Author's Response

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This document contains the replies to all comments provided by the reviewers for this paper, as well as a marked up version of the document containing all changes made to the text and structure of the original paper. We would like to thank the reviewers for their time and comments, as we believe they have contributed greatly to improving the quality of this paper through the individual recommendations and wholescale changes to paper structure. The following sections are separated by reviewer, and then by comment type. Additionally, changes not explicitly recommended by reviewers have been made during the considerable restructuring phase that accompanied the rewriting of the results and discussion. Furthermore, corrections were made to values that have been identified as mis-calculated.

1 Reviewer 1

1.1 General

Reviewer: This a personal opinion. The article's title could be changed to something more appropriate. When I received the article I thought that it was related to large chains in the sense of boulders or macro-roughness elements. Given that most steep channels do have boulders and other (actual) large grains, and those are neglected in this study, the title was misleading to me. Again, this is a personal opinion but please consider it if you think the same.

Authors: We agree that confusion may arise from the wording of this title, and have changed aggrading to self-forming to imply their mobility (rather than confusion as boulders).

Reviewer: The article structure does not convey the information in a fluid manner. The introduction has little information about aggrading systems and it seems to me that it gives more importance to degrading systems. Although, I understand that the idea was to make clear that we know more about degrading systems more information and references to what we really know about aggrading systems is required. There are virtually no references to any study that may have discussed aggrading systems.

Authors: We agree that the introduction lacked discussion of the very systems it set out to replicate, although the direct field comparison is somewhat limited. Therefore, we have included additional reference to studies of aggrading channels as well as restating the focus of this paper. We have also re-structured the introduction in order for the information to flow more smoothly. In addition, and in response to one of the specific comments, more background information and references were added to ensure that the justification is presented in a clear and defensible manner. Furthermore, changes to the other sections were made so that the overall coherency of the article is maintained.

Reviewer: The article presents the study using Lane (1955) balance expression. Then, the assumptions of this expression are called into question and by doing so the hypothesis is formulated. The problem is that Lane 1955 did not consider a mixture of sediment and therefore does not intended to explain the responses of different GSD, even when they have the same D50. Only later in the paper, in the discussion (page 10, line 4), this is explained. So, as a reader, I had problems trying to understand why this is not explained right away. The major concern about this is how the information flows in the article.

Authors: Following from the previous comment, the section from the discussion has been relocated to the introduction to provide a more immediate justification for the study. Lane (1955) is still used, but only as *a tool to demonstrate the issues with using Church (2006) and the role of grain size distributions in bed material. We believe that this reorganisation makes the mission statement clearer.*

Reviewer: The hypothesis needs to be reformulated. I understand the idea of the study is to compare responses to different GSD and boundary conditions. This was welldeveloped in the text. However, if I just take the hypothesis, it doesn't say that. "We hypothesise that, like degrading systems, the presence of the large grains will resultin different transport regimes, as in MacKenzie and Eaton (2017), and thus different channel morphodynamics and depositional slope" It says that it is just the presence of large grains, what about boundary conditions? The article shows that is not just the presence of these large grains but discharge is a fundamental control.

Authors: We agree that the hypothesis does not fully present the same ideas that this study addresses. Therefore, we will reformulate the hypothesis to better represent the information conveyed in the updated introduction, where we tried to impress the importance of large grains upon the reader. In addition, the role of boundary conditions was explicitly included.

Reviewer: A lot of information about bed structure, for example bars, is given by theend of the discussion. There is no data about this and only observations. This shouldbe presented in a more formal way.

Authors: A formalised representation of the data was added into the results section to demonstrate the ideas discussed later on. Instead of relying solely on the qualitative data in the supplemental videos, we have added Figures 8 and 9 of the bed and major process observed during the experiments.

1.2 Line Comments

Reviewer: 1) Abstract - line 2 - there is no need to say "shape", it is already included in the distribution.

Authors: We have included this change.

Reviewer: 2) Abstract - line 4 - Is it correct to talk about "fan" if we are in a 1D system? The fan part is where the system spreads and here it does not occur.

Authors: This system was designed to simplify a three-dimensional fan into a single slice that represents the system slope, like the experimental design of Guerit et al., 2014. So, whilst the system is not fan-like, we believe it represents the fundamental interaction between surface organisation and slope in a manner that approximates self-formed deposits such as fans.

Reviewer: 3) Introduction - line 11 - There is one problem when we use the discharge as a variable to explain a certain response. If we double (or 3X, 4X, ...) the channel width while holding the discharge we may have different geomorphological responses. Therefore, is not actually the discharge, but some other characteristic (e.g., unit discharge) what is better for comparisons. This may be discussed somewhere.

Authors: We used discharge as our system defining metric because it was the boundary condition we had control over in this case. Actual channel width varied in a manner that was not constant along the length of the flume, therefore specific discharge was avoided. Similarly water depths were unknown, so shear stress would not have beena useful metric.

Reviewer: 4) Intro - line 11 - There are several other references to this statement (sed supply and discharge controls)

Authors: We have provided additional examples.

Reviewer: 5) Intro - Most of the Intro - Generally only one reference is given for a certain statement. More references are required. For example, when talking about armour layers (line 24) only Andrews and Parker, 1987 is cited.

Authors: The number of references has been increased throughout the introduction.

Reviewer: 6) Intro - Page 2 - Line 8 - References are needed for this statement.

Authors: Removed as part of the reorganisation.

Reviewer: 7) Intro - Page 2 - Line 9 - Would it be better to start the discussion with something relatively newer than Lane (1955)? The experiments are really interesting, but starting the analysis based on this relatively old study (there is more information available related to stream power). It doesn't mean that this expression is not important, but, it does not fit what we know about sediment mixtures.

Authors: This has been changed so the introduction of Lane's equation is the manner in which we introduce Church's 2006 relation. As such, we restructured the overall introduction.

Reviewer: 8) Intro - Page 2 - Line 21 - The text is confusing. However what? Please notice that the idea does not flow starting with "however". There are some equations, definitions, and other text that makes this "however" confusing.

Authors: Removed, and reincorporated to the text during the reorganisation.

Reviewer: 9) Intro - Page 2 - Line 23 - This is critical, Lane never said that this works for a sediment mixture, as you mentioned in the discussion. Therefore, up to this line, calling into question the assumption is not valid. please try to find another way to present the hypothesis.

Authors: This has been integrated into the restructured introduction.

Reviewer: 10) Methods - general - This is the strong part of the article, it was really interesting.

Authors: Thank you.

Reviewer: 11) Methods - general - It would be really interesting to analyze the evolution of the slope, that is, change of slope in time. I was wondering if the experiment came to a final equilibrium slope, or how do you decide to finish an experiment. Do we find the mean slope by the end of the experiment or by the middle of it. A simple plot would answer these interesting questions.

Authors: Equilibrium slope was never explicitly reached, where the output matches theinput rate of sediment; this value was approached but not used as a criterion in other studies (e.g., Eaton and Church, 2004). Instead, our experimental limit was set by the volume of sediment we could supply. We believed that the morphodynamics were similar enough over the course of the experiment that it was not undergoing a substantial flux. We expanded upon the nature of the evolution of the deposits. We have attached a plot of the temporal trends of slope, however we feel that this is not relevant to our discussion as it stands. As we have focussed more generally on the experiments, the temporal evolution of slopes have been excluded from our discussion.

Reviewer: 12) Results - page 6 - line 8 - This statement is only true for 0.1 ml s^{-1}. Notice that in panel a) for 0.2 ml s^{-1}, there is no "strong distinction"

Authors: We have corrected this.

Reviewer: 13) Results - page 7 - line 3 - Notice that you need to reference Table 5 when you talk about the efficiency

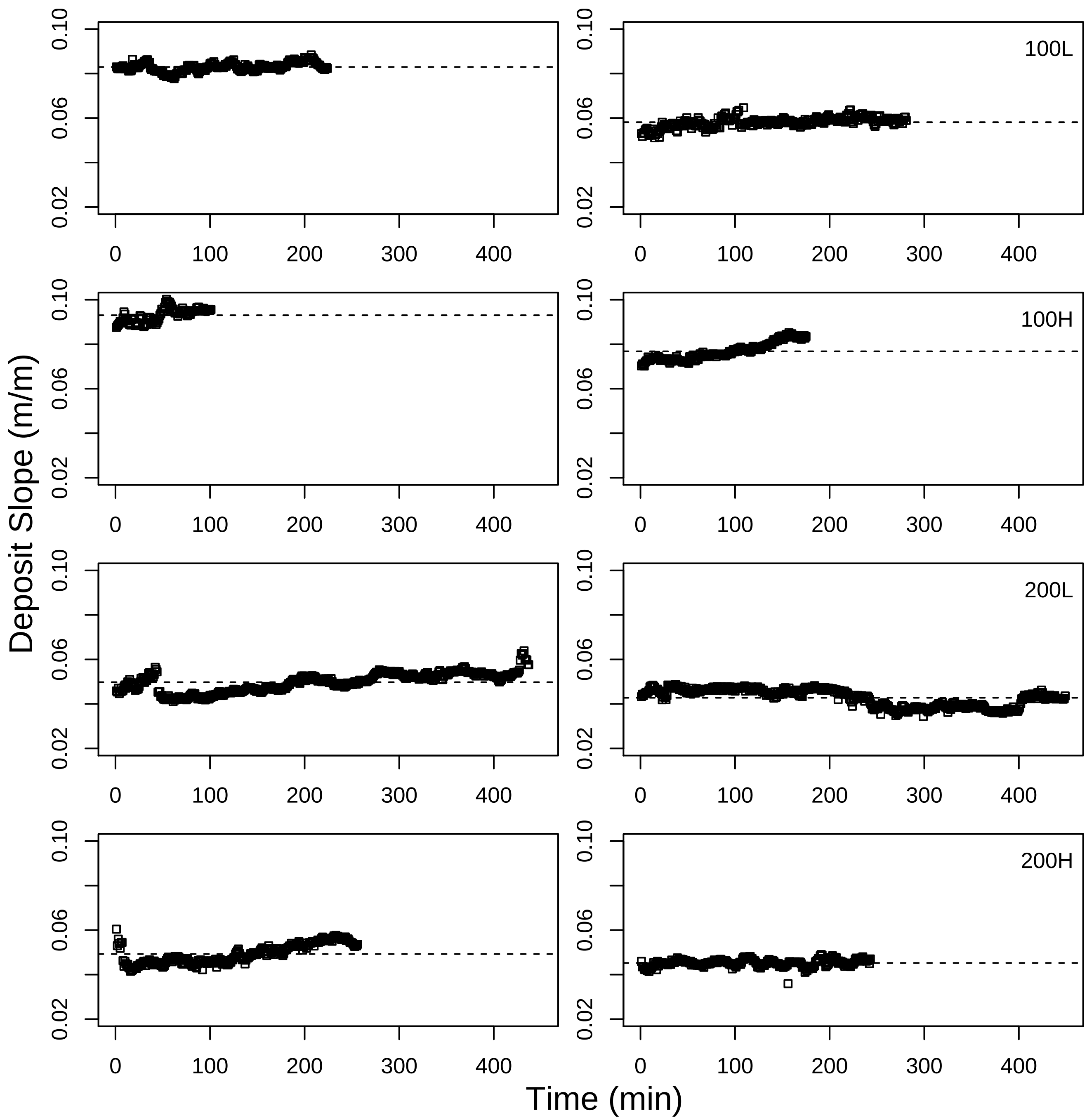

Figure 1: Temporal relationships of slope values, separated into GSD_{broad} on the left, and GSD_{narrow} on the right. Frames are paired by the run conditions in the topright corner of the GSD_{narrow} plot.

Authors: This is a mistake held over from also talking about the output efficiency (Table 4) rather than considering it from a storage efficiency lens. The reference to which has been changed in the text and table.

Reviewer: 14) Results - General - It would be good to have more information about the properties of the bars that are mentioned at the end of the discussion.

Authors: This section was added.

Reviewer: 15) Discussion - General - Some parts can be moved to the intro for a better motivation for the study. Also, it would help understand the hypothesis

Authors: The more introduction leaning sections, that improve message clarity, were moved to the beginning of the paper.

Reviewer: 16) Discussion - General - Like in the intro, more references are needed. It is generally poor in important references

Authors: More references have been included during the rewrite of the discussion section.

17) Discussion - General - I'm not making a lot of detailed comments in the discussion because it seems to me that inthe new version it will change significantly. Only the most important specific points are considered here

Authors: The overall structure has changed, with the reorganisation encompassing other sections also.

Reviewer: 18) Discussion - Page 9 - Line 30 - It seems that Church's relation can be a better way to motivate the study.

Authors: agreed, and the introduction has been changed to reflect this.

Reviewer: 19) Discussion - Page 10 - Line 10 - It would be interesting to consider a little discussion about what may happen if we have the same D84 and different D50.

Authors: We have included a short discussion of the possibility of pairing experiments by a coarser grain, towards the end of the discussion.

Reviewer: 20) Discussion - Page 10 - Lines 12 to 17 - These lines are confusing. First, you mentioned that in low slopes sand plays an important role and that you can make the same inference. Then you said it is not actually sand what is the control in your experiments but the absence of large grains. Notice that your statement is correct (it is the absence of large grains), but relating it to Curran and Wilcock does not make any sense, because they attributed to sand

Authors: We clarified this, as the analogy is meant as a natural opposition to the mobility changes observed by Curran and Wilcock (2005). Instead, it is supposed to evoke the stabilisation effects of a mobile armour, or coarse bed organisation.

Reviewer: 21) Discussion - Page 10 -Lines 20 to 32 - A lot of confusing statements are given here. a) One important aspect that you are considering is channel slope. The analysis made using Eq. 4 does not include channel slope, even though it is known that slope plays a role critical shear stress Lamb has published a number of studies related to this topic. b) Comparing a change in critical stress change for D84 to a change in slope is confusing. Why can we do that? The problem is that for a given discharge if we vary slope water depth changes as well, therefore changes in slope and not directly comparable to changes in shear stresses. Maybe I'm missing something but if you explain a little more about this rationale it would be clearer.

Authors: a) We have clarified this position to introduce Recking (2013), which includes the role of slope on increasing Shields stress.
b) The original comparison was simply a neat similarity between the differences in the reference shear stress and slope, which when calculated using DuBoys' formula is directly related.

Reviewer: 22) Discussion - Everything related to bars and beyond reach average - Most of the text is not clearly related to data or measurements. It need to be better justified.

Authors: We have included a section of the results dedicated to this.

Reviewer: 23) Discussion - Page 12 - Line 6 - There are two more (more more mobile)

Authors: We removed one 'more'.

Reviewer: 23) Conclusion - Page 12 - Line 34 - Change you in " as you increase". Also a period is missing.

Authors: We have included these changes.

2 Reviewer 2

2.1 General

Reviewer: Reorganization of introduction - I think the introduction reads fairly well, but that further motivation could be provided by discussing the predictions of Lane's balance at the beginning of the article. One could use the idea that Lane's balance would predict the same slope for a give D50, regardless of the rest of the GSD as a null hypothesis, then reference the known importance of large grains in degrading systems and the lack of complementary work on aggrading systems in order to more directly motivate this work. I think this reorganization could help to streamline the logical progression of the manuscript.

Authors: This feedback agrees with those made by the first referee, with a reorganisation of the information displayed in the introduction necessary to improve the communication of this importance. As a result, the structure was re-written to relocate Lane (1955) and introduce Church's (2006) conceptualisation as the crux of the argument. We also agree that this will improve the flow of logic within this article.

Reviewer: Methods clarification - While I generally follow the experimental set-up, I think some more detail can be provided regarding a few points. (1) How where the discharges determined? Are they specified to span the range of partial transport to full bed mobilization? It would also be useful to provide the calculated/estimated shear (or Shields) stresses related to each of these discharges of both flows. I'm aware that this may require some assumptions in relation to the sidewall correction, but given that most of the literature on this topic is presented in terms of Shields stress, it would be useful to also provide this estimate, especially for the discussion of relative transport capacity.

Authors: Discharges were determined based on initial conditions used during trial ex-periments, as well as their ease of calibration in setting up these experiments. The discharges were not calculated to correspond to any given shear stress value; as the deposit slope was set by the sediment transport dynamics, we were unable to predictthe corresponding slopes. Without controlling the slope of the deposit, as is traditionally done in such experiments, we could therefore not relate discharge to shear stress during experimental design.

Reviewer: (2) It took me until halfway through the results to recognize that the multiple measures of slope presented were from different time steps following the onset of sediment transport out of the flume. How long were the experiments run after this point and how were the experiments determined to be over? Was an equilibrium slope/transport rate reached or were adjustments still occurring when the experiment ended? If equilibrium was reached, how was it determined?

Authors: In these experiments, equilibrium was not a concept explicitly used in the determination of any experimental condition as sediment output had to be dried and weighed, in order to feedback this information during the experiment. Therefore, we are careful to avoid usage of the term "equilibrium" in discussion of the dynamics involved here. As a result, the length of each experiment was solely determined by the volume of input material available for sediment feed. In addition, during the experiments themselves we used the morphodynamics as in-situ justification; we believed that they had not substantially changed between when sediment was output and the end of the experiment. Therefore, we believed that the system behaviour was not in flux when the sediment supply ran out.

