Virtual velocity of sand transport in water

SCHOLARONE™
Manuscripts

1   **Introduction**

2   In a recent ESEX commentary, Parsons *et al.* (2015, p.1419) argued that "there is no inherent

3   physical difference between so-called suspended sediment and bedload or saltating load, and

4   that, in reality, all sediment transport lies along a continuum of hop lengths and virtual

5   velocities" They further commented (p. 1419) that because the concepts of hop length and

6   virtual velocity have not "been thought relevant to so-called suspended sediment, details of

7   how fast suspended sediment moves in relation to the velocity of flow, either as virtual

8   velocity including the periods of rest on the bed or as actual velocity during movement, is

9   lacking." Obtaining such information is inherently difficult because the typical size of such

10   sediment renders impossible many of the tracking techniques that have been used to study the

11   movement of bedload in water (e.g. Hassan *et al*., 1991; Ferguson and Wathen, 1998;

12   Lammare *et al*., 2005). However, this information is important for estimation of bed material

13   yield and sediment residence times, and for understanding morphological change, catchment

14   connectivity and particulate pollutant transport.

15   Recent work by Mao *et al*. (2017) has used spray-painted sections of river beds, and

16   been able to extend the information on virtual velocity to particles as small as 4 mm.

17   However, if particles are small enough to be considered conventionally as suspended load it

18   would seem intuitively likely that their virtual velocities are a relatively large fraction of

19   water velocity, so that detecting them after a transport event may be difficult. Whereas Milan

20   (2013), for example, reported virtual velocities of particles with D_{50} of 61 mm in terms of

21   m/day, virtual velocities of sand-sized particles transported at high values of excess shear

22   stress are likely to be of the order of m/s. Here, we report on an experiment using a long

23   flume to provide a first attempt at determining the virtual velocity of such sand-sized

24   sediment in water.

25

26   **Methods**

27   A single experiment was performed using the large flume facility at the University of

28   Tsukuba, Japan. This flume is 160-m long, 4-m wide and 2-m deep, has a fixed slope of

29   1/100, and discharges into a 2000-m^3-capacity settling tank from which water is recirculated

30   through an underground pipe system to large tanks located approximately 40 m upslope of

31   the flume from which the discharge is pumped (Ikeda, 1983). It was constructed between

32   1976 and 1979 but has been little used in recent years. In consequence, the flume floor is now

33   rusty, but free of all sediment (Figure 1a). In parts, the floor has a pseudo-granular roughness

34   created by the irregularity in the rusted surface. Elsewhere the flume floor has rust layers

35   peeling off, creating larger-scale roughness. In addition, where sections of the flume are

36   joined together, channel-like depressions (<1 cm deep) cross the flume floor (Figure 1a).

37   Within this flume a steady flow discharge of 0.95 m^3 s^{-1} was used to create a uniform flow

38   depth of 0.12 m that persisted to a distance of 145 m within the flume. The width/depth ratio

39   (w/h = 33) was much greater than 5, ensuring two-dimensional flow (Nezu and Nakagawa,

40   1993). This discharge gave a mean flow velocity (estimated from the depth and discharge) of

41   1.98 m s^{-1} and a mean flow shear velocity of 0.109 m s^{-1}. The hydraulic roughness,

42   calculated using this mean flow velocity (Keulegan, 1938), was 0.99 mm giving a relative

43   roughness (depth/roughness) of 122 [-]. Thus the surface roughness was very small relative to

44   the depth of flow, such that no water surface effects interfered with the transport processes

45   (Bettess, 1984). Beyond a distance of 145 m the flow was gradually varied and a hydraulic

46   jump formed at a distance of approximately 155 m due to a weir at the downstream end of the

47   flume. Into the upstream end of the flume we poured 25 kg of sand with a median diameter

48   of 1.32 mm and a maximum size of 2.36 mm. This small quantity enabled the sand to be

49   introduced into the flow in a short time and minimized any possible effect of grain-to-grain

50   collision on sediment velocity (Abrahams and Atkinson, 1993). For studying sediment

51   transport, we restricted our analysis to that part of the sand < 2mm, which comprised 96% of

52   the total sand weight. During later analysis this part was separated it into three size classes;

53   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

54   each of these size classes was 0.79 mm, 1.20 mm, and 1.61 mm, respectively.

