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Quantification of Bed-Load Transport on the Upper Mississippi River Using Multibeam Survey Data and Traditional Methods

by David D. Abraham and Thad Pratt

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the progress made in using multibeam bathymetric data to determine bed-load transport in large sand bed rivers. Work was conducted as part of the Monitoring of Completed Navigation Projects (MCNP) Program in coordination with the Coastal Inlets Research Program (CIRP).

INTRODUCTION: The need for quantifying bed-load transport is universal in riverine and coastal processes. In the past many analytic and mechanical methods have been devised to try and quantify bed-load transport on large sand bed rivers. To date, most methods are only marginally successful. In this MCNP work unit, being able to quantify the bed load accurately would be extremely helpful in determining whether or not river training structures in combination with a drawdown of the navigation pool would have an effect on net sediment movement through a given reach of river. In other words, accurate measurements would help resolve whether or not the altering of the pool stage and flow schedules might also be used as a sediment management tool. With these considerations in mind, a new methodology for the computation of bed-load transport was developed using multibeam bathymetric data. This methodology could also be applicable in evaluating transport in and around coastal structures throughout a tidal cycle.

MEASUREMENT METHOD: Two methods were initially conceived. One would be based on the celerity of the traveling sand waves, the other on the difference of surfaces. At this writing, the surface difference method was pursued and implemented. It is called the Integrated Surface Difference Over Time (ISDOT) technique. The method processes multibeam data and quantifies a bed-load transport rate for a given river cross section. This is accomplished by taking at least two sets of bathymetric data, at different times, for the same spatial location. The two data sets are interpolated to a spatial grid and a difference plot is produced. Incremental volumes are calculated and summed over the entire cross section. The total volume change with time, when multiplied by the density of the water sediment mixture, yields a mass transport rate.

As of this date the method is still in the developmental stage, but has shown surprisingly close results with some of the other standard estimation methods. The method of wave celerity, previously mentioned, might prove more reliable if worked out, but presents more computational obstacles than the ISDOT method. In this technical note, only the ISDOT method is considered.

DEFINITIONS: For purposes of defining the limitations and applicability of the ISDOT method, the following definitions of bed load are considered: Einstein (1950); Colby (1963); Bagnold (1966); van Rijn (1984). At first glance all these seem to define bed load in similar terms. That is,

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the material of which the bed is composed that is transported by rolling and sliding,... and by skipping, hopping, or jumping. These three words seem to be interchangeably used in a loose sense by many authors, and might even be what authors refer to when they speak of saltating particles. However, the important distinctions should be noted. Einstein defines jumping as leaps of no more than 100 grain diameters long. Bagnold calls bed load the movement of particles whose successive contacts with the bed are limited by the effects of gravity. That means that the particles do not go into suspension. The suspended bed-load material is then defined as that in which the excess weight of the particles is supported by the upward impulses of turbulence. Van Rijn chooses a similar definition. For this study a definition similar to that of Bagnold and van Rijn was preferred. Bedload for the purposes of the ISDOT method, is defined as sediment that is transported in a stream by rolling, sliding, or saltating along the bed and very close to it. For the calculations of bed load moving in dunes or sand waves, the following condition should be added. If particles temporarily go into suspension for distances greater than the length of the smallest of the dune lengths, then these particles should be considered as suspended. Otherwise they can be considered as bed load. The reason for this distinction will be presented in later papers.

CONSTRAINTS: The movement of a sand wave occurs when the upstream surface to the crest is scoured and then this material is subsequently deposited on the downstream face of the wave. With this mechanism of movement in mind, several limitations exist in order for this computational procedure to provide meaningful results. First, as noted in the definitions, the particles that move the sand wave cannot completely jump over an entire wave. Second, the speed of the wave must be such that the length that it travels in a given time must not be greater than the length of the computational grid. Third, it is assumed that within a given control volume the bed-load transport rate is in a steady state. Finally, with regards to sand wave regime theory, the flow cannot be such that the dune bed will transition into plane bed or antidunes.