Reviewer: (3) For the slope-derivation, I think more information should be provided regarding the random-Forests model, how it works, and the degree of user-specification it requires. How many images are input in order to determine the slope? How are the sub-classes determined? Are there uncertainties associated with these slope measurements based on the method or number of sample images input? A citation here providing the relevant background information could also help. The authors later report the mean slope and standard deviation for each experiment, but it is unclear if this is from multiple time slices (if so, how many?), multiple locations in the flume, or related to some uncertainty in the slope estimation. Organization-wise, I don't necessarily think this needs its own section in the methods. Alternatively, I might suggest splitting the methods section into (1) Experimental set-up, (2) Measurements, and (3) Slope derivation.

Authors: We clarified the methods used in the derivation of the water surface slope, expanding upon the use of randomForests models which are typically used in more involved machine automation processes than simple supervised RGB classification. We have also updated the slope values with the number of observations used in each calculation (Table 1).

Reviewer: (4) I find GS1 and GS2 not to be very informative variable names. I would suggest changing them to GSnarrow and GSbroad or something more information so it is easier for the reader to keep track of throughout the paper. Even H and L are a bit confusing to keep track of, but less so.

Authors: We have updated the names of the mixtures, but the manner in which the experiments are referred is simple enough in our view.

Reviewer: Organization of the results section - I found this section to be a bit muddy, with parts of the motivation, methods, and discussion being mixed in. While I am okay with some intermingling of these sections, in this cas, I found it to make this particular section a bit difficult to follow. Below I've made some suggestions to streamline this section. (1) Move Lane's balance discussion to introduction. See above. (2) Move sediment transport efficiency calculation to methods. I would suggest adding this following the slope derivation. If Lane's balance has already been presented in the introduction, it would naturally follow to calculate the sediment transport efficiency. Introduction of this calculation in the methods would allow the authors to more cleanly step through the results. Again, some information of the number of samples used to make these calculations would be helpful (table 5).

Authors: The paper has been reorganised to result in a better flow of information throughout the paper. Primarily, this is through the relocation of the Lane and Church equations to a more justifying position at the beginning of the introduction. The number of observations are the same for all calculations using the slope (given in Table 1).

Reviewer: (3) This is a style thing, but I would suggest avoiding things like "Panel A of Figure 3 shows.." and instead simply say "There is a significant difference between equilibrium slopes as a function of the supplied grain size distribution (Figure 3A)." I think this would help with readability.

Authors: We have changed the occurences of this to a more passive presentation, that helps with the flow of information.

Reviewer: (4) Much of the information in the tables is not fully presented in the paper. I would recommend more explicitly discussing these results in the main text. Lots of the results are presented in a fairly vague way (e.g. - ". . .both systems retaining a higher proportion of sediment" even though the authors have quantified these effects more directly. I would suggest rephrasing to provide these values directly in the text (e.g. - ". . . in response to a doubling of sediment supply, both systems retained a higher proportion of sediment, XX% for the narrow GSD and XX% for the broad GSD." This in-text quantification would also help to clarify the main differences between the experiments.

Authors: We have taken this into account for the results section, highlighting the most useful of the values rather than blanket reporting the comparison between every experiment.

Reviewer: Argument for large grains - While I find the argument that the transition between partial transport and full mobilization of the GSD drives the observed differences in slopes observed in the experiments reasonable, I am not entirely convinced that the data presented really show this. I agree given the results that D50 is a poor metric for predicting behavior in aggradation systems, but I think more could be done to support the argument of the importance of large grains. Do the authors have any observations from the experiments to be show this? For example, was the sediment exiting the flume sieved to determine the GSD of the transported sediment compared to the supplied sediment? Can the photos/videos of the bed be used to determine if there is significant sorting that arises during the experiments that may support this idea? I imagine that the videos could be used to track the mobility (or immobility) of the largest grains (or the bed surface as a whole) in the flume to better evaluate this idea.

Authors: We do not have the capability of quantising bed surface data, we have tried in the wider work these experiments were taken from but failed to yield a robust or replicable system of quantification. However we have included some static images taken from the videos in order to better represent these ideas in the paper. In addition we have included Recking's (2013) mobility transition calculations (Table 6) to help support the argument presented for the role of large grains. In addition flume sieve data has been included (Figure 7 and Table 4).

Reviewer: The portion of the discussion where shear stress calculations are made is quite confusing. It is unclear what inputs are being used and what information is being drawn from the calculation. Specifically, this sentence is quite unclear "Equation 4 produces a shear stress 44.4% greater for entrainment of the D84 than the entrainment of the median in GSD1 than in GSD2." I assume the authors are solving for τ_{ri} with reference to the D84 of both GSDs, but the reference stress value and the actual calculated values should be made explicit to better support this point. Additionally here, a comparison to the estimated shear (shields) stresses applied in the experiments (see previous comment) would help to bolster this point.

Authors: We recalculated these values, and clarified the statement in this section. Additionally, its importance is reduced when considered next to the Recking (2013) equation. As for the comparison to estimated shear, please see previous comment.

Reviewer: Discussion of bar formation and effects - Currently, I think this point of the discussion appears as an afterthought. While I agree that this might not be the main result of the paper, the authors describe the differences in bar presence and morphology between GS1 and GS2 experiments in order to support their conclusions regarding the role of large grains. If this is a main point to bolster the argument related to the importance of large grains, mapping of these bar formations and quantifying their differences between runs should be included in the methods/results sections of the manuscript. This discussion would be better supported with photos or measurements in the text to more clearly illustrate the argument made

Authors: We have added a section, at the end of results, to describe the bar morphodynamics more explicitly. In addition, a cartoon and description of the bar sweep process (a prominent erosion mechanism) has been added to the body of the text.

2.2 Figure comments:

General - Yellow is difficult to see, consider changing.

Authors: We feel that the contrast holds up well.

Reviewer: Figure 1 - Provide flume dimensions

Authors: We haved added dimensions.

Reviewer: Figure 2 - on plot report D50, D84, and sigma as part of the legend (eliminates the need for Table 1)

Authors: This was added.

Reviewer: Figure 3 - Could combine with Figure 1? I'm not sure this particular image adds very much. Also revise run name fro G2Q100H (as this is not how the experiments are referenced in the main text).

Authors: We included additional frames to expand upon range of submergences referenced in text. Removed old reference to experimental conditions.

Reviewer: Figure 4 - Higher contrast between sediment and water would make this easier to differentiate. Here different run times are referenced which appear nowhere in the text.

Authors: We have changed the colours to the same as the others used throughout the paper. Run times are taken as the first frame after the onset of transport, but incorrectly reported the minute (amended and see Table 4).

Reviewer: Figure 5 - H and L could be expanded to "high supply" and "low supply" . Consider rephrasing terms "normal" and "not normal". Provide sample sizes for each box plot and include labels for mean and standard deviation. Would eliminate need for additional tables.

Authors: We have amended these for clarity. Sample sizes are provided in other tables; it adds too much visual noise to the graph otherwise.

Reviewer: Figure 6 - Add "Calculated sediment transport efficiency" to y-axis label. Provide sample sizes for each box plot and include labels for mean and standard deviation. Would eliminate need for additional tables

Authors: This was added. See above.

Reviewer: Table Comments: Table 1 - See Figure 1 comment.

Authors: This has been corrected.

Reviewer: Table 2 - See Figure 4 comment.

Authors: This was kept as separate for noise, and added number of observation
Reviewer: Table 3 - A bit confusing, I would maybe separate the GSDs as done in other tables.

Authors: We have left this in for comparison's sake along a grain size distribution, it helps to show the differences using the same GSD.

Reviewer: Table 4 - This isn't discussed much in the text. I'm also a bit worried about averaging over different timescales here and also whether or not the average is the best metric if the experiment is still moving towards equilibrium when sediment begins to exit the flume. It would be useful to see how the sediment transport rates vary as a function of time since the experiment begins. See general comments regarding time to equilibrium.

Authors: We expounded this data in the text, fleshing out the points made. We believe that this data is still useful in spite of its different timescales of averaging. If a system is slow to adjust its sediment output over the course of the experiment, it is fundamentally operating in a different manner to one which does adjust its output more readily. Whilst the time may not be long enough for equilibrium to be attained, equilibrium was not an experimental design condition and the use of grade is to allow for holistic system scale adjustments that reflect the processes operating within these systems. Additionally, the number of collections is too coarse relative to the changes on the bed surface (bar destruction events, for example) to show any useful trends in sediment transport and appears as noise.

Reviewer: Table 5 - See Figure 5 comment.

Authors: Ditto.

Reviewer: Table 6 - See Table 3 comment.

Authors: Ditto.

Reviewer: Table 7 - Not sure this adds very much, as this comparison with Lisle is not a main part of the discussion.

Authors: We placed a heavier emphasis on the observations of Lisle et al. (1991), linking their observations with ours.

2.3 Line comments (Apologies for some differences in style that arise here):

General: The term here-in is used a number of times, I'd suggest removing all appearances of it

Authors: We have removed this from the paper.

Reviewer: Abstract: P1 1 - consider revising to "sedimentary deposits"

Authors: We changed this to alluvial.

Reviewer: P1 2 - remove "shape"

Authors: Shape was removed.

Reviewer: Introduction: P1 14 - remove "the"; consider rewording to remove "new stimuli"

Authors: We have changed both.

Reviewer: P1 16 - remove "procilivity for adjustment"

Authors: This has been removed.

Reviewer: P1 21 - replace "that results from" with "due to"

Authors: We have changed the phrase.

Reviewer: P2 3 - Remove sentence starting with “accordingly”

Authors: We incorporated this into other changes.

Reviewer: P2 13 - Consider revising “The superposition of change upon a pre-existing mass”; a bit awkward

Authors: We reworded this for clarity.

Reviewer: P2 14 - Consider changing “Four pairs of experiments” to “Two sets of four experimental runs”

Authors: This has been rewritten.

Reviewer: Methods: P2 23 - consider changing to “each experiment”

Authors: The text has been changed for clarity.

Reviewer: P2 25 - relative used twice in this sentence, consider rephrasing

Authors: The first relative was removed.

Reviewer: P2 25-30 - consider adding numbers to the list. That said, I’m not sure the list adds much here.

Authors: Numbers were added for ease of reading.

Reviewer: P3 4 - Add comma after “at the beginning of the experiment”

Authors: The comma has been added.

Reviewer: P3 8 - Change “to be output from” to “to exit”

Authors: Changed for clarity.

Reviewer: P3 8-10 - Consider rephrasing, is a bit unclear

Authors: Extra text added to make wording clearer.

Reviewer: P4 3 -A randomForests is not, as I’m aware, a standard way to extract this data, so some citations here providing details of the model/method would be useful.

Authors: We added citations for support.

Reviewer: Results: P5 1-10: I think this entire section can be made more clear and that providing the measured values in the text will help make the results read more directly.

Authors: This has been rewritten and organised, with data provided from the tables in the text to make it clearer.

Reviewer: P6 10 - I don’t think the authors have enough data to argue for a threshold change in behavior here. This transition could very well be a continuum that the authors may just be unable to capture given the data they’ve collected. I would be cautious using threshold here.

Authors: We agree that this state was overreaching, and removed this.

Reviewer: P7 4-5: Saying the "two systems behave more similarly" is quite vague. Again, I think actually including the measured values in the text here would better demonstrate the differences between the experiments.

Authors: We have specified the statement, and provided additional evidence for support.

Reviewer: P8 5 - Remove "a number of key observations can be made regarding the distribution of transport efficiencies". Rephrase next sentence to "The distribution of calculated transport efficiencies for. . .". Again, values here would help. Another option for rephrasing would be "The mean transport efficiency for GSD1 is XX% lower than for GSD2. . ."

Authors: We have adapted the text to include these changes.

Reviewer: Discussion: P9 9-10 - Consider changing "poorly sorted" and "narrowly graded" to "broadly" and "narrowly" graded to make comparison more straightforward.

Authors: We changed text for continuity.

P9 Equation 3 - small d remains undefined in the text.

Authors: We relocated this equation, but added the missing definition.

Reviewer: P10 Equation 4 - Ds50 remains underfined, consider rewriting all references to median grain size with the same convention (even if they differ in original references)

Authors: We have changed the designation to omit the 's' subscript, in line with the treatment of grain sizes throughout the paper.

Reviewer: P10 25-30 - I have a very hard time following this section. Please consider rewriting to make calculation more explicit.

Authors: We have shortened the section, and used it as justification for the inclusion of Recking (2013).

Reviewer: P11 9-10 - Reconsider using poorly and well-sorted here and instead use broad and narrow GSD

Authors: Amended for clarity.

Reviewer: Conclusion: P12 23-34 - Consider replacing GSD1 and GSD2 with "narrow" and "broad" GSDs

Authors: We have changed the wording in the conclusion, as this enables readers to use the conclusion, without having to go through the paper's methods.

P12 4 - Revise to remove "as you increase"; Missing period.

Authors: We have removed this.

3 Reviewer 3

3.1 General

Reviewer: 1. The Discussion section is outsized relative to the Intro, Methods, and Results. It feels quite speculative in light of the sparse data presented in the Figures and Tables. Specific notes provided below. The discussion of grain size sorting, armoring, and partial mobility ought to be supported by data on the bed surface grain size in the experiment, but none were presented. Is it possible that the coarsest grains were preferentially deposited along the upstream end of the experimental channel? Was the grain size distribution of the outflow material the same as the feed? These data seem to be essential information if the authors plan to provide a detailed discussion of the impact of the coarsest grains on armoring, size selective transport, etc. The discussion of bar forms is interesting, though it is unsupported by the results, as currently presented. A set of images, a few simple calculations (e.g. sinuosity), would go a longway.

Authors: We agree that the relative sizes of the sections needed addressing, therefore we restructured the introduction with material from the discussion (as also recommended by other reviewers) to more logically and evenly distribute the information. Furthermore, photos were added into the results section to bolster the evidence provided for our arguments in the paper, rather than presented in the supplemental information provided alongside the paper. Our argument does not rely on an immobility or complete cessation of motion of the coarse material, but rather a relative immobility that allows material to deposit into bed features resulting in a sorting of the bed surface. Thus, this material may still come out as bed load as this is solely an armouring based process. We included the output data, which shows a mild coarsening of the bed load, but we offer suggestions in text.

Reviewer: 2. In the final paragraph of the Discussion the authors summarize their findings as "3 lines of evidence for GSD2 as less stable": a. Lower slopes (very effectively demonstrated), prograde more quickly (I don't see this demonstrated anywhere, though it seems that the authors have the water surface profiles extracted with which to easily create plots to demonstrate this). b. Grains were more equally mobile due to a lower maximum threshold stress. (I don't see threshold stress quantified anywhere here, and it seems to me that any discussion of equal mobility should be supported by some sort of grain size data). c. Fewer, and less persistent bedforms (I don't see this demonstrated anywhere, though it seems that the imagery the authors collected should allow them to demonstrate this in a figure without too much trouble).

Authors: We added additional data to support each of these statements: Table 4 was added to address 2a, Equation 5 was used to calculate mobility transition points for 2b, and Figures 8 and 9 were added as an example for 2c.

Reviewer: 3. The authors should thoroughly proof-read their re-submission. The language was unnecessarily complicated in many places in the manuscript. For example: "raw values for which are shown in. . ."; "The difference varying alongside discharge. . ."; ". . .the superposition of change upon a pre-existing mass. . ."

Authors: We bore this in mind during the restructuring and rewriting phases of the resubmission, endeavouring to simplify sentence structure as well as word choices.

Reviewer: Page 1 Line 26) I'm not convinced that armor formation is inherently degradational. Couldn't an armor form through selective deposition of only the coarsest grains from the supply GSD?

Authors: We have corrected the introduction to reflect the differences between static and mobile armour formation. The text had previously focussed on degradational armour only, neglecting the ability for bed surfaces to form a coarser surface with sediment exchange active.

Reviewer: Page 2 Presentation of Lane balance) This feels like a bit of a straw man, especially given the great set of papers that have come out of Eaton's lab recently. I wonder if a stronger introduction for this manuscript could focus more thoughtfully on the existing questions about the role of the largest grains, and how the impact of the largest grains has the potential to be very different in aggradational systems (this paper) when compared to degradational systems (e.g. the Mackenzie and Eaton papers).

Authors: We have reoriented the introduction to include Lane as a justification for the reanalysis of the dimensionally adjusted Church (2006) equation. We have also included the importance of the role of larges grains, and their likelihood of influencing aggrading channels as well, tangential to the reviewer's original comment.

Reviewer: Line 14) This reviewer has not thought about transport efficiency in this framework, and would have benefited from a bit more context. Transport efficiency is η (eta), yes? What are the units? How should I think about it?

Authors: We have clarified transport efficiency and moved the discussion of it to the introduction, given its importance in the analysis of systems as a wholescale indicator.

Reviewer: Line 24) This hypothesis is quite vague. "Different transport regimes"? I would have assumed that referred to bedload vs suspended. . .

Authors: We have clarified the hypothesis, altering the statement to represent mixture mobilities rather than confusing the statement with other terms in use elsewhere.

Reviewer: Line 29) ". . .the superposition of change upon a pre-existing mass. . ." I'm not sure what the authors mean here.

Authors: We have changed the phrasing to a more direct explanation and example.

Reviewer: Page 5 Line 5) Is "relative sediment storage efficiency" the same as "transport efficiency"?

Authors: We have corrected the wording, this was a mistake in both the text and table and has been corrected for clarity.

Reviewer: (General Methods) When did the experiments end? How long were the runs?

Authors: We have added this to the text.