55   Several formulae exist to calculate the critical shear velocity above which a particle of

56   a given size is conventionally considered to be transported in suspension. Some of these

57   formulae are based on the assumption that a particle is in suspension when the upward

58   velocity of turbulent eddies (estimated by the shear or flow velocity) exceeds the settling

59   velocity of the particle (Rubey, 1933; Rouse, 1937; Lane and Kalinske, 1939; Engelund,

60   1965; Bagnold, 1966, Middleton, 1976; Engelund and Fredsoe, 1982; Egiazaroff, 1965),

61   whereas others are empirically derived (van Rijn, 1984; Komar and Clemens, 1986; Sumer,

62   1986; Celik and Rodi, 1991; Paphitis, 2001; Cheng, 2008). For particles in the size range

63   studied here, these formulae give critical shear velocities that range over an order of

64   magnitude. However, for the majority of them, and certainly all of those that are empirically

65   derived, the sediment used in this study satisfies the suspension criterion (Table 1).

66   Once the steady discharge was established, the sand, which had previously been

67   sprayed with fluorescent paint to aid later identification, was poured steadily into the top end

68   of the flume from three containers positioned at 1, 2 and 3 m from the right-hand side of the

69   flume. Introduction of the sand into the flow took 50 s, and observations of the sediment

70   plume indicated that it was transported in suspension away from the points of introduction.

71   After the introduction of the sand, the discharge was run for 180 s, after which time the

72   pumps were ramped down over a period of 240 s, and the flume bed was left to drain and dry.

73   If all particles had remained in suspension and travelled at the same velocity as the water

74   during the transporting discharge, that discharge was of sufficient duration to ensure all

75   particles could be easily transported the complete length of the flume (in the time of the

76   experiment the water would travel a minimum of 356 m (after the completion of the

77   introduction of the sand) and a maximum of 455 m (after the start of the introduction of the

78   sand), compared to the flume length of 160 m). Observations of the flume bed, however,

79   using a UV light showed that fluorescent sand particles were present on the bed. The flume

80   floor was then swept from the top end of the flume in 5-m-long sections and the combination

81   of sand grains and rust particles bagged for later analysis. Collection of material for analysis

82   was terminated at 145 m because of the backwater effect caused by the weir at the end of the

83   flume. In addition to collecting the material for analysis, further material from the backwater

84   area was also collected downflume for a further 10 m beyond which the density of

85   fluorescent particles became very low compared to the quantity of rust particles. This further

86   material was required to estimate a recovery rate.

87   The analysis of the 29, 5-m-length samples comprised preliminary riddling down to 4

88   mm to remove the coarsest rust particles, sieving and discarding material coarser than 2 mm

89   and finer than 0.5 mm, and separating of rust and sand grains in the retained portion using an

90   electromagnet. Observations with a UV light indicated that some of the introduced sand was

91   lost in this technique because it was picked up along with the rust particles. We estimate this

92   loss to be no more than 5%. Finally, the retained sediment was washed to remove rust dust,

93   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

94   to 2.0 mm. For the further material collected beyond 145 m, we employed a similar

95   methodology, but because of the amount of material involved, after riddling (when

96   approximately 100 kg of rust and sand particles still remained), the sample was riffled down

97   to a one-eighth sample prior to further treatment.

98

99   **Results**

100   A few grains of the sand were identified less than 5 m from the point of introduction and

101   progressively (but irregularly) more downflume (see Figure 2). The total amount of sand

102   recovered (including that from the backwater area) was 20.4 kg, which represents 85% of the

103   introduced sediment in the size range from 0.5 to 2.0 mm. Most likely, the unrecovered

104   sediment was left in the unsampled last 5 m of the flume, or passed beyond the weir at the

105   lower end of the flume into the settling tank. Amounts of deposited sand were small over the

106   first 120 m. No 5-m section contained more than 100 g of the sediment, and only four

107   contained more than 10 g. However, beyond this point deposition increased markedly, so that

108   up to 145 m (well upflume of the part affected by the backwater effect of the weir; backwater

109   length was 8.4 m based on Samuels, 1996) almost 4.5 kg (or more than 18%) was deposited.

