Virtual velocity of sand transport in water

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Introduction

In a recent ESEX commentary, Parsons *et al.* (2015, p.1419) argued that “there is no inherent physical difference between so-called suspended sediment and bedload or saltating load, and that, in reality, all sediment transport lies along a continuum of hop lengths and virtual velocities” They further commented (p. 1419) that because the concepts of hop length and virtual velocity have not “been thought relevant to so-called suspended sediment, details of how fast suspended sediment moves in relation to the velocity of flow, either as virtual velocity including the periods of rest on the bed or as actual velocity during movement, is lacking.” Obtaining such information is inherently difficult because the typical size of such sediment renders impossible many of the tracking techniques that have been used to study the movement of bedload in water (e.g. Hassan *et al*., 1991; Ferguson and Wathen, 1998; Lammare *et al*., 2005). However, this information is important for estimation of bed material yield and sediment residence times, and for understanding morphological change, catchment connectivity and particulate pollutant transport.

Recent work by Mao *et al*. (2017) has used spray-painted sections of river beds, and been able to extend the information on virtual velocity to particles as small as 4 mm. However, if particles are small enough to be considered conventionally as suspended load it would seem intuitively likely that their virtual velocities are a relatively large fraction of water velocity, so that detecting them after a transport event may be difficult. Whereas Milan (2013), for example, reported virtual velocities of particles with D_{50} of 61 mm in terms of m/day, virtual velocities of sand-sized particles transported at high values of excess shear stress are likely to be of the order of m/s. Here, we report on an experiment using a long flume to provide a first attempt at determining the virtual velocity of such sand-sized sediment in water.

Methods

A single experiment was performed using the large flume facility at the University of Tsukuba, Japan. This flume is 160-m long, 4-m wide and 2-m deep, has a fixed slope of 1/100, and discharges into a 2000-m^3-capacity settling tank from which water is recirculated through an underground pipe system to large tanks located approximately 40 m upslope of the flume from which the discharge is pumped (Ikeda, 1983). It was constructed between 1976 and 1979 but has been little used in recent years. In consequence, the flume floor is now rusty, but free of all sediment (Figure 1a). In parts, the floor has a pseudo-granular roughness created by the irregularity in the rusted surface. Elsewhere the flume floor has rust layers peeling off, creating larger-scale roughness. In addition, where sections of the flume are joined together, channel-like depressions (<1 cm deep) cross the flume floor (Figure 1a). Within this flume a steady flow discharge of 0.95 m^3 s^{-1} was used to create a uniform flow depth of 0.12 m that persisted to a distance of 145 m within the flume. The width/depth ratio (w/h = 33) was much greater than 5, ensuring two-dimensional flow (Nezu and Nakagawa, 1993). This discharge gave a mean flow velocity (estimated from the depth and discharge) of 1.98 m s^{-1} and a mean flow shear velocity of 0.109 m s^{-1}. The hydraulic roughness, calculated using this mean flow velocity (Keulegan, 1938), was 0.99 mm giving a relative roughness (depth/roughness) of 122 [-]. Thus the surface roughness was very small relative to the depth of flow, such that no water surface effects interfered with the transport processes (Bettess, 1984). Beyond a distance of 145 m the flow was gradually varied and a hydraulic jump formed at a distance of approximately 155 m due to a weir at the downstream end of the flume. Into the upstream end of the flume we poured 25 kg of sand with a median diameter of 1.32 mm and a maximum size of 2.36 mm. This small quantity enabled the sand to be introduced into the flow in a short time and minimized any possible effect of grain-to-grain collision on sediment velocity (Abrahams and Atkinson, 1993). For studying sediment transport, we restricted our analysis to that part of the sand < 2mm, which comprised 96% of the total sand weight. During later analysis this part was separated it into three size classes; 0.5 to 1.0 mm, 1.0 to 1.4 mm, and 1.4 to 2.0 mm. The median diameter of the particles in each of these size classes was 0.79 mm, 1.20 mm, and 1.61 mm, respectively.

