Dear editor/reviewer,

We’d like to take this opportunity to broadly elaborate on the reviews and how our paper was modified based on those comments.

Dr. Legleiter had very good comments and suggestions related to using a single sample pathway. We reanalyzed all of our data and modified all text and figures using a common sample pathway. We mapped all of the flow dependent pathways to one single line and that certainly made interpreting the results easier for the reader. Dr. Legleiter had several other suggestions and comments that we also considered, mostly taking his advice except for cases where we disagreed. Our main disagreement was related to terminology and we thoroughly addressed this point in our responses, as well as updating the manuscript to provide more clarity.

Dr. Thompson's comments were very good in that he emphasized more detail on the study river and how prior flows may have led to the observed results. Based on his comments we rewrote part of the introduction, the entire study site section, as well as made our discussion more focused. Both reviewers suggested we shorten section 5.1, so that section was greatly reduced. Lastly, we modified the title of the paper to better reflect the main conclusions of the paper.

Overall, we are very happy with the changes brought about by the peer review process and hope the revision lives up to the high standards of the journal.

Sincerely,

Rocko Brown

Authors response to RC1, reviewer Carl Legleiter

General comments

This paper examines the relationship between bed elevation and water surface width in a large gravel-cobble bed river and attempts to do so in a spatially explicit manner intended to quantify variability at different scales. While this objective is important, the present manuscript falls short of this goal. Although the topic is of broad, general interest and the underlying data are suitable for this type of analysis, the implementation is flawed in several critical ways. For example, what the authors refer to as a geomorphic covariance structure is not, in fact, a covariance at all, just a local product of detrended and standardized width and elevation. Similarly, although a stated objective of the study is to make comparisons among discharges, the use of a different spatial reference for each flow stage complicates if not precludes such comparisons. The authors use auto-correlation functions and frequency domain analyses to examine scale dependence, but a simpler approach based on correlograms or variograms would be more insightful. Although the study has potential, major revisions, including substantive re-analysis, will be required before the paper can be published in this or any other geomorphic journal.

Response to general comments

In the reviewers general comments and throughout specific comments there are two primary critiques, related to terminology and methodology. Here we address these critiques broadly before addressing specific comments.

Terminology

One of the reviewer comments is related to terminology. In our paper we demonstrate and apply a new method of analysis, called geomorphic covariance structures. The reviewer contends a lack of understanding in that what we are calculating is not covariance, as defined in classical statistics. We agree that we are not calculating covariances as defined in classical statistics, and did not in any part of the text, state so. For example, lines 1-9 of the discussion paper clearly define what a GCS is, and further, state that it is a relatively new form of analysis. What we are calculating is a spatially explicit metric that analyzes the literal co-varying structure of two series of geomorphic data. In using the term covariance over correlation we have sought to make this metric intuitive to all scientists, not just those in the field of statistics, who frankly, are not concerned with the broader aims of this paper or geomorphology. In describing and defining this methodology we were very explicit in its basis and calculation. We state that a geomorphic covariance structure is a spatial series that describes how two variables vary and do not vary with each other. Taking two variables X and Y, the GCS value at each node i is defined as x^i*y^i, and in this paper, where x and y are detrended residuals standardized by their mean and variance. It is important to highlight that the GCS is not any one point, or related to samples of points, but the entire series of products at every location. So it should be obvious that we are not calculating either correlation or covariance in our geomorphic covariance structures. Regardless, we have added text to clarify that the GCS is neither covariance nor correlation as described in classical statistics.

We did label the Y axis of figures 4 and 5 as covariance, and we will revise that so as to avoid confusion, instead using the term “magnitude” to denote the strength of the local products within the GCS.

One could argue that within the term geomorphic covariance structure perhaps correlation could replace covariance. We aim to discuss here why the former was chosen. Correlation and covariance have similarities in their basis, and many textbooks discuss this along with their differences. A key aspect is that correlations can be derived from covariance by dividing by the product of the standard deviations of the two variables analyzed (Newland, 1983; Schumway and Stoffer, 2006). For example, Newland (1983) even refers to correlation coefficients as a normalized covariance (e.g. page 23).

Further, we have already had the idea of a "geomorphic covariance structure" as defined in this paper peer reviewed in 3 previous journal articles and it was embraced by the reviewers in all those cases (Brown et al., 2014; Brown and Pasternack, 2014; Brown et al., 2016). Also, the other reviewer of this article is well versed in statistics and had no problem with our using the terminology as we have. Of course we fully understand statistics, but we would like reviewer to also consider and recognize that it is very common in science to take a word and employ it for another reasonable purpose in a different discipline.

In many cases words used in scientific nomenclature have different meanings in different disciplines. For example in power spectral density analysis "power" is used to describe the strength and distribution of variance to a statistician, as sometimes shown on the Y axis of spectral density plots. However, in physics "power" is defined as the rate at which work is or can be performed. This has not stopped the use of the term power in either case, because presumably both disciplines are comfortable and knowledgeable with the lexicon of each discipline.

In our article, the word "covariance" is being deployed in its sight word literal translation to mean, how two variables co-vary with each other. Given that correlation is so similar to covariance, and is a derivative of covariance we believe it is more intuitive to use that word within our overall term of geomorphic covariance structures. We should not be required to reserve any one word for only one jargon usage in one other discipline, as exemplified above with the case of the word "power", which is used differently in different disciplines. There are countless examples of this. The key is that we have provided our definition of covariance very clearly for readers to understand, and it was been accepted as a reasonable usage.

<u>Methodology</u>

Outside of terminology the reviewer contended that the use of different sample pathways with flow was incorrect. In the early stages of this paper we analyzed several approaches for sample pathways and performed the analyses in this paper for each one. This included using the thalweg, a smoothed conveyance pathway for the bankfull discharge, and the valley centerline – all constant with discharge.

As stated in the text the thalweg is too tortuous to have cross sections that are orthogonal to the flow. To illustrate this we created a figure some of our preliminary work (Figure 1). Figure 1 shows the traditionally defined thalweg and flow dependent sample pathways used in this study with 5m spaced cross sections clipped to the 8.5 cms flow. Visual inspection of this section of the river reveals that the thalweg in many places changes direction in otherwise straight sections of river flow when compared to the momentum based sample pathway. For example the momentum grid shows multiple downstream oriented bands where the thalweg moves left and right. As can be seen the cross sections generated using the thalweg would cause significant overlaps from the tortuous path in areas where flow is otherwise straight (Figure 1b). This is just one example of why the thalweg is not appropriate at low flow, but we found this to be prevalent throughout the study reach.

Similar issues arise for higher flows. For example Figure 2 shows the momentum grid for the 8.5, 141.5, and 3,126 cms flows along with the sample pathways. First, this figure shows that the thalweg would not be appropriate as a sample pathway for generating sections because it remains tortuous and static, while flow paths change with increasing flow as more of river corridor is inundated. It can also be seen clearly from Figure 2c that when the gravel bars are overtopped at 3,126 cms flows follow the valley walls more closely and deviates considerably from the thalweg pathway. Using flow width sections generated from the thalweg for higher flows would lead to incorrect estimates of flow width. Overall we have found that the thalweg overestimates flow width at moderate to high flows in areas where it angles where flow is straight. Similarly, the valley centerline underestimates low flow widths because it does not account for the flow steering that occurs from gravel bars.

Understanding that the thalweg and valley centerlines are not appropriate due to flow steering we developed flow –dependent sample pathways as discussed in the text. Initially, we mapped all data to the bankfull sample pathway (e.g. 141.5 cms). However, given the strength of C(W,Z) at the bankfull flow of 141.5 cms we thought mapping to that sample pathway could be interpreted as bias our results. Thus, our approach was meant to deal with the issues stated, but by all means was not deemed perfect and as we stated it remains an area of future research. Given that both reviewers had confusion with figures 4 and 5, and using different sample pathways we decided to revise our work. To do this we mapped each flow dependent width series to the pathway associated with the lowest flow (e.g. 8.5 cms) using the spatial join tool ARCGIS. So each flow width series was referenced to a single sample pathway with minimum bed elevation, while preserving the fact that flow is steered by variable topography with increasing flow discharge.