110   Examination of the percentage of sediment deposited in this first 145 m showed marked

111   variation with particle size. Almost 40% of the sediment 0.5 to 1.0 mm was deposited,

112   compared to 14.6% and 12.2% of the 1.0 to 1.4 mm and the 1.4 to 2.0 mm sediment,

113   respectively. Paradoxically, more of the finer sediment was deposited than the coarser

114   sediment (Fig 2). The distributions of the travel distances of the sand in three particle-size

115   classes shown in Figure 2 are slight overestimates of the true travel distance during the

116   experiment because (i) loss of sediment along with the rust particles in the separation method

117   results in an underestimate of sediment deposited at each distance; (ii) the recovery location

118   will also include some (additional) distance in transport as bedload in the waning phase of the

119   flow; and (iii) anything less than 100 % recovery rate of the introduced sediment leads to

120   overestimation of travel distance. We have estimated that these factors will introduce no

121   more than a 10% error. On the other hand, it is inconceivable that the pattern of sediment

122   deposition is simply the result of deposition in the waning phase of flow, given the

123   experimental conditions described above. The amount of sediment recovered, the size of the

124   flume, the weir at the downstream end, the capacity of the settling tank at the bottom end and

125   the duration of the experiment make it impossible for deposition to be a result of particles

126   having been transported off the end of the flume, re-circulated and re-entered into the

127   upstream end of the flume.

128   We have no data on which to base an expected distribution function for the travel

129   distance of sand-sized sediment. Work on bedload (Bradley and Tucker, 2012; Yang and

130   Saye, 1971) suggests the distribution function is right-skewed. Accordingly, we have fitted a

131   gamma distribution and compared it to a normal distribution fitted to our data (Figure 3),

132   optimizing these fits according to the known total amount of sediment that must be

133   accommodated within the distributions and the proportion of the distribution observed in our

134   data up to 145 m downflume. Although neither distribution is a particularly close fit to the

135   data (Figure 3), Nash-Sutcliffe efficiencies for the two models are quite high (Table 2) and all

136   but one of the Kolmogorov-Smirnov tests for goodness of fit is significant at $p<0.001$ (Table

137   2). Such evidence as we have therefore suggests a normal distribution fits our data better

138   than a gamma distribution. However, we have used both distributions to estimate the mean

139   travel distances of the three particle size classes. For the normal distribution, these distances

140   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

141   classes, respectively. For comparison, mean travel distances estimated from a gamma

142   distribution are 150 m, 161 and 163 m. Assuming a travel time of 205 s (half the duration of

143   the sediment input plus the experiment duration after sediment input was complete), gives a

144   virtual velocity (simply defined as the mean travel distance for the size class divided by 205s)

145   of the three sediment size classes of 0.74, 0.80 and 0.82 m s^{-1}, respectively, under the

146   assumption of a normal distribution, compared to the water velocity of 1.98 m s^{-1}. In

147   comparison, the mean travel distances from the gamma distributions give virtual velocities of

148   0.73, 0.79 and 0.80 m s^{-1}. These results give a virtual velocity lower than that for saltating

149   particles obtained by Chatanantavet *et al.* 2013), who found an average virtual velocity of 0.8

150   of the water velocity over a range of channel slopes. These authors also found no difference

151   in virtual velocity with particle size in contrast to our inverse relationships with particle size.

152   The irregularity of the deposition is also noteworthy. Sections at 40-45 m, 90-95 m

153   and 120-135 m all show exceptionally high amounts of deposition. In contrast, sections 45-

154   80 m, 100-105 m 110-115 m and 135 -140 m show less deposition than might be expected.

155   The former group coincide with joints between sections of the flume or significant rust

156   layers. Many of the latter group coincide with smoother sections of the flume bed. Since

157   joints are regularly spaced along the flume and rust shows no downflume spatial pattern,

158   these factors affect the irregularity of the deposition but not its overall distribution. Natural

159   channels have significant roughness induced by reach-scale bedforms (e.g. point bars, riffle-

160   pools) and patch- and grain-scale bedforms (e.g. transverse ribs, pebble clusters) so that the

161   trapping of suspended sediment in such channels may be akin to that found in the rougher

162   sections of the flume used in this study.

163

164   **Comparison with virtual velocities of bedload**

165   Mao *et al* (2017, Fig 10) plotted virtual velocities of particles between 4 and 160 mm as a

166   function of dimensionless shear stress for two rivers in northern Italy. For their dataset,

167   virtual velocities and dimensionless shear stress ranged from 0.0406 to 3.236 m h^{-1} and from

168   0.0196 to 0.0548, respectively. In contrast, our data (using the estimates based on the normal

169   distribution) range from 2664 to 2952 m h^{-1}, and from 0.868 to 0.26 (Fig. 3). Mao *et al*. fitted

170   linear regressions to their data, but these equations substantially underpredict our observed