Reviewer: Page 6 Line 3) Given this description of the slope calculation, I think it would be very helpful to add several panels to Figure 4 depicting the method of slope calculation for early/middle/late stage profile evolution, showing the points of max and min elevation selected and length over which the slope is calculated. Along these lines, is it possible that the slope in the experiment varied along the profile? Is the channel concave?

Authors: We have added example plots of the beginning, middle and end values used to calculate slope. The maximum and minimum points of elevation would not necessarily elucidate the process; the calculations are made with between 1200 and 1800 points, so the effects of the extremes are limited by the number of points included, as shown by Figure 5.

3.2 Figures

Reviewer: Fig 1) What is the scale of the experimental setup? That is a great thing to put on a figure of this sort.

Authors: We have added this to Figure 1, as well as Figure 4, to clarify the image.

Reviewer: Fig 2) Is it possible that the x axis scales are offset between Figure 2a and 2b? How can 100% of the grains be finer than $\sim$6 mm, yet $>$ 3% of the mass is $\sim$8mm?

Authors: We have adjusted the range of x values to the correct range.

Reviewer: Fig 3) This figure would benefit from annotations. I couldn't figure out what the roughness elements were until I watched one of the associated videos. A multi-panel figure would help here: Start of experiment, showing roughness elements, progradation of deposit wedge, etc.

Authors: We have updated the figure to include more demonstrative photos and description.

Reviewer: Fig 4) Needs horizontal and vertical scales.

Authors: We have added these.

Reviewer: Fig 5) Caption is confusing. What is ”normal” relative sediment concentration?

Authors: We have clarified the caption by removing usage of the “normal” relative sediment concentration.

Reviewer: Fig 6) What are (a) and (b)?

Authors: We have included their description in the caption.

Stabilising ~~Large Grains~~ large grains in ~~Aggrading Steep Channels~~self-forming, steep channels

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Abstract. It is understood that the interaction between sediment supply and discharge drives first-order behaviour of alluvial deposits. The influence of the grain size distribution ~~shape~~ over the mobility and resultant evolution is, however, unclear. Four experiments were conducted in a scaled physical model for two grain size distributions, analogous to a one-dimensional self-formed alluvial fan. We demonstrate the unsuitability of the median grain size as a predictor of deposit behaviour at flows when the material is not equally mobile. The results instead suggest, during conditions of unequal mobility, that largest grains control the transport efficiency of the overall sediment mixture, and thus also the morphodynamics of the deposit and its tendency to store or evacuate material. Deposits appear to show a dependence upon the rate of material supply more strongly when the likelihood of its motion is less equally distributed (i.e., under partial transport conditions). If the coarse fraction (e.g., greater than 84^{th} percentile) is instead mobile due to increased discharge or because of their relative size, transport rates will increase and the behaviour of the mixtures converge to a common state, with morphology influenced by the material's mobility.

1 Introduction

Gravel bed rivers adjust their boundaries from the grain to the reach scale in response to the supplied sediment and water discharges ~~(Eaton and Church, 2004)~~(Leopold and Maddock, 1953; Lane, 1955; Howard and Kerby, 1983; Madej and Ozaki, 1996; Eaton an . The feedbacks and interactions between antecedent flow and sediment discharge control ~~the~~ river channel form (Fukuoka, 1989) ~~,~~ and thereby influence channel response~~to new stimuli~~, for example as a response to flow increases (Masteller and Finnegan, 2017) . Natural channels are likely to experience a distribution of flow rates and, therefore, corresponding modes of transport (e.g., Ashworth and Ferguson, 1989; Warburton, 1992). Central to the behaviour of gravel bed rivers is this ~~proclivity for adjustment in~~ response to their environment as the flow does not regularly or greatly exceed the threshold of sediment mobility (e.g., Church, 2006). ~~Instead surficial adjustment, bed forms and macroforms modulate bed material sediment transport rate, acting to dissipate energy and provide stability to the overall channel (Cherkauer, 1973). For example, grains may stabilise through rotation (Masteller and Finnegan, 2017), their organisation into cells (Church et al., 1998) and the formation of alternate bars (Lisle et al., 1991).~~

~~One of the most well studied of these phenomena is the coarsening of the bed surface that results from the preferential removal of fine grains, until an armour layer develops that approximately equalises the threshold entrainment stress of the bed (Parker and Klingeman, 1982; Parker et al., 1982b; Andrews, 1983). Armour may develop in both sediment-starved reaches, as~~

~~static armour (e.g., Kondolf, 1997), or where sediment supply is present, as mobile armour (e.g., Andrews and Parker, 1987). It is the formation of an armour layer that prevents continued transport of the bed material and stabilises the channel against further deformative work. However, armour formation is inherently a degradational process that acts to limit the mobility of the bed surface and is therefore suppressed in environments where material is being deposited. In general, aggrading gravel bed river systems are poorly studied, despite their frequent occurrence on alluvial fans and in mountainous environments with high sediment loads. Accordingly, our knowledge of the controls over stability in such environments is limited. These systems maintain sediment conveyance through the processes acting in opposition to those observed during degradation. Chiefly this has been observed as sediment mobility changes through bed organisation (Lisle et al., 1991) and slope changes to increase shear stress (Bryant et al., 1995). In contrast to degrading channels it appears as if there are fewer mechanisms acting to limit change to channel dimensions (i.e., confer stability).~~

In a channel the aggradation or degradation of material will lead to changes in its elevation, representing a balance between the amount of energy and material provided to it. Lane (1955) proposed that grade represents this balance as:

$$\frac{Q_b}{QS} \propto \frac{1}{D} \tag{1}$$

wherein the left hand side of the proportionality represents the sediment transport efficiency, given by the ratio between sediment supply (Q_b) and the product of discharge (Q) and slope (S). The right hand side ~~represents the calibre~~ is the reciprocal of the sediment flux calibre (D)~~, and is typically assumed~~. Church (2006) recast this relation in a dimensionally balanced version, which can be written as follows:

$$\frac{Q_b}{QS} \propto \frac{d}{D} \tag{2}$$

where d is the flow depth. In Church's version, D is specifically defined to be the median ~~size of the bed material (D_{50}).~~ bed surface size, based on the understanding of the hiding/exposure processes controlling the entrainment of sediment from a mixture.

Accordingly, mixtures of the same median grain size, under the same water and sediment discharges, should form to the same slope ~~given by their~~ because of their equal transport efficiency. Transport efficiency ~~is used~~ (η) is defined in the same manner as Bagnold (1966), in that it relates the work rate of the flow to the stream power available and describes the efficiency of the system in converting stream power into work (i.e., sediment transport) and is therefore higher in more efficient systems. That is, systems with higher η values will organise to lower slopes because it is more capable of transporting the supplied material, as described by its discharge. Here, it is reformulated neglecting the mass flux term from its original form, instead replicating the dimensionless, volumetric consideration used by Eaton and Church (2011):

$$\eta = \frac{Q_b}{QS} \tag{3}$$

whereby it functions as a relationship between the system's mass and energy inputs, outputs and processes.

~~However, recent work has~~ The validity of using a single characteristic grain size as a descriptor of a whole system's state is, however, fundamentally flawed. We know that surficial adjustment, bed forms and macroforms modulate bed material sediment transport rate, acting to dissipate energy and provide stability to the overall channel (Cherkauer, 1973; Montgomery and Buffington, 1997; V . For example, it has been thought that grains may stabilise through rotation (Masteller and Finnegan, 2017), their organisation into cells (Church et al., 1998) and the formation of alternate bars (Lisle et al., 1991). One of the most well studied of these adjustment phenomena is the coarsening of the bed surface due to the preferential removal of fines or their kinetic sieving into the subsurface, until an armour layer develops that approximately equalises the threshold entrainment stress of the bed (Parker and Klingeman, 1982; Parker et al., 1982b; Andrews, 1983). Armour may develop in both sediment-starved reaches as static armour (Sutherland, 1987; Parker and Sutherland, 1990; Kondolf, 1997; Vericat et al., 2006), or where sediment supply is present as a mobile armour layer (Parker and Klingeman, 1982; Andrews and Parker, 1987; Parker, 1990). It is the formation of an armour layer that prevents continued transport of the material and stabilises the channel against further deformative work. In addition, MacKenzie and Eaton (2017) demonstrated that it is the largest grains found in the bed material that control channel stability during degradation ~~, and~~ because of their role in protecting the underlying fine grains. Their work concludes that channel stability cannot be fundamentally linked to the median bed surface grain size~~(MacKenzie and Eaton, 2017). If thisis the case, then the assumptions underlying the use of Eq. (1)in degrading settings are~~ , as in models developed by Parker (1990) and Wilcock and Crowe (2003).

In contrast to this, our knowledge of the processes stabilising aggrading systems is substantially lacking in direct study; the omission of their explicit focus in the Treatise of Geomprohology is noticeable, in comparison to the myriad studies based in degrading channels. Aggrading systems are often studied, but are often treated at a greater scale (i.e., channel planform) in the field (e.g., Gilbert, 1917; Harvey, 1991; Benda and Dunne, 1997) or neglected in non-fan experiments. For example, Madej (1982) attributed increases in sediment transport rates to channel geometry changes induced by aggradation in the channel, rather than the manifestation of system variables such as slope (as would be expected with Eq. (1)). As a singular process, avulsion acts as a mechanism for channel 'stabilisation' in aggrading systems, where sediment transport capacity is maintained through the creation or re-occupation of an alternate channel position (Ashmore, 1982; Field, 2001) . Studies also focus upon the influence of supplied material, of which the calibre is important for the resulting trajectory of changes to hydraulics and morphology. An influx of fine sediment will increase sediment transport through increased exposure effects on coarser material (Wilcock et al., 2001; Wilcock and Crowe, 2003; Curran and Wilcock, 2005). On the other hand, coarse material will accumulate either through supply of unentrainable material (Harvey, 2001) or the role of coarse grains as stabilising loci (Lisle et al., 1991). We could argue, therefore, that there exists a precedent for the role of large grains in controlling the behaviour of aggrading channels, derived from the deposition of those grains supplied to the channel (e.g., Moss, 1963; Dunkerley, 1990).

The applicability of using Eq. (2) to predict the changes of system slope is thus called into question when we consider the role of large grains in the stability of aggrading or degrading systems. We hypothesise that ~~, like degrading systems,~~ the presence of the large grains will result in different ~~transport regimes, as in MacKenzie and Eaton (2017), and~~ sediment mixture mobilities for aggrading channels, thus different channel morphodynamics and depositional slope~~.~~ , as in MacKenzie and Eaton (2017) . In addition, we expect that this effect will not be maintained under discharge increases, as the D_{84} is suggested to strongly influence the thresholds of mobility within a mixture MacKenzie et al. (2018). The goal of this paper, therefore, it to test whether or not large grains influence channel stability in aggrading systems, wherein many of the processes thought to produce stabilisation in degrading systems are suppressed. To that end, we present the results ~~of four pairs of experiments ,~~ for two sets of four experiments paired by median grain size but differentiated by the shape of their distributions, for which Eq.~~(1)~~ (1) and Eq. (2) would predict similar behaviour. In most studies, slope ~~responds through the superposition of change upon a pre-existing mass~~acts as a response of an existing deposit; for example, degradation into a bed surface (e.g., Parker et al., 1982a). Here, sediment may freely aggrade or degrade and thus slope acts instead as an emergent indicator of the system state, thus allowing its form to fully represent the suite of process acting upon it, a methodology reserved mostly for fan studies (e.g., Schumm et al., 1987; Clarke et al., 2010). The results described ~~herein~~ here show that the grain size distribution used affects the ~~resultant behaviour~~ resulting behaviour of the deposit and its slope, and the differences between paired experiments are controlled by the experimental boundary conditions.

2 Methods

Eight experiments were run in the recently constructed steep mountain channel flume at the University of British Columbia. The flume is acrylic walled, 2 m long by 0.128 m wide with a foam insert creating a transition from a steep (slope = 0.1 m$\cancel{m^{-1}}$/m) upper and flat (slope = 0 m$\cancel{m^{-1}}$/m) lower section (~~Fig.~~ Figure 1), upon which a fan deposit can develop. These deposits that form within the flume are analogous to a one dimensional fan, or to the channel bed of a steep river confined by bedrock walls. Design and methodological cues were taken from previous experiments concerning self formed deposition (Guerit et al., 2014) and steep channel stability (Lisle et al., 1991).

During the runs reported ~~herein~~here, feed and flow were held constant for the length of ~~the~~ each experiment. These were conducted under one of four conditions: 100L, 100H, 200L or 200H, where the number refers to the flow rate (in ml s^{-1}) and the letter to the feed rate (L = 1 g s^{-1}, H = 2 g s^{-1}). The experiments also have a relative sediment concentration compared to the 100L experiment, where a value of 1 represents both factors increasing (i.e., 100L and 200H), 0.5 is a halving of feed relative to flow (i.e., 200L) and 2 is a halving of flow relative to feed (i.e., 100H). This range of values allows us to consider five ~~relative~~ changes in relative sediment concentration mediated by changes to discharge or sediment feed rate. ~~Those are:~~ These are: (1) no change in concentration but changes in the total flux magnitude (100L vs. 200H), (2) doubling concentration through increasing sediment feed (100L vs. 100H), (3) doubling concentration through decreasing discharge (200H vs. 100H), (4) halving concentration through increasing discharge (100L vs. 200L) and (5) halving concentration through sediment feed (200H vs. 200L). ~~Similar to MacKenzie and Eaton (2017), the sediment is roughly~~ As in MacKenzie and Eaton (2017), sediment is scaled from gravel-bedded streams found in Alberta, Canada and truncated at 0.25 mm at the lower end to remove unscalable laminar sub-layer effects for sediment finer than this size limit (Peakall et al., 1996).

These eight experiments primarily serve to distinguish between the behaviour of two grain size distributions across a range of run conditions. The two grain size distributions share nearly the same D_{50} (GSD$_{\cancel{1}\,broad}$ = 2.03 mm, GSD$_{\cancel{2}\,narrow}$ = 2.02 mm). The first grain size distribution (GSD$_{\cancel{1}broad}$) comprises a log-normal distribution from 0.25 mm to 8 mm (~~Fig.~~ Figure 2). The second distribution (GSD$_{\cancel{2}narrow}$) is only comprised of two size classes; 1.4 to 2.0 mm and 2.0 to 2.8 mm (~~Fig.~~ Figure 2).

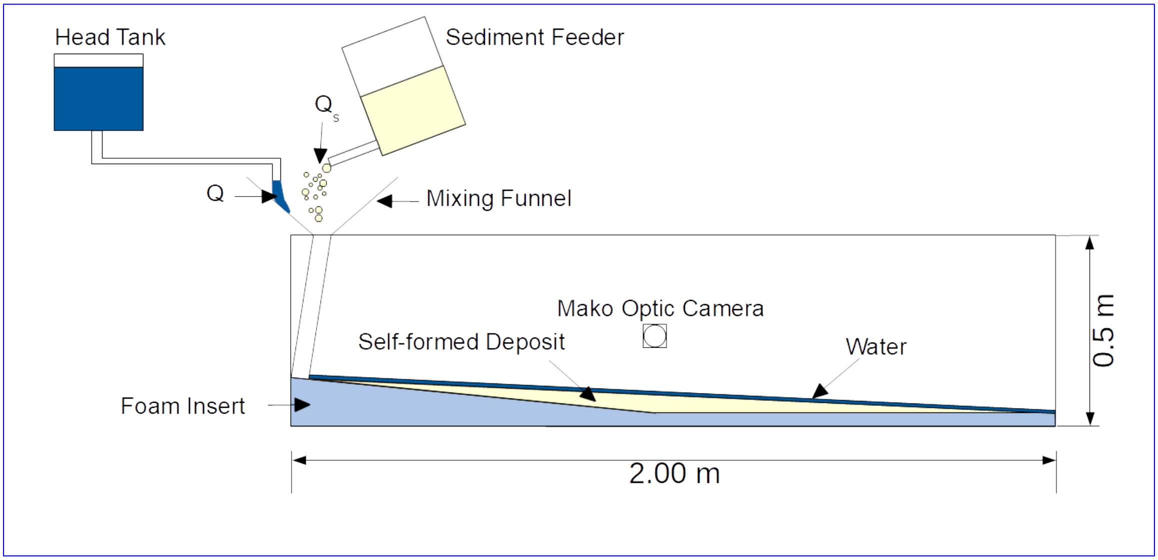

Figure 1. Simplified diagram of the experimental setup for the steep channel flume.

As a result GSD~~$_1$~~$_{broad}$ has a substantially higher D_{84} and standard deviation (σ), as would be expected from its substantially coarser and finer tails~~(Table ??)~~.

At the beginning of the experiment, roughness elements were placed on the bed to ensure that the flow remained subcritical during the initial deposit building stages. Once the sediment feed and water supply were turned on, bed material deposited around the initial roughness elements, burying them and creating a freely adjustable self-formed deposit with a configuration dictated by the grain size distribution of the sediment supply. The data presented here is collected after sediment has begun to ~~be output from~~ exit the flume. That is, sediment has deposited along the length of the flume, ~~and begun to be transported out and collecting in~~ sediment transport out of the flume has begun and the sediment trap ~~(see Fig.~~ is collecting this output (see Figure 3). By which time the channel has a self adjusted roughness and the influence of the roughness elements themselves is limited. Data collection ended when the supply of sediment was exhausted, thus run time is proportional to the feed rate.

