'Influence of network geometry on long-term morphodynamics of alluvial rivers'

Response to reviewer comments

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We thank Alan Howard and an anonymous referee for taking the time to review our manuscript and for their constructive feedback. We have carefully considered their criticisms and suggestions and made substantial revisions to the manuscript as a result. Following comments from Reviewer 1, we made several changes to Sections 3 and 4, as well as Figure 3 (previously Figure 2), to separate more clearly new results from those of our previous paper (M^{c}Nab et al., 2023). We also added a new discussion section (Section 6.4) in which we discuss consequences of our choice of network-generation scheme. Howard brought to our attention his previous paper (Howard, 1982), which indeed shares some similarities with our analysis and results. Throughout our revised manuscript, we aimed to provide appropriate acknowledgment of this prior work. Following Howard's suggestion, we also now include an additional discussion section (Section 6.5) focused on similarities and differences between our results and the concept of signal 'shredding'. Below, we respond to each of the Reviewers' comments in more detail and outline the specific changes we made as a consequence. Quotations from the Reviewers' reports appear in bold throughout.

Separate to the Reviwers' comments, we made the following additional changes (note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one; we use the new figure numbers in the following):

1. We include a new introductory figure (Figure 1) showing some example network planforms from the western US. We think this addition is useful for setting the scene and also provides evidence for the diversity of network structures that can arise in natural catchments.

2. We previously used Pearson's correlation coefficient to quantify correlations between network effective lengths and various network metrics (Figures 11, S18). Pearson's correlation coefficient assumes, however, assumes linear relationships between variables, whereas several of the relationships we obtain are in fact strongly non-linear (Figures S5–S6, S19–S20). In our revised manuscript, we therefore switched to using Spearman's rank correlation coefficient. This change has a small effect on correlation coefficients for some of the more poorly correlating metrics, but our main conclusion that network effective lengths correlate strongly with network mean lengths is unchanged.

3. We have adjusted the formatting of Figure 11a–d to make better use of the space. The figures include bar charts showing correlation coefficients between the empirical network effective length and various network metrics. A small number of metrics correlate negatively with effective length which led to a large amount of white space in the earlier figure. We have switched to showing the magnitude of correlation, with solid bars representing positive correlations and hatched bars showing negative correlations. We believe this change makes visible more detail in the figure without any loss of information.

4. To aid visualisation of the spatial patterns of aggradation and incision we discuss in Section 5.4.3, we created a Video Supplement (GIF) showing the evolution of an example network for variation in sediment

supply at three forcing periods ($P = \widehat{T_{eq}}/10$, $P = \widehat{T_{eq}}$ and $P = \widehat{T_{eq}} \times 10$). We included the GIF in our revised Supplementary Material .zip archive, and it is also available in our software and data supplement at '`./Video_Supplement/Video_Supplement_Network_Example.gif`' (M^{c}Nab, 2025). (We are happy to discuss with the editor and/or journal staff the best way to present this.)

5. We include a new figure (Figure 17), and an additional paragraph in Section 5.5 discussing it, focused on controls on lag times at short forcing periods for the network cases with only upstream supply of sediment and water. Here, the relationship between $P/\widehat{T_{eq}}$, $\varphi_{z,L}$ and $\varphi_{Q_s,L}$ deteriorates, which we show reflects a greater influence of the local rather than wider network structure. This addition provides an explanation for an aspect of the network behaviour that otherwise appears to contradict our previous findings, and reinforces concepts of signal propagation and damping that we invoke elsewhere.

Reviewer 1

The manuscript presents an extended follow-up of the authors' 2023 GRL on "Diverse Responses of Alluvial Rivers to Periodic Environmental Change". The authors explore the parameter space of an erosional longitudinal profile model for alluvial rivers. In the current manuscript, the main focus is to explore how network properties and lateral sediment supply influence the evolution in comparison to single profile models. While the paper is rather extensive and contains some overlap with the previous publication, its text is well-written, and the methods and steps of the analysis are clearly explained. However, a clearer separation of the new content from the previous results would be helpful.

We agree that a clear separation of new results from those of our previous paper (M^{c}Nab et al., 2023) is important. We have made several changes to address this issue, which we detail in response the Reviewer's specific comments below.