171   values (yielding values between 24 and 52 m h^{-1}, compared to observed velocities of between

172   2664 and 2952 m h^{-1}). Comparable data to that of Mao *et al*. can be extracted from

173   Haschenburger & Church (1998) who examined movement of tracer particles ranging from

174   16 to 180 mm in a small stream on Vancouver Island, and from Wong *et al*. (2007) who

175   undertook a flume study of the movement of particles with a median size of 7.1 mm. Taking

176   all of these data together yields a power relationship (Fig. 4)

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

178   in which V is virtual velocity (m h^{-1}) and τ^* is dimensionless shear stress that fits the

179   combined data well ($R^2 = 0.837$). Although the strength of this relationship indicates promise

180   for "an holistic approach to sediment transport" (Parsons *et al*., 2015, p.1419), the paucity of

181   data in the finer size range makes it better to regard this relationship as an hypothesis rather

182   than a predictive model. Nonetheless, it is instructive to compare these datasets with those of

183   Huxman *et al*. (2004) who examined rain-use efficiency across biomes in a similar attempt to

184   identify a common relationship. Looking at ecosystems varying by an order of magnitude in

185   annual precipitation, these authors were able to find a common relationship between net

186   annual primary production and annual precipitation, but noted that there was substantial

187   variation in the sensitivity relationships between the 14 sites (including one site with an

188   inverse relationship), indicating local characteristics could mask a trend only visible at a

189   global scale. Likewise, for the five datasets of Figure 4. Individual relationships differ

190   markedly from site to site (as indicated by the individual regression lines), but over order-of-

191   magnitude scales a common behaviour may be discerned.

192

193   **Discussion and Conclusion**

194   Although not ideal, because of its rusty state, the large flume at the University of Tsukuba has

195   provided an opportunity for a first attempt to measure the virtual velocity of sand-sized

196   sediment in water at high values of excess shear stress. The experiment clearly demonstrates

197   that the sediment does travel intermittently because it has a virtual velocity that is less than

198   that of the flow in which the sediment is travelling. In that sense, the transported sand

199   exhibited behaviour no different from bedload or saltating load. For the sediment-size range

200   and flow velocity used in our experiment this virtual velocity is 37-41 % of the flow velocity.

201   Much sediment in rivers conventionally termed suspended is finer than that used in this

202   experiment, so that this virtual velocity may not be representative of most fine sediment.

203   However, if our observation that finer sediment has a lower virtual velocity than coarser

204   sediment extends beyond the size range used here, and is not an artefact of our experiment, it

205   may, in fact, be an underestimate. Such a lower virtual velocity of finer sediment is not

206   inconceivable. First, trapping, and hence virtual velocity, of the sediment appears to be a

207   function of bed roughness, and there is a probable relationship between bed roughness and

208   trapping efficiency for particles of different sizes (Lisle, 1989; Niño *et al*., 2003; Fries and

209   Taghon, 2010; Hamm *et al*., 2011; Gibson *et al.*, 2009). Secondly, finer particles are more

210   likely to find sheltered positions on a rough bed and thus experience lower mobility, relative

211   to the more exposed coarser grains, as observed for bedload transport (Parker *et al*., 1982).

212   Thirdly, the virtual velocity of particles undergoing bedload transport has been found, in

213   some instances, to be lower for finer clasts (Milan, 2013). Our data show that trapping of

214   sand-sized sediment is strongly controlled by the nature of the bed, specifically in our case by

215   roughness of the flume bed. The role of bed roughness in determining the virtual velocity of

216   sand-sized sediment, in particular as it is controlled by bed-material calibre in natural rivers,

217   clearly needs further study, as do the hop lengths of fine sediment. However, better and more

218   time-efficient methods than the one employed here will be required. Combining our results

219   with those for bedload virtual velocities has allowed us to propose, for the first time, an

220   hypothesis for an holistic analysis of sediment movement in rivers.

221

222

223

230

231   **References**

232   Abrahams AD, Atkinson JF. 1993. Relation between grain velocity and sediment

233   concentration in overland flow. *Water Resources Research* **29**: 3021–3028.

234   Bagnold RA. 1966. An approach to the sediment transport problem from general physics.

235   *Professional Paper 422-1*, US Geological Survey.

236   Bettess R. 1984. Initiation of sediment transport in gravel streams, *Proc. Inst. Civ. Eng.*, *Part*

237   *2* **137**: 79– 88.