Specific Comments (responses in italics):

1. Page 3, line 8: Another relevant citation in this context is Legleiter (2014a,b), a two-part paper in Geomorphology outlining a geostatistical framework for describing the reach-scale spatial structure of river morphology. Legleiter used variograms rather than covariances, but the two quantities are closely linked and both serve as metrics of spatial structure and variability. Omitting this reference entirely is an oversight.

We are well aware of the reviewers work in geostatistics. In reviewing the discussion paper in its typeset form we are not seeing where this citation would be appropriate. Page 3, line 8 refers to scale-dependent organization in natural rivers, and not particular methods that analyze only one scale of variability, as in the reviewers suggested papers.

2. Page 3, line 17: You state "self-maintained bankfull river channel," but then go on to emphasize the influence of bedrock and tailings piles – is this contradictory?

No. The channel is partially confined by bedrock and tailing piles that are activated above the bankfull channel and associated flow discharge. We have rewrittem the study background section to clarify this. Also, see discussion in Section 3 for more clarity.

3. Page 4, line 4: 9 km or the 6.4 km in the abstract, which is correct?

Thank you, we have corrected this. It is 6.4km.

4. Page 5, line 5: "removing the initial bed profile"? This is unclear and does not adequately describe the D & R (2012) study.

Reworded for clarity.

5. Page 5: Your review of empirical/modeling studies of pool-riffle sequences is thorough, and then you go into extremal hypotheses, but I think a more well-rounded background section also would include some discussion of a more process-oriented approach to channel morphology. For example, the classic work by Dietrich on Muddy Creek and subsequent studies of the importance of topographic steering effects, such as Whiting and more recently by Legleiter et al.

We thank the reviewer for his suggestion, but feel our review adequately characterizes existing literature, while not being superfluous. Adding more references related to the papers suggested would further encumber the reader on background information that is not essential to understanding this paper.

6. Page 6, lines 8-10: Provide citations to support these claims regarding remote sensing and larger-scale modeling.

We have added the following citation: Carbonneau P, Fonstad MA, Marcus WA, Dugdale SJ. 2012. Making riverscapes real. Geomorphology. 137:74-86. DOI: 10.1016/j.geomorph.2010.09.030

7. Page 6, line 24: Maybe not width and bed elevation, but Legleiter et al. (2007) examined stage-dependent spatial structure of flow hydraulics in a mountain channel using a geostatistical approach similar in many respects to your covariances.

No comment needed.

8. Page 7, lines 12-15: This is a key point throughout the paper that first comes up here: in calculating a GCS, you must have some sort of moving window to obtain a sample for estimating the covariance, whereas this sentence implies that you are just pairing one observation of x with one observation of y. To estimate the covariance, you must have at least a handful of data points. Perhaps I'm missing something, but how the data are pooled to obtain a covariance value for each location along the spatial series needs to be spelled out more clearly and explicitly.

We have addressed this point in the introduction of this reply. To reiterate, we are not calculating covariance in the classic statistical sense, but a new metric.

9. Page 7, lines 19-20: Why were these particular flows selected for analysis? Were these discharges for which you had field data to calibrate/validate the flow model? Please provide some brief rationale for the specific flow studied.

We have added text to clarify the selection of flows investigated.

10. Page 7, line 21: The word "preference" seems subjective and anthropomorphic; something like "tended to" or "more frequently exhibited positive values" seems more appropriate. This sentence is also passive and much longer than necessary. Please replace "preference" with "tendency" throughout.

That is a fair and good suggestion incorporated in the paper. Modified as recommended.

11. Page 8, line 6: The phrase “but other complex responses are possible” goes without saying and doesn’t really sound like a concrete, specific hypothesis. I’d just delete this phrase.

Deleted as recommended.

12. Page 8, line 17-18: For the spacing of features, presumably you want some kind of average spacing, which implies a long reach to encompass several “cycles” of the morphology, but your examples are very local – is this a dichotomy? Also note that this hypothesis implies an assumption of stationarity that you should make explicit –basically the analysis is assumed to be invariant under translation within the domain of your study.

Within the 6.4 km study reach there are approximately 10 riffles and pool units, depending on whether a topographic or hydrodynamic basis is used. The examples are meant to show, well, examples of areas within the study reach, and not to imply that only a few morphologic units are present.

13. Page 9, lines 18-19: What is “it” referring to in this case?

We have reworded this for clarity, but in this case “it” is in reference to the wetted extents of water.

14. Page 11, line 20: All data in the supplement should be in metric units, not feet.
Corrected as recommended.

15. Supplement, line 34: Define TBR.

Corrected as recommended.

16. Page 12, line 11: Are you defining the thalweg as the location of deepest flow for a given cross-section? Please be explicit about this.

No, we are referring to the traditional definition of thalweg, as the path connecting the deepest parts of a river with downstream direction.

17. Page 12, lines 16-26: I have to question whether a series of flow-dependent centerlines, or sample pathways as you call them, is appropriate. Under this framework, the same location would have a different streamwise spatial reference at each discharge and so your results would not necessarily be comparable from one flow to the next because the streamwise series would not be “lined up.” For example, you emphasize the importance of bedrock outcrops, etc., that are not going to move as a function of discharge and yet would have different streamwise coordinates under your scheme. This point also relates back to my comment about stationarity. I think a more robust approach would be to use a single, representative centerline across the full range of flows so that you can be confident that your analyses are in sync with one another. I realize this would involve major re-analysis, but with a separate spatial reference for each stage, I just don’t think your results are comparable among discharges.

We have considered this comment and others, and have ultimately revised the analysis using a single centerline to help readers and reviewers have a more simplified framework for comparison. To do this we mapped each flow dependent width series to the pathway associated with the lowest flow (e.g. 8.5 cms) using the spatial join tool ARCGIS. This tool can map, or join, features to another based on whether they directly overlap. Our revision of our original approach is based primarily on making the examples easier to understand by having a common reference.

However, as stated in the text we do not believe having different sample pathways has any effect on the statistical tests applied in our article, except for the correlation comparison between stage dependent wetted widths, which were mapped to a common centerline. In any case, we have gone ahead and used a common sample pathway in our revision to make it easier for the reader to understand the zoomed comparisons.

18. Page 12, line 25: Constructal theory – how is this relevant? Either elaborate and define this concept or omit.

Given that we are now mapping to a common sample pathway we have deleted this sentence.

19. Page 12, line 27: Why square the velocity? Wouldn't dividing by the lateral cell size be more appropriate to give you a discharge per unit width as the product of depth and velocity?

We clarified the text to address this comment. Note that in classical physics momentum is defined as the product of mass and velocity squared. Therefore, unit momentum can be calculated on a grid of depth and velocity as $(d_i * v_i^2)$, where d_i is the depth and v_i is the velocity at node i in the 2D model hydraulics rasters. Most importantly, the patterns generated by using $(d_i * v_i^2)$ and $(d_i * v_i)$ are identical, so the choice between either one is not that important.

20. Page 13, line 5: How was this smoothing accomplished? See Fagherazzi et al. (2004) and Legleiter and Kyriakidis (2006) for one approach to this problem.
We used a Bezier curve approach and clarified text to reflect this.

21. Page 13, lines 15-17: Does your analysis consider the cross-stream position of the minimum bed elevation, or is it essentially 1-D? You might want to consider a full coordinate transformation to a channel-centered frame of reference. Otherwise, you're underestimating the distance by assuming that all z values are on your sampling path when they could occur some distance to either side.

Yes, it is 1D. The cross section sampling interval is 5 m, or 6% of the average bankfull width for the reach, and we consider this relatively "tight". There are no cases where the deepest part of the channel immediately zig zag, so we had no issues underestimating distance. In reference to the channel centered frame of reference that is what our current approach does. It uses a sample pathway within the channel to reference bed elevation and channel width. However, given that the bed elevation is now referenced to the lowest flow sample pathway, it is analogous and similar to the thalweg.

22. Page 13, lines 25-26: De-trending the width series is not appropriate because the trend is so weak and probably not statistically significant, given the R2 values in Table 2. Unless there's a compelling physical reason to de-trend, as there clearly is for bed elevation, this step is not necessary. Just use residuals from the reach-averaged width instead.