1. **For example, the section "background" ends in line 171, and Section 4, including "numerical results," repeats several findings already reported in the 2023 manuscript (c.f. Fig. 4 closely resembles a combination of Fig. 2 and Fig. 3 of the 2023 paper).**

   [Note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one. We use the new figure numbers in the following.]

   We acknowledge that Section 4.3 contains some information previously reported in M^{c}Nab et al. (2023). Our goal in this section was to present our new results for the single-segment, along-stream supply case, and compare them with those of our previous paper for the single-segment, upstream supply case. Figure 5, for example, while following a similar format to Figures 2 and 3 from the earlier paper, contains both previously published results for both the upstream supply (grey, dashed lines) and new results for the along-stream supply (solid, coloured lines) cases.

   An effective comparison clearly necessitates some repetition of the earlier results. We considered an alternative structure in which we first described results from both cases separately, with details for the upstream supply case appearing in the earlier 'Background' section, and then compared them. However, this structure would lead to substantial repetition within the present manuscript, particularly since there are numerous similarities between the two cases. Maintaining the narrative flow with such a structure would also arguably require separate figures for results of the upstream supply case, which are currently shown in the background in Figures 5–7, where we present the new along-stream supply results. We are keen to avoid both these outcomes, since the manuscript is already somewhat long and detailed.

For these reasons, we have decided to retain our original structure, but have taken steps to distinguish explicitly between this manuscript's new results and those of our previous paper. The end of Section 4.2, leading into the results/comparison of Section 4.3, now reads: 'We then explore how gain and lag vary along stream, as functions of forcing period and discharge exponent, and compare with those for the single-segment, upstream supply case (*all results shown for the latter case are derived from numerical simulations and analytical solutions previously presented by* M^{c}Nab et al., 2023).' (Italic text is new.) The opening of Section 4.3 now reads: We first show simulated aggradation, incision and sediment discharge of an example valley with $p_{x,Q_w} = p_{x,Q_s} = 1.6$ at three forcing periods (Figure 5). *For comparison, we also include results from an equivalent simulation with sediment and water supplied only upstream (i.e., with* $p_{x,Q_w} = p_{x,Q_s} = 0$*; M^{c}Nab et al., 2023).* To elucidate further how the valley response varies spatially, with forcing timescale, and with the power-law exponent, we then show gain and lag for each valley as functions of downstream distance (Figure 6) and forcing period (Figure 7), *again with comparison to the upstream supply case (M^{c}Nab et al., 2023).* We have ensured that all figures in which results from M^{c}Nab et al. (2023) are shown contain an explicit acknowledgment in the caption (Figures 5–7, 10, 13, 15–16). Below, we outline some further changes made to the 'Approach' section and Figure 2 that also address this general issue.

2. **Also, the section "Approach" outlining the course of the paper is somehow squeezed in between two modeling sections. I would suggest moving the approach section to the end of the introduction, outlining explicitly which part comes from Wickert and Schildgen (2019) (the basic profile equilibrium equations), which has been derived in M^{c}Nab et al. (2023) (single segment solution) and what is the actual new part of the paper (lateral along segment inputs and network considerations).**

   Our intention in 'Section 3 – Approach' was to state briefly how we plan to build on the model of Wickert and Schildgen (2019) and the framework of M^{c}Nab et al. (2023) throughout our analysis of, first, the single-segment, along-stream supply case, then second, the network cases. It relies on information introduced in 'Section 2 – Background' and therefore cannot appear before it. We have however, rewritten the opening so that it now reads: 'Here, we extend M^{c}Nab et al.'s (2023) application of Wickert and Schildgen's (2019) model to explore how along-stream sources of water and sediment and the geometries of alluvial valley networks influence their responses to changing water and sediment supply. In turn, we explore how distributions of terraces and their ages within valley networks, as well as patterns of sediment accumulation in downstream basins, are related to external change. Specifically, complementing M^{c}Nab et al.'s (2023) analysis of the single-segment, upstream supply case, we analyse numerical simulations of two additional geometric representations of a river system.' This opening more clearly expresses our intention and makes a more explicit connection to the preceding 'Background'. Throughout the 'Approach' section, we have also included additional direct references to our revised Figure 3 (see below), which brings further clarity to the differences between the cases and which aspects are derived from the earlier paper.

3. **Keep the sections concise and omit the title "results" when talking about previous findings, even if they are extended with more detailed plots, etc.**

   We have changed the title of Section 4.3 to: 'Results and comparison with single-segment, upstream-supply case', which we feel accurately reflects its content.