Additional constraints are related to the collected data. For either the ISDOT or wave celerity method to provide valid results, the sequential “snapshots” of the bathymetric features must be accurate in space and time and measured to the same datum. All of these constraints have been considered in the development of the ISDOT method.

SITE: The location of the monitoring site and specific study area used to develop this measurement technique is Pool 8 on the Upper Mississippi River, just south of LaCrosse, WI. Several photographs and descriptions of this site are shown in Figures 1-5.

A schematic of the study area in Pool 8 is shown in Figure 1. This is a small portion of the pool. The entire bathymetry of the reach was mapped during the first trip. In subsequent trips, only the area between river miles (RM) 688.7 and 689.2 was mapped. The sediment transport and effects of structures 54 and 55 will be monitored in this area.

DATA COLLECTION: Figure 6 shows a close-up of some results of the data collection in the study area. The results of the trip 1 bathymetric survey are shown in the yellow-green-blue color background. The bathymetric features are clearly visible. Sediment samples and static velocity measurements were taken at the numbered locations. Additional swaths of bathymetric data were acquired at four separate times on the same day. These are represented by the brown sections in which points 7, 6, 5, and 2 are located.

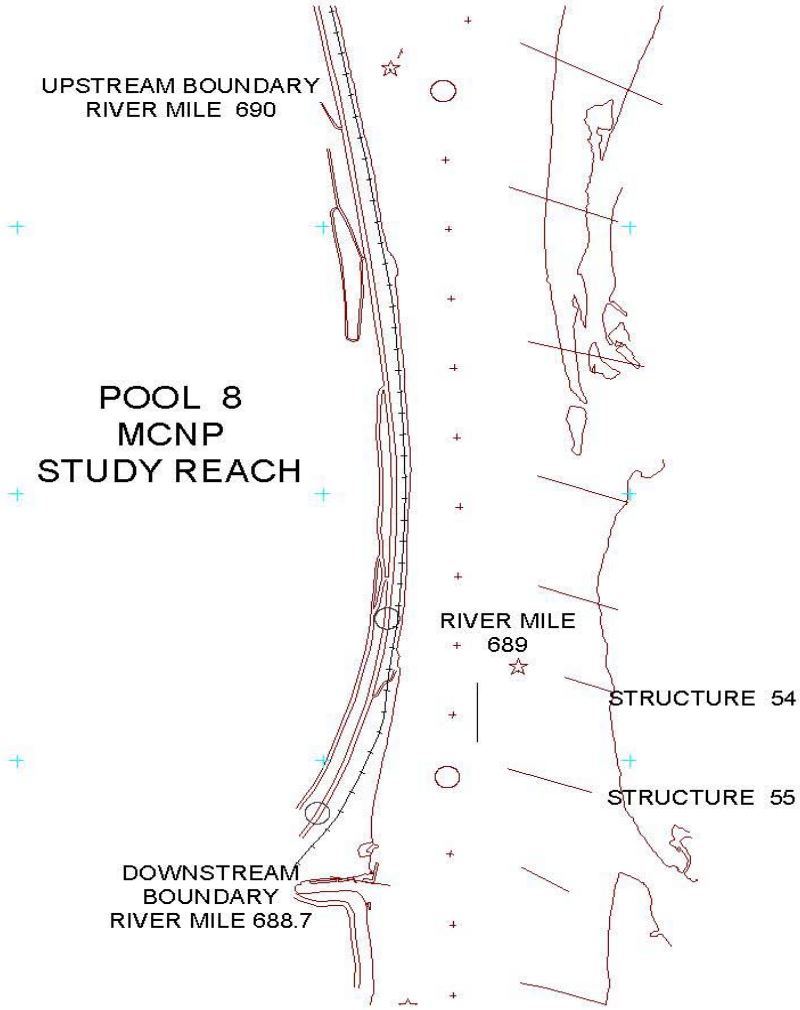

Figure 1. Schematic of study area in Pool 8

The elevation data represented in Figure 6 are very dense. These data are being used in the ISDOT methodology for quantifying bed-load transport. For example, Figure 7 shows a longitudinal profile through the north-south swath at four separate times.

