DETERMINING CRITICAL CONDITION FOR INITIATION OF BED LOAD TRANSPORT

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Abstract

This investigation was designed to develop bed load transport initiation model. The data from four UK sites (Northern England Region), two USA sites (Rocky Mountains Region) and from a flume study (carried out in old brewery hydraulics laboratory, University of Newcastle Upon Tyne, UK) were collected and analysed. By using this data a bed load transport initiation model based on the maximum lower size (MLS, the largest size for which all smaller tracers moved) was developed, using individual particle sizes (i.e. fractional sizes) along with the discharge based approach (initially introduced by Schoklitsch). This model comprised bed material size gradation parameter (D_{84}/D_{16}), shape factor (SF) and slope (S) parameters (three parameters that play a significant role in the initiation of motion). The performance of the model (hereafter called MLS model) was compared with the collected field and laboratory data. It performed quite satisfactorily with the Roaring River data (upstream site), as generated data points were located in the close proximity of the line of perfect agreement (LPA) and 10% margin lines. Likewise, its performance was found well with the four flume data sets as majority of the generated points were situated close to LPA and within 10% margin lines. In another comparison test with MUS model its performance was found much better. All the comparisons have showed encouraging results. However, the data used for model development and testing was limited; more data therefore need to be collected to generalize the application of the model further.

Keywords Critical condition, Discharge theory, Initiation, Maximum upper size, Maximum lower size, models, Model performance, Relative position

Introduction

The critical/threshold condition at which initiation (i.e. beginning of movement of bed particles that were stationary some time before) of bed load transport starts has been described by different investigators. DuBoys [1] stated "excess of some quantity above the critical level at which transport begins"; Simons and Sentürk [2] said "when the flow over movable boundaries of a channel has hydraulic conditions exceeding the critical condition for motion of the bed-material, sediment transport will start"; also they mentioned that "most transport equations calculate the sediment transport as a function of the excess of some flow quantity, such as shear stress or discharge, above the critical level"; Carson and Griffiths [3] described this condition as "some critical or threshold level of discharge, velocity or related parameter must be attained before the gravel on a channel bed will start to move downstream"; Klingeman and Matin [4] stated that "transport initiation process requires larger flows that must exceed the threshold-motion values"; Dancey et al. [5] said it is "beginning of movement of bed particles that previously were at rest and that subsequently roll or slide along the bed"; and Dey [6] stated it "condition being just sufficient to initiate sediment motion". However, this "critical condition" as described by the well known scientists is an assumption that there is no sediment transport at lower flows. In reality there can be, but of such a small amount that in practical terms it can be ignored [7]. How can this critical condition be determined accurately? Why is there a need to determine it? A large variety of models are available for determining this condition, so why is it necessary to develop another model? These are the likely questions that could arise in minds of the sediment investigators/scientists working in this field. To find answers to these

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questions this study was designed, with special emphasis on the first question how this condition can be determined accurately. This was answered through the development of an optimal model that incorporates effects of all the significant parameters relevant to initiation process. To achieve this objective two models, based on the maximum lower size (MLS, the largest size for which all smaller tracer particles moved) and maximum upper size (MUS, absolute maximum size of moved tracer particles), were developed by using individual particle size and discharge based theory - a theory which is more practical and used (relatively) infrequently in the available models and found better (i.e. more practical) than the other theories (i.e. shear stress, stream power and velocity) in the recent studies [8]. The MUS model was developed for the purpose of comparison and to prove that how results could fluctuate with the use of model based on the maximum upper size of moved bed particles. Data used in the development of these models were collected from four UK sites (Harwood Beck Upper and Lower sites at Harwood, River Wear site at Stanhope, and South Tyne River site at Alston - all sites located in the Northeast England) and two USA sites (Ypsilon Lake Trail Bridge site, upstream site, and Alluvial Fan Road Bridge site, downstream site, located at the Roaring River in the Rocky Mountain National Park Colorado, USA - collected during July 1995). The performance of the MLS based model was compared with the MUS based model and with the laboratory data (collected at the Newcastle University, UK) and field data (collected from the Roaring River during May-June 1995 period); these data which were not used in the development of the models.

Why to Investigate Initiation Process?

The following salient features described by different investigators highlight the significance of the process and reflect why it is important to understand and further investigate initiation phenomena, especially, in coarse bed-material rivers [7].

1. For determining maximum flows required to flush out the fine sized sediment and organic matter present on the river bed among the gravel particles. The presence of these fine size sediment particles reduces the permeability by filling the spaces between the gravels necessary for aquatic habitat.
2. For maintaining bed stability in navigational channels that otherwise may be affected by the waves generated by the ships or boats.
3. To explain the difference between river bed stability and mobility.
4. To provide premises for the analysis and design of stable river beds.
5. For creating certain types of bed form on river beds that may be useful for the dual purpose of flood control and navigation.
6. For maintaining the stability of toxic substances hazardous for human and aquatic life when present in river beds.
7. To understand the bed load process which is necessary in the development of bed load transport functions/models.

Effects of Particles Position on Their initiation

It was observed (frequently) during this investigation at the UK and USA sites and in the flume channel investigation that larger bed particles (tracers) moved while smaller ones didn't, depending upon their position across and along the channel bed. The position of particles played a role in their movement in two ways.

a) *Their position relative to other particles*: The tracer particles which were located behind larger particles or located in depression or located in small pools were moved infrequently compared with those located without any shelter or those which were not hidden or situated outside the pools, having the same sizes and experiencing the same water discharge.

b) *Their position relative to flow currents/flow depths*: The tracer particles which were facing (relatively) stronger water currents, especially, those located in flow threads moved earlier compared with those which were facing weaker water currents or located outside the threads, even though the particle sizes and flow rates were the same. As in natural rivers slope changes (commonly) across the channel width and along the channel length, therefore, particles located in the shallower places/depths did not move with the same value of water flow rates as those located at places with greater water depths.

Model Development

Bases for Model Development

Owing to the advantages associated with the discharge based approach (e.g. more practical) and certain flaws/problems with available models, such as not including particle shape effect (SF, a significant parameter to account for the particle shape effects) while some only account for the absolute grain size. Also, these models have been developed using the maximum upper size of the moved particles with the maximum value of water discharge. This is not a realistic approach to deal with the initiation condition as it is possible that with the same value of water discharge larger size particles may move earlier due to their position in the channel bed, whereas smaller size particles move later or do not move at all. A particle located in a flow thread is likely to move earlier than a particle located out of the flow thread or located at a shallow place. Because of these and other reasons when the existing critical discharge theory based (initiation) models are applied to the real field conditions they generally perform poorly and the computed critical discharge values differ drastically from the observed ones. The poor basis of the existing models [4] suggests a need to develop a model (or models) that can predict critical condition accurately for the initiation of bed material movement in coarse bed material rivers. Two such models, therefore, are suggested below, one based on the maximum lower size (MLS, largest size for which all smaller tracers moved) and other on the maximum upper sizes (MUS, absolute maximum size of tracer moved) of the moved tracer particles. These models are

$$q_{ci(MLS)} = \alpha_{MLS} \left(D_{i\ (MLS)}\right)^{\beta_{MLS}} \quad (1)$$

$$q_{ci(MUS)} = \alpha_{MUS} \left(D_{i\ (MUS)}\right)^{\beta_{MUS}} \quad (2)$$

where $q_{ci(MLS)}$ and $q_{ci(MUS)}$ are the critical unit water discharges (m^3/sec/m) required to move the maximum lower size (MLS) and maximum upper size (MUS) of the bed material particles, respectively; α_{MLS} and β_{MLS} are the coefficient and exponent for the maximum lower size based model; α_{MUS} and β_{MUS} are the coefficient and exponent for the maximum upper size based model; and $D_{i(MLS)}$ and $D_{i(MUS)}$ are the ith maximum lower and maximum upper sizes of the moved particles with $q_{ci\ (MLS)}$ and $q_{ci(MUS)}$ discharges, respectively.

