Using High Resolution Bathymetric Data for Measuring Bed-Load Transport

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Abstract: A new methodology for measuring bed-load transport in sand bed rivers is presented. This methodology uses high-resolution multi-beam bathymetric data taken over discrete time intervals to infer a transport rate. The method is called ISSDOT, which stands for Integrated-Section Surface Difference Over Time. The paper will present a general overview of the concept, and some results obtained to date. These results come from a flume study carried out at the National Sedimentation Laboratory in Oxford Mississippi. A reference is also made to results obtained from actual field measurements on the Mississippi River. The preliminary results show close correspondence to bed load transport rates derived from ISSDOT and an independent measurement technique.

INTRODUCTION

The measurement of bed-load transport in large sand bed rivers has remained elusive and problematic to the present time. Many types of physical sampling methods have been devised and tested over the last century. For examples of such methods see Van Rijn, L. C., and Gaweesh M. (1994), USACE (1995), and Hubbell, D. W., (1964). No method is universally accepted and there is no standard against which to measure an outcome. Analytic and statistical techniques have also been developed to estimate bed-load transport, Nakato (1990). Although successful to varying degrees, even these methods are often sediment-type specific, and still without an absolute standard to measure against with regards to large rivers. A need remains for a methodology of quantifying bed-load transport that is consistent and repeatable. Recent advances in non-intrusive echo scanning devices have resulted in an ability to accurately measure and resolve bathymetric features, Saenz (1997). Thus the bottom of a river can be mapped in fine detail, accurately resolving all sand dunes and ripples. Under lower regime flow conditions much or all of the bed-load moves in dunes and ripples, thus it seems reasonable to try and measure the bed-load transport by measuring changes in the bedforms. The idea was pursued extensively in the past by studying 2-d sand waves, Simons D. B., Richardson E. V., Nordin C. F. Jr., (1965). Some studies were carried out on 3-d waves, Mahmood, Khalid, (1985) but the data were difficult to obtain and process. That is not the case anymore, and so a new methodology for the computation of bed load transport should be developed that will take advantage of the three-dimensional bathymetric data that is now available. This paper introduces the ISSDOT (Integrated Section Surface Difference Over Time) method.

METHODOLOGY

Definition: ISSDOT stands for Integrated Section Surface Difference Over Time.

Integrated Section simply means that the process divides the river or flume cross-section into many small divisions. A value of the transport rate difference across the upstream and downstream boundaries of the cell is computed for each small division. In cases when the bed load transport rate, or sediment flux across one boundary is near zero, this difference will approach the bed load transport rate at the location. At such locations the individual quantities are summed over the entire section. The values obtained can be taken as the total transport for the section, or averaged and presented as a rate per width of channel.

Surface Difference is the resulting surface obtained by mapping a portion of the surface of a sand wave at some initial time, then mapping the exact same location again at some second point in time, and finally subtracting surface-one from surface-two.

Over Time indicates that some measured time difference is allowed to elapse between the mapping of surface one and surface two. This change in time (ΔT) is necessary to infer rates of transport.

An Intuitive Approach to the ISSDOT Concept: The idea is to take the vertical difference of the two measured surfaces for a defined area of the concurrent surfaces, and to compute a volume. For ease of computations, a simple square is used. One square foot, meter, or any other unit can be used. However, a carefully selected size of surface area is important with regards to the sand wave speed and size. Figure 1 shows a schematic of the defined volume.

As can be seen, if surface one was the surface at t1, and surface two was the surface at t2, then the volume inscribed as surface one dropped to the level of surface two, is the area of the square (dY x dX) times the change in height, dη. In this case it would be the volume of scour that occurred in the time interval ΔT. These measurements indicate a change in volume for a given change in time. If this is multiplied by density, then at first glance it would appear that the process has defined a mass transport rate. But, these measured quantities constitute a difference of bed-load transport except in the special case when the fluxes through one boundary or the other may be taken as near zero. This topic will be addressed in more detail in a later paper. In the cases in which ISSDOT yields a value approaching the bed load transport rate, the entire surface of the river or flume was divided into 2-d square surface cells. The size of the cells was chosen such that two or more cells could be used to resolve the deposition side of the smaller waves. Thus in practice, for all the other waves, the resolution is much greater than that. All the cells together form a grid that covers the entire surface area of any selected study location. Some cells of the grid will be located over scour areas on the back side of dunes and ripples, and some will be located over the front side of the dunes. Additionally, some cells will also be located over the troughs of the dunes. Figure 2 shows an example of such a grid superimposed over actual Mississippi River bathymetric data. Though the bathymetric data is real, the grid is for demonstration purposes only and was not used in any calculation.