4. **Explicitly refer to the parts that are different from M^{c}Nab et al. (2023) (such as lateral sediment input) and what is the same. For example, it looks like Fig. 2(a) describes the model used in M^{c}Nab et al. (2023), and (b) an extension with lateral inputs. But it is not clear where "network geometry" comes into play. Maybe it would be good to have a third plot of a "junction" outlining the last step from single profile to combined profiles, forming a network. Note that this last step is not trivial, as it requires the conservation of several quantities to be satisfied at each junction.**

   [Note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one. We use the new figure numbers in the following.]

   As described above, we have added explicit statements at various points separating our new results for the along-stream supply case from those of our earlier paper (upstream supply case). In Figure 3, we have added a reference to M^{c}Nab et al. (2023) on panel (a), and 'This study' to the remaining panels. We have followed the Reviewer's suggestion to include a third panel showing a network junction, which we think is a substantial improvement. Figure 3 now serves as a useful, more complete summary of the various scenarios we explore, which we hope will also make the 'Approach' section clearer. Our artistic capabilities are unfortunately insufficient to ensure accurate conservation of physical quantities across the network junction, but we hope the outcome is adequate as a schematic cartoon.

5. **At some point, I simply gave up trying to decipher what is from M^{c}Nab et al. (2023) and what is new, and jumped to Sec. 5. A table summarizing the parameter space may also be useful.**

   We have extended the notation table in Appendix A to include parameter values, or ranges of values, we used in the simulations.

6. **Note that there is a typo in L 200:** $10^{-2} = 10^2$**.**

   We have corrected this mistake.

7. **Line 320: Sentence: "We set segment lengths to a uniform value of 5 km and supply water and sediment only at the valley inlets (Figure 7a,e)", However, when looking at Fig. 7a the segments are of very different lengths, which is confusing. While the visualization on a square lattice is simple, a more "realistic" network geometry (with constant segment lengths in the case of 7a and adjusted junction angles) may be easier for the reader to understand. There should be some tools from complex networks, which may help to visually construct a network of nodes (junctions) and edges of fixed size.**

   [Note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one. We use the new figure numbers in the following.]

   In Figure 8a–d, and elsewhere we show network planforms, only the horizontal lines represent network segments, while vertical lines show only the connection between segments. As such, the segments of the networks show in Figures 8a and 8c are indeed of uniform length. We made this choice for two reasons. First, it allows us to use a consistent 'downstream distance' axis across each of the sets of panels in Figure 8, as well as in subsequent figures showing spatial variation in gain and lag (Figures 15 and 16), which we hope facilitates simple comparison between the various network properties. Second, neither does our method for constructing synthetic networks provide, nor does our longitudinal profile modelling framework require, a two-dimensional network planform. Constructing such a planform would therefore require assigning additional network properties (such as branching angles) which are not used in the analysis, and could be distracting.

We have, on balance, decided to retain our original scheme for visualising network planforms. We acknowledge, however, that it may not be intuitive and requires clear explanation. We have therefore revised our figure caption, which now includes the phrase: 'Horizontal lines represent network segments while vertical lines represent connections between segment and have no physical meaning; the planforms are intended only to illustrate relationships between segments.'

8. **Similarly, I could not interpret the main plots in panels (e-h).**

   Panels (e–h) follow a similar logic to (a–d). We also added the following sentence to the caption, which we hope is sufficient to avoid confusion: 'Similar to panels (a–d), horizontal lines represent network segments while vertical lines connect segments.'

9. **For visualizing the network, order, and discharge, one could opt for a plotting scheme, where the line width of the network changes with order and the color indicates the discharge. Fig. 7 i-l: It's not very clear to me how downstream distance, elevation, and stream order are so uniquely related. Note, for one pair of distance/elevation, one could imagine finding channels with very different stream order, which is not what the figure suggests.**

   [Note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one. We use the new figure numbers in the following.]

   We tested various options along the lines suggested by the Reviewer. We have opted to retain our original colour scheme, in which network segments are shaded by stream order, but additionally scale line thickness by water discharge (we also use this same scheme in Figures 15 & 16). We thank the Reviewer for this useful suggestion which we think helps emphasise the accumulation of water along the higher order streams.