For determining the parameters (i.e. α_{MLS}, β_{MLS} α_{MUS}, and β_{MUS}) of these models (i.e. Equations (1) and (2) - hereinafter called as MLS model and MUS model) data collected from the four UK and two USA sites have been used and following steps were taken.

<u>Step -I</u>

Development of Individual Models Using Maximum Lower Size (MLS) of Moved Particles:

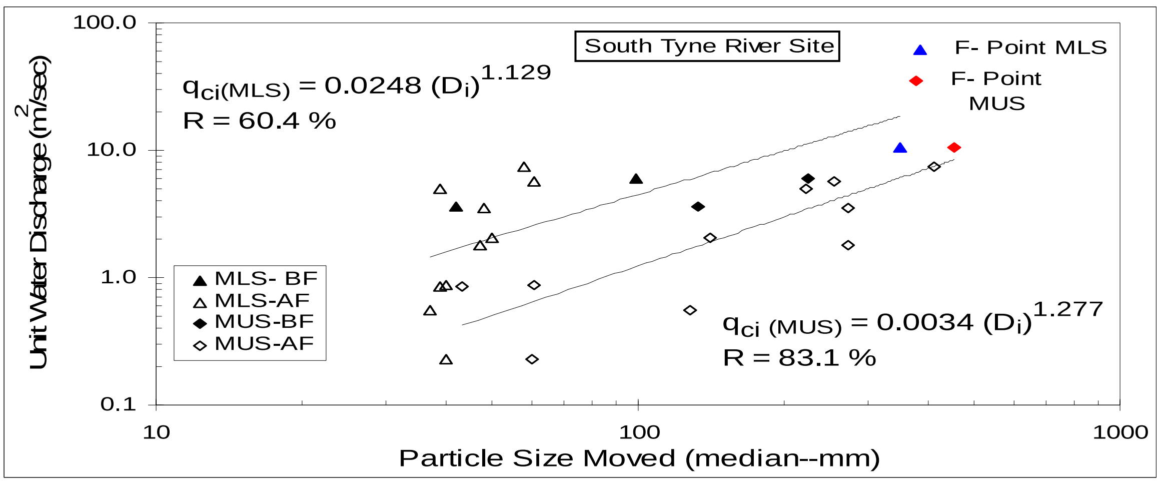
Various empirical models defining the relationship between the unit critical water discharge and the maximum lower size (MLS) of the moved particles were developed for the UK and US sites data. For each of the UK sites five different models were developed, because a high flood passed on 31 January 1995 altering the channel cross-sections and bed material formation. These five models were developed for five different data cases for each site: a) combined data (using combined data for before flood, BF; after flood, AF; and flood point, F), b) before 31

January 1995 (BF, before flood), c) after 31 January 1995 (AF, after flood), d) before 1 February 1995, and e) after 30 January 1995. For demonstration purpose out of these five cases models based on the combined data (i.e. for the South Tyne River site) and those based on post 31 January data

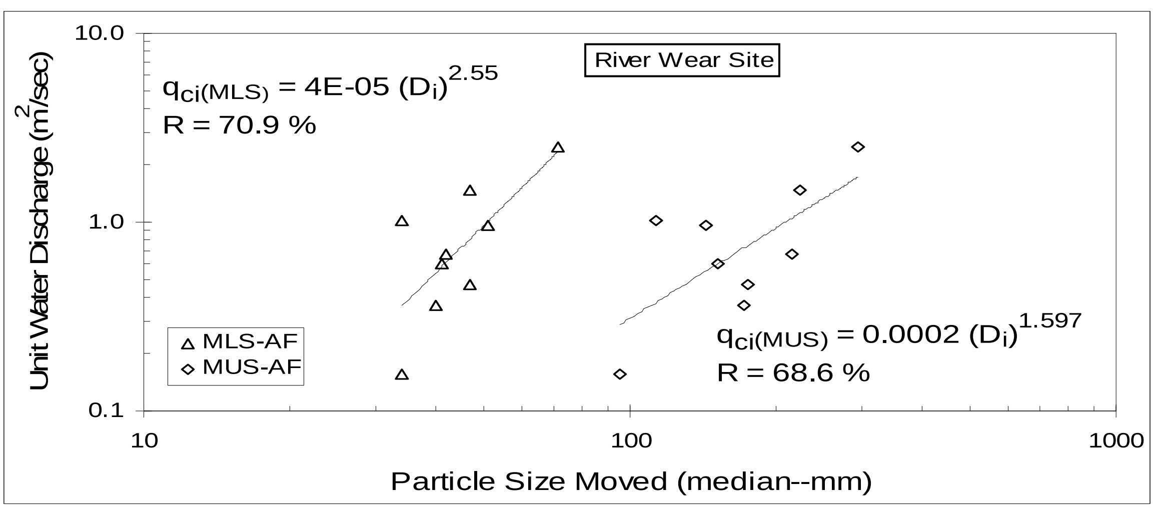
(i.e. for River Wear site) are depicted here in Figure 1, whereas the models themselves for all the five cases are given in Table 1. For the River Wear site after 31 January data were used for model development because of the significant variations in channel cross-section and bed material formation caused by the high flood passed on 31 January 1995. As a result of these variations the river channel characteristic changed and the river could have acted as if it was two different channels before and after the flood. The involvement of only one single flood point caused substantial variation in the coefficient and exponent values of the models, which is evident from the difference in cases 'c' (data after 31 January 1995) and 'e' (data after 30 January 1995). Likewise, a significant effect of a single flood point is also evident for the different cases 'b' (i.e. data before 31 January 1995) and 'd' (i.e. data before 1 February 1995).

On the other hand for each of the USA sites these models were developed using three data cases as a very high flood that passed after the May-June 1995 study period significantly changed the channel cross-sections and bed material formation. These three cases were: a) combined data (before + after flood i.e. May-June 1995 and July 1995 periods together); b) before flood, BF (May-June 1995 period); and c) after flood, AF (July 1995 period). The developed models for both of the USA sites for the three cases are given in Table 1. The effects of the high flood on model parameters (i.e. coefficient and exponent values) are evident from difference of cases 'b' (before flood) and 'c' (after flood), in comparison with the case 'a' (combined data).