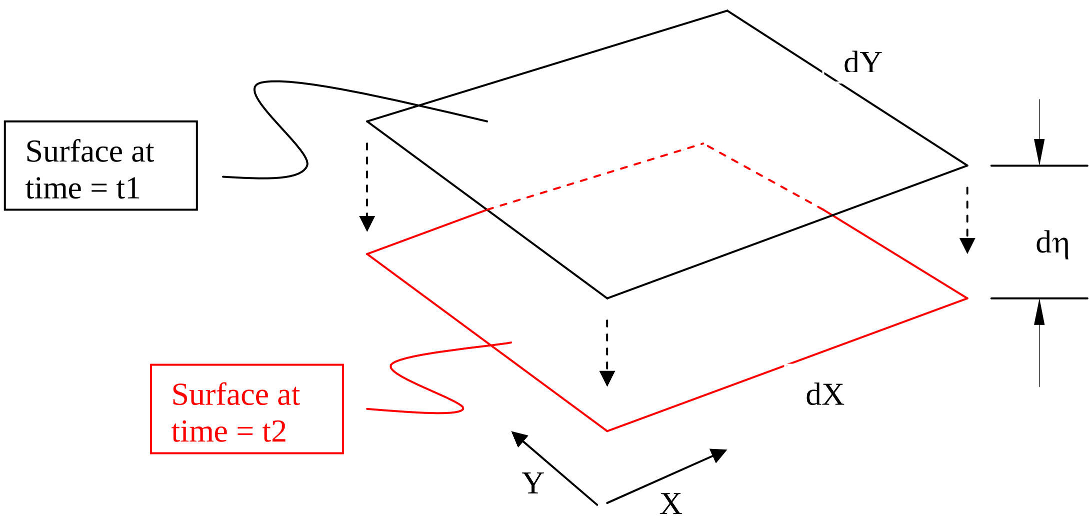

Figure 1 Schematic defining the scour volume.

The intuitive idea of ISSDOT is that each of these cells is an incremental measurement of the sediment transport at that location when the sediment flux through one boundary of the computational cell is near zero. It was found that the cells with negative changes in elevation (scour) approached the bed load transport rate. When the negative change in volume in each cell during a given time span is individually evaluated, then all the cells in any given row can be summed across the entire width of that row to give the total bed-load transport rate for that section. For example, in Figure 2, computations could be made for every cell in row 1. By summing all the cells in row 1 the total for the section can be determined. This is in a sense integrating across the section, thus the IS initials in ISSDOT. The computations for each cell stand alone as a transport measurement much the same way as any physical bottom sampler. For instance, the Helley-Smith or Dutch-Nile samplers are set on the channel bottom for a short period of time to allow sand to enter the collection bag. When the sample is retrieved the mass of sand collected during the time interval that the sampler was in place provides a direct measurement of mass per time per incremental channel width. The time interval must be short enough so that the bag does not completely fill; otherwise the time it took to fill it is unknown. When many samples are taken both laterally and longitudinally in a given channel study area, then some type of statistical average of all samples can be taken as the average transport for that part of the river. It is usually reported as mass per time per unit width of channel. In any case, each sample at each individual location stands alone as one measurement of the transport. A single cell in ISSDOT also stands alone as a single measurement of transport. So in this sense, it might be thought of as a virtual, non-intrusive sampler. In order to test this concept, a flume study was devised. The details of the experimental plan and results are presented in the remainder of this paper.