The main source of data used ~~herein~~ in this study was collected using a side-looking camera to map the evolution of the channel's long profile. A Mako Optic camera was positioned perpendicular to flume orientation, and took photographs at 60 second intervals. The camera itself contains a routine to flatten these images and correct for radial lens distortion, resulting in a nearly perfect orthometric image. An image calibration routine translated pixel values to real space coordinates, from which a linear regression was fit to estimate the bulk sediment deposit gradient from the channel profile. Additionally, at 30 second intervals oblique images of the bed were captured by a GoPro oriented upstream. The images were compiled into videos and submitted alongside this paper to record the bed state evolution (see Video availability).

Sediment output data was also recorded through the use of a sediment trap emptied at 15 minute intervals. The material was captured, dried and then weighed, giving us mean transport rates for the preceding period and allowing us to calculate relative sediment storage efficiency, as the difference between output and input. That is, a relative storage efficiency of 100% represents

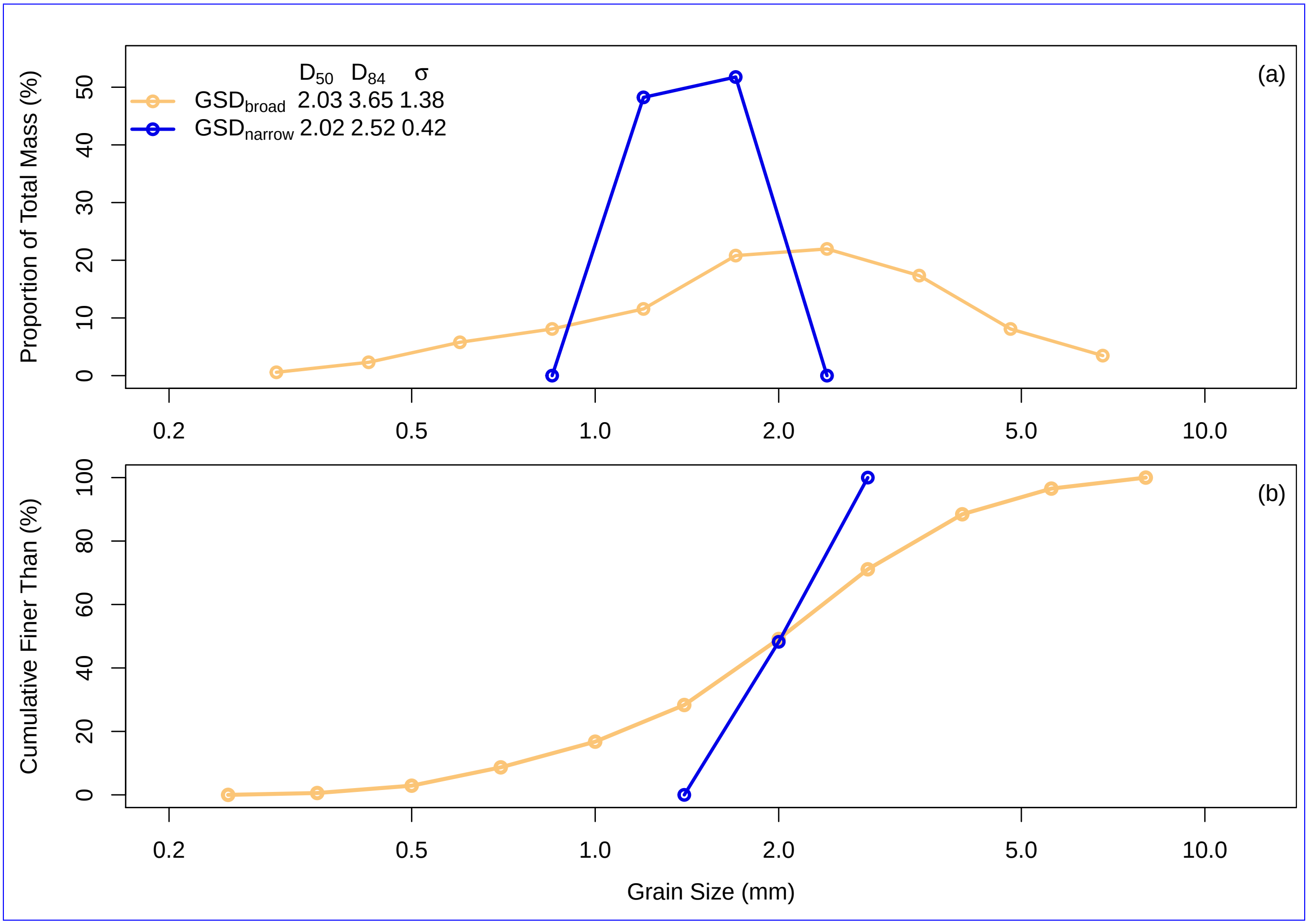

Figure 2. Grain size distributions for half-phi classes (a) individually and (b) cumulatively. Grain size metrics are shown in mm.

all sediment that is input is stored during a timestep (Table 3). Additionally, the mean transport rate is the value used in Eq.~~(2)~~ (3) in order to calculate η values reported later.

2.1 Slope Derivation

In order to derive a water surface slope from the profile images, a simple supervised image classification process was applied to each frame ~~. First a randomForests~~ to automate the process. First, a randomForest model was used to assign one of seven sub-classes to RGB pixel values built from a smoothed training image ~~.~~ (Liaw and Wiener, 2002). Random forests utilise decision trees, that minimise some factor, built on different, random samples of the training observations and then averaging the results of each of these decision trees to make predictions from that dataset (Breiman, 2001). Averaging the results of the myriad regressions built in the model thus improves its predictive strength, and randomForest models have been employed

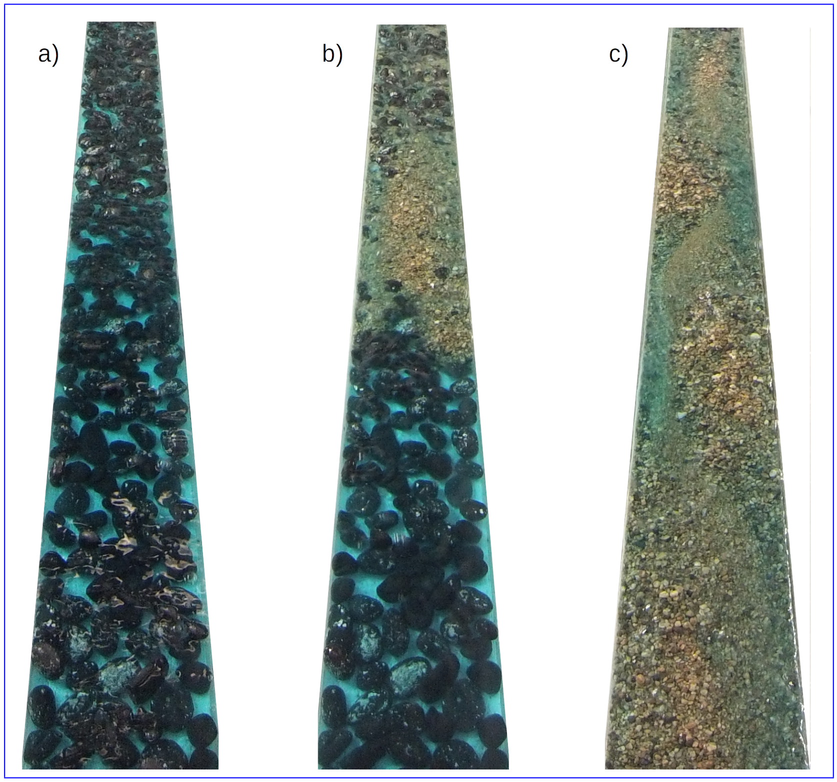

Figure 3. Example ~~image~~ images of the black roughness ~~element sediment~~ elements used to force subcritical flow, and their submergence taken during ~~sediment output~~(a) beginning of experiment with full emergence, (b) partial submergence and (c) onset of transport, almost complete burial and submergence, from experiment ~~G2Q100H~~200H using GSD$_{broad}$.

during supervised classification of remotely sensed images (see Belgiu and Drăguţ, 2016). The sub-classes ~~within these~~ are: sediment, clear water, water with sediment behind it (pool), water surface, background, background with shadow and the roughness elements. These sub-classes were then grouped into four umbrella classes as sediment, water, background and roughness elements, with the latter treated as NA values, and then smoothed using a 7 x 7 mode pixel filter to reduce noise (~~Fig.~~ Figure 4). The ~~slope values reported herein~~ training image was chosen such that each of these sub-classes were present, and then a model built between the red, green and blue pixel values of each class that was applied to every other image in the dataset. The slope values are the water surface slopes defined as the boundary between background class pixels and the highest of either water or sediment class pixels, until the downstream-most extent of sediment. As sediment may infill between the roughness elements but not contiguously deposit up to that point, a manual mask was applied to the height of the roughness elements to prevent the erroneous reporting of slope values. Example slope profiles show the typical calculation of the regression, at the beginning, middle and ends of runs (Figure 5).

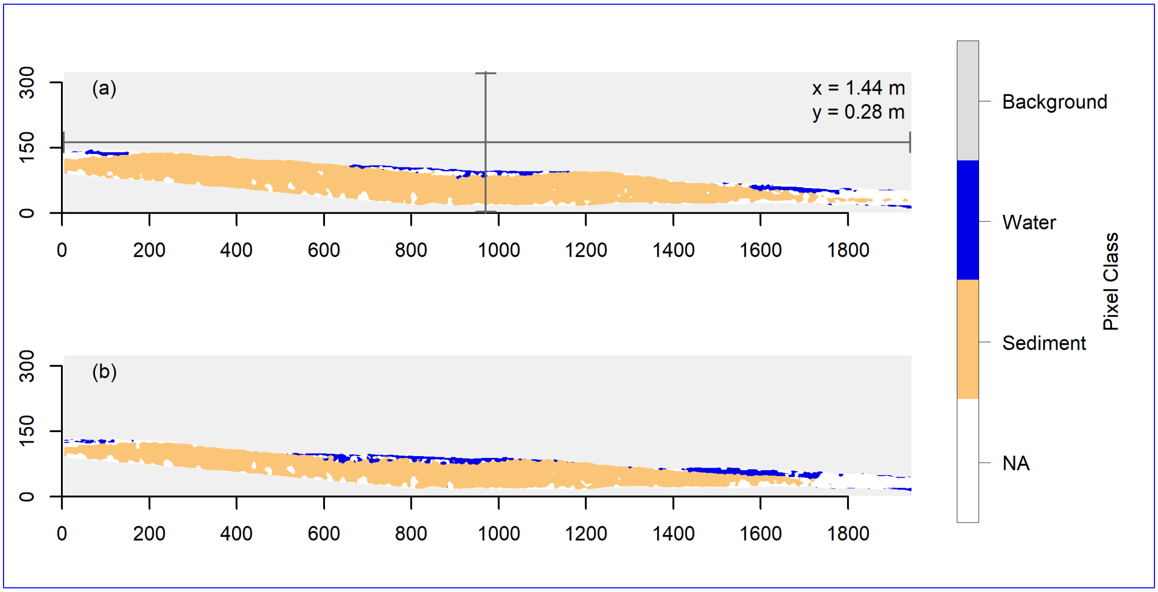

Figure 4. Output after image classification at ~~end~~ the onset of ~~aggradational phases~~ output for Exp. 100L using (a) GSD~~$_1$~~$_{broad}$ (T = ~~327~~ 326 min) and (b) GSD~~$_2$~~$_{narrow}$ (T = ~~150~~ 149 min). Axes are pixel values of the raster, and real distances are provided for scale.

3 Results

~~Panel (a) of Fig. 6 (relative sediment concentration = 1) shows a strong distinction between GSD$_1$ and GSD$_2$ for the full~~ There is a substantial difference between the distribution of slopes ~~, with the former organising to significantly higher values.~~ for GSD$_{broad}$ and GSD$_{narrow}$ under 100L conditions; GSD$_{broad}$ organised to a mean 42.7% higher than GSD$_{narrow}$ (Figure 6). Similarly, for twice the relative sediment concentration ~~,~~ (i.e., 100H), a clear separation exists between the distributions of slopes formed by GSD~~$_1$ and GSD$_2$~~$_{broad}$ and GSD$_{narrow}$, albeit with a lower difference between the two; the mean slope of GSD$_{broad}$ is 22.1% higher. In contrast, at higher discharges ~~the~~ but the same relative sediment concentration (200H) the slopes for both sediment feed rates are distributed about a lower mean ~~,~~ (GSD$_{broad}$: 0.0492 m m^{-1}, GSD$_{narrow}$: 0.0452 m m^{-1}), and substantial overlap occurs between the lower bound of GSD~~$_1$~~$_{broad}$ and the upper bound of GSD~~$_2$~~$_{narrow}$. The mean slope value decreases for both grain mixtures at ~~higher discharges~~lower feed rates and higher discharge (200L), although it decreases more sharply for GSD~~$_1$. The raw values for which are shown in Table 1~~$_{broad}$ (0.0497 m m^{-1}) than GSD$_{narrow}$ (0.0428 m m^{-1}), and occupies a similar distribution as those for 200H. Mean slopes are given in Table 2, and differences resulting from changes between run conditions for the same grain size distribution are shown in Table ~~2~~1.

Sediment output rates ~~are shown in Table 3, and they show an increase in sediment transport efficiency~~ show a decrease in the proportion of sediment storage in response to ~~changes in discharge~~ increases in discharge (Table 3). For both grain ~~sizes~~ size distributions more material is stored at lower discharges~~correlating to the steeper angles of the~~ , resulting in steeper sloped deposits. Doubling the feed rate results in both systems retaining a higher proportion of sediment within the system at 100

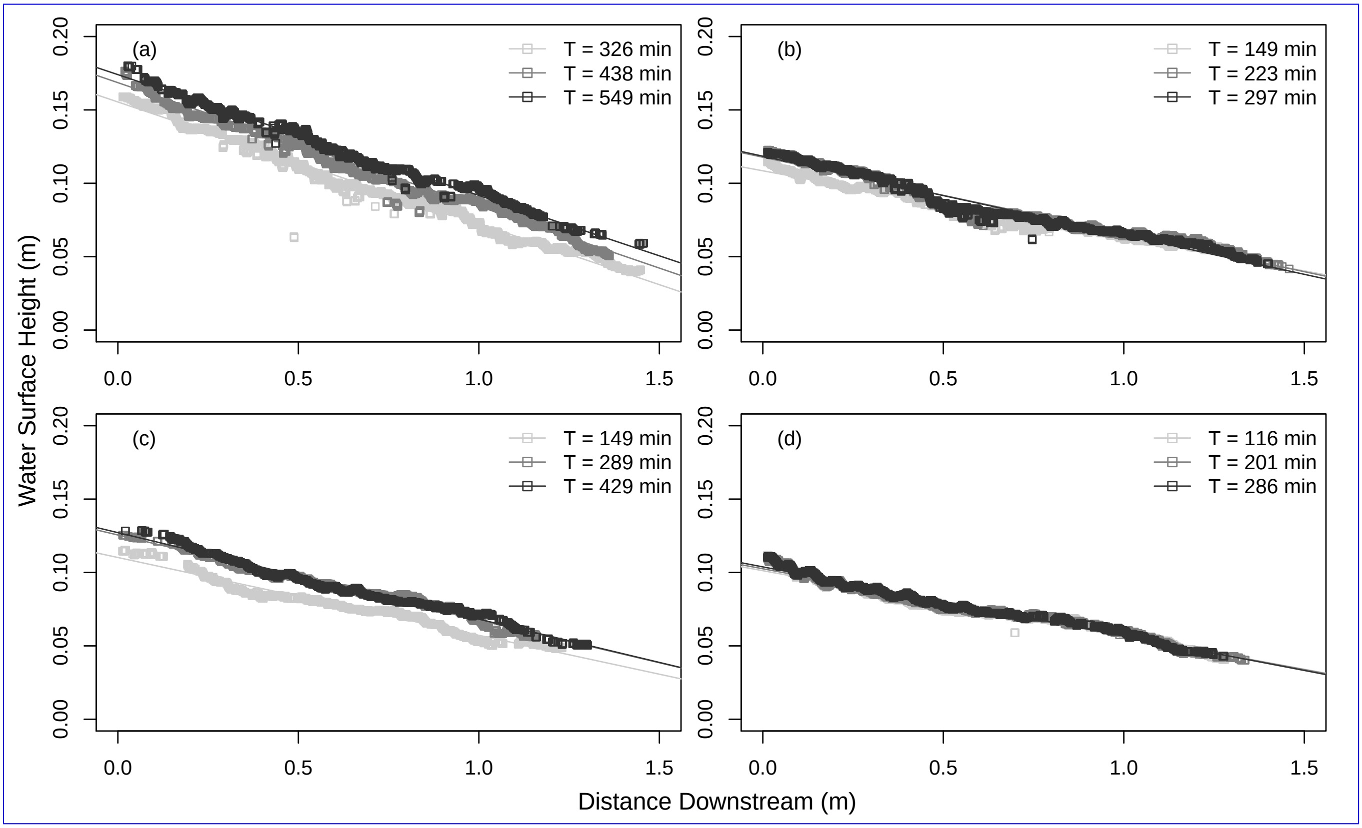

Figure 5. Example water surface profiles, and regressions used to derive slope, for experiments (a) GSD$_{broad}$ 100L, (b) GSD$_{broad}$ 200H, (c) GSD$_{narrow}$ 100L and (d) GSD$_{narrow}$ 200H. Times given in legend correlate to the onset of output, approximately halfway through the experiment, and the end of the experiment.

ml ~~s^{-1}~~ s^{-1}, although this effect is more prominent in GSD$_{broad}$; 59.1% to 91.5%, and 27.1% to 33.6%, for GSD$_{broad}$ and GSD$_{narrow}$ respectively. However when discharge is increased, regardless of feed rate, the two systems behave more similarly both with respect to feed rate and with each other. Here, 16.3% and 18.3% of material is stored for GSD$_{broad}$ under low and high feeds respectively, and only 9.4% and 8.6% for GSD$_{narrow}$. At higher discharges and higher sediment supply rates, the onset of transport occurs earlier regardless of grain size distribution (Table 5). In addition, output starts later using GSD$_{broad}$ for all experiments barring 200H, where transport begins at almost the same time.