As is evident from Table 1 (for maximum lower size), variations in the model exponent values between sites and at-a-site generally do not have any specific trend except that the exponent values for the UK sites are generally larger than the exponent values for the USA sites, which are ≤ 1 for all the three cases. The lack of any specific trend in the exponent values is mainly because each river has characteristics of its own and the number of data points for each case was different. The value of exponents (for combined data case 'a') varies between 0.80 and 1.58 (Table 1) for the UK sites. The variations in exponent values found for the maximum lower size (Table 1) are less than the variations for the maximum upper size (Table 2). Nevertheless, the maximum lower size based exponents has a realistic base, as movement of bed particles does not only depend on the absolute and relative grain size effects but also their position on channel bed relative to the flow current/flow depth. It should be remembered that the relationships (given in Table 1) based on less than four data points may have little meaning and are included for completeness only. Thus no physical interpretation should be made of equations based on less than four data points. Figures plotted (not given) based on combined data, which include the flood peak, for the UK sites showed that the maximum lower size (MLS) and maximum upper size (MUS) data points are situated close to each other at very high flows. This showed a possibility of equal mobility of bed material at very high flows. The results of equal mobility at very high flows are in agreement with the results of Ashworth and Ferguson [9] who said that "precise equal mobility of small and large particles was approached in the data set with the highest shear stresses and transport rates". These results partly supported the view point of Ferguson [10], when he mentioned the recent consensus of opinion (based on Ashworth and Ferguson [9], Wilcock [11] study results) according to which transport may approach equal mobility at high excess stresses and transport rates. These field investigations regarding equal mobility of bed material were different than those observed in the flume channel investigation in the Old Brewery Hydraulics Laboratory (Civil Engineering Department, Newcastle University, UK). In the flume investigation it was observed that after the movement of few particles just with 5-10 % increase in water discharge the whole bed material started to move. The probable reason for this equal mobility could be the smaller size distribution variation of bed materials (used in experiments) as the values of D_{84}/D_{16} were 1.46, 1.93, 1.49 and 1.64 for the I, II, III and IV set of materials, respectively. On the other hand D_{84}/D_{16} values for the field sites were 6.03, 5.07 and 5.53, respectively. Beside the D_{84}/D_{16} parameter, other parameters that may have played an important role in the mobility of bed material are the shape factor (SF, which incorporates the effect of long, median, and short axes of the bed material particles) and slope (S) parameters, as these parameters were considerably different for the field and flume investigations.



(a)



(b)

Figure 1. Relationship between unit water discharge and maximum lower size (MLS) and maximum upper size (MUS) of the moved tracer particles for: a) combined flow case of South Tyne Riversite; and b) after flood case for River Wear site (i.e. for after 31 January.

Table 1. Models defining relationship between critical unit water discharge and maximum lower size (MLS) of moved particles for the UK and USA sites.

Site	Data Points	Function	R (%)
Harwood Beck Upper			
a. Combined data (i.e. before and after flood)	14	$q_{ci(MLS)} = 0.0021\ (D_i)^{1.580}$	73.42
b. data before 31 January (flood date) 1995	3	$q_{ci(MLS)} = 0.050\ (D_i)^{0.898}$	99.89
c. data after 31 January 1995	10	$q_{ci(MLS)} = 0.0001\ (D_i)^{2.308}$	63.56
d. data before 1 February 1995	4	$q_{ci(MLS)} = 0.027\ (D_i)^{1.052}$	99.85
e. data after 30 January 1995	11	$q_{ci(MLS)} = 0.001\ (D_i)^{1.709}$	77.97
Harwood Beck Lower			
a. Combined data (i.e. before and after flood)	13	$q_{ci(MLS)} = 0.0383\ (D_i)^{0.800}$	51.28
b. data before 31 January (flood date) 1995	3	$^{*}q_{ci(MLS)} = 3.0E{+}6(D_i)^{-4.162}$	65.27
c. data after 31 January 1995	9	$q_{ci(MLS)} = 1.0E{-}5\ (D_i)^{2.881}$	47.11
d. data before 1 February 1995	4	$q_{ci(MLS)} = 0.143\ (D_i)^{0.603}$	93.06
e. data after 30 January 1995	10	$q_{ci(MLS)} = 0.009\ (D_i)^{1.126}$	67.31
River Wear at Stanhope			
Table 1 Continued	13	$q_{ci(MLS)} = 0.0025\ (D_i)^{1.524}$	82.34
a. Combined data (i.e. before and after flood)	3	$q_{ci(MLS)} = 2.0E{-}6\ (D_i)^{3.412}$	99.50
b. data before 31 January (flood date) 1995	9	$q_{ci(MLS)} = 4.0E{-}5\ (D_i)^{2.550}$	70.92
c. data after 31 January 1995	4	$q_{ci(MLS)} = 0.025\ (D_i)^{1.057}$	97.67
d. data before 1 February 1995	10	$q_{ci(MLS)} = 0.002\ (D_i)^{1.522}$	85.73
e. data after 30 January 1995			
****South Tyne River at Alston**			
a. Combined data (i.e. before and after flood)	13	$q_{ci(MLS)} = 0.0248\ (D_i)^{1.129}$	60.42
c. data after 31 January 1995	10	$q_{ci(MLS)} = 5.0E{-}08\ (D_i)^{4.572}$	71.41
d. data before 1 February 1995	3	$q_{ci(MLS)} = 0.588\ (D_i)^{0.496}$	99.65
e. data after 30 January 1995	11	$q_{ci(MLS)} = 0.022\ (D_i)^{1.133}$	60.25
U/S Site Roaring River			
a. Combined data (i.e. before and after flood)	7	$q_{ci(MLS)} = 0.007\ (D_i)^{1.053}$	96.95
b. Data before flood (May-June 1995 period)	3	$q_{ci(MLS)} = 0.072\ (D_i)^{0.408}$	82.64
c. Data after flood (July 1995 period)	4	$q_{ci(MLS)} = 0.425\ (D_i)^{0.064}$	4.24
D/S Site Roaring River			
a. Combined data (i.e. before and after flood)	7	$q_{ci(MLS)} = 0.007\ (D_i)^{0.993}$	78.87
b. Data before flood (May-June 1995 period)	3	$^{*}q_{ci(MLS)} = 0.425(D_i)^{-0.185}$	54.86
c. Data after flood (July 1995 period)	4	$q_{ci(MLS)} = 0.236\ (D_i)^{0.181}$	84.68

Step-II

Development of Individual Models Using Maximum Upper Size (MUS) of Moved Particles:
Similar to the maximum lower size (MLS) case the empirical models were also developed for the maximum upper size (MUS) of the moved particles for the UK and USA sites and are presented in Table 2. For demonstration purpose these models for the South Tyne River and River Wear sites for the combined data case are shown in Figure 1.

Like the MLS model for the MUS model the exponent values for the UK sites were generally greater than the exponent values for the USA sites (i.e. ≤ 1.1). The value of exponents for the UK sites, which include the flood peaks, vary between 1.28 and 1.47. On the other hand the exponent values for the Roaring River (Colorado), during three different periods in 1984-1985 (recorded by Bathurst [12]), ranged between 0.20 and 0.39 [10]. Inpasihardjo [8] recorded the exponent value of 0.54 for the Pitzbach (Austria), whereas for the UK sites his values ranged between 0.93 and 1.17. All these exponent values, recorded by three different researchers, have been obtained using a discharge based approach. From these values a significant difference in the exponent values (within and between rivers) is evident. Bathurst [12] developed a function for the exponent value (exponent, b = $fn(D_{84}/D_{16})$ which was subsequently modified by Inspasihardjo [8], however their functions do not explain the variations, therefore further explanation is needed which may be achieved by incorporating other parameters (e.g. shape).