   We hope this change also brings added clarity to the longitudinal profiles in Figure 8i–l. The Reviewer is correct that segments of different stream order can arise at similar elevations and distances downstream. The issue is that, since we chose to assign a constant background ratio of sediment to water supply across the network, the steady-state slope is the same for all segments. This consistent steady-state slope means that segments plot on top of one another in the longitudinal profiles, and some of the segments are obscured. Our revised plotting scheme, where line thickness increases with water discharge, makes visible segments of different discharge that are otherwise superimposed. For completeness, we also added the following sentence to the caption: 'Note that, since steady-state slope is consistent across the network, segments with the same downstream distance are superimposed.'

10. **In L 340-385, the authors describe different characteristics of network trees, however, it remains unclear how they actually create synthetic networks obeying these constraints, e.g.,**

one could use OCN networks or RSN (Seth A. Veitzer, Vijay K. Gupta, 2000), or other techniques to create stream networks with a specific Tokunaga connectivity and then add geometric lengths to the reaches according to some Horton scaling relation.

We constructed synthetic networks using the method presented by Shreve (1974). The method is outlined in detail in Section 5.1. First, we use Shreve's algorithm to generate randomly binary trees with specified numbers of valley inlet segments. We then assign either uniform segment lengths or randomly select lengths for each segment from a gamma distribution with shape parameter of two (Shreve, 1966, 1969, 1974). This approach does not impose *a priori* any of the 'constraints' discussed in the following Section 5.2, to which the Reviewer refers. Any adherence to Horton's or Tokunaga's 'laws' arises naturally in networks and network populations generated in this way. We added the sentence: 'Typical values of Horton's ratio in natural networks are: $3 < R_B < 5$, $1.5 < R_L < 3$ and $3 < r_A < 6$, and Shreve (1966, 1969) show that populations of random networks generated using his approach (which we adopt here) return similar values', where introducing Horton's ratios, which hopefully clarifies this point.

We have an added an addition section to the discussion (Section 6.4) in which we further discuss some implications of our choice of network generator and how other options may provide additional insights.

11. **Figs. 9, 10, and 11 suggest that there is almost no difference between simulations with and without along-stream supply, thus the along-stream supply may be negligible, particularly downstream in the network. Maybe it would be interesting to plot the difference between with and without an along-stream supply. I also would expect that the along stream component is more important in lower-order streams because at some point, the fraction between upstream sediment input and lateral input may be dominated by the upstream sediment supply.**

[Note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one. We use the new figure numbers in the following.]

There are indeed many similarities between the behaviour of networks only with upstream supply of sediment and water, and those with additional along-stream supply. In particular, amplitudes of aggradation and incision and variations in sediment transport are similar across the different network cases. As a consequence, we also obtain similar empirical equilibration times for the different network cases, though those with along-stream supply have slightly lower equilibration times. An important difference that does arise between the different network cases is for their lag times: for short forcing periods, lag continuously increases for the upstream supply cases, but stabilises for the along-stream supply cases (compare Figure 13e–f,m–n with 13g–h,o–p). We believe this difference is important and worth discussing, hence our decision to include both cases and treat them separately throughout the manuscript. We agree that differences in Figures 10–12 are subtle, and could be brought out more clearly by explicitly plotting differences between the cases. However, in a paper that is already long and detailed, we feel that, because these differences are indeed small, including additional material focused on them is not warranted. We have therefore chosen not to implement the Reviewer's suggestion in this case.

We have, however, added a paragraph to the network interpretation section (Section 5.5), discussing similarities and differences between the two cases. We share the Reviewer's intuition that, in the along-stream supply case, the increasing fraction of sediment that is derived from upstream means that ultimately signals propagating from upstream dominate, leading to the similarity with the upstream-supply case. We have included this logic in the new paragraph. This discussion also leads on that associated with our additional Figure 17.

12. **L 495: Sentence: "It is impractical to show here results from each of the 796 networks we tested; we do, however, provide a script in the accompanying software repository allowing interested readers to plot the entire dataset". Are Figs. 14/15 typical examples of the full dataset? If so, it would be good to state this explicitly, because although it is impractical to show all 796 plots, readers may still be interested in seeing representative examples without downloading and invoking a complex software tool.**

    [Note that, in our revised manuscript, we added a new figure so that all original figure numbers are incremented by one. We use the new figure numbers in the following.]