The distributions of the output material show a variable agreement between the fed load and the output material (Figure 7 and Table 4). The D_{50} of the output is coarser at all discharges, whereas the D_{84} is finer at 0.1 l s^{-1} and coarser at 0.2 l s^{-1}. The output mixture also only equals the feed σ at high feed rate and discharge. In contrast, GSD$_{narrow}$ has a slightly higher output D_{50} at low discharge and finer at high discharge, with an almost constant D_{84}. In addition, the σ is always higher than the feed rate. This, caused by the addition of a fine tail, is an artefact of the rotary feeder used in these experiments; the action

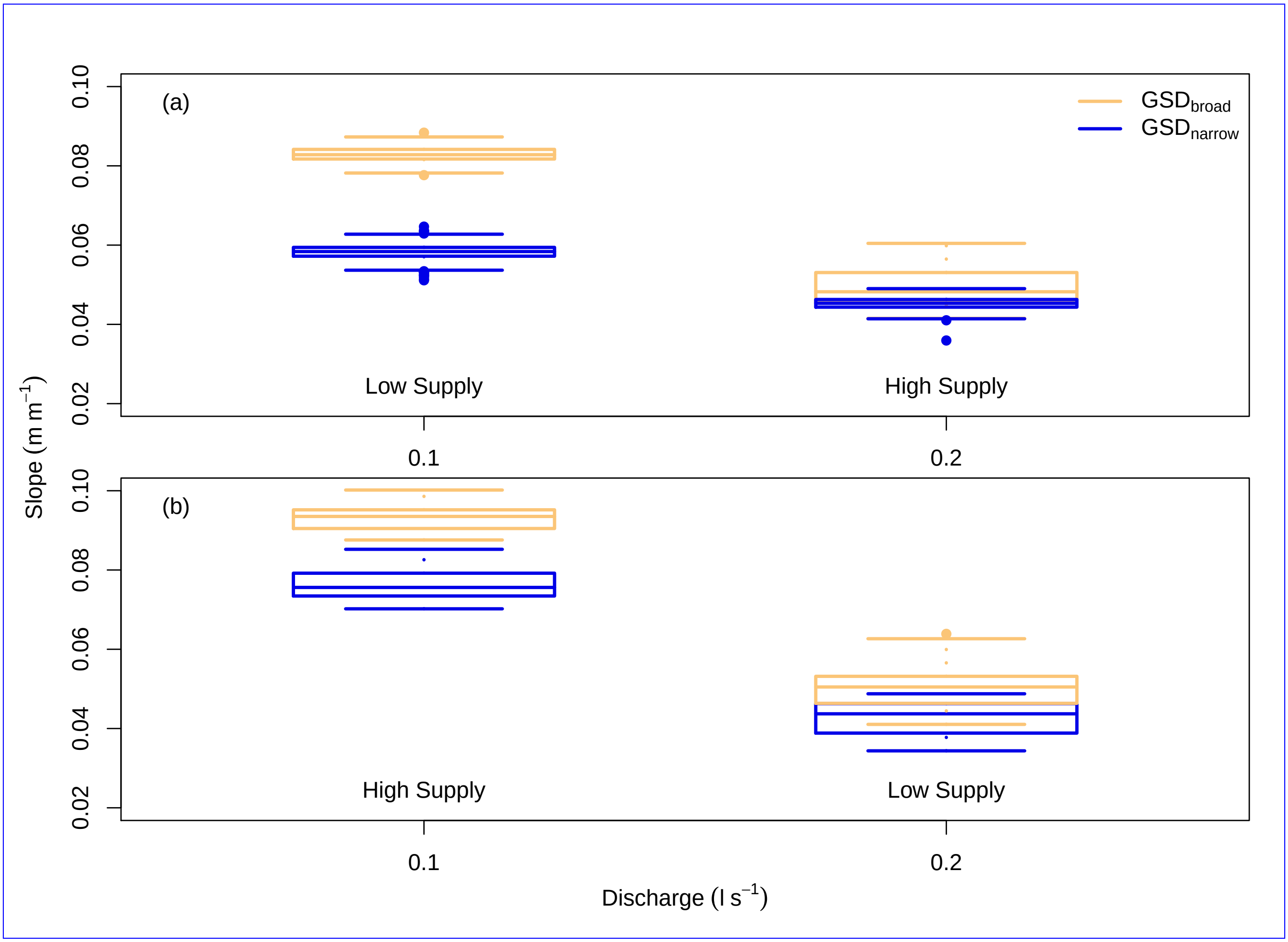

Figure 6. Distribution of slope values from the onset of transport onwards. Plots separate experiments by relative sediment concentrations of (a) ~~normal (i.e.,~~ 1 ~~)~~ and (b) not ~~normal~~ 1 (i.e., 0.5 or 2)~~relative sediment concentration~~. Text indicates sediment feed rate (~~L~~ low supply = 1 g ~~s^{-1}~~ s^{-1}, ~~H~~ high supply = 2 g ~~s^{-1}~~ s^{-1}).

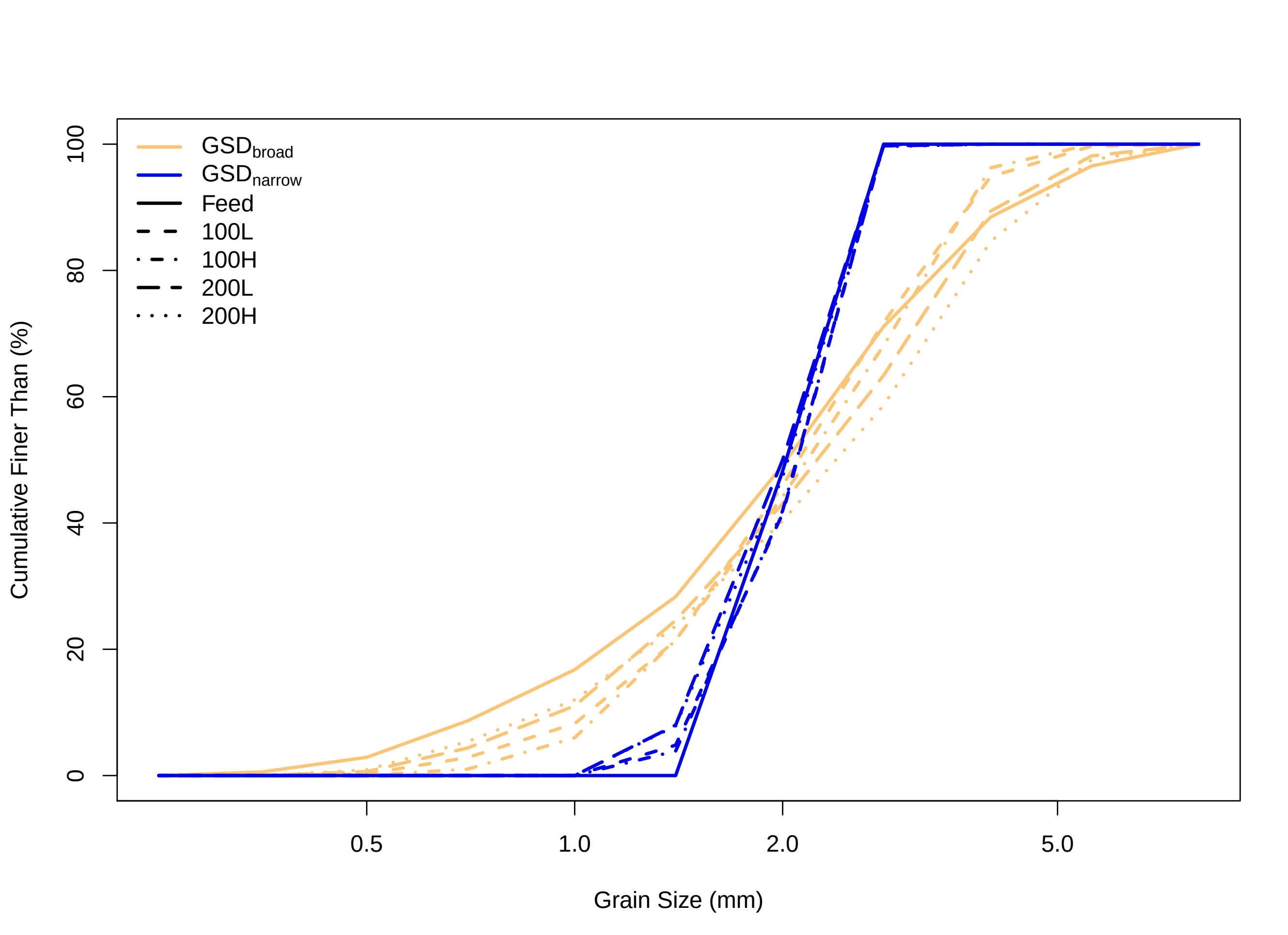

Figure 7. Size distributions of material output across the length of each experiment. Original grain size distributions are also provided.

of the rotating feeder pipe crushed a small amount of sediment as it was input into the flume. Overal, however, there is strong agreement between the feed and output grain mixtures.

Three key observations can be made regarding the distribution of transport efficiencies (~~Fig.~~ Figure 8). First, the distribution of calculated transport efficiencies of GSD~~$_1$~~$_{broad}$ are consistently lower than those of GSD~~$_2$~~$_{narrow}$ (Table 6), following from the differences in slope reported above. For example, the mean transport efficiency of GSD$_{narrow}$ is 154% greater than GSD$_{broad}$ for experiment 100L. Second, increasing water discharge, for a given feed rate, increases the efficiency of both grain size distributions ~~under both feed scenarios~~ except for GSD~~$_2$~~$_{narrow}$ under low feed, where a decrease is observed (Table 7); efficiency for GSD$_{broad}$ is 17.2% higher under 100L than 100H. Third, increasing feed rate, for a given discharge, increases the efficiency of both grain size distributions except for GSD~~$_1$~~$_{broad}$ with low discharge, where a decrease is observed (Table 7).

The mean slope values were also used to calculate the reference shear stress necessary to entrain the D_{84}, using the approach of Wilcock and Crowe (2003):

$$\frac{\tau_{ri}}{\tau_{rs50}} = \left(\frac{D_i}{D_{50}}\right)^b \quad (4)$$

where τ_{rs50} is the reference stress for the median surface grain size (D_{50}), and b is an exponent of value 0.67 when i is larger than the mean surface grain size. Equation (4) produces a shear stress 48.1% greater for entrainment of the D_{84} than the entrainment of the median in GSD$_{broad}$, and 15.5% greater for GSD$_{narrow}$. This value is static for each mixture, solely based on the grains comprising the mixture and not on deposit characteristics, slope or bed state. We also calculated the mixture mobility transition point (τ^*_m) from Recking (2013), which is adapted from Recking (2010), using:

$$\tau^*_m = (5S + 0.06)\left(\frac{D_{84}}{D_{50}}\right)^{4.4\sqrt{S}-1.5} \quad (5)$$

where S is energy slope and the transition point represents the Shields stress where partial mobility transitions to full mobility (Table 8). GSD$_{broad}$ has substantially higher values than GSD$_{narrow}$ at low discharge, but they decrease and approximate those of GSD$_{narrow}$ at higher discharges, albeit slightly lower in value. That is, both mixtures exhibit similar transitions between partial and full mobility under the higher discharges, but GSD$_{narrow}$ remains substantially lower at lower discharges.

In addition, the experiments also demonstrate differences in the morphologies, particularly centered around the form and behaviour of bars in the flume. The full suite of evidence is available in the supplemental videos submitted alongside this paper, but key frames are also included here. The bars formed using GSD$_{broad}$ seem to form from the coarser end of material and exhibit greater curvature, whilst those of GSD$_{narrow}$ form bars that deflect flow to a lesser extent, that are texturally indistinguishable from the bulk mix. At lower discharges, both grain size distributions exhibit higher numbers of bars with lower wavelengths, with GSD$_{broad}$ typically organising to shorter wavelengths than GSD$_{narrow}$ (Figure 9(a) and (c)). At higher discharges, the number of bars decreases for both mixtures and their wavelengths increase to compensate, with GSD$_{broad}$ continuing to exhibit a shorter wavelength (Figure 9(b) and(d)). We also observed the occurrence of erosional events we will refer to as “thalweg sweeps”, presented as a series of frames in Figure 10 and also observable in the supplemental videos. During these events the thalweg laterally erodes through the adjacent bar and then either remains on the new side, or migrates back to its original position. These bar sweeps do occur in both grain mixtures, however they are relatively limited in their frequency and magnitude in GSD$_{broad}$ and are a more defining feature of the morphodynamics of GSD$_{narrow}$.

4 Discussion

The results of these experiments clearly demonstrate that the range of grain sizes present in the bed material, and load, exerts first-order control over self-formed deposition, and it is therefore inappropriate to simply use the median surface grain size in order to characterise the system under all conditions. The extent of this influence does, however, vary with the boundary conditions under which the experiments are conducted. At lower discharges, differences between the two grain size distributions

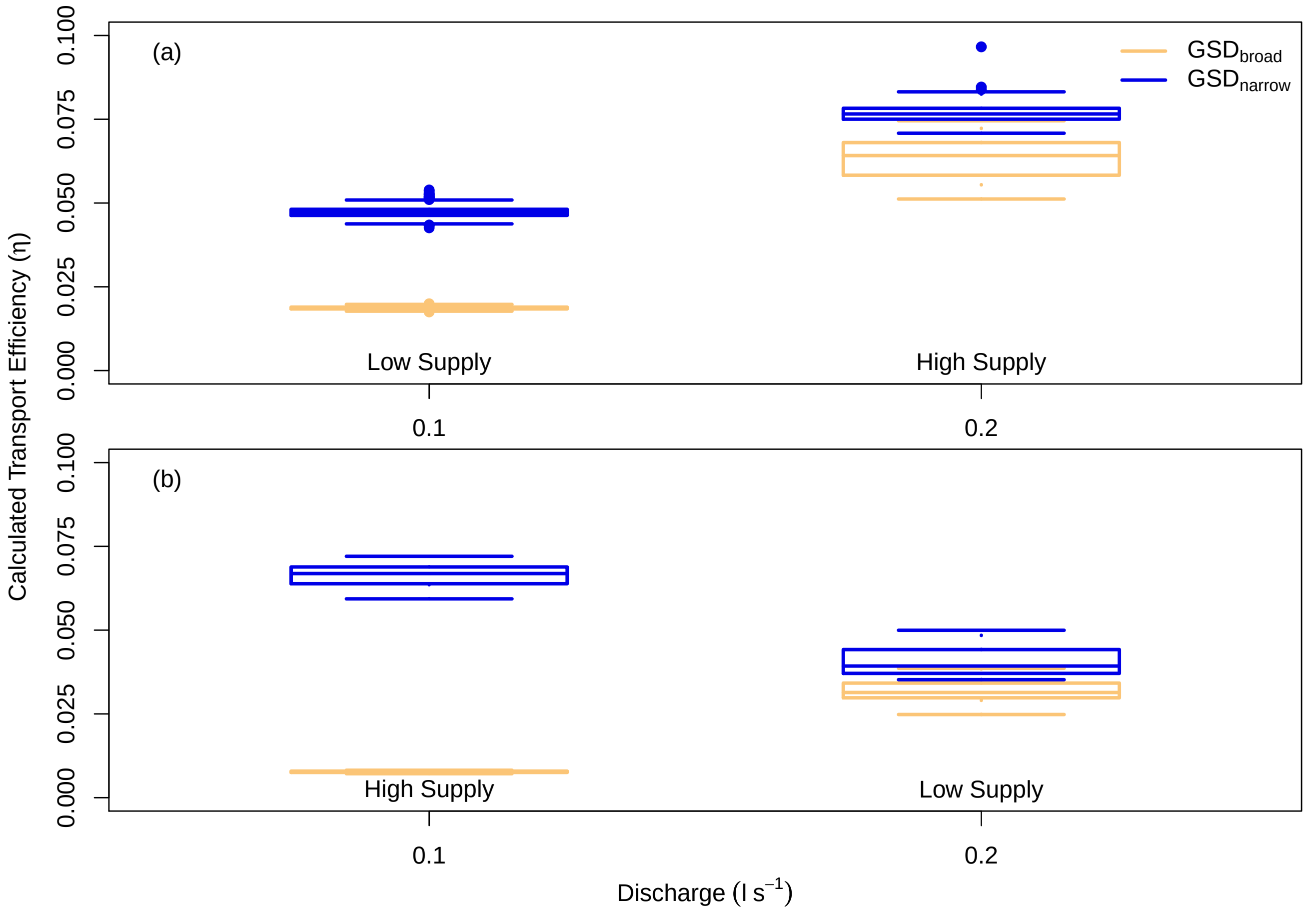

Figure 8. Distribution of transport efficiencies~~(η from~~, calculated using Eq. (3). Plots separate experiments by relative sediment concentrations of (~~??~~a) 1 and (b) ~~for experiments 100L~~not 1 (i.e., ~~100H~~0.5 or 2). Text indicates sediment feed rate (low supply = 1 g s^{-1}, ~~200L and 200H~~high supply = 2 g s^{-1}).