Table 2. Models defining relationship between critical unit water discharge and maximum upper size (MUS) of moved particles for the UK and USA sites.

Site	Data Points	Function	R (%)
Harwood Beck Upper			
a. Combined data (i.e. before and after flood)	14	$q_{ci(MUS)} = 0.001(D_i)^{1.399}$	85.73
b. data before 31 January (flood date) 1995	3	$q_{ci(MUS)} = 0.122\ (D_i)^{0.515}$	78.99
c. data after 31 January 1995	10	$q_{ci(MUS)} = 0.001\ (D_i)^{1.315}$	96.22
d. data before 1 February 1995	4	$q_{ci(MUS)} = 0.002\ (D_i)^{1.307}$	79.25
e. data after 30 January 1995	11	$q_{ci(MUS)} = 0.0004(D_i)^{1.500}$	90.44
Harwood Beck Lower			
a. Combined data (i.e. before and after flood)	13	$q_{ci(MUS)} = 0.0004(D_i)^{1.465}$	87.98
b. data before 31 January (flood date) 1995	3	$q_{ci(MUS)} = 8.0E\text{-}5(D_i)^{1.743}$	86.20
c. data after 31 January 1995	9	$q_{ci(MUS)} = 0.001(D_i)^{1.260}$	91.21
d. data before 1 February 1995	4	$q_{ci(MUS)} = 2.0E\text{-}8(D_i)^{3.291}$	92.79
e. data after 30 January 1995	10	$q_{ci(MUS)} = 0.0004(D_i)^{1.450}$	87.64
River Wear at Stanhope			
a. Combined data (i.e. before and after flood)	13	$q_{ci(MUS)}=7.00E\text{-}5(D_i)^{1.816}$	87.01
b. data before 31 January (flood date) 1995	3	$q_{ci(MUS} =1.0E\text{-}16(D_i)^{6.823}$	83.73
c. data after 31 January 1995	9	$q_{ci(MUS)} = 0.0002(D_i)^{1.597}$	68.63
d. data before 1 February 1995	4	$q_{ci(MUS)} = 0.0001\ (D_i)^{1.706}$	96.64
e. data after 30 January 1995	10	$q_{ci(MUS)}=8.0E\text{-}05(D_i)^{1.772}$	87.06
****South Tyne River at Alston**	13	$q_{ci(MUS)} = 0.0034(D_i)^{1.277}$	83.07
a. Combined data (i.e. before and after flood)	10	$q_{ci(MUS)} = 0.0044(D_i)^{1.199}$	82.16
b. data after 31 January 1995	3	$q_{ci(MUS)} = 0.051\ (D_i)^{0.877}$	99.89
c. data before 1 February 1995			
U/S Site Roaring River	7	$q_{ci(MUS)} = 0.0096(D_i)^{0.854}$	97.21
a. Combined data (i.e. before and after flood)	3	$q_{ci(MUS)} = 0.090\ (D_i)^{0.305}$	31.78
b. Data before flood (May-June 1995 period)	4	$q_{ci(MUS)} = 0.098\ (D_i)^{0.366}$	84.08
c. Data after flood (July 1995 period)			
D/S Site Roaring River	7	$q_{ci(MUS)} = 0.0024(D_i)^{1.108}$	62.93
a. Combined data (i.e. before and after flood)	3	$^*q_{ci(MUS)}= 0.272(D_i)^{-0.055}$	15.81
b. Data before flood (May-June 1995 period)	4	$q_{ci(MUS)} = 0.234\ (D_i)^{0.167}$	67.90
c. Data after flood (July 1995 period)			

*The reason for these models having negative exponents is too few data to define a realistic relationship.
** South Tyne River don't have model for case b, as there were only two data points for this case.
NB: In all these models confidence levels were fixed at 95 % which provided significance levels = 0.05.

The main possible factors for difference in the exponent values within and between rivers are:

a) Bed sediment size distribution, that could vary temporally and spatially. A good example of the temporal variation in the exponent values is the difference of values obtained by Bathurst [8] using Roaring River data and the values obtained by the author using the same river site but with data recorded in 1995 [6, 9]. Likewise, the difference of exponent values obtained by the author and Inpasihardjo or Bathurst indicated the effect of spatial variations. The effects of temporal and spatial variation in the bed size distribution on the exponent values for different sites are also evident from Figure 2;

b) Shape of sediment particles, which could vary with the geology of the catchment. The effect of geology on the exponent values is evident from the difference of exponent values obtained by the author (using UK river data) and those obtained by the Inpasihardjo (using Austrian data) - data from two different catchments. However, the exponent values obtained by the Bathurst and Inpasihardjo (for Austrian data) are based upon data that were collected using the Helley-Smith sampling technique, while the author's data were collected by using the tracer technique. Another example of the shape effect on the exponent values is clear from difference of exponent values obtained by the first author and the Inpasihardjo, although both used the UK data and same sampling technique was followed but with different sites.

The effect of the above mentioned factors on the exponent values is also evident from the discussion by Ferguson [10]. In contrast to the discharge based approach, investigators including Andrews and Erman [15], Ashworth and Ferguson [9] used a shear stress based approach (using maximum particles size moving with different flows) to determine the exponent value [10]. Their exponent values varied between 0.65 and 1.00. By using the same shear stress approach Parker and Klingman [13] obtained the exponent value of 0.98 (for Oak Creek, using subsurface grain size distribution), which was revised to 0.90 (based on surface grain size distribution). Based on the results by different researchers, Ferguson [10] said "critical stress to move an individual particle depends far less on its own size than on the ambient size, or perhaps (in the case exponent = 1) entirely on the latter and not at all on the individual size. In this case, termed 'equal mobility' by Parker and Klingman [13], particles of all sizes will move at the same stress, and by implication the same critical discharge;

c) Sampling technique followed for data collection may have affected the collected data (i.e. whether data were collected by using the tracer technique or Helley-Smith sampling technique) [14].

d) Lack of data points may be a reason to effect the exponent values, as it affected the exponent values in Tables 1 and 2.

Step -III

Development of Models' (Equation 1 and 2) Parameter: In order to determine the values of parameters (i.e. α_{MLS}, $\beta_{MLS,}$ α_{MUS}, and β_{MUS}) of Equation (1) and (2) only the combined case models were taken (from Tables 1 and 2) for the three UK sites, no considerable variations occurred in the channels' cross-section for these sites during the 31 January 1995 flood. For the River Wear site significant changes in channel cross section and bed material size distribution were recorded after a high flood passed on 31 January 1995. Also, more data points were available for the after flood case compared with the before flood case. Therefore the after flood(AF) model is used for the River Wear site. The selected models in terms of coefficient (α) and exponent (β) for both of the MLS and MUS sizes are given in Table 3 along with some other parameters.

Likewise, for the USA sites out of the three cases (given in Table 1 and 2) only the after flood case (i.e. for July 1995 period) was taken, as the high flood which passed after the May-June 1995 study period altered the channel cross-sections and coarsened the bed material. Also, the after flood case has more data points. The selected cases and other corresponding variables that were used to develop functions for parameters (i.e. α_{MLS} and β_{MLS}) of Equation (1) and parameters (i.e. α_{MUS} and β_{MUS}) of Equation (2) are given in Table 3. The statistical technique used for the development of these functions was multi-variative analysis.