FLUME STUDY

Proof of concept: Initial tests of ISSDOT on Pool 8 of the Upper Mississippi River indicated that this method showed promise as a non-intrusive technique to measure bed-load transport, Abraham and Hendrickson (2003). So it was decided to test this method under the controlled conditions of a laboratory flume. By doing so the problems of concurrently measuring the bed-load and the suspended load could be addressed. The flume study was conducted at the USDA-Agricultural Research Service, National Sedimentation Laboratory (ARS-NSL) in Oxford Mississippi from December 2002 to February 2003. The purpose of the flume study was to test the ISSDOT concept for measuring bed-load transport. As mentioned earlier, the ISSDOT method depends on being able to accurately measure or map the surfaces of sand waves at two different times. When this is possible, ISSDOT will provide an estimate of the transport of bed-material moving in the sand wave. In the flume, it was possible to measure the suspended bed material as well as the total bed-material load. Thus the basic idea to test ISSDOT was to measure the total bed-material load (Q_{BT}) and to concurrently measure the suspended bed material (Q_S). When the suspended is subtracted from the total, the remainder should be the bed material that is moving in the sand waves, Q_B. When the bed material moving in the sand waves is independently measured at the same time by the ISSDOT method, which we will call Q_{BI}, then Q_{BI} can be compared to Q_B. The foregoing discussion is shown by Equation 4.

$$Q_{BT} - Q_S = Q_B \cong Q_{BI} \tag{4}$$

Figure 3 shows the flume that was used for this study. This flume is 30.5 m (100 ft) long, 1.2 m (4 ft) wide and 0.6 m (2 ft) deep. The sediment-water mixture is recirculated from downstream to upstream via a return pipe running under the flume. Figure 4 shows a schematic diagram (not to scale) identifying the major features of the flume. To reduce clutter in the figure, the head bay, flow diffuser, pump, viewing window and other details are not shown.

The total bed-material load (Q_{BT}) was measured in the return pipe using a density meter. The density meter operated on the principle of vibration amplitude/frequency changes associated with density changes in a vibrating U-tube (Willis, 1977). The change in voltage from the density cell was proportional to the change in density. The density cell was calibrated by passing known concentrations of sand and water through the meter using a test stand similar to that used by Willis (1977). Total sediment load being transported through the flume channel was calculated from mean sediment concentrations measured with the density cell times the flow rate measured from the Venturi meter. The mean sediment concentrations in the return pipe were calculated from a 4-hour record of the density cell stored on a PC.

The suspended sediment (Q_S) was calculated using a combination of acoustic backscatter data collected over the lower 40% of the flow depth with isokinetic physical samples collected in the upper 60% of the flow. These were added together and multiplied by flow rate to yield the suspended load. The basis for the validity of these measurements is described in Kuhnle, Wren (2004). The suspended load was subtracted from the total load to yield a value for the bed load (Q_B) moving in the sand waves.

The bed material moving in the sand waves and computed using the ISSDOT method (Q_{BI}) was mapped with special sensors manufactured by SeaTek Instrumentation and Engineering (http://seatek.com/) and are discussed under the Flume Data heading.

Flume Data: To apply the ISSDOT concept it is necessary to accurately map the sand wave surfaces. This must be done several times over the same location and at known time intervals between each mapping. This was done in the flume by using two sets of sonic transducers. These are shown in Figure 5.

Each sensor bank consisted of 8 transducers for which the acoustic operating frequency was 5 MHz. A signal processing electronics package was also supplied to allow communication with a PC via a RS232 communications port. The electronics package is capable of running up to 32 transducers, and sampling up to 2 external analog channels. Three methods were used to test how well the sensors recorded the distance to the bottom. The results of

