REPLIES TO COMMENTS OF REFEREE 1 ON: MACRO-ROUGHNESS MODEL OF BEDROCK-ALLUVIAL RIVER MORPHODYNAMICS

We very much appreciate your comments, which have been both encouraging and helpful.

COMMENT Does the new cover formulation break down at any point? For example, it is possible to conceive of a situation with patches of sediment on a very smooth bedrock bed. The sediment depth (spatially averaged over both patches and bedrock) could be greater than the bedrock macro-roughness length, and yet pc would not be one (contrary to equation 16b). I think that the model is problematic when grain size is larger than the bedrock roughness length; given that some bedrock rivers can contain very coarse sediment and smooth surfaces, this is not an impossible combination.

REPLY The reviewer is correct. We were very much amiss in not defining our premises here, even though we were well are of them. The model in the paper only applies for the case for which the size of the macro-roughness elements is large compared to alluvial clast size. We have made this explicit with the following added statements.

“The specific case we consider here is one for which a) the bedrock surface is rough in a hydraulic sense (as opposed to a hydraulically smooth or transitional surface; see Schlichting, 1979), and b) the characteristic vertical scale of bedrock elevation fluctuation about a mean value based on an appropriately defined window, here denoted as the macro-roughness L_{mr} of the bedrock, is large compared to the characteristic size of the clasts constituting the alluvium. We use the term “macro-roughness” so as to clearly distinguish it from hydraulic roughness, which is specifically defined in terms the logarithmic velocity profile. Inoue et al (2014) have introduced the terms “clast-rough” and “clast-smooth”, the former referring to a bedrock surface roughness that is large compared to the characteristic size of the alluvium, and the latter referring to a bedrock surface macro-roughness that is small compared to the size of the alluvium. Here we consider the clast-rough case.”…

The form of the cover relation of Eq. (17a, b) serves to introduce the MRSAA model in a simple way. It does, however, contain a flaw in regard to the clast-rough case considered here. Specifically, p_c vanishes for the case $\eta_a = 0$. This implies that there no deep pockets in the bedrock which retain sediment that is not available for transport. This physical limitation places a limitation on the applicability of the MRSAA model, which we identify and use to amend the formulation in this section.

According to Eqs. (23b) and (17), as alluvial cover thickness η_a goes to 0, the cover fraction p_c also tends to 0, and thus the downstream-directed alluvial wave speed c_a tends to infinity. That is, alluvial waves of infinitesimal amplitude travel with infinite speed. In physical terms, this corresponds to a very few grains racing over a very smooth surface.”

COMMENT The MRSAA model implies that sediment cover fills up the bedrock topography sequentially from the lowest elevations to the highest. The added complexities of the flow pattern induced by the bedrock topography may mean that this is not necessarily the case. In some cases, this may not matter, if the rate at which bedrock area is covered still increases in the same manner with sediment depth. On the other hand, flow (and indeed topographic) patterns could instead mean that as average sediment depth increases, some sediment patches will get steadily deeper rather than increase in aerial extent, in which case pc will not change with sediment depth.

REPLY This is a point that needs to be clarified. There are two points to be made here: the sequential filling and the 1D nature of the model. We address these in the following two sequential paragraphs that we have added.

"It should be noted that in Fig. 4, no bed elevation variations are shown over part of the bed where alluvium is exposed. This is done only for simplicity, and reflects the condition that in the clast-rough case considered here, grain size is small compared to macro-roughness height. Fig. 4 also contains another simplification, in that all pockets are assumed to be filled to the same level by alluvium. While this condition not likely to be true at the local scale, it is a reasonable first approximation when averaging over an appropriately defined window.

The formulation presented here has an obvious limitation. Since it is a 1D expression of sediment conservation over a bedrock surface, it cannot capture 2D variation, which will result in a more complex pattern that shown in Fig. 4, and in particular will provide more connectivity between adjacent pockets. This two-dimensionality is known to have an effect on the pattern of incision, as illustrated by Johnson and Whipple (2007). The extension of the formulation to the 2D case represents a future goal; some relevant comments can be found in the section "Discussion"."

COMMENT I don't think that you necessarily need to perform runs with different relationships between sediment depth and pc, rather just give some indication of the situations under which the current formulation is valid, and to indicate that future runs could use a different formulation.

REPLY We think that we have done that now, as illustrated above. It is a generalization of the model of Inoue et al (2014), referenced in the text, from CSA form to MRSAA form that has the best hope for achieving a wider range of applicability. We now explicitly state this in the text, in the section "Discussion".

COMMENT What field/lab data would be needed to establish the form of the relationship between sediment depth and pc? There are also interesting questions about what is an appropriate macro-roughness length for a bedrock bed, and what properties and processes it is affected by.

REPLY In the laboratory, at least, it would be of great value to perform experiments similar to those of Chatanantavet and Parker (2008). This is now explicitly mentioned in the text. Thank you for the comment.

COMMENT Sediment transport: In the model, sediment flux from a bedrock-alluvial bed is calculated assuming a fully alluvial bed, which is then scaled by pc (page 310). Exposed bedrock will not only affect sediment flux through sediment availability; sediment grains are entrained at lower shear stresses from bedrock surfaces, and will travel easily over them once in transport. This might have the impact of increasing sediment fluxes over bedrock-alluvial beds; what implications might this have for the model results?

REPLY The referee is quite correct. We have modified the text: "In the above formulation, it is assumed that the gravel transport rate q_b over a bedrock surface can be estimated by simply multiplying the capacity rate q_{bc} times the areal cover fraction p_c. While this is the simplest first-order assumption, it should be recognized that the roughness of the bedrock itself can change the flow resistance, leading to a relationship that is more complex than Eq. (2) (Inoue et al., 2014; Johnson, 2014).