As explained earlier and found during the field and flume investigations the bed material gradation parameter (D_{84}/D_{16}), shape factor (SF) and slope (S) play an important roles in bed material movement. These results are supported by the results depicted in Figure 2 (based on data given in Tables 3 and 4. In this figure data points from the UK sites (recorded by [3] and [16]) are located far above the other than UK data points. The reason for this different data distribution may be that UK rivers have different particle shapes (as evident from shape factor values in Table 3) compared with the other data in main cluster, which are mostly from the USA sites. Thus in the development of functions (for Equation (1) and Equation (2)) beside the D_{84}/D_{16} parameter other parameters such as shape factor (SF), slope (S), channel width (W) and reference particle size (D_r) have to be involved to account for effects of all the significant variables. The developed functions are

<u>For Maximum Lower Size</u>

α_{MLS} (R = 93.2 %)

$$\alpha_{MLS} = \left(-26.9 - 15.6S - 1.38\frac{D_{84}}{D_{16}} + 83.1SF\right)\left(\frac{\sqrt{g}D_r^{1.5}}{W^{\beta_{MLS}}}\right) \quad (3)$$

β_{MLS} (R = 85.7 %)

$$\beta_{MLS} = 6.66 - 11.5SF \quad (4)$$

<u>Maximum Upper Size</u>

α_{MUS} (R = 95.3 %)

$$\alpha_{MUS} = \left(-0.58 + 36.2S + 0.101\frac{D_{84}}{D_{16}}\right)\left(\frac{\sqrt{g}D_r^{1.5}}{W^{\beta_{MUS}}}\right) \quad (5)$$

β_{MUS} (R = 89.1 %)

$$\beta_{MUS} = 7.16 - 13.28SF \quad (6)$$

where SF = shape factor = $c/(ab)^{0.5}$, c = shortest particle axis, b = intermediate axis, and a = longest axis); and D_r = reference particle size (m), represents the relative size effects of the mixture and equals D_{50} for log-normal size distribution and D_{63} for non log-normal size distribution. For these functions (Equations (3) to (6)) channel slopes used ranged between 0.008 and 0.047 (m/m), D_{50} of the bed material ranged between 0.065 and 0.140 m, and channel width (mean) between 6 and 30 m.

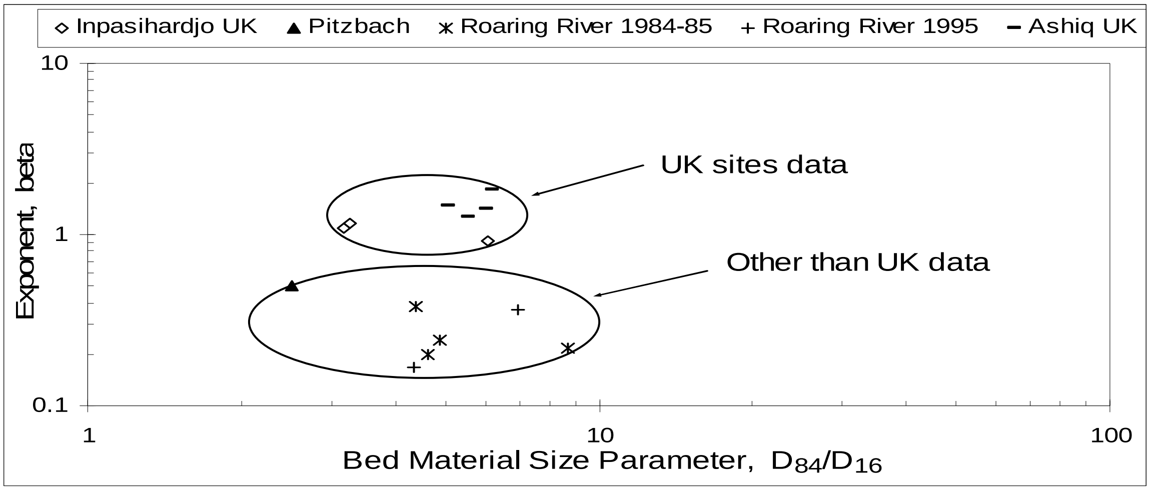


Figure 2. Relationship between exponent, beta and bed material size parameter, D_{84}/D_{16} using UK sites data and other than UK sites data.

Table 3. Variables used for the development of models (Equation 1 and 2) parameter (α_{MLS}, β_{MLS}, α_{MUS}, and β_{MUS}).

Site	Slope (S) (m/m)	D_{84}/D_{16}	Shape Factor (SF)	Maximum Lower Size (MLS)		Maximum Upper Size (MUS)	
				α	β	α	β
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Harwood Beck Upper (Combined Data Case)	0.008	6.03	0.454	0.0021	1.580	0.0008	1.399
Harwood Beck Lower (Combined Data Case)	0.0189	5.07	0.478	0.0383	0.800	0.0004	1.465
River Wear (After 31 Jan. 1995 Data Case)	0.0162	6.02	0.447	4.0E-05	2.550	0.0002	1.597
South Tyne River (Combined Data Case)	0.0105	5.53	0.482	0.0248	1.129	0.0034	1.277
U/S Site Roaring River (July 1995 Data Case)	0.0350	6.92	0.541	0.425	0.064	0.098	0.366
D/S Site Roaring River (July 1995 Data Case)	0.0473	4.36	0.585	0.236	0.181	0.234	0.167

Table 4. Parameters of Equation, $q_{ci} = \alpha (D_i)^{\beta}$ fitted for each site and corresponding reference particle size.

Site	Equation Parameters α	Equation Parameters β	Equation R^2 (%)	Reference Particle Size (mm)	Bed Material Size Gradation Parameter(D_{84}/D_{16})
1	2	3	4	5	6
(a) Bathurst's [8] Roaring River Data					
Ypsilon Lake Trail Bridge 1984 and 1985	0.0967	0.378	63.7	91	4.37
Fall River Road Bridge					
15/6 - 24/7/84	0.103	0.219	54.9	67	8.68
18/5 - 27/5/85	0.0944	0.241	93.3	76	4.88
27/5 - 6/6/85	0.170	0.199	72.2	95	4.32 - 4.88
(b) Inpasihardjo's [16] Data					
Table 4 continued Kilder Burn	0.0444	0.921	83.9	164	6.09
Glen	0.0095	1.164	93.6	75	3.26
South Tyne	0.0149	1.096	91.8	184	3.16
Pitzbach	0.0486	0.500	71.2	88	2.50
(c) Ashiq's [3] Data -UK sites					
Harwood Beck Upper site at Harwood, 1994 -1996	0.0008	1.399	0.735	97	6.03
Harwood Beck Lower site at Harwood,1994-1996	0.0004	1.465	0.774	112	5.07
River Wear Site at Stanhope, 1994 - 1996	7.00E-05	1.816	0.757	115	6.154
South Tyne River site at Alston, 1994 - 1996	0.0034	1.277	0.690	130	5.53
(d) Ashiq's [3] Data -USA sites					
Ypsilon Lake Trail Bridge (i.e. downstream site) July 1995	0.098	0.366	0.707	130	6.97
Alluvial Fan Road Bridge (i.e. downstream site) July 1995	0.234	0.167	0.461	111	4.35