Several formulae exist to calculate the critical shear velocity above which a particle of a given size is conventionally considered to be transported in suspension. Some of these formulae are based on the assumption that a particle is in suspension when the upward velocity of turbulent eddies (estimated by the shear or flow velocity) exceeds the settling velocity of the particle (Rubey, 1933; Rouse, 1937; Lane and Kalinske, 1939; Engelund, 1965; Bagnold, 1966, Middleton, 1976; Engelund and Fredsoe, 1982; Egiazaroff, 1965), whereas others are empirically derived (van Rijn, 1984; Komar and Clemens, 1986; Sumer, 1986; Celik and Rodi, 1991; Paphitis, 2001; Cheng, 2008). For particles in the size range studied here, these formulae give critical shear velocities that range over an order of magnitude. However, for the majority of them, and certainly all of those that are empirically derived, the sediment used in this study satisfies the suspension criterion (Table 1).

Once the steady discharge was established, the sand, which had previously been sprayed with fluorescent paint to aid later identification, was poured steadily into the top end of the flume from three containers positioned at 1, 2 and 3 m from the right-hand side of the flume. Introduction of the sand into the flow took 50 s, and observations of the sediment plume indicated that it was transported in suspension away from the points of introduction. After the introduction of the sand, the discharge was run for 180 s, after which time the pumps were ramped down over a period of 240 s, and the flume bed was left to drain and dry. If all particles had remained in suspension and travelled at the same velocity as the water during the transporting discharge, that discharge was of sufficient duration to ensure all particles could be easily transported the complete length of the flume (in the time of the experiment the water would travel a minimum of 356 m (after the completion of the introduction of the sand) and a maximum of 455 m (after the start of the introduction of the sand), compared to the flume length of 160 m). Observations of the flume bed, however, using a UV light showed that fluorescent sand particles were present on the bed. The flume floor was then swept from the top end of the flume in 5-m-long sections and the combination of sand grains and rust particles bagged for later analysis. Collection of material for analysis was terminated at 145 m because of the backwater effect caused by the weir at the end of the flume. In addition to collecting the material for analysis, further material from the backwater area was also collected downflume for a further 10 m beyond which the density of fluorescent particles became very low compared to the quantity of rust particles. This further material was required to estimate a recovery rate.

The analysis of the 29, 5-m-length samples comprised preliminary riddling down to 4 mm to remove the coarsest rust particles, sieving and discarding material coarser than 2 mm and finer than 0.5 mm, and separating of rust and sand grains in the retained portion using an electromagnet. Observations with a UV light indicated that some of the introduced sand was lost in this technique because it was picked up along with the rust particles. We estimate this loss to be no more than 5%. Finally, the retained sediment was washed to remove rust dust, dried and resieved to separate it into three size classes; 0.5 to 1.0 mm, 1.0 to 1.4 mm, and 1.4 to 2.0 mm. For the further material collected beyond 145 m, we employed a similar methodology, but because of the amount of material involved, after riddling (when approximately 100 kg of rust and sand particles still remained), the sample was riffled down to a one-eighth sample prior to further treatment.

Results

A few grains of the sand were identified less than 5 m from the point of introduction and progressively (but irregularly) more downflume (see Figure 2). The total amount of sand recovered (including that from the backwater area) was 20.4 kg, which represents 85% of the introduced sediment in the size range from 0.5 to 2.0 mm. Most likely, the unrecovered sediment was left in the unsampled last 5 m of the flume, or passed beyond the weir at the lower end of the flume into the settling tank. Amounts of deposited sand were small over the first 120 m. No 5-m section contained more than 100 g of the sediment, and only four contained more than 10 g. However, beyond this point deposition increased markedly, so that up to 145 m (well upflume of the part affected by the backwater effect of the weir; backwater length was 8.4 m based on Samuels, 1996) almost 4.5 kg (or more than 18%) was deposited. Examination of the percentage of sediment deposited in this first 145 m showed marked variation with particle size. Almost 40% of the sediment 0.5 to 1.0 mm was deposited, compared to 14.6% and 12.2% of the 1.0 to 1.4 mm and the 1.4 to 2.0 mm sediment, respectively. Paradoxically, more of the finer sediment was deposited than the coarser sediment (Fig 2). The distributions of the travel distances of the sand in three particle-size classes shown in Figure 2 are slight overestimates of the true travel distance during the experiment because (i) loss of sediment along with the rust particles in the separation method results in an underestimate of sediment deposited at each distance; (ii) the recovery location will also include some (additional) distance in transport as bedload in the waning phase of the flow; and (iii) anything less than 100 % recovery rate of the introduced sediment leads to overestimation of travel distance. We have estimated that these factors will introduce no more than a 10% error. On the other hand, it is inconceivable that the pattern of sediment deposition is simply the result of deposition in the waning phase of flow, given the experimental conditions described above. The amount of sediment recovered, the size of the flume, the weir at the downstream end, the capacity of the settling tank at the bottom end and the duration of the experiment make it impossible for deposition to be a result of particles having been transported off the end of the flume, re-circulated and re-entered into the upstream end of the flume.