238   Bradley DN, Tucker GE. 2012. Measuring gravel transport and dispersion in a mountain river

239   using passive radio tracers. *Earth Surface Processes and Landforms* **37***:* 1034-1045.

240   Chatanantavet P, Whipple KX, Adams M, Lamb MP. 2013. Experimental study on coarse-

241   grain saltation dynamics in bedrock channels. *Journal of Geophysical Research-*

242   *Earth Surface* **118**: 1161-1176.

243   Celik I, Rodi W. 1991. Suspended sediment-transport capacity for open channel flow.

244   *Journal of Hydraulic Engineering*, *ASCE* **117**: 191–204.

245   Cheng N-S. 2008. Comparison of settling-velocity-based formulas for threshold of sediment

246   motion. *Journal of Hydraulic Engineering*, *ASCE* **134**: 1136-1141, doi:

247   10.1061/(ASCE)0733-9429(2008)134:8(1136).

248   Egiazaroff IV. 1965. Calculation of nonuniform sediment concentrations. ASCE Journal of

249   the Hydraulics Division 91 **HY4**: 225–247.

250   Engelund, F. 1965. A criterion for the occurrence of suspended load. *La Houille Blanche* **8**: 7.

251   Engelund F, Fredsoe J. 1982. Sediment ripples and dunes. *Annual Review of Fluid Mechanics*

252   **14**: 13–37.

253   Ferguson RI, Wathen SJ. 1998, Tracer-pebble movement along a concave river profile:

254   virtual velocity in relation to grain size and shear stress. *Water Resources Research*

255   **34**: 2031-2038.

256   Fries JS., Taghon GL. 2010.   Particle fluxes into permeable sediments: comparison of

257   mechanisms mediating deposition. Journal of Hydraulic Engineering **136**: 214-221.

258   Gibson S, Abraham D, Heath R, Schoellhamer D. 2009. Vertical gradational variability of

259   fines   deposited   in   a   gravel   framework.   *Sedimentology* **56**:   661–676.

260   doi:10.1111/j.1365-3091.2008.00991.x

261   Hamm NT, Dade WB, Renshaw CE. 2011.   Fine particle deposition to porous beds. *Water*

262   *Resources Research* **47**: W11508, doi:10.1029/2010WR010295.

263   Haschenburger JK, Church M. 1998.   Bed material transport estimated from the virtual

264   velocity of sediment. *Earth Surface Processes and Landforms* **23***: 791-808.

265

266   Hassan MA, Church M, Schick AP. 1991. Distance of movement of coarse particles in gravel

267   bed streams. *Water Resources Research* **27**: 503-511.

268   Huxman TE, Smith MD, Fay PA, Knapp AK, Shaw MR, Loik ME, Smith SD, Tissue DT,

269   Zak JC, Weltzin JF, Pockman WT, Sala OE, Haddad BM, Harte J, Koch GW,

270   Schwinning S, Small EE, Williams DG. 2004. Convergence across biomes to a

271   common rain-use efficiency. *Nature* **429**: 651-654.

272   Ikeda H. 1983. Experiments on bedload transport, bed forms, and sedimentary structures

273   using fine gravel in the 4-meter-wide flume. *Environmental Research Center Papers*,

274   2. Environmental Research Center, The University of Tsukuba.

275   Keulegan GH. 1938, Laws of turbulent flow in open channels, *Journal of the Research of*

276   *the National Bureau of Standards* **21**: 707-741.

277   Komar PD, Clemens KE. 1986. The relationship between a grain's settling velocity and

278   threshold of motion under unidirectional currents. *Journal of Sedimentary Petrology*

279   **56**(2): 258-266.

280   Lammare H, MacVicar B, Roy AG. 2005. Using passive integrated transponder (PIT) tags to

281   investigate sediment transport in gravel-bed rivers. *Journal of Sedimentary Research*

282   **75**: 736-741.

283   Lane EW, Kalinske AA. 1939. The relation of suspended to bed material in rivers.

284   *Transactions of the American Geophysical Union, Section of Hydrology* **20**(4): 637-

285   641.

286   Lisle TE. 1989. Sediment transport and resulting deposition in spawning gravels, north

287   coastal California. *Water Resources Resea*rch **25**: 1303–1319.

288   Mao L, Picco L, Lenzi MA, Surian N. 2017. Bed material transport estimate in large gravel-

289   bed rivers using the virtual velocity approach. *Earth Surface Processes and*

290   *Landforms* **42**: 595-611.