In above mentioned equation q_{ci} has dimensions $m^3 s^{-1} m^{-1}$; D_i has dimensions mm

Performance Test of Developed Models

The performance of the developed models (Equation (1) and (2)), in conjunction with the model parameters (i.e. α_{MLS}, β_{MLS}, α_{MUS} & β_{MUS} - Equations (3) to (6), respectively), was tested using both the flume and field data. The flume data used were that collected in the Old Brewery Hydraulics Laboratory and comprised four set of materials, whereas the field data used were from the upstream (u/s) and downstream (d/s) sites of the Roaring River for the period of May-June 1995. These data were not used in the development of the models and comprised long, median, and short axes of the bed material particles, required for determining the shape factor (SF, values for flume data are given in Table 5) - a parameter used in the models. In this performance test values of the unit critical water discharges ($q_{c(c)}$) were computed using both the flume and field data. These computed discharges were than compared with the measured (observed) critical water discharge ($q_{c(m)}$) values. The values of mean error (ε_m) and root mean square error (ε_{rms}) were determined by using Equations (7) and (8). Also, values of mean discrepancy ratio (DR, ratio of computed to observed discharges) and standard deviation

(SD) were determined to further verify the performance of the models.
Mean Error (ε_m)

$$\varepsilon_m = \sum_{i=1}^{n} \frac{q_{ci(m)} - q_{ci(c)}}{n} \qquad (7)$$

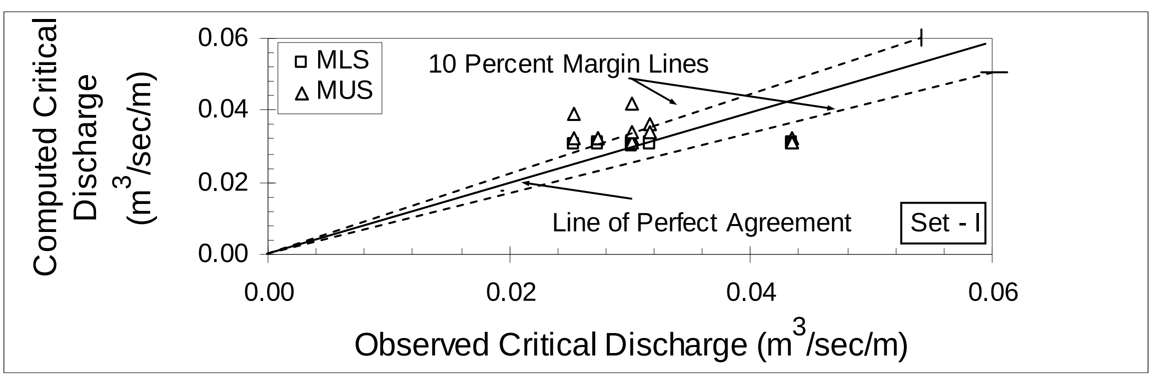
Root mean square error (ε_{rms})

$$\varepsilon_{rms} = \left[\sum_{i=1}^{n} \frac{\left(q_{ci(m)} - q_{ci(c)}\right)^2}{n} \right]^{1/2} \qquad (8)$$

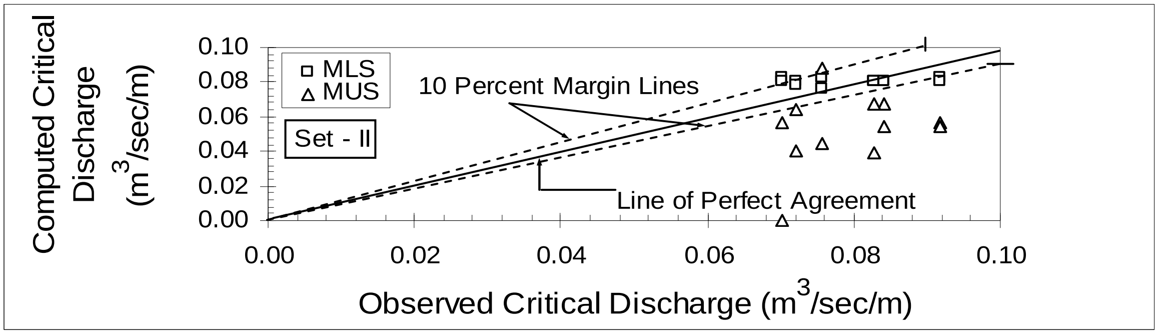
Where
$q_{ci(m)}$ = measured (observed) unit critical water discharge (m^2/sec) for particle size D_i; $q_{ci(c)}$ = computed unit critical water discharge (m^2/sec) for particle size D_i; and n = total number of observations.

MLS Model Performance Test

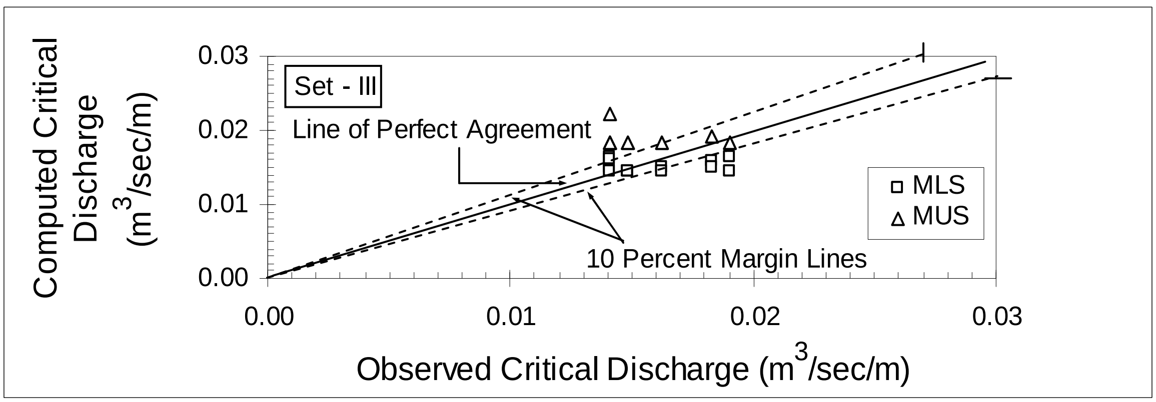
Model (Equation (1), in conjunction with the Equations (3) and (4)) performance was first tested by using four sets of flume data. As is evident from Figure 3 the data points generated by this model are mostly scattered close to the line of perfect agreement (LPA) and within the 10 % margin lines. Generally, a mixed pattern of overestimation and underestimation is evident from these figures. However, during the tests with the flume data, in some cases, the variation in the computed critical discharge was small. A possible reason for this is that the model is based on mixed-size (non-uniform) bed material data while the data used for testing (i.e. flume data) were somewhat uniform in nature. A performance test was then made with the Roaring River tracer data for May-June 1995 (Figure 4a) which shows good agreement for the upstream (u/s) site data, as data points are scattered close to the LPA.