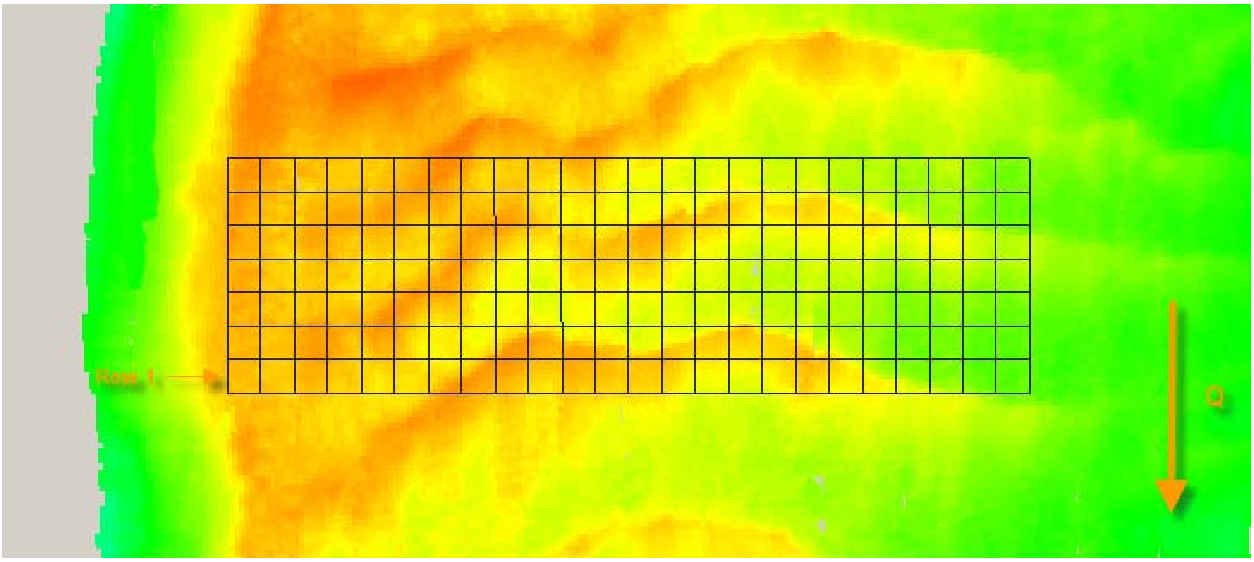

Figure 2 Sample grid superimposed over a plot of bathymetric data.

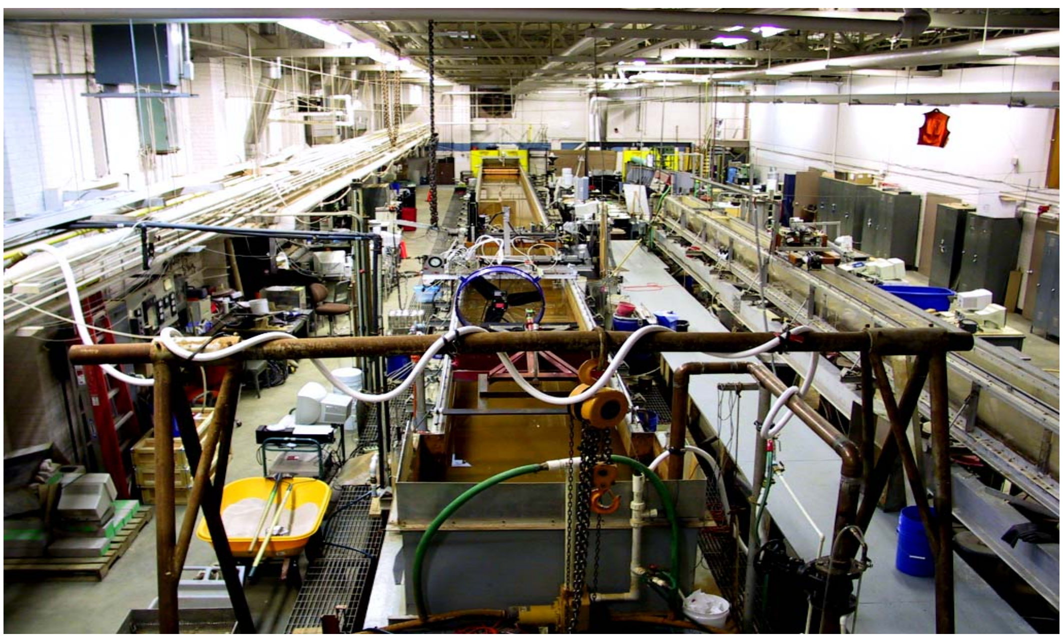

Figure 3 View of experimental flume.

these tests determined the instrument resolution and error. The tests consisted of the following scenarios; multiple depth measurement samples using stationary sensors in still water, two sensors each taking one sample at the same location in still water, and moving sensors in still water.   The maximum average error of the eight sensor pairs was found to be about 2.2 mm. Additionally, the tests indicated that the speed at which the sensor banks traversed the flume did not influence the measurement error.