COMMENT Model results: The different applications of the MMRSA model demonstrate its applicability to a range of scenarios. Would it be possible to compare any of these to measured field data, in order to provide some evidence that the model behaviour is reasonable? For example, are there any datasets that demonstrate that channel slope is insensitive to uplift at certain uplift rates? Or flume data of the translation of a sediment pulse over a bedrock surface – Chatanantavet's work maybe? How about any examples where there is a difference in behaviour between the CSA and MMRSA models? (On which, I'd expect a river to flow along a graben, not across it.)
REPLY The main purpose of this paper is to illustrate the expanded capabilities of MRSAA as compared to CSA. We have chosen realistic problems and realistic parameters. We have a nearly-completed MS that goes into more depth in regard to specific applications to the field. As for the graben case, we have used a 1D format to illustrate behavior. Suppose, however that the graben was of distinct finite length? Lake Baikal is in a graben; the Selenga River flows in and the Angara River flows out. Were the lake to be filled with sediment (cessation of faulting), one would obtain a configuration not too greatly different from our 1D setting.

Specific comments by page/line:
COMMENT 299/12: Assuming that all incision is through saltation-abrasion, which is not necessarily the case.
REPLY The referee is correct. We have redefined the text to reflect our restricted viewpoint. "Although there are multiple processes that can lead to incision into bedrock, we here focus on incision driven by abrasion of a bedrock surface as moving particles collide with it".

COMMENT 301/7: In the model, cover is not completely independent of sediment transport properties, because the balance between sediment supply and sediment transport affects the depth of the sediment layer, and hence the sediment cover.
REPLY What we are saying here is that CSA has no way of distinguishing between bedrock surfaces of differing roughnesses. We believe this to be correct.

COMMENT 304/9: Change to equation 5a?
REPLY Correct, thank you!

COMMENT 304/10: Define tau *c
REPLY Sorry, it is a long paper, but the definition is given on 303/23.

COMMENT 313/13: This paragraph is repeated on 314.
REPLY Thanks for catching this; we have eliminated the duplication.

COMMENT 318/2: Any particular reason for using this equation instead?
REPLY The original data set used by Meyer-Peter and Muller is much more extensive than that of Fernandez Luque and van Beek. Wong and Parker (2006a) re-analyzed the MPM data and obtained the coefficient and exponent used herein. Of course it is unclear as to whether or not

these relations are valid for partial cover of bedrock-floored channels. But if one is going to use such a relation as a first-order approximation, one ought to try to use the best relation available.

COMMENT 323/17: How is the 1 m estimated; from the total range of bedrock elevations, or another measure?
REPLY It was estimated by spot measurements in the field. It is approximate.

COMMENT 324/8: Maybe clarify with 0.12 years of high flow.
REPLY Thank you , but please see 223/15: "In addition, flood intermittency I_f is set to unity so as to illustrate the migration from feed point to the end of the reach under the condition of continuous flow."

COMMENT 324/13: Can you explain this change in wave speed in a more physical way? In a river this could be because grains are more mobile over a predominantly bedrock surface, but I don't think that this behaviour is encoded in the model.
REPLY Such behavior is not encoded into the model. The change in wave speed comes from the form of the equation, but the most relevant factor is that wave speed must drop to 0 when the bed becomes fully allluviated. We think that our original statement holds for this. "The reason the wave does not spread is the nonlinearity of the wave speed ca in Eq. (23b); since p_c enters into the denominator of the right-hand side of the equation, wave speed is seen to increase as p_c decreases, and thus as η_a decreases. As a result, the lower portion of the wave tends to migrate faster than the higher portion, so sharpening the wave and opposing diffusion."

COMMENT 324/18: What controls the steady state thickness, and what is the value of pc? I think that pc is about 0.8, which is the same as if predicted from the ratio of sediment supply to transport capacity; is this another example of the models converging under steady state conditions?
REPLY 324/20. "The steady-state thickness of alluvium is 0.83 m; by 0.1 years it has been emplaced only down to about 5 km from the source" We have added the sentence; "This steady state condition, and only this condition corresponds to a convergence of results from MRSAA and CSA."

COMMENT 327/13: Wouldn't the models be more comparable if they were not set up with different initial and boundary conditions?
REPLY As we note in the paper, "MRSAA is implemented with somewhat different initial and downstream boundary conditions, in order to model the case of bed that remains alluviated at the downstream end. This condition thus corresponds to an alluviated river mouth." Since CSA cannot treat a fully-alluviated case, we have matched everything except for the forced condition of alluviation at the downstream end for MRSAA.

COMMENT 328/14: What about size selective transport, and how size-selectivity could vary as a function of pc?
REPLY We have not considered size-selective transport in this model. We already refer, however to how this might be done. "…size mixtures of sediment (Wilcock and Crowe, 2002)…

COMMENT 329/6: Change to ‘modified form of’ Figure 7: Useful to redefine chi in the caption.
REPLY Done. In fact, we have reviewed the captions of all figures, and made sure that symbols are defined therein. Your comment has been very helpful.

COMMENT Figure 8: Define S, Cz and Qbf in the caption and/or axes. Make sure all axes have labels. Several other figure axes/captions also need definitions; it’s useful to be able to understand a figure without having to search the body of the paper for definitions. (The nomenclature table is helpful though.)
REPLY The caption has been corrected. Figure 8b was a mess in other ways. These have now been corrected. Thank you for noticing this.