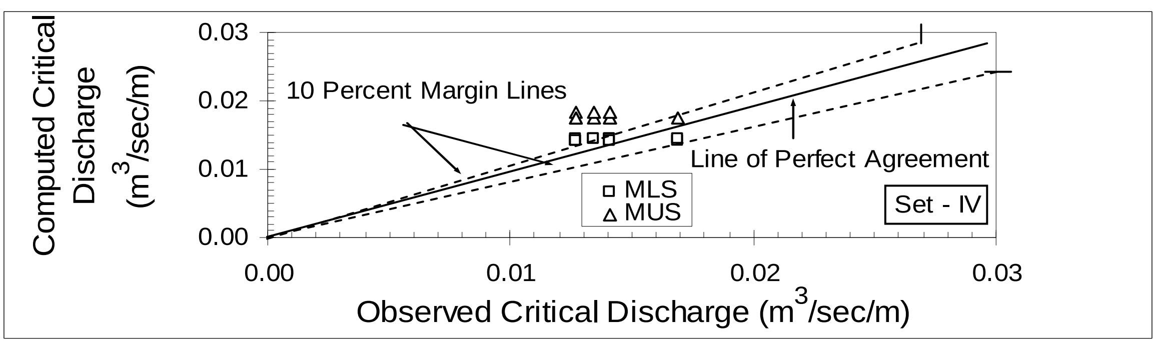
(a)



(b)



(c)



(d)

Figure 3. Comparison of computed (by MLS and MUS models) and observed unit water discharges using flume data (having four sets of material) collected in the Old Brewery hydraulics laboratory: (a) Set - I; (b) Set -II; (c) Set - III; and (d) Set - IV.

Table 5. Mean error (ε_m) and root mean square error (ε_{rms}) in the prediction of critical water discharges using MLS and MUS models for the flume and field data, along with the values of mean DR and SD.

Site	Errors, Mean DR Values and SD of DR Values							
	MLS Model				MUS Model			
(1)	ε_m (m^2/sec) (2)	ε_{rms} (m^2/sec) (3)	Mean DR (4)	SD of DR (5)	ε_m (m^2/sec) (6)	ε_{rms} (m^2/sec) (7)	Mean DR (8)	SD of DR (9)
Flume Data								
a) Set-I	0.00076	0.00584	1.004	0.140	-0.0028	0.00794	1.124	0.211
(SF=0.582)	-0.0006	0.00743	1.016	0.098	0.0266	0.03320	0.660	0.280
b) Set-II	0.00092	0.00224	0.960	0.126	-0.0027	0.00362	1.187	0.177
(SF=0.595)	-0.0003	0.00144	1.030	0.098	-0.0038	0.00413	1.290	0.132
c) Set-III(SF=0.572)	0.0581	0.0597	0.880	0.045	-0.4270	0.4280	2.362	0.182
d) Set-IV(SF=0.575)								
	0.0521	0.0535	0.759	0.053	0.02290	0.02560	0.896	0.059
Field Data								
a) u/s site Roaring River								
b) d/s site Roaring River								

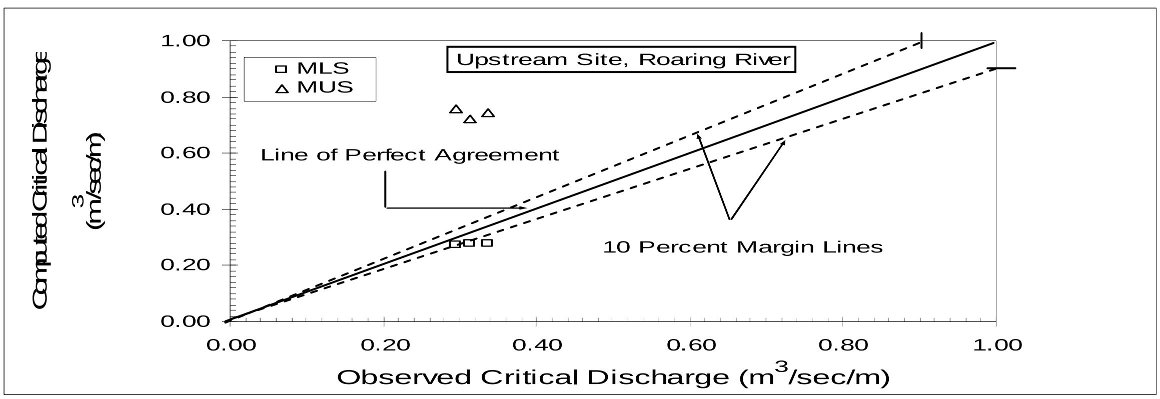
On the other hand, for the downstream site data (Figure 4b), this model did not perform well as data points are located below the 10 % margin line. For this site the data scatter is nearly horizontal, which shows that model is not very sensitive for the data. However, test data are too few to comment on the model trend. The performance of the model is also highlighted by the mean error (ε_m) and root mean square error (ε_{rms}) values given in Table 5. Mean DR(discrepancy ratio, ratio of computed to observed values) values vary between 0.759 and 1.004 (Table 5) which shows that the model has performed satisfactorily. Similarly, the model's validity is evident by the SD (standard deviation) values.

During this performance test it has been found that the model is quite sensitive to the shape factor (SF) value, therefore SF value should be determined accurately, otherwise results could fluctuate considerably. As, at this stage it was not possible to test the model performance with sufficient (mixed-size material) data, due to the non availability of data (with measured short, median and long axes), therefore further model tests are suggested before generalising it for the common use.

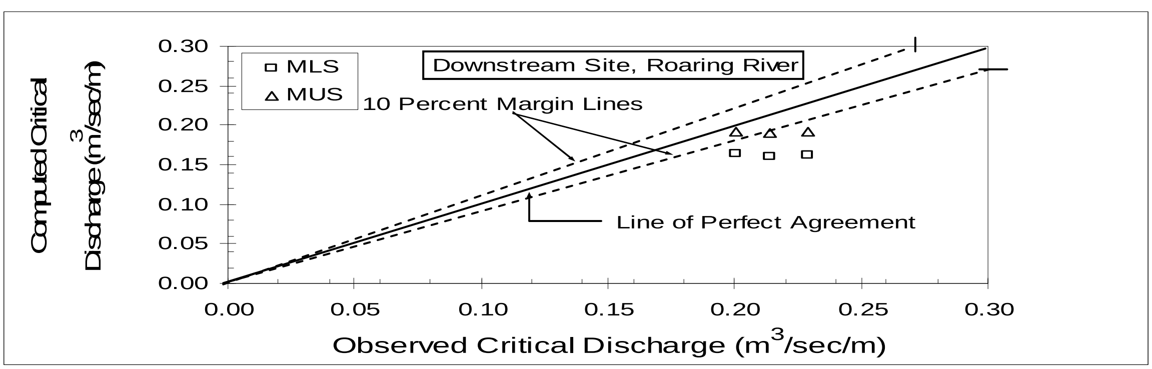
MUS Model Performance Test

Like the MLS model, the performance of this model was investigated using the flume data and field data. Computed unit critical water discharges (q_c) were compared with the observed unit water discharges (q_c), as depicted in Figure 3 (for flume data) and in Figure 4 (for field data). A relatively wide range of data scatter was found for this model compared with the MLS model, as is evident from the figures. This model has significantly underestimated the computed values for the dataset II (Figure 3b) of the flume study and overestimated for the upstream site data of the Roaring River (Figure 4a), as data points are scattered below and above the line of perfect agreement (LPA). However, the overall performance of the model was not very satisfactory as mean DR values for the upstream site were greater than 2. These results are also supported by the mean error (ε_m) and root mean square error (ε_{rms}) values given in Table 5. Average grade performance of the model is also evident from the SD values (Table5). This model, in-contrast to its rival the MLS model, overestimated the computed discharges, possibly due to two reasons: a) movement of particles on the channel bed is affected not only by the absolute and relative grain size effects but also influenced by the position of particles relative to the flow currents/flow depth; and b) a lack of test data points (only three).