This plot shows the longitudinal profile of the four "snapshots" represented by the four swaths. Each color therefore represents the same wave at different points in time. From this profile the distance the wave front traveled from time 1 to 2, etc. can be determined and thus the wave celerity. Also, the basic wave shape and dimensions can be quantified.

The following aerial photos show different views of Pool 8 and the study area.

Figure 2. Lower portion of Pool 8 looking south. Brownsville, MN and study area are at center and right of photo

Figure 3. Full length of study area looking south. Brownsville, MI, is at top right

Figure 4. Data collection boat. Multibeam bottom profiling, ADCP velocity, and sediment data are all collected from this single platform. This boat is GPS equipped and fully compensated for pitch, heave, and roll

Figure 5. Onboard computers show boat location at any time and monitor all data collection activities. Boat position is monitored and used by multibeam and ADCP instruments and computers

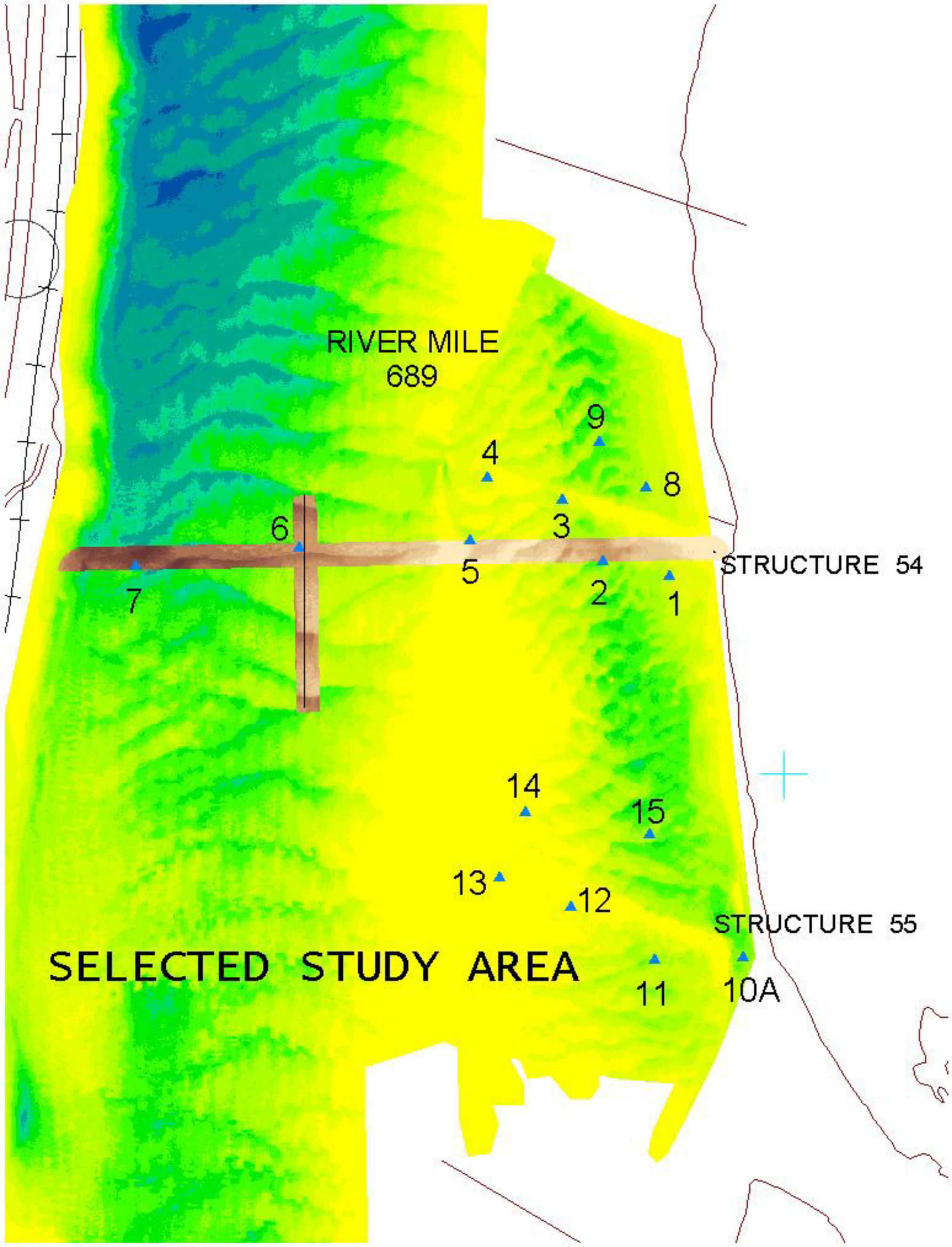

Figure 6. Results of data collection in study area

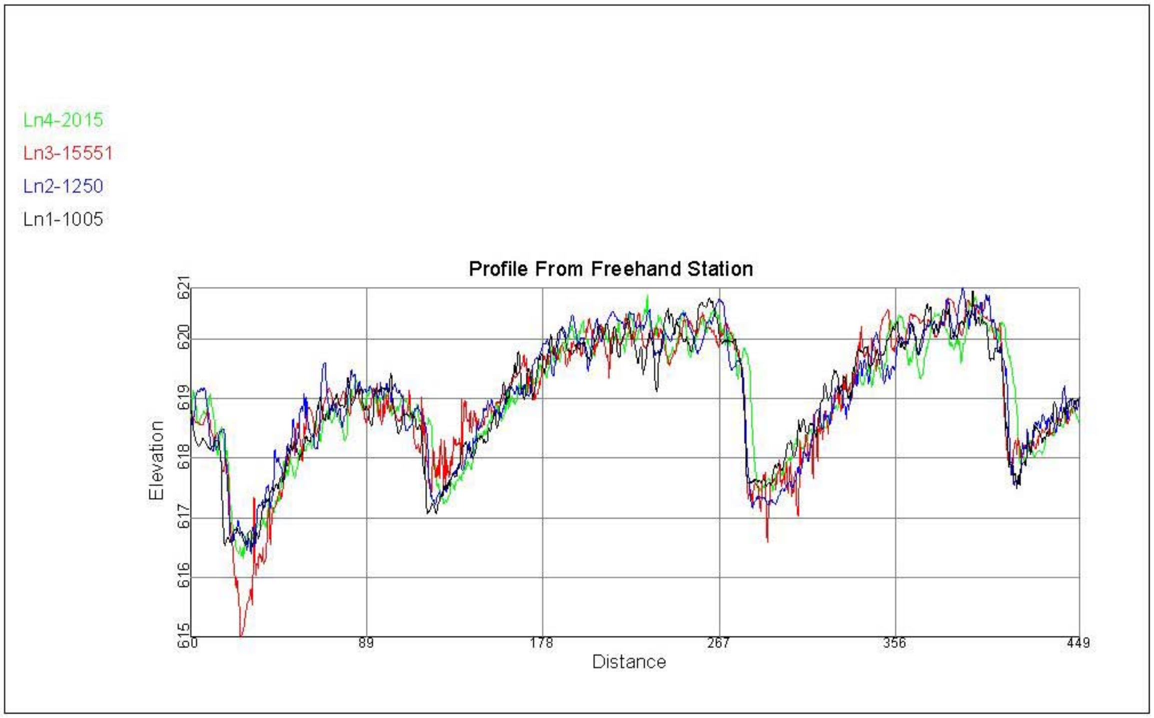

Figure 7. Longitudinal profile through north-south swath

METHODOLOGY: When it was determined that the swaths had captured sufficient bed wave movement during their time spans, 2.3 to 4.8 hours, the ISDOT method was applied. The coordinates of a rectangle common to all four swaths were identified. Then a computational grid consisting of 0.3048-m- (1-ft-) squares was made. The data from each of the four swaths ("snapshots") were interpolated to four separate grids. These grids with their associated bathymetric elevations represented the exact same surface at four different points in time. Any one grid can be subtracted from another to produce a difference plot. The difference for any square foot between surface 1 or 2, for example, represents the change in volume over time for that incremental area. Presently, both deposition into and scour out from any element are considered as positive transport. Adding up all the incremental changes in volume across the section produces the net change in volume over time for the section. This value can then be multiplied by the density of the sediment-water mixture to yield a bed-load transport rate.