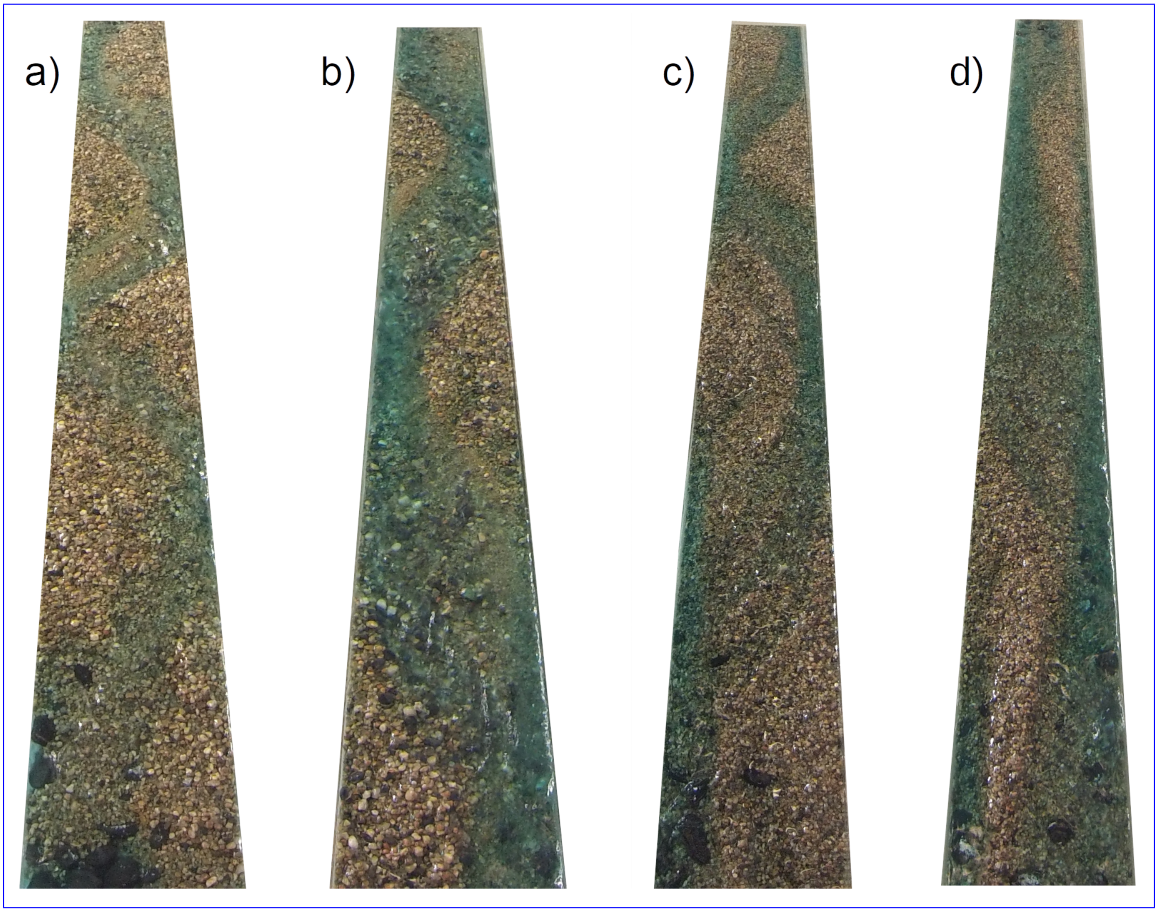

Figure 9. Example images of bed state taken from GSD$_{broad}$ at low (a) and high (b) discharge, and GSD$_{narrow}$ at low (c) and high (d) discharge.

can be attributed to the relative difficulty of the channel to mobilise the larger grains~~. Thus~~ , thus it is the volume of supplied material that influences the efficiency of transport. At higher discharges, the difference in behaviour between the two mixtures decreases as the mobility differences also decrease.

The difference in mobility varying alongside discharge is shown by our primary response variable, slope. Slope acts as an indicator of system's ability to transport the material supplied to it, as mediated by the energy supplied to it (Mackin, 1948; Lane, 1955; Chu . If we were to predict behaviour of the systems from the Lane ~~relation~~ and Church relations (Eq.~~(1))~~ (1) and Eq. (2)), we would assume that both grain size distributions would behave in the same manner. Additionally, those experiments of the same relative sediment concentration (100L and 200H) would have the same values of slope. Further, where sediment concentration was increased or decreased, we would expect commensurate increases or decreases in slope respectively. However, one set of systems (i.e., those of the ~~poorly sorted GSD~~~~1~~ broadly graded GSD$_{broad}$) consistently organise to higher slopes and lower transport efficiencies than those for the more narrowly graded (i.e., GSD~~2~~$_{narrow}$) systems for each experimental condition. As all systems

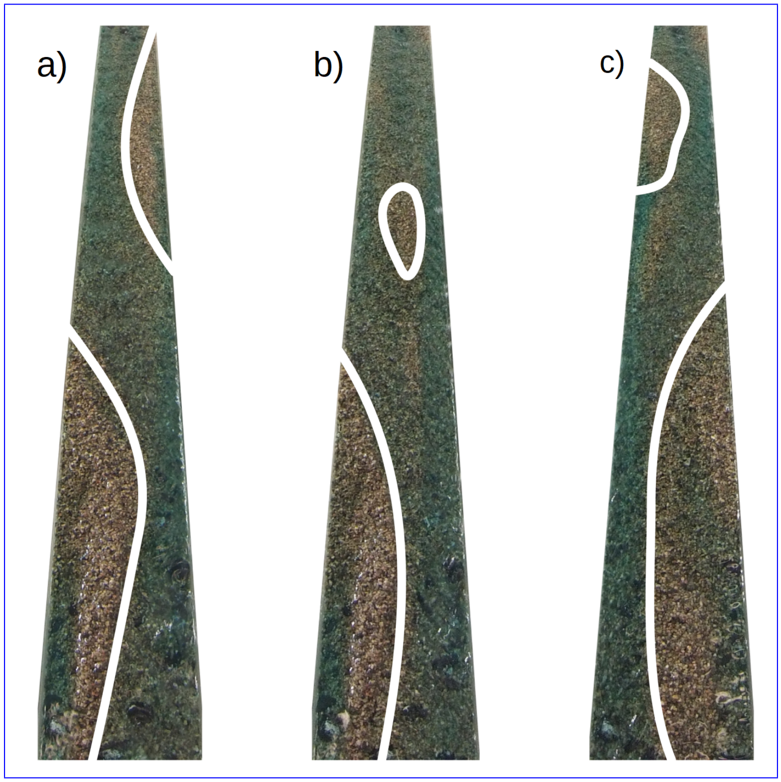

Figure 10. Three frames taken from the beginning, middle and end of a thalweg sweep event from the left side of the flume to the right and resulting in a switching of the thalweg position, in experiment 200H using GSD$_{narrow}$. These frames correspond to approximately 28 s to 30 s of the accompanying video.

were continuously accumulating, static sediment surface armouring (e.g., Sutherland, 1987; Parker and Sutherland, 1990; Gomez, 1994) could not occur due to the ~~supression~~ suppression of selective transport and subsequent equivalence between the bed surface and sediment feed grain size distributions. ~~Therefore,~~ Instead, here the bed surface resembled the bed states Iseya and Ikeda (1987) and Lisle et al. (1991) observed, in which the mixture is laterally organised. Bennett and Bridge (1995) also observed lack of bed texture adjustments under aggrading settings, when the accumulation is induced either through flume slope or feed rate changes. Therefore, we believe that the observed differences in slope cannot be attributed to differing degrees of surface armouring ~~. Instead, it is more likely due to bed surfacesorting.~~ across the bed surface.

The strongly differing depositional slopes ~~occurring~~ that occur at low discharges are at odds with what we know about sediment entrainment. Previous studies suggest that most of the bed material becomes entrained at about the same shear stress ~~due to~~ as a result of the relative hiding and exposure of grains smaller and larger than the median surface size ~~(Parker et al., 1982b; Parker and Klin~~ ~~. In addition, previous work indicates~~ (Parker et al., 1982b; Parker and Klingeman, 1982; Andrews, 1983), and that the entrainment threshold for a unimodal mixture is similar to the entrainment threshold for a bed surface having the same median size ~~(Komar, 1987b)~~(Komar, 1987a). If we therefore extend this concept to the prediction of sediment deposition angles, then the existing body of work seems to suggest that the angles for our two grain size distributions ought to be effectively the same under the same boundary conditions given their shared bulk sediment mobility.

A potentially critical explanation for this disparity is that equal mobility does not apply to all of the bed sediment. For example, Andrews (1983) found equal mobility applied only to sediment finer ~~than~~ that about the bed surface D_{84} in his field study, and nearly all of the data on bed mobility published by Haschenburger and Wilcock (2003) showed similar relative stability of the largest grains at even the highest shear stresses. We believe that this suggests that the size of the largest sediment in the bed may determine the deposition threshold for a mixture, at least for those situations in which competence controls sediment deposition, not sediment transport capacity. The implication of this position is that the gradient of fans, floodplains and other self-forming alluvial deposits is likely to be related to the size of the largest sediment in transport, not the median bed surface size as previously assumed.

~~Interestingly, there is also a marked difference in the efficiency of the two systems with respect to sediment transport (Fig. 8). For GSD~~$_1$~~, the characteristic efficiency was substantially lower than it was for GSD~~$_2$~~. This is at odds with the concept of channel grade proposed by Lane (1955), at least in its commonly used form (Eqn. (**??**)). Church (2006) recast this relation in a dimensionally balanced version, which can be written as follows:~~

$$\frac{Q_b}{QS} \propto \frac{d}{D}$$

~~In Church's version,~~ D ~~is specifically defined to be the median bed surface size, based on the understanding of the hiding/exposure processes controlling the entrainment of sediment from a mixture. Therefore, metrics derived from this relation, such as the transport efficiency consideration from Eaton and Church (2011), implicitly include this assumption and suffer the same limitation.~~

According to the conventions established by Lane (1955) and Church (2006), both of our grain size distributions had the same sediment calibre, so why did they not equilibrate at the same slope, and achieve the same transport efficiency? The average size of the sediment feed calibre is almost identical for both GSD~~$_1$ and GSD$_2$~~$_{broad}$ and GSD$_{narrow}$. While we can explain the failure of Eq.~~(**??**)~~ (1) as stemming from its original intention to be used as a qualitative guide for thinking about channel grade, Eq. ~~(**??**)~~ (2) is based on the existing semi-empirical representations of bed sediment entrainment, so the discrepancy between Eq. ~~(**??**)~~ (2) and the results in ~~Fig.~~ Figure 8 point to a more fundamental problem. Simply put, these results clearly indicate that D_{50} is a poor choice for the characteristic grain size, at least when considering the processes forming alluvial deposits at lower discharges (i.e., the majority of the time), rather than those eroding them or at least responsible for high rates of bedload transport. Our preliminary analysis suggests that some representation of the coarse tail is probably more appropriate (such as the D_{84}, which is commonly used in flow resistance equations (e.g., Lenzi et al., 2006; Ferguson, 2007; Recking et al., 2008)).

At a basic level, the observed ~~differences in slopes are~~ difference in slopes is associated with the ~~varying~~ differential ability of two experimental systems to transport sediment, which in turn is related to the relative thresholds of motion of the largest grains. Curran and Wilcock (2005) observed ~~increased transport rates of coarse sediment at lower slopes , for the same discharge and coarse feed rate, as sand supply increased in their flume experiments. The same inference can be made here: deposits organise to~~

a ~~lower slope for GSD$_2$ because the sediment is more mobile. However, unlike the experiments by Curran and Wilcock (2005) the increased mobility is not due to the increased sand presence but the absence of~~ gravel-sand mixture organising to lower slopes in response to increased proportions of sand, implying that the higher sand presence decreased the critical shear stress necessary to transport coarser material, a common feature in bed organisation studies (e.g., Iseya and Ikeda, 1987). When the bed is organised as such, the ~~large immobile grains (e.g., MacKenzie and Eaton, 2017).~~

~~The idea that the stable slope angle for these experiments is determined by the mobility of the largest grains in the bed is consistent with existing equations predicting entrainment thresholds based on relative grain size. The reference stress (τ_r) required to mobilise a grain size fraction (i) is calculable using the approach published by Wilcock and Crowe (2003):~~

$$\frac{\tau_{ri}}{\tau_{rs50}} = \left(\frac{D_i}{D_{s50}}\right)^b$$

~~where τ_{rs50} is the reference stress for the median surface grain size and b is an exponent of value 0.67 when i is larger than the mean surface grain size. Equation (4) produces a shear stress 44.4% greater for entrainment of the D_{84} than the entrainment of the median in GSD$_1$ than in GSD$_2$. This difference in mean slope values isapproached during experiment 100L (GSD$_1$ is 42.7% higher than GSD$_2$), but is otherwise much higher than the observed differences in slope for the other experiments~~variance of force exerted upon the grain and thus the likelihood of entrainment increases (Schmeeckle et al., 2007), hence the lower deposit slope and higher mobility. Here we infer that the inverse is in operation, with the presence of coarser grains decreasing the overall transport rate by increasing the entraining stresses of the mixture in a similar manner to their behaviour in degrading settings (Church et al., 1998; MacKenzie and Eaton, 2017), antithetical to the influence of sand. That is, their presence acts in a manner similar to those in kinematic waves and traction clogs in slowing the overall bed load motion (Leopold and Wolman, 1957; Moss, 1963; Langbein and Leopold, 1966; Ashmore, 1991).

~~The decreasing difference in slope values as discharge increases indicates a cessation in the influence of the D_{84} and grain scale processes in driving larger scale behaviour. That is, the 8.88% difference in mean slopefor 200H indicates that the mobility of the two mixtures are more similar and the role of the previously individual stabilising grains are reduced, minimising the differences between the two mixtures. Whilst the behaviours of the two mixtures never fully converge, the differences at low discharges~~

Based solely on the differences in reference stress values (Eq. (4)) we would expect a fixed difference in slopes between the two grain mixtures. However, our observations of the differential system state reponses (i.e., slope) show that the degree of this difference changes with discharge. We see the output feed Our calculations of the transitional Shields stress, from Recking (2013), indicates that this value changes alongside discharge, as a product of slope. The differences in slope at low discharge and similarities at high ~~discharges do suggest the presence of a threshold evident through these experiments that, once exceeded, causes the mobilities of the two mixtures to approach parity.~~

~~This suggestion of behaviour issimilar to~~ discharge indicate the importance of the ~~observations of~~ absolute mobility of the bed material, and the coarser fraction, in conjunction with its relative mobility. That is, if the material is subjected to a larger fluid force (i.e., higher discharge) it performs the same role as removing those grains which cause the immobility, and hence a convergence in behaviour.

The threshold calculation used in Eq. (5) invokes the partial and full mobility conditions under differing flow strengths by Wilcock and McArdell (1993). Although we cannot calculate a shear stress, given the lack of water depths, it is a useful indicator of the state of the system at a more generic scale, regardless of the actual values of τ_m^*. This separation between transport regimes at low and high discharges is also similar to the observation of the three phase transport ~~model of Ashworth and Ferguson (1989) , where equal~~ models of Ashworth and Ferguson (1989) and Warburton (1992), where full mobility is achieved above a threshold discharge following the cessation of a given influence. However, ~~unlike Ashworth and Ferguson (1989) ,~~ the increased transport rates are not generated through the destruction of previously organised structures ~~, which necessarily require a range of flows without transport to form.Instead,~~ (e.g., Laronne and Carson, 1976; Cudden and Hoey, 2003; Recking et al., 2009) .Instead the difference is sourced from an increase in the maximum grain size entrainable by the flow, and the likelihood of that grain's entrainment. That we see a ~~poorly sorted~~ broadly graded mixture (GSD~~$_1$~~$_{broad}$) acting in a manner similar to one that is ~~well sorted (GSD$_2$~~narrowly graded (GSD$_{narrow}$) at higher discharges suggests that Eq. ~~(??)~~ (2) is applicable when there is equal sediment mobility ~~.~~ as the characteristic grain size approaches the median.

We also observed two further phenomena that may contribute to the observed output distributions. First, the finest material would often be found at the base of the flume during preparation for the next run, having filtered through the coarser matrix; a phenomenon limited to GSD$_{broad}$. The hiding of this finer material through vertical sorting explains the observed differences in the fine tail (Figure 7) as well as the constant coarser D_{50} for GSD$_{broad}$. Second, there was a degree of coarse material deposition at the mouth of the feeder. However, as shown by the similarities of the output and input D_{84} (Table 4), this only affected GSD$_{broad}$ at the low discharges. Presumably, when these grains were not mobile throughout the mixture regardless of their deposition upstream. Therefore, we believe the mobility differences are systematic between the two distributions.