Large variations in the MUS model's performance for the laboratory and field data showed how unreliable it is to use this model for the computation of critical discharge values. The reason for the fluctuation in the model's performance was that initiation of motion of maximum particle sizes depends not only upon the discharge value but also upon the particle position across/along the channel bed. Many times during this study the larger size tracer particles were moved but smaller ones were not. This condition depended upon the location of the tracer particles in the channel bed. Therefore, it is more likely to find fluctuation in the computed results with the use of the MUS model, while the MLS model by its very nature is likely to produce better results. Like the MLS model the MUS model was also found to be very sensitive to the shape factor (SF) values, therefore it should be determined carefully



(a)



(b)

Figure 4. Comparison of computed (by MLS and MUS models) and observed unit water discharges using field data collected from the Roaring River (Colorado, USA) during May-June 1995 period: (a) upstream site; and (b) downstream site.

Results and Discussion

The performance of the existing bed load transport initiation models, based on critical discharge theory and individual particle sizes, was investigated using data from the four UK sites (i.e. Harwood Beck Upper and Lower sites, River Wear site and South Tyne River site). Among the tested models Bathurst's [12] model performed (relatively) better, even though its performance was not satisfactory. In this investigation the models performed poorly, partly because: 1) they need to incorporate other process e.g. particle shape effects - a parameter that plays a significant role in the bed material movement; 2) their basis on absolute maximum size is inaccurate; and 3) different authors use different measurement techniques for data collection (which are used for model development and testing) whose compatibility is unknown [14].

The significance of the particle shape for the bed material movement has also been proved by Li and Komar [17] and Gomez [16]. Li and Komar [17] while investigating the pivoting angle applications to the selective entrainment of gravel, stated that "order of increasing difficulty of entrainment is spheres, ellipsoidal grains, angular grains, and imbricated grains". The effects of particle shape have also been proved by Gomez [16] who described that hiding functions likely vary with particle shape. He further stated that "for a given imposed shear stress the order of increasing nominal particle diameter is flat, angular, and rounded gravels".

The second probable reason for the poor performance of the models was that they have been developed by using the absolute maximum size of the moved tracer particles which is not a realistic approach. Initiation of bed material movement depends not only upon particle size but it also upon particle position on the channel bed relative to other particles and flow depth/flow current. Wilcock [11] mentioned this source of error in his criticism of the classic concept of flow competence. He stated that "the larger errors and unknown bias suggest that the largest sampled mobile grain is not a reliable predictor of either critical shear stress or flow magnitude".

Particle shape plays a significant role in bed load initiation and it could vary from catchment to catchment. Therefore, two models were developed for determining the critical condition for the initiation of bed load transport, both including a shape factor (SF) parameter to account for the particle shape effects. One of these models is based upon the maximum lower size (MLS)(Equation (1) in conjunction with Equations (3) and (4)) of moved tracer particles, while the other is based on the maximum upper size (MUS)(Equation (2) in conjunction with Equations (5) and (6)) of moved tracer particles. The performance of these models was verified in an independent test with the flume and field data. The MLS model performed well compared with the MUS model, which showed considerable fluctuation in the results. However, before further generalisation the models need to be tested with more field data. In this study, due to the shortage of shape data (with measurements of particle long, median and short axis), it was not possible to carry out further performance tests, since most available data sets have just median particle axis.

Conclusions

The following specific conclusions may be drawn from this study.

- To strengthen the existing weak data base (and to test performance of the existing and developed models) field and laboratory data (under uncontrolled and control conditions, respectively) were collected from the four UK and two US sites and from the Old Brewery Hydraulics Laboratory.
- Before developing the new model for the initiation of bed load transport the performance of existing critical discharge theory (as this theory was used in model development) based models was tested with the four UK sites' data. In this performance test both the models (generally) performed poorly, however, Bathurst model's performance was relatively better.

- Considering the poor performance of the available bed load initiation models a model (Equation (1) along with Equations (3) and (4)) based on the maximum lower size of moved tracer particles (MLS model) and discharge theory was developed using the collected field data. This model applies to each size fraction in a non-uniform distribution. This model is valid for channel slope ranging between 0.8 and 4.7% and D_{50} of bed material between 0.065 to 0.140 m. It showed encouraging results in an independent test (with the collected laboratory data and field data) with mean discrepancy ratio ranging between 0.759 and 1.004.

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Notation

(L = length; M = mass; T = time; (-) = dimensionless)

a longest particle axis;
b intermediate particle axis;
c shortest particle axis;
D_i diameter of ith size fraction (L);
D_r reference particle size (L);
D_{16} particle size for which 16% of the sediment mixture is finer (L);
D_{35} particle size for which 35% of the sediment mixture is finer (L);
D_{50} particle size for which 50% of the sediment mixture is finer (L);
D_{63} particle size for which 63% of the sediment mixture is finer (L);
D_{65} particle size for which 65% of the sediment mixture is finer (L);
D_{84} particle size for which 84% of the sediment mixture is finer (L);
D_{90} particle size for which 90% of the sediment mixture is finer (L);
g acceleration due to gravity (LT^{-2});
LPA line of perfect agreement;
MLS maximum lower size of moved tracer particles (L);

MUS maximum upper size of moved tracer particles (L);
n total number of observations;
q_{bi} unit bed load for ith size fraction (L^2T^{-1});
q_c critical unit water discharge (L^2T^{-1});
$q_{ci,}$ critical unit water discharge for ith size fraction (L^2T^{-1});
$q_{ci(c)}$ computed unit critical water discharge (m^2/sec) for particle size $D_{i;}$
$q_{ci(m)}$ measured (observed) unit critical water discharge (m^2/sec) for particle size $D_{i;}$
$q_{ci(MLS)}$ critical unit water discharge for ith size fraction for the maximum lower size of the moved tracer particles (L^2T^{-1});
$q_{ci(MUS)}$ critical unit water discharge for ith size

fraction for the maximum upper size of the moved tracer particles (L^2T^{-1});
R correlation coefficient (-);
S slope (-);
SD standard deviation;
SF shape factor (-);
W channel width (i.e. surface flow width of channel) (L);
$\sum$ summation (-);
α coefficient (-);
α_{MLS} intercept value for the maximum lower size of the moved tracer particles (-);
α_{MUS} intercept value for the maximum upper size of the moved tracer particles (-);
β exponent (-);
β_{MLS} exponent value for the maximum lower size of the moved tracer particles (-);
β_{MUS} exponent value for the maximum upper size of the moved tracer particles (-);
ε_m mean error; and
ε_{rms} root mean square error.

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