We have no data on which to base an expected distribution function for the travel distance of sand-sized sediment. Work on bedload (Bradley and Tucker, 2012; Yang and Saye, 1971) suggests the distribution function is right-skewed. Accordingly, we have fitted a gamma distribution and compared it to a normal distribution fitted to our data (Figure 3), optimizing these fits according to the known total amount of sediment that must be accommodated within the distributions and the proportion of the distribution observed in our data up to 145 m downflume. Although neither distribution is a particularly close fit to the data (Figure 3), Nash-Sutcliffe efficiencies for the two models are quite high (Table 2) and all but one of the Kolmogorov-Smirnov tests for goodness of fit is significant at $p<0.001$ (Table 2). Such evidence as we have therefore suggests a normal distribution fits our data better than a gamma distribution. However, we have used both distributions to estimate the mean travel distances of the three particle size classes. For the normal distribution, these distances are 151 m, 165 m and 168 m for the 0.5-1.0mm, 1.0-1.4 mm and 1.4-2.0 mm particle-size classes, respectively. For comparison, mean travel distances estimated from a gamma distribution are 150 m, 161 and 163 m. Assuming a travel time of 205 s (half the duration of the sediment input plus the experiment duration after sediment input was complete), gives a virtual velocity (simply defined as the mean travel distance for the size class divided by 205s) of the three sediment size classes of 0.74, 0.80 and 0.82 m s^{-1}, respectively, under the assumption of a normal distribution, compared to the water velocity of 1.98 m s^{-1}. In comparison, the mean travel distances from the gamma distributions give virtual velocities of 0.73, 0.79 and 0.80 m s^{-1}. These results give a virtual velocity lower than that for saltating particles obtained by Chatanantavet *et al.* 2013), who found an average virtual velocity of 0.8 of the water velocity over a range of channel slopes. These authors also found no difference in virtual velocity with particle size in contrast to our inverse relationships with particle size.

The irregularity of the deposition is also noteworthy. Sections at 40-45 m, 90-95 m and 120-135 m all show exceptionally high amounts of deposition. In contrast, sections 45-80 m, 100-105 m 110-115 m and 135 -140 m show less deposition than might be expected. The former group coincide with joints between sections of the flume or significant rust layers. Many of the latter group coincide with smoother sections of the flume bed. Since joints are regularly spaced along the flume and rust shows no downflume spatial pattern, these factors affect the irregularity of the deposition but not its overall distribution. Natural channels have significant roughness induced by reach-scale bedforms (e.g. point bars, riffle-pools) and patch- and grain-scale bedforms (e.g. transverse ribs, pebble clusters) so that the trapping of suspended sediment in such channels may be akin to that found in the rougher sections of the flume used in this study.

Comparison with virtual velocities of bedload

Mao *et al* (2017, Fig 10) plotted virtual velocities of particles between 4 and 160 mm as a function of dimensionless shear stress for two rivers in northern Italy. For their dataset, virtual velocities and dimensionless shear stress ranged from 0.0406 to 3.236 m h^{-1} and from 0.0196 to 0.0548, respectively. In contrast, our data (using the estimates based on the normal distribution) range from 2664 to 2952 m h^{-1}, and from 0.868 to 0.26 (Fig. 3). Mao *et al.* fitted linear regressions to their data, but these equations substantially underpredict our observed values (yielding values between 24 and 52 m h^{-1}, compared to observed velocities of between 2664 and 2952 m h^{-1}). Comparable data to that of Mao *et al.* can be extracted from