The concept, although simple in principle, has not been used previously by any other researcher(s). There are probably at least two very good reasons. First, all literature seems to focus on the longitudinal profiles of the waves. Thus in quantifying these characteristics of the waves, different methods of bed-load calculations are carried out to determine the bed-load transport rate of a given wave. There are many excellent studies carried out in this manner as in Simons, Richardson, and Nordin (1965), Willis and Kennedy (1977), and Mahmood (1985). Kennedy and Odgaard (1991) present an excellent review of riverine sand dune literature. Other than empirical methods based on sediment and hydraulic characteristics, they all appear to focus on two-dimensional (2-D) wave shape and celerity, or some type of statistical analysis of 2-D dune profiles. A bed-load transport rate calculated in either of these last two manners is applicable to only the 2-D wave under consideration. In large sand bed rivers the general rule is that the sand waves are anything but consistent in size and celerity both longitudinally and laterally. Inevitably many assumptions and extrapolations must be made in order to say anything of the bed-load transport rate of the entire section. This is the main difference with the ISDOT method. It was conceived as a control volume type of consideration in order to circumvent the necessity of dealing with the spatially varying wave celerities and or dune profile statistics. The second possible reason why this has not been considered as practical before is the change in technology. The quality and quantity of detailed bathymetric data required to make this method work was not available even just a few years ago.

PRELIMINARY RESULTS: The initial results are encouraging. Since no one is able to actually measure bed-load transport rates in large sand bed rivers, the question arises as to how accurate this method might be. There are at least two possibilities for determining whether or not the computed values are even meaningful. One would be to compare with mechanically measured values on the same or similar rivers. A second way would be to compare with accepted analytic transport functions. Both comparisons were made.

Data taken on the Nile River in Egypt in 1991 (van Rijn and Gaweesh 1994) using the Delft-Nile Sampler was used as a comparison for mechanically collected data. These data were used because the hydraulic and sediment characteristics of the Nile River in the vicinity of the measurements were very close to those of Pool 8. The average bed-load transport was determined by averaging the data for six measurement sites on the Nile recorded in Table 3, page 1374, (van Rijn and Gaweesh 1994). The result was .0175 kg/sec/m (0.0118 lb/sec/ft) of width. For Pool 8 using the multibeam data and the ISDOT method, a value of .0041 kg/sec/m (0.003 lb/sec/ft) was calculated (149 metric tons/day (164 tons/day)). Thus the measured value is four times that of the ISDOT value.

Three transport functions were selected and run using average channel parameters and the sediment characteristics of Pool 8. These functions were: Einstein's bed-load function, Toffaleti's function (Toffaleti 1968), and van Rijn's function. In tons per day (bed-load portion of the bed material load), the respective values were: 2255, 312, and 1688 metric tons (2481, 344, and 1857 tons). The Toffaleti procedure results were slightly more than twice the value computed using the ISDOT method. The other two methods were substantially higher. Further investigation into which transport function gives more reasonable results for large sand bed rivers is being considered.

FUTURE PLANS: For both mechanical and analytic methods, the ISDOT method seems to underpredict the bed-load transport. Without even considering these other two methods, it was already guessed that the results of the present calculations would be a lower value than the maximum. This has to do with the time-step between successive bathymetric measurements. During some of the future trips the need to take the “snapshots” at shorter and more regular intervals will be addressed. In addition, a joint measurement field campaign is being planned with the Delft Hydraulics Laboratory and University of Utrecht researchers in which both measurement techniques will be used side by side. Additionally, the wave celerity method is still being considered and will be discussed with researchers at the University of Iowa. Finally, future cooperation is anticipated with the University of Iowa and the Agricultural Research Service (ARS) National Sedimentation Laboratory researchers for a proof of concept flume study.

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