Pfeiffer et al. (2017) proposed that ~~sediment supply~~ it is sediment supply that controls the channel's hydraulic geometry, as well as the surface size of the material. This seems to be the case where the limit over transport is competence driven (i.e., flow = ~~L~~100 ml s^{-1}) and thus the addition of greater volumes of sediment will force higher slopes, which is then reflected in the η values. However, when the systems have a higher likelihood and frequency of entraining the material at higher flows, ~~the effects of~~ given the lower threshold of full mobility, the effect of the sediment supply change ~~are~~ is taken up by greatly increased sediment transport efficiency and minimal physical slope changes. The likelihood that this distinction would hold in natural streams is contentious, given the greater degree of confinement present using this setup than would be present in most fully alluvial settings; such a degree ~~of confinement~~ would likely only be found where streams are in close proximity to the valley walls. It is the concentration of flow enabled by the flume that allows high shear values to arise, without which the stream would laterally adjust by widening. This will therefore limit the ability to form deposits at a state where competence limit is not present, meaning natural systems are more likely to behave as the low discharge cases observed ~~herein~~in these experiments.

The differences in morphodynamics extend beyond reach average, 1D parameters like depositional slope and transport efficiency. Our observations of the bed dynamics ~~has~~ have highlighted the important role that surficial organisation plays in controlling channel morphology and influencing sediment transport rates. Surface organisation is a frequent response of channels to increased sediment supply in order to maintain some sediment coherency (Lisle and Hilton, 1992; Kasai et al., 2004; Pryor et al., 2011)

. Even the relatively narrow flume that we used (i.e., $W = 0.128$ m) enabled the formation of secondary resistance elements such as bars.

The alternate bar morphodynamics we observed during some runs are not unprecedented; Lisle et al. (1991) reported ~~similar morphodynamics, albeit with a lower slope than these experiments (Table 9). Lisle et al. (1991) also observed~~ the formation of stationary (non-migrating) lateral bars with the bed surface separated into congested and smooth zones for an experiment having a similar grain size distribution ~~.~~ (Table 9).

Bed forms can influence sediment transport efficiency through the dissipation of energy and increased channel stability (Cherkauer, 1973; Hey, 1988; Prancevic and Lamb, 2015), and the bar characteristics are strongly linked to the maximum size of sediment in the bed material here. In GSD$_{\cancel{1}broad}$, bars were more persistent in time and space than in GSD$_{\cancel{2}\,narrow}$ due to the importance of large grains as stabilising features for bars. In the case of GSD$_{\cancel{1,}\,broad}$ the largest grains clearly deposited first, creating a locus of deposition around which the bar head formed, allowing additional sediment to accumulate in its wake (Leopold and Wolman, 1957; Ashmore, 1991; Ferguson, 1993). The bars formed during GSD$_{\cancel{2}\,narrow}$ were comprised of virtually the same size sediment, which can be entrained over a narrow range of shear stresses. As a result, the whole bar may be entrained at a similar shear stress, making these features more transient, and reducing their overall effect on bed stability as their relative impermanence means that the flow can freely move through them (Figures 9 and 10). It is important to note that the stabilisation of the large grains in our experiment ~~using GSD$_1$~~ GSD$_{broad}$ was not the result of jamming, as described by Church (2006). The size of our flume was such that the ratio of the flume width to D_{84} was greater than 6, ~~which is~~ the jamming ratio proposed by Zimmermann et al. (2010), and is thus solely the result of deposition.

The formation of lateral bars allows the transport of bed load through the contraction of the channel width increasing unit stream power as flow is concentrated (Lisle, 1987). This organisation of the bed surface into zones of transport and deposition thus maximises the efficiency of the channel (Iseya and Ikeda, 1987; Ferguson et al., 1989), and enables the previously limited transmittance of sediment and the growth of the depositional lobe. The wavelengths of the barforms we observed in higher sediment output experiments are longer than those of high sediment storage. ~~Pyrce and Ashmore (2005)~~ Experiments by Pyrce and Ashmore (2003a) and Pyrce and Ashmore (2005), and a meta-analysis by Pyrce and Ashmore (2003b), demonstrated that the wavelength of bar spacing is a function of the transport lengths of bed load particles at channel forming flows~~;~~, therefore the material is more ~~more~~ mobile in higher wavelength reaches. Transport length is the distance between entrainment (τ_{ce}) and distrainment (τ_{cd}), therefore it is dependent on when the grain is deposited. Ancey et al. (2002) observed a type of hysteretic difference between these two thresholds, where the specific flow rate (and thus stress) necessary to induce deposition is lower than the entraining flow. Given the differences in entraining threshold between the mixtures~~it~~, assuming that it is controlled by the coarse tail, it follows that the distraining threshold for GSD$_{\cancel{1}\,broad}$ will be higher than for GSD$_{\cancel{2}narrow}$, such that a smaller decrease is needed to trigger deposition. Therefore the systems can be characterised by the difference in behaviour of the coarse grains comprising the bar head loci (Pyrce and Ashmore, 2005). For the more equally mobile GSD$_{\cancel{2}\,narrow}$ this is manifested in a decreased likelihood of deposition of these grains, triggering longer path lengths and greater bar wavelengths in the system. In other words, the likelihood of entrainment ($P[\tau > \tau_{ce}]$) is greater in GSD$_{\cancel{2}narrow}$, setting a lower overall deposit slope, whereas the likelihood of distrainment ($P[\tau < \tau_{cd}]$) is higher in GSD$_{\cancel{1}broad}$, decreasing transport length.

This difference in reduced as discharge increases because the likelihood of entrainment increases, and distrainment decreases, for both mixtures but more strongly for GSD~~$_1$~~$_{broad}$; hence the similarity between τ^*_m values at higher discharges.

Were we to pinpoint the actual characteristic grain size of the material, we might expect the slopes to actually organise to the same values. For example, if we were to pair these distributions instead by a coarser grain (e.g., the D_{84}) we might have observed more similar self-organised slopes. However, this view still assumes the same inherent grain class mobility across discharges, that is the theoretical basis behind Church (2006), merely shifted in favour of the larger grains contributing more relative stability. That is, each mixture still has different distributions of transport likelihoods; does the characteristic grain size actually represent enough of the bed processes that the overall system behaves in the same manner? If the lateral bars were composed of coarser material, with the same narrow gradation as GSD$_{narrow}$, the depositional slope and wider morphodynamics may be similar (i.e., general organisation), but the finer scale processes (i.e., sediment transport and meander wavelength) would not be. However, it might be the case that similar characteristic grain sizes are just an artefact of the experimental design, rendered irrelevant when boundary conditions are expanded to different ranges. Additionally, mobility differences can be more strongly controlled through channel widening and planform adjustments than allowed within this flume, thus the importance of grain class thresholds are reduced as there are more options for resistance to be generated (Eaton and Church, 2004). Thus, the discussion of any one characteristic size is only useful within a given comparison, and does not necessarily indicate a behaviour fundamental to self-formed channels but is merely the smallest partially mobile grain class (Wilcock, 1993).

We can therefore consider the systems generated by GSD~~$_2$~~$_{narrow}$ as less stable on three accounts. Firstly, they developed at lower slopes and, as a result, were able to prograde more quickly due to reduced deposit volume. Secondly, the grains were more equally mobile due to a lower maximum threshold stress (i.e., smaller coarse fraction). Thirdly, the degree of surficial organisation was lower and bedforms were less persistent. The combination of these factors results in a system that does not need to concentrate flow in order to exceed threshold stress, despite the flow's lower slope and stream power, indicating its ability to transport sediment more efficiently than in experiments using GSD~~$_1$~~$_{broad}$.

5 Conclusions

The eight experiments presented here demonstrate a difference in the self-adjusted slope and morphodynamics of aggrading systems derived from the difference of their grain size distributions and mediated by the relative sediment concentration. According to the prevailing theory that the median grain size is predictive of channel behaviour, the systems described within this paper should have exhibited similar slopes and patterns of morphodynamics under the same boundary conditions. Instead, the deposit formed from the more widely ~~distributed GSD$_1$~~ graded distribution (GSD$_{broad}$) developed to a higher slope, with lower transport efficiency, and demonstrated a greater degree of surface organisation. We argue that this is the result of the large grains ~~in GSD$_1$~~ present in this mixture that exceed the competence of the flow, and require channel narrowing in order to mobilise. Where these grains are absent (i.e., ~~GSD$_2$~~the narrowly graded GSD$_{narrow}$) the channel fails to achieve the highest state of organisation (i.e., lateral bars with narrow thalweg) as regularly because of the equally mobile sediment and bars. This difference decreases as ~~you increase the discharge~~ discharge is increased (i.e., entraining stresses). Thus channel stability is linked not to the mobility of the median grain size, but to the mobility of the largest grains (e.g. ~~,~~ D_{84}). We therefore conclude that the difference in behaviour between these systems is driven by a competence limitation of the larger grains. These findings indicate that models ~~including~~ that include sediment transport and ~~conceptualising~~ conceptualise stability, such as regime models, need to consider the characteristic grain size as a coarser fraction than the median in order to more realistically replicate behaviour in aggrading systems.

Code and data availability. Both the code and data used to create Figures 2, 4, 5 and 6 are available online (http://doi.org/10.5281/zenodo.2672918).

Video supplement. Videos of the bed morphodynamics are available online; GSD$_{broad}$: Q100L (http://doi.org/10.5446/41771), Q200H (http://doi.org/10.5446/41772), Q100H (http://doi.org/10.5446/41773), Q200L (http://doi.org/10.5446/41774). GSD$_{narrow}$: Q100L (http://doi.org/10.5446/41775), Q200H (http://doi.org/10.5446/41776), Q100H (http://doi.org/10.5446/41778), Q200L (http://doi.org/10.5446/41777).

Author contributions. W.H. Booker collected and analysed the code and data used in the paper, drafted the manuscript, and created the figures and tables; B.C. Eaton organised, reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

References

Ancey, C., Bigillon, F., Frey, P., Lanier, J., and Ducret, R.: Saltating Motion of a Bead in a Rapid Water Stream, Physical Review E, 66, 036 306, https://doi.org/10.1103/PhysRevE.66.036306, 2002.

Andrews, E. D.: Entrainment of Gravel from Naturally Sorted Riverbed Material, Geological Society of America Bulletin, 94, 1225–1231, https://doi.org/10.1130/0016-7606(1983)94<1225:EOGFNS>2.0.CO;2, 1983.

Andrews, E. D. and Parker, G.: Formation of a Coarse Surface Layer as the Response to Gravel Mobility., in: Sediment Transport in Gravel-Bed Rivers, edited by Thorne, C., Bathurst, J., and Hey, pp. 269–300, Wiley, New York, 1987.

Ashmore, P. E.: Laboratory Modelling of Gravel Braided Stream Morphology, Earth Surface Processes and Landforms, 7, 201–225, https://doi.org/10.1002/esp.3290070301, 1982.

Ashmore, P. E.: How Do Gravel-Bed Rivers Braid?, Canadian Journal of Earth Sciences, 28, 326–341, https://doi.org/10.1139/e91-030, 1991.

Ashworth, P. J. and Ferguson, R. I.: Size-Selective Entrainment of Bed Load in Gravel Bed Streams, Water Resources Research, 25, 627–634, https://doi.org/10.1029/WR025i004p00627, 1989.

Bagnold, R. A.: An Approach to the Sediment Transport Problem from General Physics, U.S. Government Printing Office, 1966.

Belgiu, M. and Drăguţ, L.: Random Forest in Remote Sensing: A Review of Applications and Future Directions, ISPRS Journal of Photogrammetry and Remote Sensing, 114, 24–31, https://doi.org/10.1016/j.isprsjprs.2016.01.011, 2016.

Benda, L. and Dunne, T.: Stochastic Forcing of Sediment Routing and Storage in Channel Networks, Water Resources Research, 33, 2865–2880, https://doi.org/10.1029/97WR02387, 1997.

Bennett, S. J. and Bridge, J. S.: An Experimental Study of Flow, Bedload Transport and Bed Topography under Conditions of Erosion and Deposition and Comparison with Theoretical Models, http://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-3091.1995.tb01274.x, https://doi.org/10.1111/j.1365-3091.1995.tb01274.x, 1995.

Breiman, L.: Random Forests, Machine Learning, 45, 5–32, https://doi.org/10.1023/A:1010933404324, 2001.

Bryant, M., Falk, P., and Paola, C.: Experimental Study of Avulsion Frequency and Rate of Deposition, Geology, 23, 365–368, https://doi.org/10.1130/0091-7613(1995)023<0365:ESOAFA>2.3.CO;2, 1995.

Cherkauer, D. S.: Minimization of Power Expenditure in a Riffle-Pool Alluvial Channel, Water Resources Research, 9, 1613–1628, https://doi.org/10.1029/WR009i006p01613, 1973.

Church, M.: Bed Material Transport and the Morphology of Alluvial River Channels, Annual Review of Earth and Planetary Sciences, 34, 325–354, https://doi.org/10.1146/annurev.earth.33.092203.122721, 2006.

Church, M., Hassan, M. A., and Wolcott, J. F.: Stabilizing Self-Organized Structures in Gravel-Bed Stream Channels: Field and Experimental Observations, Water Resources Research, 34, 3169–3179, https://doi.org/10.1029/98WR00484, 1998.

Clarke, L., Quine, T. A., and Nicholas, A.: An Experimental Investigation of Autogenic Behaviour during Alluvial Fan Evolution, Geomorphology, 115, 278–285, https://doi.org/10.1016/j.geomorph.2009.06.033, 2010.

Cudden, J. R. and Hoey, T. B.: The Causes of Bedload Pulses in a Gravel Channel: The Implications of Bedload Grain-Size Distributions, Earth Surface Processes and Landforms, 28, 1411–1428, https://doi.org/10.1002/esp.521, 2003.

Curran, J. and Wilcock, P. R.: Effect of Sand Supply on Transport Rates in a Gravel-Bed Channel, Journal of Hydraulic Engineering, 131, 961–967, 2005.

Dunkerley, D. L.: The Development of Armour in the Tambo River, Victoria, Australia, Earth Surface Processes and Landforms, 15, 405–412, https://doi.org/10.1002/esp.3290150504, 1990.

Eaton, B. C. and Church, M.: A Graded Stream Response Relation for Bed Load–Dominated Streams, Journal of Geophysical Research: Earth Surface, 109, F03 011, https://doi.org/10.1029/2003JF000062, 2004.

Eaton, B. C. and Church, M.: A Rational Sediment Transport Scaling Relation Based on Dimensionless Stream Power, Earth Surface Processes and Landforms, 36, 901–910, https://doi.org/10.1002/esp.2120, 2011.

Ferguson, R. I.: Understanding Braiding Processes in Gravel-Bed Rivers: Progress and Unsolved Problems, Geological Society, London, Special Publications, 75, 73–87, https://doi.org/10.1144/GSL.SP.1993.075.01.03, 1993.

Ferguson, R. I.: Flow Resistance Equations for Gravel- and Boulder-Bed Streams, Water Resources Research, 43, W05 427, https://doi.org/10.1029/2006WR005422, 2007.

Ferguson, R. I., Prestegaard, K. L., and Ashworth, P. J.: Influence of Sand on Hydraulics and Gravel Transport in a Braided Gravel Bed River, Water Resources Research, 25, 635–643, https://doi.org/10.1029/WR025i004p00635, 1989.

Field, J.: Channel Avulsion on Alluvial Fans in Southern Arizona, Geomorphology, 37, 93–104, https://doi.org/10.1016/S0169-555X(00)00064-7, 2001.

Fukuoka, S.: Finite Amplitude Development of Alternate Bars, in: River Meandering, edited by Ikeda, S. and Parker, G., pp. 237–265, American Geophysical Union, https://doi.org/10.1029/WM012p0237, 1989.

Gilbert, G. K.: Hydraulic-Mining Débris in the Sierra Nevada, U.S. Geological Survey Professional Paper 105, U.S. Government Printing Office, 1917.

Gomez, B.: Effects of Particle Shape and Mobility on Stable Armor Development, Water Resources Research, 30, 2229–2239, https://doi.org/10.1029/94WR00770, 1994.

Guerit, L., Métivier, F., Devauchelle, O., Lajeunesse, E., and Barrier, L.: Laboratory Alluvial Fans in One Dimension, Physical Review E, 90, 022 203, https://doi.org/10.1103/PhysRevE.90.022203, 2014.

Harvey, A. M.: The Influence of Sediment Supply on the Channel Morphology of Upland Streams: Howgill Fells, Northwest England, Earth Surface Processes and Landforms, 16, 675–684, https://doi.org/10.1002/esp.3290160711, 1991.

Harvey, A. M.: Coupling between Hillslopes and Channels in Upland Fluvial Systems: Implications for Landscape Sensitivity, Illustrated from the Howgill Fells, Northwest England, CATENA, 42, 225–250, https://doi.org/10.1016/S0341-8162(00)00139-9, 2001.

Haschenburger, J. K. and Wilcock, P. R.: Partial Transport in a Natural Gravel Bed Channel, Water Resources Research, 39, 1020, https://doi.org/10.1029/2002WR001532, 2003.

Hassan, M. A., Smith, B. J., Hogan, D. L., Luzi, D. S., Zimmermann, A. E., and Eaton, B. C.: 18 Sediment Storage and Transport in Coarse Bed Streams: Scale Considerations, in: Developments in Earth Surface Processes, edited by Habersack, H., Piégay, H., and Rinaldi, M., vol. 11 of *Gravel-Bed Rivers VI: From Process Understanding to River Restoration*, pp. 473–496, Elsevier, https://doi.org/10.1016/S0928-2025(07)11137-8, 2007.

Hey, R.: Bar Form Resistance in Gravel-Bed Rivers, Journal of Hydraulic Engineering, 114, 1498–1508, https://doi.org/https://doi.org/10.1061/(ASCE)0733-9429(1988)114:12(1498), 1988.