Haschenburger & Church (1998) who examined movement of tracer particles ranging from 16 to 180 mm in a small stream on Vancouver Island, and from Wong *et al*. (2007) who undertook a flume study of the movement of particles with a median size of 7.1 mm. Taking all of these data together yields a power relationship (Fig. 4)

$$V = 58209\tau^{*3.4434} \quad (1)$$

in which V is virtual velocity (m h^{-1}) and τ^* is dimensionless shear stress that fits the combined data well ($R^2 = 0.837$). Although the strength of this relationship indicates promise for "an holistic approach to sediment transport" (Parsons *et al*., 2015, p.1419), the paucity of data in the finer size range makes it better to regard this relationship as an hypothesis rather than a predictive model. Nonetheless, it is instructive to compare these datasets with those of Huxman *et al*. (2004) who examined rain-use efficiency across biomes in a similar attempt to identify a common relationship. Looking at ecosystems varying by an order of magnitude in annual precipitation, these authors were able to find a common relationship between net annual primary production and annual precipitation, but noted that there was substantial variation in the sensitivity relationships between the 14 sites (including one site with an inverse relationship), indicating local characteristics could mask a trend only visible at a global scale. Likewise, for the five datasets of Figure 4. Individual relationships differ markedly from site to site (as indicated by the individual regression lines), but over order-of-magnitude scales a common behaviour may be discerned.

Discussion and Conclusion

Although not ideal, because of its rusty state, the large flume at the University of Tsukuba has provided an opportunity for a first attempt to measure the virtual velocity of sand-sized sediment in water at high values of excess shear stress. The experiment clearly demonstrates that the sediment does travel intermittently because it has a virtual velocity that is less than that of the flow in which the sediment is travelling. In that sense, the transported sand exhibited behaviour no different from bedload or saltating load. For the sediment-size range and flow velocity used in our experiment this virtual velocity is 37-41 % of the flow velocity. Much sediment in rivers conventionally termed suspended is finer than that used in this experiment, so that this virtual velocity may not be representative of most fine sediment. However, if our observation that finer sediment has a lower virtual velocity than coarser sediment extends beyond the size range used here, and is not an artefact of our experiment, it may, in fact, be an underestimate. Such a lower virtual velocity of finer sediment is not inconceivable. First, trapping, and hence virtual velocity, of the sediment appears to be a function of bed roughness, and there is a probable relationship between bed roughness and trapping efficiency for particles of different sizes (Lisle, 1989; Niño *et al.*, 2003; Fries and Taghon, 2010; Hamm *et al.*, 2011; Gibson *et al.*, 2009). Secondly, finer particles are more likely to find sheltered positions on a rough bed and thus experience lower mobility, relative to the more exposed coarser grains, as observed for bedload transport (Parker *et al.*, 1982). Thirdly, the virtual velocity of particles undergoing bedload transport has been found, in some instances, to be lower for finer clasts (Milan, 2013). Our data show that trapping of sand-sized sediment is strongly controlled by the nature of the bed, specifically in our case by roughness of the flume bed. The role of bed roughness in determining the virtual velocity of sand-sized sediment, in particular as it is controlled by bed-material calibre in natural rivers, clearly needs further study, as do the hop lengths of fine sediment. However, better and more time-efficient methods than the one employed here will be required. Combining our results with those for bedload virtual velocities has allowed us to propose, for the first time, an hypothesis for an holistic analysis of sediment movement in rivers.

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Table 1 Suspended sediment criteria for sediment used in the experiment. Y denotes sediment satisfies the suspension threshold, N denotes it does not.