    We added the following sentence to the paragraph in question: "Although, in detail, spatial patterns of aggradation and incision are unique to each individual network, some general features can be identified, of which the examples in Figures 14–16 are representative."

13. **L. 600: structure dependence: it may be interesting (maybe not here in this manuscript) to see if and how different structure classes described by OCN, Tokunaga parameters etc have similar behavior or not. (see comment above)**

    We agree that alternative approaches to network generation may provide interesting opportunities to explore in more detail and more systematically structural controls on network behaviour. We have added a note to this effect in our new discussion section (Section 6.4) on the impact of our choice of network generator. Given that the paper is already long and detailed, however, we do not think it is appropriate to explore this avenue further here.

Reviewer 2 — Alan Howard

The paper is well-written, the citations to previous literature are extensive, the methodology as presented in the paper is clear, the simulations concerning single channel and stream network response to sinusoidal variation of water and sediment supply are comprehensive, and the conclusions of the paper seem reasonable.

We are pleased that Howard found our manuscript to be clear and comprehensive on the whole.

1. **My main comment concerns incomplete references to some relevant past research on the patterns of response of both single channels and networks to various types of perturbations in the forcing factors of water and sediment inputs as well as base level changes. In particular, Howard (1982, ESPL, 7, 303-325) conducted simulations of the response of both single channel and channel networks to sinusoidal variations in water and sediment yield, as well as response to impulse inputs and base level changes. The channel and network response time is discussed in detail. This modeling was in the context of sand-bed channel systems so that that threshold of motion was not a factor. The application in that paper was primarily on concepts of grade and equilibrium in geomorphic systems, but the computational and**

analytic treatments for sand bed channels are very similar in conclusions to the present paper. That paper did not consider changes in valley and channel width in response to the modeled responses, e.g., it did not consider channel narrowing in response to incision or changes in channel planform. A particular correspondence between the present paper and Howard (1982) is the change between close adjustment of channel response to low frequency inputs and the strong averaging (or muting of response) to high frequency variation.

We thank Howard for drawing our attention to his previous paper (Howard, 1982), which it was an oversight on our part not to cite in our previous draft (and, indeed, in our earlier paper, M^{c}Nab et al., 2023). We agree that various similarities arise between our analysis and that in Howard (1982), which we summarised in our response to Howard's previous Commuminity Comment (`https://doi.org/10.5194/egusphere-2025-2468-AC1`).

In revising our manuscript we made efforts to acknowledge relevant aspects of Howard's (1982) work, specifically: in the Introduction (Section 1), where we introduce the concept of equilibration/response time, and where we summarise previous work on networks; in the second part of the Background section (Section 2.2), where we introduce the analytical solutions of M^{c}Nab et al. (2023), which resemble those of Howard (1982) for a generic linear system; in the Interpretation part of the single-segment, along-Stream supply section (Section 4.4), where we introduce the concept of signal damping at high frequencies and transmission at low frequencies; in the Network section, where we outline our approach to constructing synthetic networks (Section 5.1), where we first note a broad similarity between the behaviour of networks and single segments (Section 5.3), where we discuss the spatial distribution of lag times throughout networks note reduced lag times and their relative uniformity along stream compared to the single-segment case (Sections 5.4.2, 5.4.3 and 5.5), and where we again discuss the importance of the forcing timescale relative to the system response timescale in determining the system response (Section 5.5); and in the Discussion, where we discuss our estimates of network equilibration time (Section 6.1), and where we discuss consequences of spatial variation in lag (Section 6.2).

2. **The paper could also reference other recent research on filtering of channel responses to upstream inputs due to network response time, such as the Jerolmack and Paola (2010, GRL, 37, L19401) concept of signal "shredding".**

   We agree that the concept of signal shredding is prominent in the literature and therefore worth referring to and discussing here. We already discussed some similarities and differences between our framework and the concept of shredding, which arises in stochastic transport systems, in our response to Howard's earlier Community Comment (`https://doi.org/10.5194/egusphere-2025-2468-AC1`). In our revised manuscript, we note the concept in our Introductory paragraph discussing previous work on the response of alluvial systems to external change. We also added a new discussion section (Section 6.5 – High frequency fluctuations in sediment transport and signal 'shredding'), where we refine and expand on some of the ideas in our previous response.

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