We believe for consistency all of the data should be detrended to satisfy the statistical assumptions inherent to our data analysis methods.

23. Page 13, line 26: Standardize by the variance? I think standard deviation is, well, more standard.

No comment required.

24. Page 14, lines 5-8: This dependence on length (and location) is the essence of the critical assumption of stationarity, but you should be more explicit about this as it really is critical to this type of analysis.

We have considered the authors suggestion and have added text to the data analysis section.

25. Page 14, line 9: Just multiplying one Z value by one W value at a given location does NOT give you the covariance, as this text implies. The covariance describes how two random variables co-vary with one another and thus requires some kind of sample. Under the critical assumption of stationarity, this sampling is achieved by pooling observations over some spatial extent, not just a single point. Think of it as analogous to the R2 of the scatter plot with points drawn from within a moving window. Also, if you're using standardized variables, the correct term would be correlation, not covariance. This oversight suggests a fundamental lack of understanding about the statistical concepts involved and casts doubt upon the entire analysis. What you have calculated is not the covariance, so if nothing else the title you have given to your metric is incorrect and must be modified, but I think you will need to revisit the entire analysis.

We have addressed this broader comment in the introduction of this response and no further comment needed.

26. Page 14, line 13: What do you mean by "normative"? This is a very vague term that should be replaced throughout.

Normal conditions in this context refer to areas where both variables are close to the mean and thus the GCS~0. We have clarified this in the text.

27. Page 14, lines 25-26: Without a sample size, which your point-by-point product does not provide, you have no basis for assessing statistical significance. I'm sorry, but I think a major overhaul is needed to address this important issue.

We have removed the term significant from the examples, which are meant to show how inundation patterns, and thus the GCS, change with flow. Because we are not calculating covariance as the reviewer has assumed the comment of not having a sample size is without merit. However, please refer to Brown and Pasternack (2014) to see how we have assessed statistical significance using bootstrapping in the past.

28. Page 15, lines 10-11: The term "significant" is not appropriate for the quantity you have calculated.

As stated above, we have deleted this sentence and do not use the term significant in the examples.

29. Page 15, line 20: This is what you should be doing within a moving window if you really want to get a covariance. Another approach would be to use variograms, where you pool pairs of points separated by a set of lag distances – see Legleiter (2014) for the details. I think that

paper might help you gain some more insight into the spatial statistical concepts you're talking about but not really doing in this paper.

We appreciate the reviewer's suggestion for this reference, to which we are familiar.

30. Page 15, lines 21-24: This is why a common centerline would be a better choice, then you wouldn't have to resample from one discharge to the next.

No comment needed.

31. Page 16, line 10: Need to define n and k. This ACF is analogous to the variograms and would be a more appropriate way of examining spatial structure. Not clear what x is in this equation, but if you use Z as x in this equation, then you'd have a correlogram, which would be a more appropriate metric than your simple cross-product. To get at the spatial correlation between Z and W you could generalize your equation 1 to use both variables and obtain a cross-correlogram.

Given the similarities between variograms and autocorrelation in measuring variance with respect to distance we are not convinced that it would be more appropriate without further explanation. We have provided clarification on the variables listed in the equation.

32. Page 16, line 12: Be more explicit about the lags used, it's tucked into the distance and number of lags but you should state the lag interval.

Addressed as recommended.

33. Page 16, line 15: explain what a first order Markov process means in terms of geomorphology, and likewise for white vs. red noise.

We decided that the reference to Markov processes was not needed in this section. However, text was added to clarify red and white noise.

34. Page 16-17: The discussion of autoregressive models and red noise is opaque – what was the rationale for this analysis?

Page 16, Line 16 describes two reasons for this analysis so no further comment is needed.

35. Page 17: The level of sophistication implied by this discussion of spectral analysis, etc., is inconsistent with the lack of basic understanding of the covariance and so the paper comes across as unbalanced. Moreover, this section gives the reader the impression that you're just using advanced methods without really knowing what they are doing. I would advise dropping the frequency domain analysis completely, scrapping your so-called (but not) covariance, and focusing on appropriately calculated correlograms or variograms.

We strongly disagree with this comment. The reviewer has assumed we do not understand basic differences between correlation and covariance. We have addressed this earlier in this response and no further comment or revision needed. The frequency domain analyses are important, because they distill information from the ACF more compactly, and in the process allowing inferences to be made across statistical tests. This are scientifically meaningful and technically sound tools to use for the purpose of this study. As is common in data analyses, many approaches exist and would also yield similar findings, but these are the ones we deemed meaningful for geomorphologist, and so we used them.

36. Pages 17-18: OK, so you acknowledge the impact of different sample pathways and apparently compared results from static vs. dynamic as you called them, but I still think a single pathway would be more logical and save you (and the reader) the confusion of having to line up the same feature at different streamwise locations for different discharges. The last couple of sentences of this paragraph are very confusing and need to be re-worded.

As stated above we have altered our approach and have mapped all sample pathways to a single one, so that it is not confusing to the reader.

37. Figure 3: Add numbers to your quadrants, as you haven't followed the mathematical convention of quadrant 1 in the upper right, then cycling counter-clockwise. I find this figure very confusing and I think your (b) and (c) might be mislabeled as positive and negative – revisit to confirm this.

We have modified this figure based on these comments.

38. Page 18, starting on line 12 and Figure 4: Need to specify flow direction an whether stationing increases upstream or downstream.

We have added an arrow for flow direction.

39. Figure 4 and related discussion on pages 18-19: Because you have a different sample pathway for each stage, the features and stationing don't line up from one panel to the next so the comparison is difficult. You need to label the same features and extents on all three panels, or, better yet, use a common centerline for all discharges.
Also, what you have labeled as broad riffle has a low bed elevation, which seems contradictory.
40. Figure 4: The image does not cover the full extent of the plot on the right, which contributes to my confusion in the preceding comment. Zoom out on the image or in on the plot so the extents are equivalent. Also unclear from the legend which line is Z and which is W.

As stated above we are now using a common sample pathway for all flows, so no further comment needed.

41. Page 18, line 19: Given your detrending and standardization, what you describe as significant for Z just means more than one standard deviation from the mean, or a 68% confidence interval – not what most statisticians would consider significant. You might want to back off this terminology.

We have dropped this terminology in the discussion as it is not necessary.

42. Page 19, line 2: Don't you mean -1?

Yes, thank you.

43. Page 19, line 9: Impossible to assess these shifts when the spatial referencing is not consistent among discharges.

We are now using a common spatial reference so no comment needed.

44. Section 5.1: Throughout this section, the discussion would be much more concrete and easier to follow if you placed letters or markers on the plots and images to identify specific locations/features, rather than qualitative descriptive terms for morphologic units with indefinite extents. I found this whole section be hard to follow and not very insightful, though it could be if done more carefully and precisely. These labels need to be on all panels and the more I think about it the more imperative it is to use a common centerline for all stages so that this kind of comparison is even possible.

We have tried to incorporate these comments in the paper and on the figures. In particular we shortened this section significantly.

45. Section 5.1: Also, this very detailed, blow-by-blow description quickly gets to be a bit overwhelming and so I would try to back off and generalize, at least to some degree.

We have considered this comment and attempted to simply where possible.

46. Page 21, line 5: See my earlier comments about "preference" – tendency would be better.

Modified as recommended.

47. Page 22, line 6: This paragraph and Figure 7 are more in line with where I think you should focus your attention, and computing correlograms would allow you to make this analysis spatially explicit and examine the variation at different scales. You should also check out Lea and Legleiter (2016) for another example of this type of analysis.

Given that we are already using correlograms (e.g. autocorrelation) no revision is needed.

48. Page 22, line 11: Yes, but these correlations are all quite weak. That is not surprising, but should be mentioned. You might want to elaborate more on what this implies in terms of the actual geomorphology, particularly the stage-dependence. The observation that the z-w correlation increases from base flow to bankfull and then declines
suggests that the bankfull flow really is the channel-forming discharge. This is a key result that you might want to emphasize.

In latter sections we emphasize the importance of this key result.

49. Page 22, lines 11-15 and Figure 8: I don't think you can make this kind of crossdischarge comparison given your different spatial referencing for each flow – one more reason to go with a common centerline.