Particle size class	Suspension Criterion									
	van Rijn (1984)*	Engelund (1965)#	Sumer (1986)*	Celik & Rodi (1991)*	Komar & Clemens (1986)*	Paphitis (2001)*	Cheng (2008)*	Engelund & Fredsoe (1982)# Bagnold (1966)#	Rubey (1933)# Middleton (1976)# Lane & Kalinske (1939)# Egiazaroff (1965)#	Rouse (1937)#
0.5mm – 1.0 mm	Y	Y	Y	Y	Y	Y	Y	Y	Incipient	Incipient
1.00 mm – 1.4 mm	Y	Y	Y	Y	Y	Y	Y	Incipient	N	N
1.4 mm – 2.0 mm	Y	Y	Y	Y	Y	Y	Y	N	N	N

* denotes an empirically derived threshold and # denotes a theoretical or assumed threshold

Table 2 Fits of normal and gamma distributions to particle-size data

Probability distribution	Particle size class					
	0.5 – 1.0 mm		1.0 – 1.4 mm		1.4 – 2.0 mm	
	Nash-Sutcliffe efficiency	K-S p-value	Nash-Sutcliffe efficiency	K-S p-value	Nash-Sutcliffe efficiency	K-S probability
gamma	0.798	0.0037	0.634	<0.001	0.594	<0.001
normal	0.933	<0.001	0.823	<0.001	0.815	<0.001

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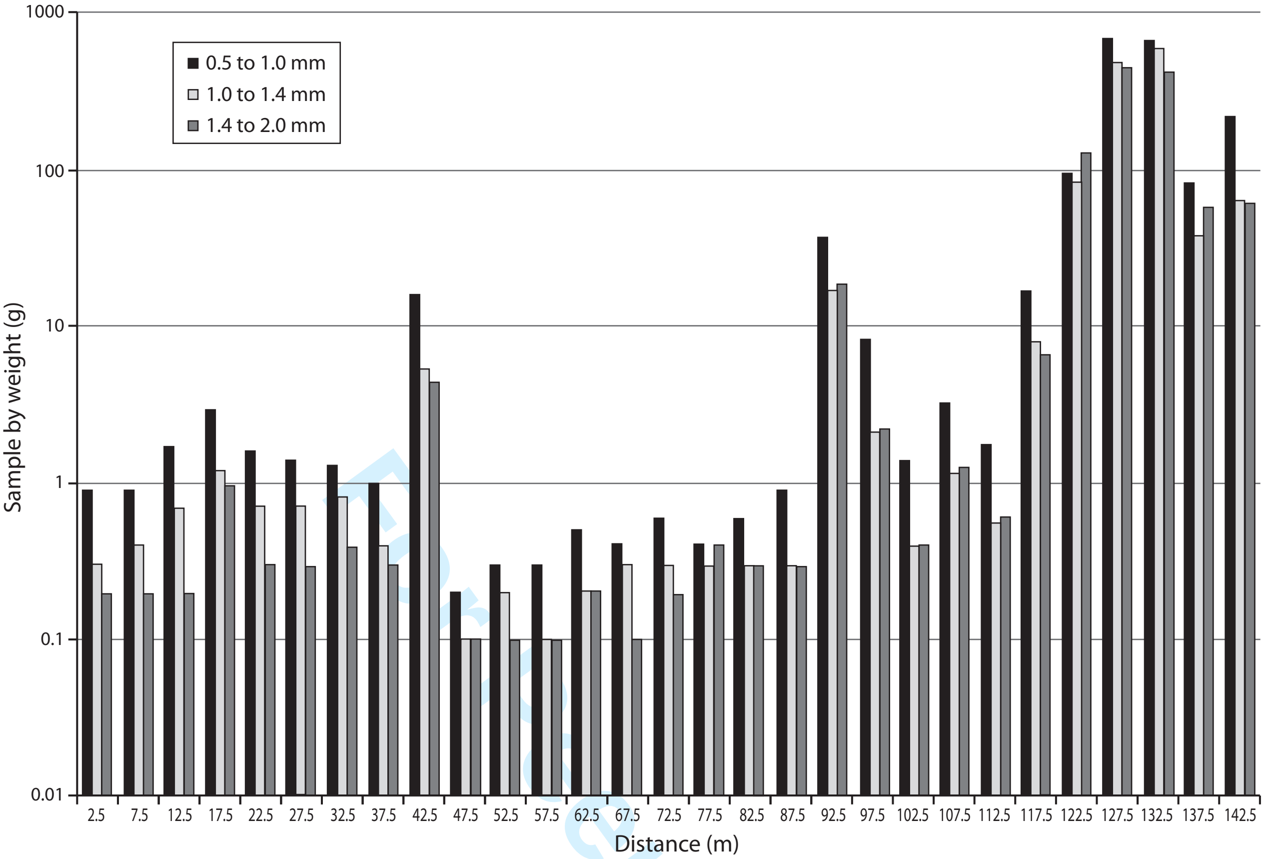
Figure 3	Fits of normal and gamma distributions to cumulative distributions of deposited particles by size class
Figure 4	Relationship of results from the present experiment with those from bedload tracer studies.