Howard, A. D. and Kerby, G.: Channel Changes in Badlands, GSA Bulletin, 94, 739–752, https://doi.org/10.1130/0016-7606(1983)94<739:CCIB>2.0.CO;2, 1983.

Iseya, F. and Ikeda, H.: Pulsations in Bedload Transport Rates Induced by a Longitudinal Sediment Sorting: A Flume Study Using Sand and Gravel Mixtures, Geografiska Annaler. Series A, Physical Geography, 69, 15–27, https://doi.org/10.2307/521363, 1987.

Kasai, M., Marutani, T., and Brierley, G.: Channel Bed Adjustments Following Major Aggradation in a Steep Headwater Setting: Findings from Oyabu Creek, Kyushu, Japan, Geomorphology, 62, 199–215, https://doi.org/10.1016/j.geomorph.2004.03.001, 2004.

Komar, P. D.: Selective Grain Entrainment by a Current from a Bed of Mixed Sizes: A Reanalysis, Journal of Sedimentary Research, 57, 1987a.

Komar, P. D.: Selective Grain Entrainment by a Current from a Bed of Mixed Sizes; a Reanalysis, Journal of Sedimentary Research, 57, 203–211, https://doi.org/10.1306/212F8AE4-2B24-11D7-8648000102C1865D, 1987b.

Kondolf, G. M.: Hungry Water: Effects of Dams and Gravel Mining on River Channels, Environmental Management, 21, 533–551, https://doi.org/10.1007/s002679900048, 1997.

Lane, E. W.: The Importance of Fluvial Morphology in Hydraulic Engineering, Proceedings of the American Society of Civil Engineers, 81, 1–17, 1955.

Langbein, W. B. and Leopold, L. B.: River Meanders - Theory of Minimum Variance, USGS Numbered Series 422-H, U.S. Government Printing Office, Washington, D.C., 1966.

Laronne, J. B. and Carson, M. A.: Interrelationships between Bed Morphology and Bed-Material Transport for a Small, Gravel-Bed Channel*, Sedimentology, 23, 67–85, https://doi.org/10.1111/j.1365-3091.1976.tb00039.x, 1976.

Lenzi, M. A., Mao, L., and Comiti, F.: When Does Bedload Transport Begin in Steep Boulder-Bed Streams?, Hydrological Processes, 20, 3517–3533, https://doi.org/10.1002/hyp.6168, 2006.

Leopold, L. B. and Maddock, T.: The Hydraulic Geometry of Stream Channels and Some Physiographic Implications, USGS Numbered Series 252, U.S. Government Printing Office, Washington, D.C., 1953.

Leopold, L. B. and Wolman, M.: River Channel Patterns: Braided, Meandering, and Straight, U.S. Geological Survey Professional Paper 282-B, 1957.

Liaw, A. and Wiener, M.: Classification and Regression by randomForest, 2, 6, 2002.

Lisle, T. E.: Overview: Channel Morphology and Sediment Transport in Steepland Streams, In: R. Beschta, T. Blinn, G. E. Grant, F. J. Swanson, and G. G. Ice (ed.), Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium, August 1987). International Association of Hydrological Sciences Pub. No. 165, p. 287-297., 1987.

Lisle, T. E. and Hilton, S.: The Volume of Fine Sediment in Pools: An Index of Sediment Supply in Gravel-Bed Streams1, JAWRA Journal of the American Water Resources Association, 28, 371–383, https://doi.org/10.1111/j.1752-1688.1992.tb04003.x, 1992.

Lisle, T. E., Ikeda, H., and Iseya, F.: Formation of Stationary Alternate Bars in a Steep Channel with Mixed-Size Sediment: A Flume Experiment, Earth Surface Processes and Landforms, 16, 463–469, https://doi.org/10.1002/esp.3290160507, 1991.

MacKenzie, L. G. and Eaton, B. C.: Large Grains Matter: Contrasting Bed Stability and Morphodynamics during Two Nearly Identical Experiments, Earth Surface Processes and Landforms, 42, 1287–1295, https://doi.org/10.1002/esp.4122, 2017.

MacKenzie, L. G., Eaton, B. C., and Church, M.: Breaking from the Average: Why Large Grains Matter in Gravel-Bed Streams, Earth Surface Processes and Landforms, 43, 3190–3196, https://doi.org/10.1002/esp.4465, 2018.

Mackin, J. H.: Concept of the Graded River, Geological Society of America Bulletin, 59, 463–512, https://doi.org/10.1130/0016-7606(1948)59[463:COTGR]2.0.CO;2, 1948.

Madej, M. A.: Sediment Transport and Channel Changes in an Aggrading Stream in the Puget Lowland, Washington, Federal Government Series PNW 141, U.S. Forest Service, 1982.

Madej, M. A. and Ozaki, V.: Channel Response to Sediment Wave Propagation and Movement, Redwood Creek, California, Usa, Earth Surface Processes and Landforms, 21, 911–927, https://doi.org/10.1002/(SICI)1096-9837(199610)21:10<911::AID-ESP621>3.0.CO;2-1, 1996.

Masteller, C. C. and Finnegan, N. J.: Interplay between Grain Protrusion and Sediment Entrainment in an Experimental Flume, Journal of Geophysical Research: Earth Surface, 122, 274–289, https://doi.org/10.1002/2016JF003943, 2017.

Montgomery, D. R. and Buffington, J. M.: Channel-Reach Morphology in Mountain Drainage Basins, Geological Society of America Bulletin, 109, 596–611, https://doi.org/10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2, 1997.

Moss, A. J.: The Physical Nature of Common Sandy and Pebbly Deposits; Part II, American Journal of Science, 261, 297–343, https://doi.org/10.2475/ajs.261.4.297, 1963.

Parker, G.: Surface-Based Bedload Transport Relation for Gravel Rivers, Journal of Hydraulic Research, 28, 417–436, https://doi.org/10.1080/00221689009499058, 1990.

Parker, G. and Klingeman, P. C.: On Why Gravel Bed Streams Are Paved, Water Resources Research, 18, 1409–1423, https://doi.org/10.1029/WR018i005p01409, 1982.

Parker, G. and Sutherland, A. J.: Fluvial Armor, Journal of Hydraulic Research, 28, 529–544, https://doi.org/10.1080/00221689009499044, 1990.

Parker, G., Dhamotharan, S., and Stefan, H.: Model Experiments on Mobile, Paved Gravel Bed Streams, Water Resources Research, 18, 1395–1408, https://doi.org/10.1029/WR018i005p01395, 1982a.

Parker, G., Klingeman, P. C., and McLean, D. G.: Bedload and size distribution in paved gravel-bed streams, Journal of the Hydraulics Division - ASCE, 108, 544–571, 1982b.

Peakall, J., Ashworth, P., and Best, J.: Physical Modelling in Fluvial Geomorphology: Principles, Applications and Unresolved Issues, in: The Scientific Nature of Geomorphology, edited by Rhoads, B. L. and Thorn, C., pp. 221–253, John Wiley & Sons, Ltd, Chichester, 1996.

Pfeiffer, A. M., Finnegan, N. J., and Willenbring, J. K.: Sediment Supply Controls Equilibrium Channel Geometry in Gravel Rivers, Proceedings of the National Academy of Sciences, 114, 3346–3351, https://doi.org/10.1073/pnas.1612907114, 2017.

Prancevic, J. P. and Lamb, M. P.: Unraveling Bed Slope from Relative Roughness in Initial Sediment Motion, Journal of Geophysical Research: Earth Surface, 120, 2014JF003 323, https://doi.org/10.1002/2014JF003323, 2015.

Pryor, B. S., Lisle, T., Montoya, D. S., and Hilton, S.: Transport and Storage of Bed Material in a Gravel-Bed Channel during Episodes of Aggradation and Degradation: A Field and Flume Study, Earth Surface Processes and Landforms, 36, 2028–2041, https://doi.org/10.1002/esp.2224, 2011.

Pyrce, R. S. and Ashmore, P. E.: Particle Path Length Distributions in Meandering Gravel-Bed Streams: Results from Physical Models, Earth Surface Processes and Landforms, 28, 951–966, https://doi.org/10.1002/esp.498, 2003a.

Pyrce, R. S. and Ashmore, P. E.: The Relation between Particle Path Length Distributions and Channel Morphology in Gravel-Bed Streams: A Synthesis, Geomorphology, 56, 167–187, https://doi.org/10.1016/S0169-555X(03)00077-1, 2003b.

Pyrce, R. S. and Ashmore, P. E.: Bedload Path Length and Point Bar Development in Gravel-Bed River Models, Sedimentology, 52, 839–857, https://doi.org/10.1111/j.1365-3091.2005.00714.x, 2005.

Recking, A.: A Comparison between Flume and Field Bed Load Transport Data and Consequences for Surface-Based Bed Load Transport Prediction, Water Resources Research, 46, W03 518, https://doi.org/10.1029/2009WR008007, 2010.

Recking, A.: Simple Method for Calculating Reach-Averaged Bed-Load Transport, Journal of Hydraulic Engineering, 139, 70–75, https://doi.org/10.1061/(ASCE)HY.1943-7900.0000653, 2013.

Recking, A., Frey, P., Paquier, A., Belleudy, P., and Champagne, J. Y.: Feedback between Bed Load Transport and Flow Resistance in Gravel and Cobble Bed Rivers, Water Resources Research, 44, W05 412, https://doi.org/10.1029/2007WR006219, 2008.

Recking, A., Frey, P., Paquier, A., and Belleudy, P.: An Experimental Investigation of Mechanisms Involved in Bed Load Sheet Production and Migration, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JF000990, https://doi.org/10.1029/2008JF000990, 2009.

Schmeeckle, M. W., Nelson, J. M., and Shreve, R. L.: Forces on Stationary Particles in Near-Bed Turbulent Flows, Journal of Geophysical Research: Earth Surface, 112, F02 003, https://doi.org/10.1029/2006JF000536, 2007.

Schumm, S. A., Mosley, M. P., and Weaver, W.: Experimental Fluvial Geomorphology, 1987.

Sutherland, A. J.: Static Armour Layers by Selective Erosion, in: Sediment Transport in Gravel-Bed Rivers, edited by Thorne, C. R., Bathurst, J., and Hey, R., John Wiley & Sons, Ltd, Chichester, 1987.

Venditti, J. G., Nelson, P. A., Bradley, R. W., Haught, D., and Gitto, A. B.: Bedforms, Structures, Patches and Sediment Supply in Gravel-Bed Rivers, in: Gravel-Bed Rivers: Processes and Disasters, edited by Tsutsumi, D. and Laronne, J. B., pp. 439–466, John Wiley & Sons, 2017.

Vericat, D., Batalla, R. J., and Garcia, C.: Breakup and Reestablishment of the Armour Layer in a Large Gravel-Bed River below Dams: The Lower Ebro, Geomorphology, 76, 122–136, https://doi.org/10.1016/j.geomorph.2005.10.005, 2006.

Warburton, J.: Observations of Bed Load Transport and Channel Bed Changes in a Proglacial Mountain Stream, Arctic and Alpine Research, 24, 195–203, https://doi.org/10.2307/1551657, 1992.

Wilcock, P. R.: Critical Shear Stress of Natural Sediments, Journal of Hydraulic Engineering, 119, 491–505, 1993.

Wilcock, P. R. and Crowe, J. C.: Surface-Based Transport Model for Mixed-Size Sediment, Journal of Hydraulic Engineering, 129, 120–128, https://doi.org/10.1061/(ASCE)0733-9429(2003)129:2(120), 2003.

Wilcock, P. R. and McArdell, B. W.: Surface-Based Fractional Transport Rates: Mobilization Thresholds and Partial Transport of a Sand-Gravel Sediment, Water Resources Research, 29, 1297–1312, https://doi.org/10.1029/92WR02748, 1993.

Wilcock, P. R., Kenworthy, S. T., and Crowe, J. C.: Experimental Study of the Transport of Mixed Sand and Gravel, Water Resources Research, 37, 3349–3358, https://doi.org/10.1029/2001WR000683, 2001.

Zimmermann, A., Church, M., and Hassan, M. A.: Step-Pool Stability: Testing the Jammed State Hypothesis, Journal of Geophysical Research: Earth Surface, 115, F02 008, https://doi.org/10.1029/2009JF001365, 2010.

~~Grain size metrics of the two distributions. D_{50} D_{84} σ GSD_1 2.03 3.65 1.38 GSD_2 2.02 2.52 0.43~~

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Table 1. Mean slope values and standard deviations, for the eight experiments reported here.

	GSD_{broad}			GSD_{narrow}		
	Mean	St. Dev.	n	Mean	St. Dev.	n
100L	8.29×10^{-2}	1.96×10^{-3}	224	5.81×10^{-2}	2.21×10^{-3}	281
100H	9.30×10^{-2}	2.99×10^{-3}	101	7.68×10^{-2}	3.93×10^{-3}	175
200L	4.98×10^{-2}	4.28×10^{-3}	437	4.28×10^{-2}	3.89×10^{-3}	449
200H	4.92×10^{-2}	4.36×10^{-3}	256	4.52×10^{-2}	1.57×10^{-3}	243

Table 2. Changes in mean slope for the column name experiment, given relative to the row name experiment, for GSD~~1~~$_{broad}$ and GSD~~2~~$_{narrow}$ respectively. Values are given in percent.

	100L	100H	200L	200H
100L	-	12.2/32.1	-40.0/-26.4	-40.6/-22.2
100H	-10.9/-24.3	-	-47.1/-41.1	-46.5/-44.3
200L	66.7/35.9	86.9/79.6	-	-1.03/5.77
200H	68.4/28.5	88.9/69.8	1.05/-5.46	-

Table 3. Output of sediment during each experiment, from the time sediment output occurred. The proportion of sediment output is relative to the volume input over the same timespan.

	Mean Output Rate (g s^{-1})		Proportion Stored of Input (%)	
	GSD~~1~~$_{broad}$	GSD~~2~~$_{narrow}$	GSD~~1~~$_{broad}$	GSD~~2~~$_{narrow}$
100L	0.41	0.73	~~40.7~~ 59.3	~~72.9~~ 27.1
100H	0.19	1.34	~~8.5~~ 91.5	~~66.4~~ 33.6
200L	0.84	0.91	~~83.7~~ 16.3	~~90.6~~ 9.4
200H	1.64	1.84	~~81.7~~ 18.3	~~91.4~~ 8.6

Table 4. Grain size statistics of output material, averaged over the total output mass and given in mm.

	GSD$_{broad}$			GSD$_{narrow}$		
	D_{50}	D_{84}	σ	D_{50}	D_{84}	σ
Bulk	2.03	3.65	1.38	2.02	2.52	0.42
100L	2.11	3.38	1.03	2.10	2.55	0.45
100H	2.17	3.42	1.00	2.10	2.55	0.44
200L	2.24	3.72	1.24	2.00	2.52	0.48
200H	2.39	3.94	1.39	2.03	2.53	0.48

Table 5. Timing of the onset of transport, given in minutes from the start of the experiment.

	GSD$_{broad}$	GSD$_{narrow}$
100L	326	149
100H	149	116
200L	103	87
200H	42	44

Table 6. Mean transport efficiencies and their standard deviation.

	GSD$_{broad}$			GSD$_{narrow}$		
	Mean	St. Dev.	n	Mean	St. Dev.	n
100L	1.87 x 10^{-2}	4.42 x 10^{-4}	224	4.75 x 10^{-2}	2.21 x 10^{-3}	281
100H	3.21 x 10^{-2}	2.81 x 10^{-3}	101	4.05 x 10^{-2}	3.82 x 10^{-3}	175
200L	7.71 x 10^{-3}	2.48 x 10^{-4}	437	6.60 x 10^{-2}	3.29 x 10^{-3}	449
200H	6.33 x 10^{-2}	5.50 x 10^{-3}	256	7.68 x 10^{-2}	2.80 x 10^{-3}	243

Table 7. Changes in mean transport efficiency for the column name experiment, given relative to the row name experiment, for GSD~~1~~$_{broad}$ and GSD~~2~~$_{narrow}$ respectively. Values are given in percent.

	100L	100H	200L	200H
100L	-	-58.7/39.1	71.9/-14.7	239/61.9
100H	142/-28.1	-	316/-38.6	721/16.4
200L	-41.8/17.2	-76.0/63.0	-	97.3/89.8
200H	-70.5/-38.2	-87.8/-14.1	-49.3/-47.3	-

Table 8. Mixture mobility transition points calculated using Eq. (5), taken from Recking (2013).

	GSD_{broad}	GSD_{narrow}
100L	0.414	0.318
100H	0.479	0.417
200L	0.228	0.240
200H	0.225	0.264

Table 9. Flume dimensions and run conditions for Lisle et al. (1991) and the two 100L experiments included here.

	Lisle et al. (1991)	~~G1Q100L~~ GSD_{broad}	~~G2Q100L~~ GSD_{narrow}
Length (m)	7.5	2	2
Width (m)	0.3	0.128	0.128
Slope (m/m)	0.03	~~0.068~~ 0.083	~~0.092~~ 0.058
Grain Size Range (mm)	0.35-8	0.25-8.0	1.4-2.8
D_{50} (mm)	1.4	~~2.02~~ 2.03	2.02
Flow Rate (ml s^{-1})	582	100	100
Feed Rate (g s^{-1})	8.4	1	1
Run Time (min)	560	549	429