As stated above we are now using a common sample pathway.

50. Figure 9: Presenting these as a continuous surface interpolated across discharges is inappropriate and misleading. I think these plots would be clearer if you made the correlation as the vertical axis, the lag as the horizontal axis, and each discharge as a separate line. As I mentioned previously, I suggest dropping the frequency domain analysis altogether.

We appreciate the reviewers comment, but no basis for plotting these data as a continuous surface is given, so we are unable to evaluate this comment. We believe the surface plots make the results easier to interpret than a plot with several lines for each flow.

51. Section 5.3 and Figure 9: Are these results aggregated over the full study area or just for one of the examples you showed? Do you have any reason to expect higher correlation at a lag of 1400 m or 2100 m? How does this relate back to the geomorphology?

These are for the entire study entire. In the discussion we related those length scales to those of bars, pools, and riffles defined in other studies, in the process relating this result back to fluvial geomorphology.

52. Page 23, lines 3-5: This is an interesting result suggesting that the flow field becomes more spatially homogeneous at the highest discharges. I think this would come across much more clearly with the correlogram approach I've suggested.

No comment needed.

53. Page 23, lines 6-19: Drop the frequency domain, not insightful.

No comment needed.

54. Page 24, line 1: Diagnostically is a curious word in this context, implying there's something wrong with the river. What are you trying to get at with this? If you're not trying to make some kind of point here, delete this word.

As stated in the introduction spatial analysis of river organization is important to assess rivers in light of worldwide degradation, so being able to diagnose functional rivers from non-functional river systems from topographic analysis would be important.

55. Page 24, lines 4-6: Regarding lagged effects, it seems like the topography would have to be lagged relative to the flow field if a perturbation has to advect downstream, which would require some time and therefore distance. This is related to the topographic steering concept and might be worth discussing further.

This is an interesting suggestion we have considered.

56. Page 24, lines 15-16: You don't really know the distance of such a shift unless you use a common spatial reference.

As addressed in the introductory response we are now using a common spatial reference, so no further comment needed.

57. Page 25, line 6: Regarding "top-down organization," these results suggest that every river is unique and contingent upon the local particulars of geology, land use, and history and that our idealized notion of purely alluvial systems might be an oversimplification,if not altogether misguided. Perhaps something to consider further for your discussion.

Thank you for this constructive comment.

58. Page 25, lines 13-14: What do you mean by "non-persistent riffle"?

One that does not persist in a location over time.

59. Page 24, lines 14-18: This idea of diagonal steering sounds interesting but I'm having a hard time picturing the process – a simple conceptual sketch here would be helpful.

We thank you for your interest, but given that the paper already has 9 figures we believe an additional figure for a peripheral discussion component of the paper is unwarranted.

60. Page 26, lines 1-4: Legleiter et al. (2011) examined the stage-dependence of topographic steering effects in a meandering channel and some of the concepts discussed in that paper are relevant here, so might be worth checking out. In general, a scaling of terms in the force balance would be insightful. I suspect that at the largest flows the topographic steering effects are negligible and the force balance simplifies to gravity and friction.

This is a good suggestion, but we feel would detract from the overall point of this paper.

61. Page 26, line 17: This is also a matter of time scale, as reconfiguring the valley walls, particularly if bedrock controlled, is going to take a lot longer than reshaping a gravel bar. That said, these grain-scale, engineering time scale kinds of processes over time could influence the larger scale valley form as well.

No comment needed.

62. Page 26, line 22: Just report lengths scales, not frequencies.

No comment needed.

63. Page 27, line 4: If you use correlograms or variograms these periodicities will emerge from the analysis more naturally, if they are present, and will be easier to interpret.

We did use correlograms (e.g. the autocorrelation function), so we are unsure of this comments merit or point.

64. Page 27, line 17: "indicative of normative conditions" is an empty phrase, what do you actually mean by this?

Normal conditions in this context refer to areas where both variables are close to the mean and thus C(Z,W^j)~0.

65. Page 27, line 19: This is another place where a consideration of the force balance would be helpful.

As stated above, this is a good suggestion, but we feel would add a level of analysis not needed for this papers original goals.

66. Page 28, line 2: Chin – a reference to step pools seems out of place in this context – can you find a similar reference for larger, alluvial rivers?

Yes, we have deleted this reference and added a different one.

67. Page 29, line 13: Legleiter (2014a,b) compared the reach-scale spatial structure

of natural and restored rivers and should be referenced in this context.

We disagree with referencing this work here. In this section our intent is not review all methods for analyzing the spatial structure of rivers, but to suggest how this newly developed method could be used.

68. Page 30, line 20: Another relevant, recent publication to cite here is Hugue et al. (2016).

Thank you for this interesting citation.