To map the bottom surfaces the two sensor banks were set a known distance from each other and moved across the flume at a known and constant speed. The bank 'A' of sensors (1 to 8) mapped the bed as it moved from left side to the right side of the flume looking downstream. Bank 'B' of sensors (9 to 16) followed bank A with a spacing of 15.24 cm (6 inches) between them. Thus sensor 9 mapped the same locations as sensor 1, separated by a known change in time (Δt). Values of Δt were selected between 48 and 3 seconds. Likewise, sensor 10 followed sensor 2 and so on for eight pairs of sensors. This produced eight rows of sensor data. The overlap of sensors on bank A and B was the middle 0.76 m (30 in) of the flume cross section. The two sensor banks moved in this case from left to right, with B following A.

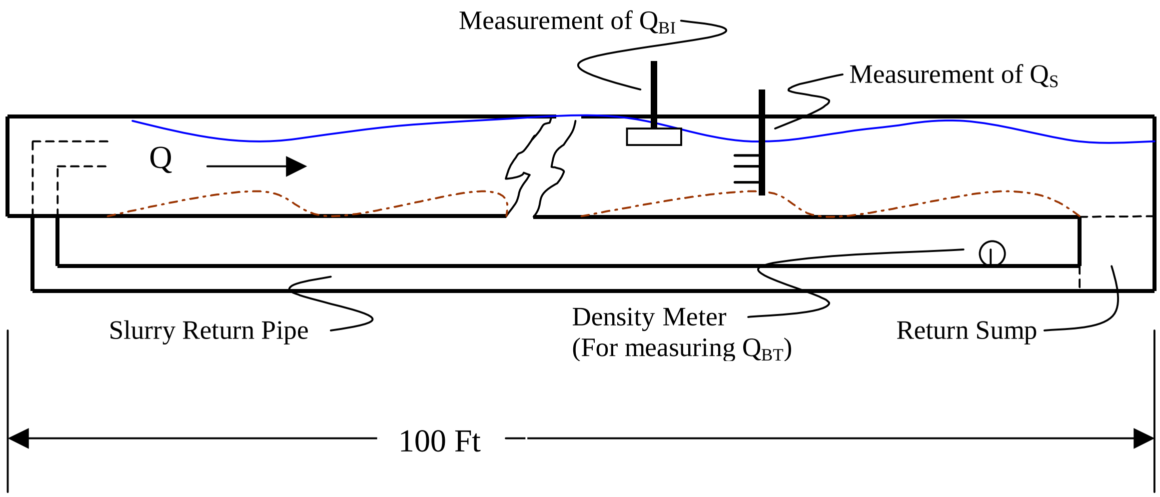

Figure 4 Schematic of experimental flume.