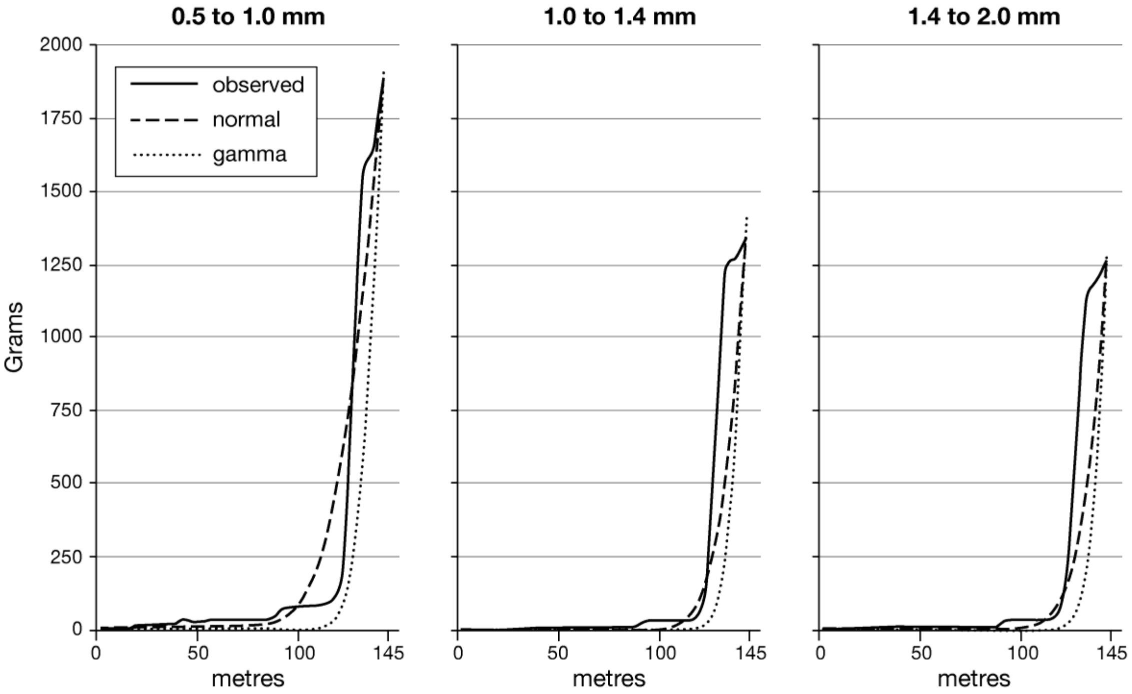
bed of flume looking downflume showing rusting flume bed

