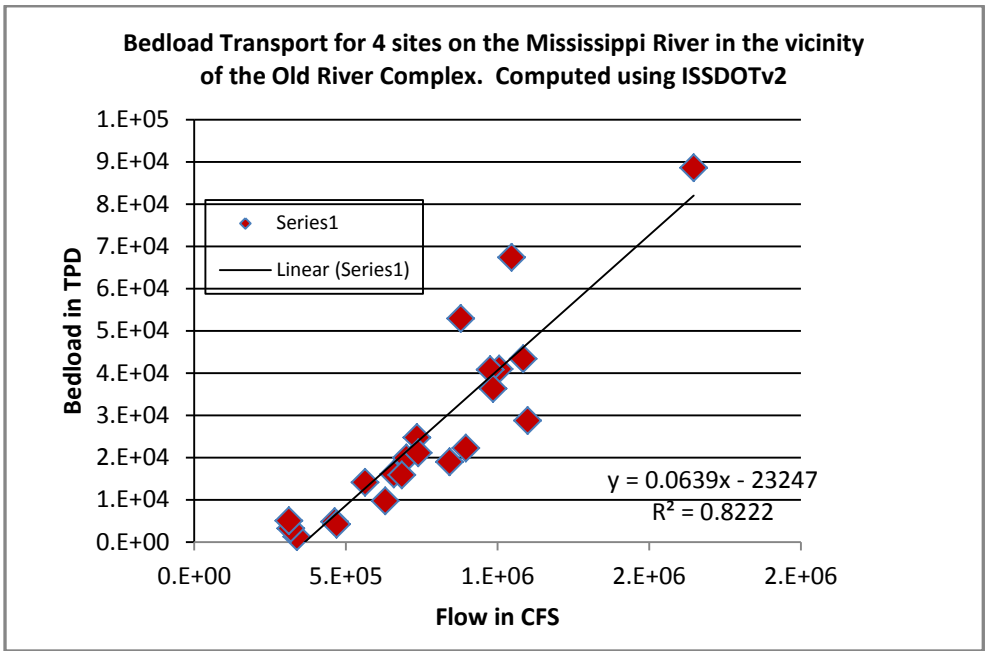

Figure 7 Mississippi River rating curve for flow versus bed-load transport.

Conclusions and Recommendations

Some of the more important conclusions noted to date are:

- The method clearly captures the lateral variability of the bed load transported in the moving sand waves for each swath, and when summed across the section provides the total bed-load transport for that river cross section.
- With sufficient measurements a bed-load rating curve can be developed.
- A bed-load rating curve can be very helpful to U.S. Army Corp of Engineers (USACE) District personnel in helping meet congressionally mandated sediment distributions as in the case of the Old River Control Complex.
- Using a bed-load rating curve and a yearly hydrograph, the net annual bed load moving through a river section can be approximated.
- Initial results on the Mississippi River indicate that bed load increases with increasing flow in a linear manner.
- Bed load is *not* a set percentage of total bed-material load, but can vary considerably depending on flow.
- Bed load *as a percentage* of bed-material load decreases with increasing flow.

The ORCC data shown here are representative of that collected and processed for 8 USACE Districts. They are St. Paul, Rock Island, Kansas City, Omaha, New Orleans, Vicksburg, Walla Walla, and Louisville, and they represent four major US Rivers; the Mississippi, Missouri, Ohio and Snake.

Corps Districts and other Federal Agencies want to know more about the method and the possibility of applying it themselves. To this end the authors have presented several workshops in the last year. An estimate of uncertainty must also be assigned to the computational results. Several proposals have been put forth for funding, including both flume and in-river studies. If funding can be secured for either case, the uncertainty of the measurements can be reduced and quantified with greater fidelity than is presently being done.

References

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