References

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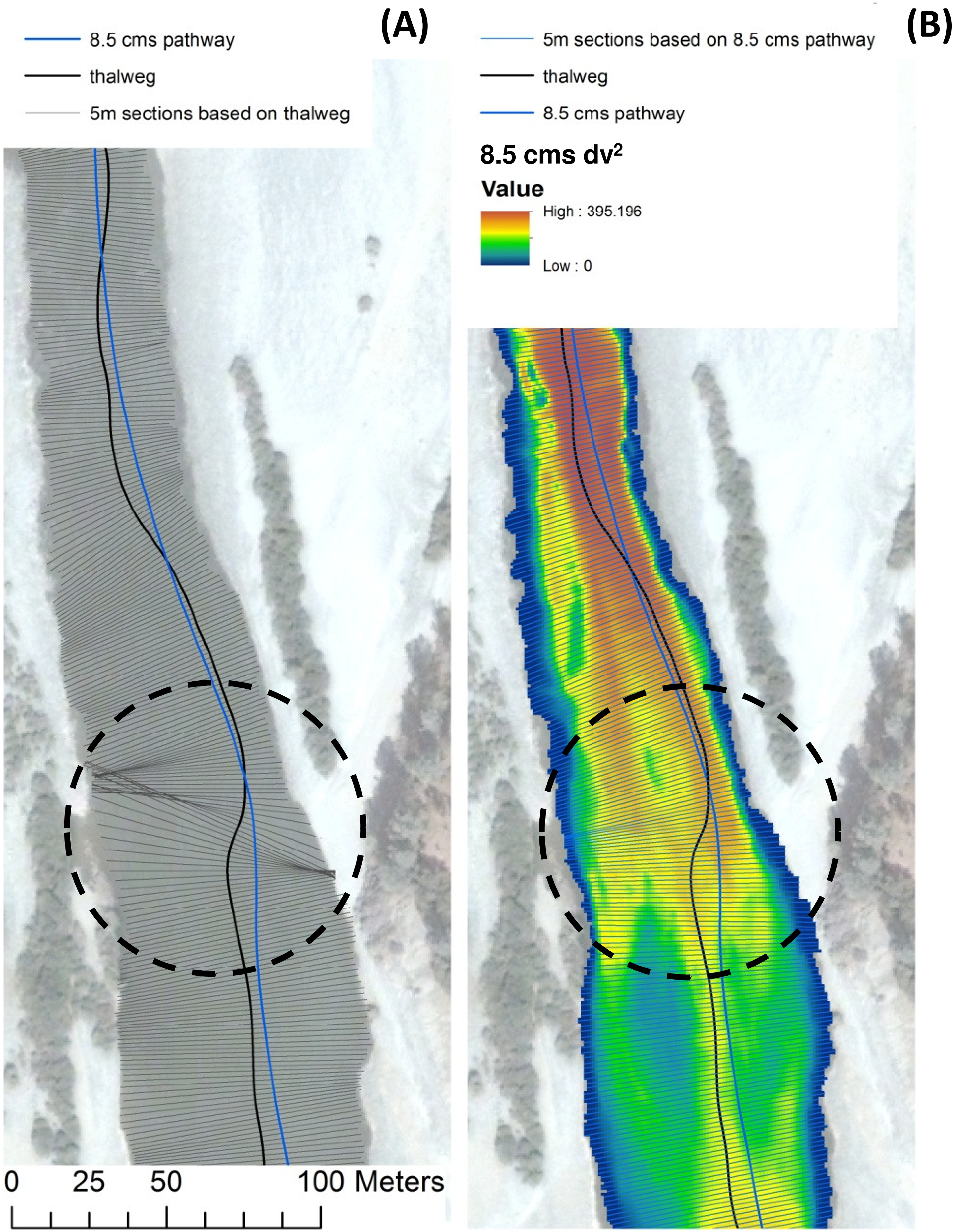
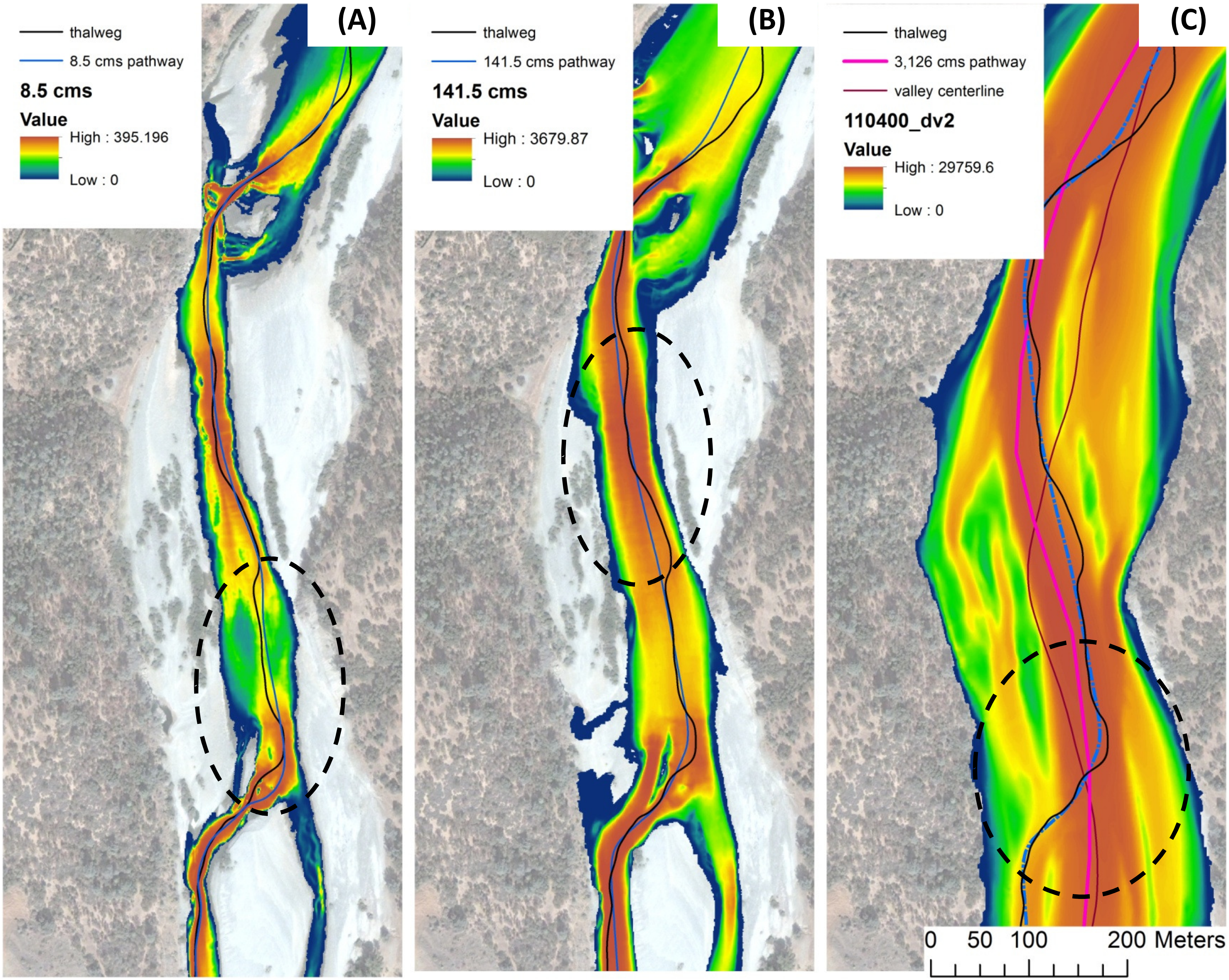


(A)
8.5 cms pathway
thalweg
5m sections based on thalweg
0
25
50
100 Meters
(B)
5m sections based on 8.5 cms pathway
thalweg
8.5 cms pathway
8.5 cms dv2
Value
High : 395.196
Low : 0


(A)
thalweg
8.5 cms pathway
8.5 cms
Value
High : 395.196
Low : 0
(B)
thalweg
141.5 cms pathway
141.5 cms
Value
High : 3679.87
Low : 0
(C)
thalweg
3,126 cms pathway
valley centerline
110400_dv2
Value
High : 29759.6
Low : 0
0 50 100 200 Meters

Author response to RC2, Doug Thompson.

General Comments

This paper describes a method for analyzing width and depth variations and different flow stages to try and look for covariance of width and depth oscillations. I agree with the author's final statement that geomorphic covariance structures (GSC's) hold promise and I especially liked the broader implications section, but I also have some concerns with the current manuscript that should be addressed before the final version is acceptable for publication.

Q1: In particular, the authors need to clearly discuss the limitations of using a single set of topographic data to infer both high-flow and low flow depth variations. The current bed morphology is a reflection of the discharge history in the last decade or so, but the authors do not discuss historic peak flows in any detail.

A: We answer the first part of this question in our response to Q3 below, so please see our response. However, we have also added more text and information related to peak flows in the study section. Hopefully this provides more clarity on the hydrology of the study river.

Q: In addition, the authors need to explain how variations in valley width are the primary control on depth variations if the covariance of depth and width are highest at intermediate flows, not the higher flows most impacted by valley width. This is particularly important given the fact that the measured bed topography might be expected to reflect the approximately 20-year recurrence interval flood that occurred just prior to LiDAR data collect, but apparently does not to a great extent.

A: We did not state that valley width is the primary control on depth variations in the text. Instead, we found that minimum bed elevation and flow width were significantly correlated for all flows, but were most correlated at low to moderate flood flows with recurrence intervals less than the 5-year event.

Q2: My main concern with the analysis stems from the fact that the authors used a single bed topography to infer depth conditions for flows that range from the mean annual flood to a 20-year recurrence interval discharge. My concern is that low flow topography is assumed to be static and is used in the 2-D model of high flow conditions on the river. It is very likely that the bed topography during the 20-year flow is very different than what is modeled, which then raises the question what does the covariance for W and Z mean if the channel morphology modeled is not a function of the discharge modeled.

A: First, we need to clarify a few things. The topography of the river is independent of flow and was mapped comprehensively for the entire lower Yuba River in one 2-year effort, with all of Timbuctoo Bend mapped in one survey effort during summer and fall 2006. Thus, the river truly has a single topography, and the goal of this study was to evaluate the coherent spatial patterns inherent to this snapshot in time. This study does not infer depth conditions and does not use depth. Instead, it uses standardized, detrended bed elevation, which is not stage dependent the way depth is, in terms of the hydraulic perspective of imposing flow on a static topography. Meanwhile, we needed some way to get at the width associated with different water stages to see how bed elevation and width relate. A way to do that is to run a numerical model at meter-scale resolution that accounts for the effects of channel non-uniformity on flow acceleration assuming a static topographic boundary condition. This study is nothing more than an analysis of topography, and thus the comments about what is going on during a flood do not apply directly to what is being tested in the goals of this study. We agree that during a flood, rivers change, but there is no way to avoid the reality that the process of mapping in a real, large river is a snapshot in time. Mapping a river's topography in real-time during a 20-year flood in meter-scale resolution over 37 km is impossible for the foreseeable future. Running a morphodynamic model with the same attributes is also impossible at this time, and even if it could be run, the results in terms of dynamic changes to bed elevation and width would be highly speculative at best given current models. Geomorphology is founded on the principle of using observable landforms to infer past processes and predict future responses (e.g., Thornbury, 1954). Therefore, the solution is to use meter-scale topography to make assessments of the processes as posited by existing theory and then see if metrics produced from topographic analyses match their expected values and/or ranges. This standard approach is what we have done, but applying it to much more detailed data and a new concept of topographic structure than attempted before. Perhaps someday geomorphologists will be able to track and evaluate dynamic fluvial changes during large floods.