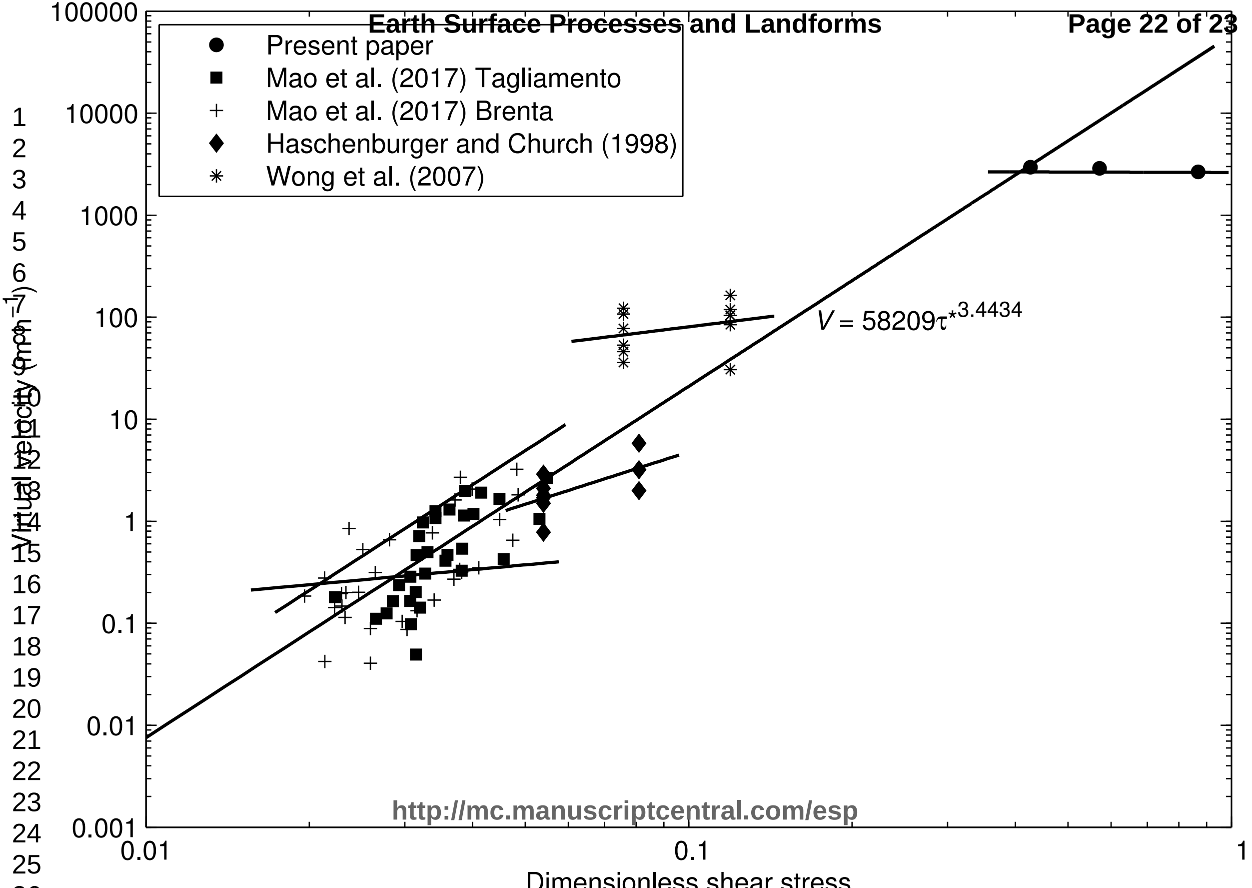
1219x1625mm (72 x 72 DPI)

flume showing flow during experiment looking upflume

1219x1625mm (72 x 72 DPI)


0.5 to 1.0 mm
1.0 to 1.4 mm
1.4 to 2.0 mm
Sample by weight (g)
1000
100
10
1
0.1
0.01
2.5
7.5
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
67.5
72.5
77.5
82.5
87.5
92.5
97.5
102.5
107.5
112.5
117.5
122.5
127.5
132.5
137.5
142.5
Distance (m)


0.5 to 1.0 mm
1.0 to 1.4 mm
1.4 to 2.0 mm
Grams
2000
1750
1500
1250
1000
750
500
250
0
observed
normal
gamma
0
50
100
145
metres


● Present paper
■ Mao et al. (2017) Tagliamento
+ Mao et al. (2017) Brenta
♦ Haschenburger and Church (1998)
✳ Wong et al. (2007)
$V = 58209\tau^{*3.4434}$
Virtual velocity (m h^{-1})
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.01
0.1
1
Dimensionless shear stress

Virtual velocity of sand transport in water

Anthony J. Parsons[*], James R. Cooper, John Wainwright and Tomohiro Sekiguichi

Sand-sized sediment that would traditionally be classed as suspended load in rivers is shown to travel intermittently and have a virtual velocity about 40% of the flow velocity. A unified relationship for virtual velocity against dimensionless shear stress is proposed for all sediment transport.