291   Middleton GW. 1976. Hydraulic interpretation of sand size distributions. *Geology* **84**: 405-

292   426.

293   Milan D J. 2013. Virtual velocity of tracers in a gravel-bed river using size-based competence

294   duration, *Geomorphology* 198: 107-114 doi:10.1016/j.geomorph.2013.05.018.

295   Nezu I., and Nakagawa H. 1993. *Turbulence in Open Channel Flows*, A. A. Balkema,

296   Brookfield, Vt.

297   Niño Y, Lopez F, García M. 2003. Threshold for particle entrainment into suspension.

298   *Sedimentology* **50**: 247-263.

299   Paphitis D. 2001. Sediment movement under unidirectional flows: an assessment of empirical

300   threshold curves. *Coastal Engineering* **43**: 227–245.

301   Parker G, Klingeman PC, McLean DG. 1982. Bedload and size distribution in paved gravel-

302   bed streams. *ASCE, Journal of the Hydraulics Division* **108**: 544-571.

303   Parsons AJ, Cooper JR, Wainwright J. 2015. What is suspended sediment? *Earth Surface*

304   *Processes and Landforms* **40**: 1417-20. DOI: 10.1002/esp.3730.

305   Rouse H. 1937. Modern conceptions of the mechanics of fluid turbulence. *Transactions of the*

306   *American Society of Civil Engineers* **102**: 463-543.

307   Rubey WW. 1933. Settling velocities of gravel, sand, and silt particles. *American Journal of*

308   *Science* **25**: 325–338.

309   Samuels P. 1989. Backwater lengths in rivers. *Proceedings of the Institution of Civil*

310   *Engineers, Part 2* **87**: 571–582.

311   Sumer BM. 1986. Recent developments on the mechanics of sediment suspension. In W.

312   Bechteler, ed. *Transport of Suspended Solids in Open Channel*, Euromech 192,

313   Balkema, Rotterdam, The Netherlands, pp3–13.

314   van Rijn LC. 1984. Sediment transport part II: suspended load transport. *Journal of*

315   *Hydraulic Engineering* **110**: 1613–1641.

316   Wong M, Parker G, De Vries P, Brown TM, Burges SJ. 2007. Experiments on dispersion of

317   tracer stones under low-regime plane-bed equilibrium bedload transport. *Water*

318   *Resources Resea*rch **43**: W03440, doi:10.1029/2006WR005172.

319   Yang C, Saye W. 1971. Stochastic model for sand dispersion. *ASCE, Journal of the*

320   *Hydraulics Division* **97**: 265-288.