Q3: The authors do a nice job referencing K.S. Richards' important work in the 1970s, but they have not addressed one of his main points, which explains that the observed channel morphology is a reflection of erosion and deposition inherited from a range of previous flow conditions. It is unlikely that the bed topography measured in the LiDAR survey conducted at very low flows corresponded exactly to the bed topography that would have existed during the 20-year event months prior. In fact, many of the features responsible for the "topographic steering" described by the authors are depositional bars, but it is unclear what flows may have created various bars and how those bars may have been reworked at lower flows. As the authors state in the discussion (page 29, line 1-15), "the topographic structure of the river change with flow." The also state "subsequent more frequent flows erode through these (flood) deposits" (Page 25, line 23-24). The authors need to address more directly how these conditions could skew their results.

A: The reviewer has drawn attention to a long standing conundrum in geomorphology. That is, it is impossible to associate channel geometry with a singular flow discharge of certain recurrence because the role of flow depends on current channel form, which is a reflection of past flows (Yu and Wolman, 1987). With that, we do not believe these analyses can untangle singular or absolute flows responsible for the observed channel topography, because as the reviewer alludes, river conditions are a reflection of past and current conditions, neither of which can be decoupled from the other (Yu and Wolman,1987). This is a general theme that we have added throughout the manuscript to avoid the notion that any one flow is more or less responsible for channel topography.

Q4: The covariance results (Figure 7) indicate a strong relation between depth (Z) and width (W) for flows near the bankfull level and lower correlation for both lower and higher magnitude flows. In looking at the USGS flow records for the Lower Yuba River, it appears that the last approximately 20-year recurrence interval flood occurred in late 2005 months prior to the LiDAR survey. It seems very likely that riparian vegetation was damaged by that flood and had little time recover. It is also likely that flow events in early 2006 reworked the flood deposits to some degree. It seems very unlikely that the bed topography immediately after the 2005 event would exactly match the bed topography during the 2006 LiDAR survey, but we have no way of knowing how much change might have occurred. It is also worth noting that even the bed topography immediately after the 2005 event would have been modified by discharges on the receding limb of the flood hydrograph. This lack of data on flood channel morphology frustrates almost all studies of this nature, but the authors still need to clearly address how this lack of information limits their study.

A: This is a valid point that we did not emphasize or discuss enough in our submission. As such, we have provided additional text throughout the manuscript that addresses this point. For example, in the experimental design section we state that "this study aimed to deconstruct and reveal the coherent topography structure of a heterogeneous river valley as it existed at the moment of its mapping. This understanding ought to inform both how the river arrived at this condition as well as how it might change into the future, but this study does not involve analysis of morphodynamic change to directly seek such linkages."

Q5: It is also important to remember that width and flow interactions are not a one-way process. Valley width does not just impact the high-flow flow conditions; the flow of the river dynamically adjusts the valley width too.

A: Because velocity and Shield stress are not uniform across a channel, but focused along a particular streamline, it is easier to cause localized erosion, especially down cutting, compared to widening in this river. If a location is undergoing noncohesive bank migration on one bank, then chances are it is experiencing point bar development on the opposite bank, yielding no net change in width. A process such as avulsion can cause rapid and effective change in wetted width though. It would be an interesting study unto itself to evaluate the relative roles of vertical change versus lateral change in the river using this dataset.

Q6: Do the authors have any data (aerial photographs through time) that might highlight areas along the study reach where valley width has been increased versus more stable sections of the valley? I would be much more comfortable with this article if the authors directly addressed these issues.

A: Valley width in this river is predominantly bedrock, with the exception of two tailing piles in the upper section of the reach. We have added text in a new study section that discusses this in more detail, including references that address the reviewers question such White et al. (2010).

Specific Comments

1. Page 4, line 4: I would appreciate seeing a general hypothesis at the end of the introduction. I have no problem with more detailed hypotheses appearing later in the paper, but I believe it is important to give the reader a general sense of what ideas are being tested at the onset of the paper.

We have added a general hypothesis at the end of introduction.

2. Page 7, line 8-10: This is the third time I have read what appears to be the exact same sentence (in abstract, introduction and experimental design sections). Obviously, the paper can be written more concisely in this specific case and in general.

This sentence and its duplicities have been edited for conciseness.

3. Page 9, line 21: It would be useful to know how flow regulation may have impacted the recurrence intervals for flows.

We have re-written the study background section to address this comment. In general flow regulation has resulted in increase flows in the summer and fall, where flows historically were highly variable.

4. Page 11, line 18-20: The authors should in the text (not just in the supplement) describe when the LiDAR data was collected and its relation to the flow conditions preceding data collection. It appears that LiDAR data and bathymetery data was collected a few months after a 3,228 m3/s event. The authors need to discuss how things might have been different if the LiDAR data was collected years after one of the larger events.

We have rewritten the study section to address this and other comments related to providing better context for the study river.

5. Page 18, line 16: I am concerned that here and elsewhere the authors talk about point bars bounding, confining and steering flow. Point bars are depositional features that are typically comprised of some of the smallest and easiest to transport sediments along a reach. Considering that these features were deposited by flowing water, it seems misleading to suggest they control flows at various stages without the flows also being able to reshape the deposits at those various discharges.

Jackson et al., 2013 report substrate mapping results for the Lower Yuba River. In the study reach during the study period surface grain sizes range from gravel to large cobble, with a mean of 164 mm (Table 1; Jackson et al., 2013). In addition to facies mapping this study also stratified sediment distributions by landform type at the sub-reach scale (e.g. morphologic unit). Their study shows that lateral, medial and point bar morphologic units all have sediment size distributions dominated by cobbles.

6. Page 19-21, Section 5.1: I found the description of the flow at various discharges overly detailed and unhelpful. I believe this section can be written much more concisely with just general trends.

We have revised this section for conciseness.

7. Page 19, line 10: Is it possible to have a negative width expansion? Are you talking about positive GSC?

This sentence has been reworded for clarity.

8. Page 20, line 26: The authors describe the river as self-formed, but flow regulation, general incision and the impact of tailings piles all suggest an adjusting system. The authors should more clearly discuss how longer-term river adjustments might be impacting the observed channel morphology from a single year. The authors hint at the impact of the tailings piles on page 24, line 18, but a more organized section of caveats would be more helpful.

We have rewritten the study section to address this and other comments related to providing better context for the study river.

9. Page 23, line 25: If pools and riffle are defined by their bed elevations, it seems selfevident that they will correspond to high topographic extrema. Am I missing somethingmore involved with this statement?

Yes, but the second half of the sentence refers to the result that areas of relatively low bed elevation also have relatively low widths, and vice versa.

10. Page 24, line 22: Suggesting that "alternate bars channelize flows" implies that the deposits are more stable than in reality. These are sediments that can be reworked by most modest flows I assume (I do understand they are discussing low flows in this case, but the term "channelize" still seems misleading).

The reviewer is correct in that this statement refers to low flow conditions. We have replaced "channelize" with "confine" to avoid potentially misleading readers. Further, we have provided more information above related to the sediment caliber of various bars in the study river that show they consist largely of cobbles, and thus at low to moderate flows can steer water flow. In many cases in the literature point bars and other sedimentary deposits can steer flow, provided the energy of the flow is not great enough to mobilize the bounding sediments (Dietrich et al., 1979).

11. Page 24, line 28: As previously stated, suggesting that a point bar "constricted" a potentially channel-forming flow seems to ignore the basic process that forms point bars.

It is important to highlight that since the river is partially confined by bedrock that there are exogenous controls on river planform. Therefore, while unconfined alluvial point

12. Page 25, line 10-12: The authors suggest that depth variations adjust to width. It certainly seems logical that bedrock outcrops and other constrictions could impact depth significantly, but the authors need to clarify that the river had recently experienced a large flood that inundated much of the floodplain. Again, the authors should discuss how the bed topography might have been different if flows had not exceed the 5-year recurrence interval for several years prior to topographic characterization.