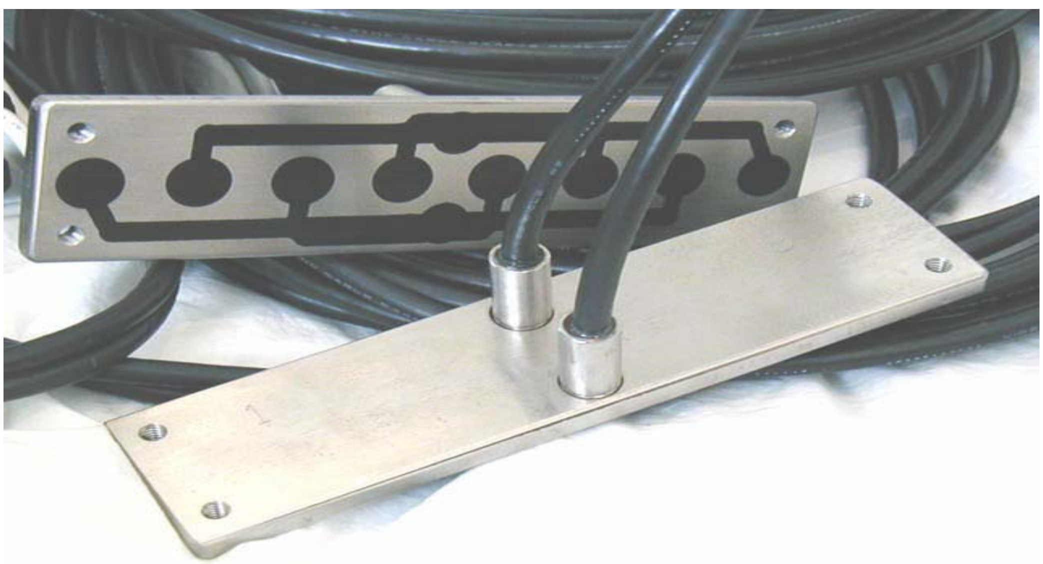

Figure 5 Acoustic sensor banks consisting of 8 transducers each.

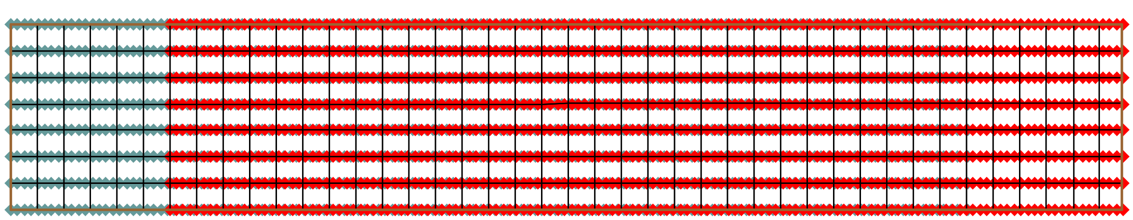

Figure 6 Plot of collected data points showing spacing and overlap on rectangular grid.

This can be seen in Figure 6. The first six inches are mapped by sensor bank B only, and the last six inches are mapped only by sensor bank A. Although shown superimposed one over another on the same grid, the data for each sensor bank were recorded and processed as separate files.

The eight lines of data traced by each sensor bank were processed to remove spurious data points and interpolated to a grid on 2.54 cm (1-in) squares. To apply the ISSDOT method, the nodal values on grid A were subtracted from those on grid B. An example of such a surface difference grid is shown in Figure 7. The overlapping computational cells are clearly visible in the center of the grid.

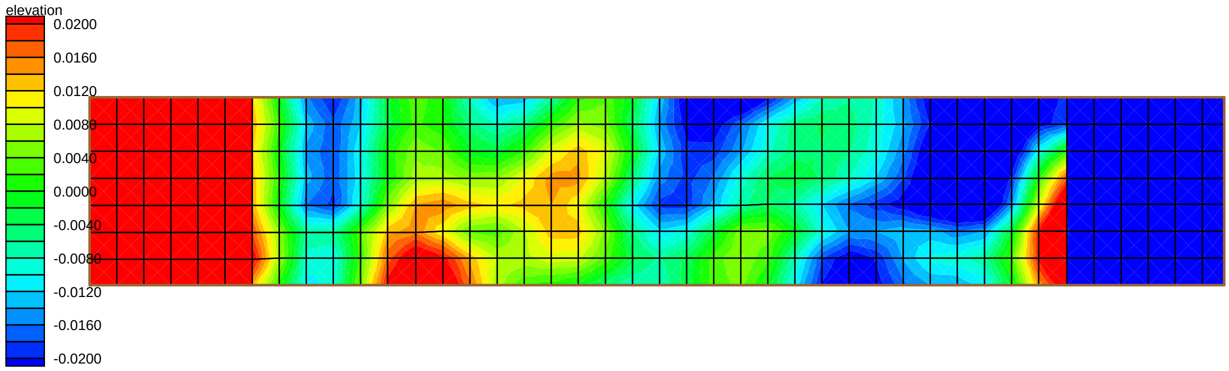

Figure 7 Contours of surface differences superimposed on computational grid.