321

322

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

1   **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

2

1
2
3   3
4
5   4   **List of Figures**
6
7
8   5   Figure 1   a) bed of flume looking downflume showing rusting flume bed
9
10
11   6   b) flume showing flow during experiment looking upflume
12
13
14   7   Figure 2   Observed distribution of deposited sediment by size class
15
16
17   8   Figure 3   Fits of normal and gamma distributions to cumulative distributions of
18
19
20   9   deposited particles by size class
21
22
23   10   Figure 4   Relationship of results from the present experiment with those from
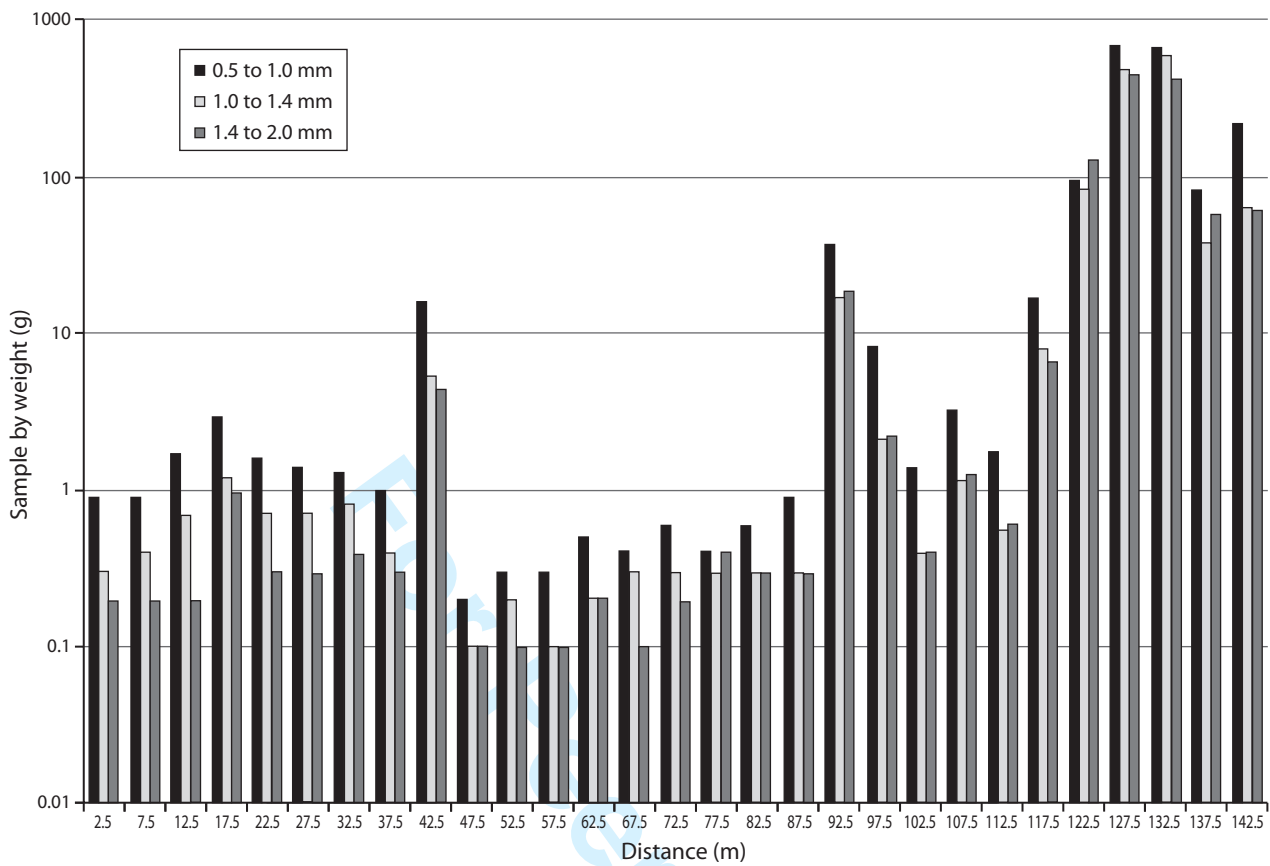24
25   11   bedload tracer studies.
26
27
28   12
29
30
...

bed of flume looking downflume showing rusting flume bed

1219x1625mm (72 x 72 DPI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

flume showing flow during experiment looking upflume

1219x1625mm (72 x 72 DPI)