We have rewritten the study section to address this and other comments related to providing better context for the study river.

13. Page 26, line 1-4: Do the authors know if the riffles in the bend were formed during or after the 2005 event. Is it possible that the riffles and bends are features created at different stages than each other?

Air photographs suggest that these riffles were present before and after the 2005 event. It is entirely possible, and likely, that the riffles and bends are created or maintained at different flows from each other.

14. Page 26, line 20-21: Does the coherent power connection with the 1.5-year event reflect the dominant control or just the most recent flow to impact the morphology?

We have addressed this general topic in Q4 above. To restate, it is not possible to associate channel geometry with a singular flow discharge of certain recurrence because the role of flow depends on current channel form, which is a reflection of past flows (Yu and Wolman, 1987). With that, we do not believe these analyses can untangle singular or absolute flows responsible for the observed channel topography, because as the reviewer alludes, river conditions are a reflection of past and current conditions, neither of which can be decoupled from the other (Yu and Wolman,1987). Again, this is a general theme that we have added throughout the manuscript to avoid the notion that any one flow is more or less responsible for channel topography.

15. Page 27, line 10-12: It is in relation to statements like these that more discussion on the flow history is needed. It is not surprising to me that moderate magnitude annual peak flows are most highly correlated with channel morphology, but it is more surprising in light of the higher flow event just prior to characterization of the bed topography in this study. Does this suggest the 20-year recurrence interval flow was unable to substantially modify the channel morphology established by the 1.2-2.5 year recurrence interval flows? Or did more recent flows modify the flood deposits?

We have tried to address this comment in Q3 above. It is also important to step back from absolute metrics of flow and appreciate that flood events consist of a range of flows as the hydrograph rises and falls. In addition to magnitude the duration of flow is also important in modulating geomorphic work in rivers (Wolman and Miller, 1960). While the flood that occurred prior to mapping had a peak flow of 2,721.25 m^3/s (96,100 ft^3/s) this peak only lasted one hour before receding.

16. Page 29, line 1: It would be wonderful if C(Z,Wj) > 0 could be used to identify spawning areas. However, if C(Z,Wj) > 0 characterize at least 55% of the reach at all flows and we then include adjacent areas, then C(Z,Wj) > 0 is not a very powerful tool to pinpoint zones that may represent a small portion of the study reach (I assume identifying spawning areas would not be an issue if the spawning areas existed over large areal extents of the study reach).

This was actually meant to be C(Z,Wj) > 1, so we have corrected this sentence.

17. Page 29, line 5: Riffles are depositional areas at high flow and it seems likely that bedload transport is fairly high at those times. Therefore, I question how valuable these areas are for flood refugia. Eddy and deadwater zones would seem to be safer places for juvenile salmon during floods. The importance of eddy zones would certainly seem to be consistent with the increased awareness that large-wood jams are critically important habitat features in many salmon rivers.

We are referring to laterally distributed hydraulics in this context, and have revised the sentence accordingly. While bedload transport will be directed within the core of the channel center, there are lateral zones where flow velocity and depths are relatively low.

18. Page 29, line 22: If you assume constant water slope, aren't you implicitly suggesting that variations in width are not important as controls on water-surface slope (no backwater effects). This seems like an odd statement to make in a paper that is trying to demonstrate the importance of valley width on channel morphology. Previous studies have shown a linkage between localized water-surface slope and channel morphology.

We qualified the idea of using a constant water surface slope for flows above bankfull discharge, since in some cases water surface slopes could be relatively constant. Given that we stated it could be a "potential" relaxation from using numerical model we do not believe this is an incorrect statement.

19. Page 29, line 25: The authors have generally described the Yuba River as a constrained system, but here there is discussion of large alluvial rivers. It seems beyond the relevance of this study to apply the results to large unconstrained rivers.

In this context we are not applying the main results of this study to other large alluvial rivers. We are referring to the potential for the methods used in this study may be used to analyze and compare amongst rivers how topographic structure may change with flow. We believe future studies can further evaluate the utility of the method on a more diverse array of river reaches and segments.

20. Page 30, line 12: The authors really need to explain why they think covarying values decrease for flows with recurrence intervals of 5-years and higher. Again, this seems to suggest valley width has less control on depth than other factors.

We have added text to the manuscript in the discussion that speaks to this result and our interpretation. As the reviewer noted, this result suggests that incision may be decoupling the relationship between valley width and minimum bed elevation.

21. Page 37: It would be useful to understand why these specific flows were selected. A hydrograph showing flows for the last 10-years would also be very helpful.

We have added text in a newly rewritten study site section that discusses the flow regime in much more detail. In addition, we have explicitly stated why the flows were selected, so we hope it is more clear.

22. Page 38: The linear trends for width have negative slopes. Is the width decreasing in the downstream direction and why?

Given that the trends are a function of distance, starting downstream, the negative sign indicates a slight narrowing in the upstream direction, or widening in the downstream direction, depending on orientation.

23. Page 46. The R2 values are fairly low for the plot and the residuals don't look randomly distributed (no values in the Z = -1.5, Wj = 1.5 range).

No response required.

Technical Corrections:

1. Page 4, line 18: comma after "discharge"

Corrected as recommended.

2. Page 4, line 20: hyphenate "riffle-pool couplet" here and elsewhere.

Corrected as recommended.

3. Page 5, line 8: Comma after "perspective"

Corrected as recommended.

4. Page 20, line 10: comma after "riffle"
This entire section has been rewritten to be more concise per earlier comment.

5. Page 29, line 5: comma after "example"
Corrected as recommended.

6. Page 42: The letter headings should be lower case in the figure to match the captions.
Corrected as recommended.

7. Page 43: The stations on the aerial map and plot do not seem to match exactly. The map begins at approximately 100 and end at 1600. The plots begin at 300 and end at 1700. It is not clear why? A similar issue is evident in Figure 5.

We were using varying sample pathways in this submission, but have since revised the analysis using a common sample pathway. This should be much clearer in the revised manuscript.

References

Dietrich W, Smith J, Dunne T. 1979. Flow and Sediment Transport in a Sand Bedded Meander. The Journal of Geology 87:3, 305-315.

Jackson JR, Pasternack GB, Wyrick JR. 2013. Substrate of the Lower Yuba River. Prepared for the Yuba Accord River Management Team. University of California,Davis.

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Wolman MG, Miller JP. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68:1, 54-74.

Yu B, Wolman, MG. 1987.Ssome dynamic aspects of river geometry. Water Resources Research 23: 3, 501–509. doi:10.1029/wr023i003p00501.

Table 1. Median grain size classes at the reach scale and morphologic unit scale for channel bars in the study reach. Note that because the data is only to the nearest 10% and because it is a median calculation, the data do not necessary sum to100%. See Jackson et al., 2013 for more information.

		Reach scale	**Morphologic unit scale**		
Substrate category	**Size class**	**Percentage**	**Medial bar**	**Lateral bar**	**Point bar**
Silt/clay	<0.0625 mm	0	0	0	0
Sand	0.0625 – 2 mm	0	0	0	0
Fine gravel	2-32 mm	0	20	10	10
Small cobble/medium gravel	32 – 90 mm	20	40	30	30
Cobble	90 - 128 mm	30	30	30	30
Large cobble	128-256 mm	30	0	10	10
Boulder	>256 mm	20	0	0	0

~~Analyzing bed~~Bed and width oscillations form coherent patterns in a ~~self-maintained~~partially confined, regulated gravel-cobble bedded river ~~using geomorphic covariance structures~~adjusting to anthropogenic disturbances