At this point the processing of the raw data is complete and the grid is ready to be used in the ISSDOT computations. The computations are carried out on each element, or cell, in the grid. The cells consist of the four nodes that make up any square in the grid. It is these cells that form the individual computational units of this method as already described in the section, **An Intuitive Approach to the ISSDOT Concept**.

RESULTS

As explained above, the general idea was to determine the bed-load transport in the sand waves using the new methodology, and compare it to the measured bed-load transport of the same waves. This is quantitatively expressed in equation 4. The outcome of measurements to determine the total bed-material load, $Q_{BT,}$ showed a measured value of 0.0695 kg/s m (0.0467 lbs/s/ft). These data were obtained using the density meter. For the suspended load, its measured value was determined to be 58.6 percent of Q_{BT}. Thus the measured value of bed-material load moving in the sand waves (Q_B) must be 41.4 percent of Q_{BT}, or approximately 0.028 kg/s/m (0.019 lbs/sec/ft). For any computations of ISSDOT, this is the value to compare to.

Table 1 is a tabulation of computations for run six for the medium flow runs, and combined data points of all runs and sweeps. Only the scour elements were considered in all computations. The file name indicates the run and sweep number as well as the fact that it is a difference geometry file. The second column shows the number of scour elements for that file. The third column shows the number of scour elements whose change in elevation was less than the measurement error bound of 2.2mm. These elements were removed from the computations. DT, in the fourth column is the time increment used in the computations The average cell transport for the entire grid in the units specified for a given run and sweep are shown in the last two columns.

The top half of the table shows run 6 with 7 sweeps across the flume, and the DT for each sweep. All other runs (run 1 to run 5) used the same DT schedule. The time dependence of computed transport can be observed in the data. For the elements with negative changes in volume, (scour cells) ISSDOT predicted rates from 0.0044 to 0.046 kg/s/m (0.003 to 0.031 lbs/s/ft). The six runs that were analyzed covered a time span of about 2 hours. This ensured that many different wave configurations were measured and that the spatial variability of the sand waves was accounted for. The average value of all runs and sweeps was 0.019 kg/s/m (0.013 lbs/sec/ft), which compares well with the measured value of 0.028 kg/s/m (0.019 lbs/s/ft). This value is 31% lower than expected, and is without regards to the time difference between measurements.

If one considers bracketing DT, then slightly different values of average transport will be computed. These are shown at the bottom of Table 1.

Table 1 Results of run six and combined sweeps of all runs.

File Name	No. of scour	Removed	DT	Avg. Trans.	Avg. Trans.
	elements	elements	seconds	lbs/s/ft	kg/s/m
r6s1b-a.geo	173	13	48	0.003	0.004
r6s2b-a.geo	106	32	24	0.004	0.006
r6s3b-a.geo	87	29	12	0.008	0.012
r6s4b-a.geo	106	39	8	0.011	0.016
r6s5b-a.geo	81	62	6	0.014	0.021
r6s6b-a.geo	57	25	4	0.021	0.031
r6s7b-a.geo	47	9	3	0.031	0.046
Below data are for all runs and sweeps:					
Avg. of all data pts. for all sweeps				0.0128	0.019
Avg. of data pts.for sweep 2-6 [dt=24 through 4]				0.0126	0.019
Avg. of data pts.for sweep 3-5 [dt=12 through 6]				0.0127	0.019
Avg. of data pts. for sweep 2-7 [dt=24 through 3]				0.0144	0.021
Avg. of data pts.for sweep 3-7 [dt=12 through 3]				0.0162	0.024

CONCLUSIONS

Although the ISSDOT method in general yields the difference between the bed load transport rate at the upstream and downstream edge of each element, it has been found that the elements with negative changes (scour) closely approximate the bed load transport. This case has been shown with data from a laboratory flume with a sand bed (D50= 0.5 mm) with equilibrium dunes on the bed. While more testing is needed, this result indicates that a subset of the ISSDOT determined values may serve as a reliable indicator of the bed load transport on a channel bed with dunes as the stable bed form. Further studies should be carried out to further validate these conclusions and to formulate an analytic basis for the methodology as well as to explore its applications and limitations.

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