$V = 58209\tau^{*3.4434}$
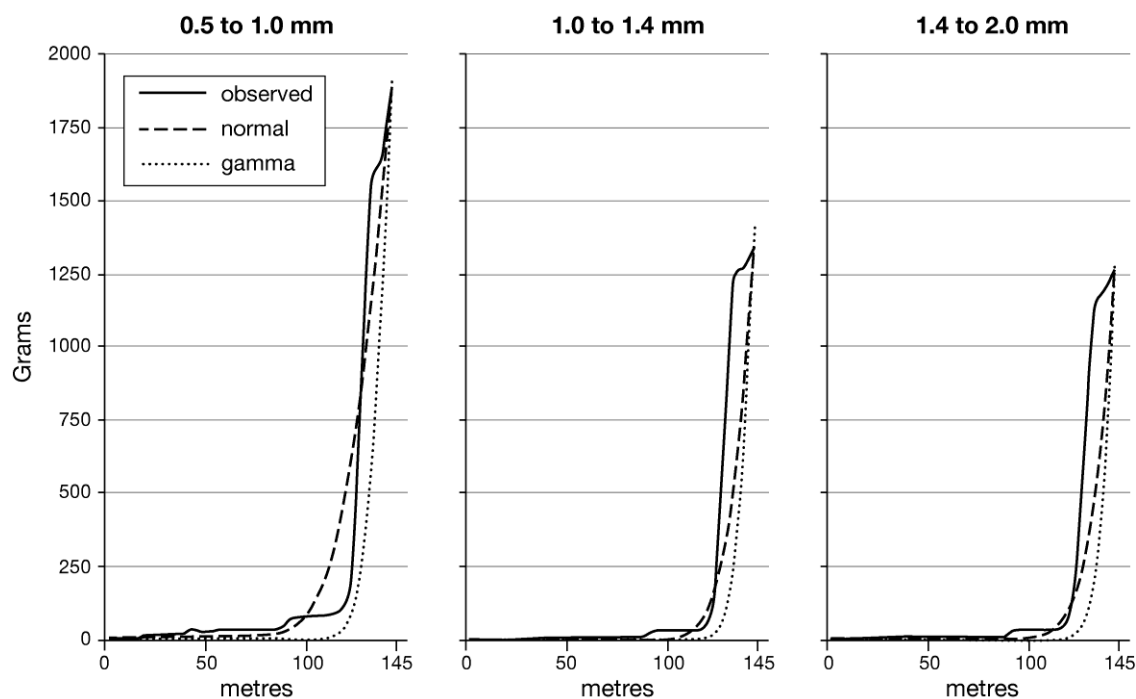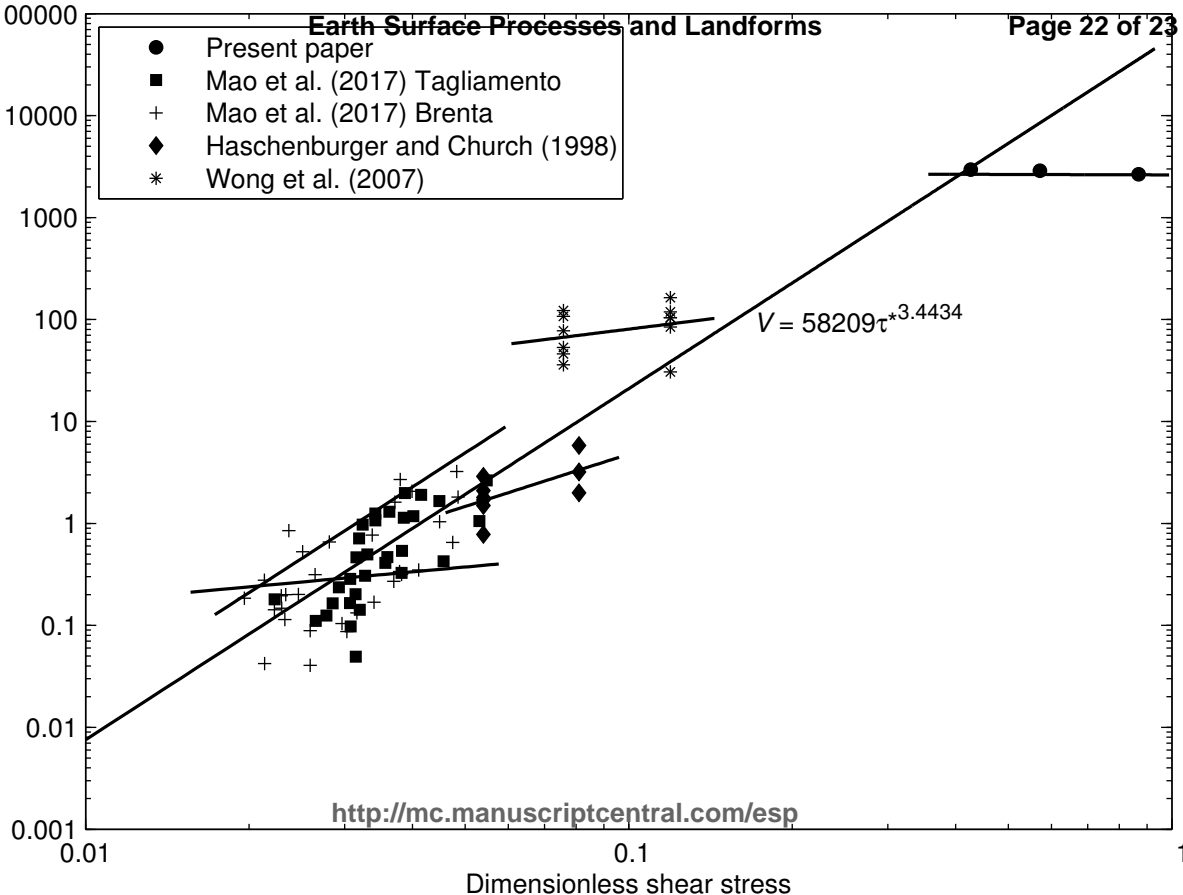
- ● Present paper
- ■ Mao et al. (2017) Tagliamento
- + Mao et al. (2017) Brenta
- ◆ Haschenburger and Church (1998)
- ✳ Wong et al. (2007)

Virtual velocity (mm h⁻¹)

Dimensionless shear stress

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

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.