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Abstract

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This paper demonstrates a relatively new method of analysis for stage~~-~~-dependent patterns in meter-scale resolution river ~~DEMs~~digital elevation models, termed geomorphic covariance structures (GCSs). A GCS is a ~~univariate and/or~~ bivariate spatial relationship amongst or between variables along a pathway in a river corridor. It is not a single metric as in statistical covariance, but a spatial series, and hence can capture geomorphic structure. Variables assessed can be flow~~-~~-independent measures of topography (e.g., bed elevation, centerline curvature, and cross section asymmetry) and sediment size as well as flow~~-~~-dependent hydraulics (e.g., top width, depth, velocity, and shear stress; Brown, 2014), topographic change, and biotic variables (e.g., biomass and habitat utilization). The GCS analysis is used to understand if and how ~~the covariance of~~ bed elevation and flow-dependent channel top width are organized in a partially confined, incising gravel-cobbled bed river with multiple spatial scales of anthropogenic and natural landform heterogeneity across a range of discharges through a suite of spatial series analyses on 6.4 km of the lower Yuba River in California, USA. A key conclusion is that the test river exhibited positively ~~covarying and quasi-periodic~~ covaring oscillations of bed elevation and channel width ~~that had a unique response to discharge as supported by several tests. As discharge increased, the amount of positively covarying values of bed elevation and flow-dependent channel top width increased up until the 1.5 and 2.5 year annual recurrence flow and then decreased at the 5 year flow before stabilizing for higher~~across all flows~~.~~ analyzed. These covarying oscillations ~~are~~were found to be quasi-periodic at channel forming flows, scaling with the length scales of pools~~, bars,~~ and ~~valley oscillations.~~riffles. Thus~~,~~ it ~~is thought that~~

~~partially confined gravel-cobble bedded~~ appears that alluvial rivers organize their ~~adjustable~~ topography ~~with a preference for covarying and quasi-periodic bed and width undulations at channel forming flows due~~ to ~~both local bar-pool mechanisms and non alluvial topographic controls~~have oscillating shallow and wide and narrow and deep cross section geometry, even despite ongoing incision.

1. Introduction

Understanding the spatial organization of river systems in light of natural and anthropogenic change is extremely important, because it can provide information to assess, manage and restore them to ameliorate worldwide freshwater fauna declines (Frissell et al., 1986; Richter et al., 1997). Alluvial rivers found in transitional upland-lowland environments with slopes ~~ranging from 0.005 to~~< 0.02 and median diameter bed sediments ranging from 8 to 256 mm can exhibit scale dependent organization of their bed sediments (Milne, 1982), bed elevation profile (Madej, 2001), cross section geometry (Rayberg and Neave, 2008) and morphological units (~~Wyrick~~Keller and ~~Pasternack, 2014).~~ Melhorn, 1978; Thomson et al., 2001). For these ~~types of river channels~~rivers a plethora of studies spanning analytical, empirical and numerical domains suggest that at channel-forming flows there is a ~~preference~~tendency for ~~positively~~ covarying bankfull bed and width undulations amongst morphologic units such as pools and riffles~~.~~ (Brown et al., 2016). That is, relatively wide areas have higher relative bed elevations and ~~the converse~~relatively narrow areas have lower relative bed elevations. While covarying bed and width undulations have been evaluated in field studies using cross section data (Richards, 1976a,b), in models of sediment transport and water flow (Repetto and Tubino, 2001), flume studies (Nelson et al., 2015) and in theoretical treatments (Huang et al., 2004), this idea has never been evaluated in a ~~self-maintained bankfull~~morphologically dynamic river ~~channel~~ corridor for which a meter-scale digital elevation model is available across a wide range of discharges, from a fraction of to orders of magnitude more than bankfull. The ~~focus~~purpose of this paper is twofold. First, ~~we aim~~it aims to demonstrate how meter-scale resolution topography can be analyzed with hydraulic model outputs to generate flow dependent geomorphic covariance structures (GCS) of bed elevation and wetted width.~~-~~ We developed this new term in recent articles (Brown et al., 2014; Brown and Pasternack, 2014; Brown et al., 2016) as a result of the growing importance of understanding the variability of rivers as a first-order control on their dynamics. A GCS is ~~a univariate and/or bivariate spatial relationship amongst or~~not the statistical metric known as covariance, which summarizes the relation between two series in one number, but is instead a spatial series created from the product of two any detrended and standardized geomorphic variables computed or measured along a pathway in a river corridor. Variables ~~assessed~~used in a GCS can be flow~~-~~-independent measures of topography (e.g., bed elevation, centerline curvature, and cross section asymmetry) and sediment size, as well as flow~~-~~-dependent hydraulics (e.g., top width, depth, velocity, and shear stress; Brown, 2014), topographic change, and biotic variables (e.g., biomass and habitat utilization).

Second, we aim to use these methods and concepts to understand if and how bed elevation and flow-dependent channel width are organized in a partially confined, incising, regulated gravel-cobbled bed river with multiple spatial scales of landform heterogeneity across a range of discharges~~through a suite of spatial series analyses on 9 km of the lower Yuba River (LYR) in California, USA~~. The analysis of geometric organization was accomplished through a suite of spatial series analyses using a 9-km reach of the lower Yuba River (LYR) in California, USA as a testbed. Our central hypothesis is that the test river reach will exhibit positively covarying and quasi periodic bed and width oscillations, and that due to river corridor heterogeneity and antecedent flow conditions these patterns may be dominant in a range of channel forming flows. Knowledge of spatial patterning is commonly used to infer the geomorphic processes that yielded that patterning (Davis, 1909; Thornbury, 1954) and/or what future processes will be driven by the current spatial structure of landforms (Leopold and Maddock, 1953; Schumm, 1971; Brown and Pasternack, 2014). However, such inferences rarely include transparent, objective spatial analysis of topographic structure, so this study provides a new concept and methodology accessible to most practitioners to substantiate the ideas behind the process-morphology linkages they envision to be driven by variability in topography.

1.1 Background

A multitude of numerical, field, and theoretical studies have shown that gravel bed rivers have covarying oscillations between bed elevation and channel width related to riffle-pool maintenance. The joint periodicity in oscillating thalweg and bankfull width series for pool-riffle sequences in gravel bed rivers was ~~first~~ identified by Richards (1976b) who noted that riffles have widths that are ~~greater~~ on average greater than those of pools, and he attributed this to flow deflection over riffles into the channel banks. Since then, many studies related to ~~bar~~processes that rejuvenate or maintain the relief between bars and ~~pool~~ pools (i.e., “maintenance” or “self-maintenance”) have implied a specific spatial ~~covariance~~correlation of width and depth between the pool and riffle at the bankfull or channel forming discharge (Wilkinson et al. 2004; MacWilliams et al., 2006; Caamano et al., 2009; Thompson, 2010). For example, Caamano et al. (2009) derived a criterion for the occurrence of a mean reversal in velocity (Keller, 1971) that implies a specific ~~covariance~~correlation of the channel geometry of alluvial channels with undulating bed profiles. ~~For~~ Specifically, for a reversal in mean velocity at the bankfull or channel forming discharge (holding substrate composition constant), the riffle must be wider than the pool and the width variation should be greater than the depth variation between the riffle and residual pool depth. Milan et al. (2001) evaluated several riffle~~-~~-pool couplets, from a base flow to just over the bankfull discharge. They found that convergence and reversals in section-averaged velocity and shear stress were complex and non-uniform, which suggests that different morphologic units may be maintained at different discharges. Wilkinson et al. (2004) explicitly showed that phase shifts in shear stress from the riffle to the pool between high and low discharge required positively covarying bed and width undulations. White et al. (2010) showed how valley width oscillations influence riffle persistence despite larger channel altering floods and interdecadal valley incision. Sawyer et al (2010) used two-dimensional (2D) hydrodynamic modeling and digital elevation model (DEM) differencing to illustrate how variations in wetted width and bed elevation can modulate regions of peak velocity and channel change at a pool-riffle-run sequence across a range of discharges from 0.15 to

7.6 times bankfull discharge. DeAlmeida and ~~Rodriquez~~Rodriguez (2012) used a 1D morphodynamic model to ~~recreate~~ explore the evolution of riffle-pool bedforms ~~after removing the initial~~from an initially flat bed, while maintaining the channel width variability. The resulting simulations had close agreement to the actual bed profile ~~and using the width profile, showing~~in their model. Thus, their study is another example that channel width can exert controls on the structure of the bed profile. The flows at which the above processes are modulated vary in the literature.

From a system perspective, bed and width undulations, both jointly and in isolation, ~~have been suggested to be~~are a means of self-adjustment in alluvial channels that minimize the time rate of potential energy expenditure per unit mass of water in accordance with the law of least time rate of energy expenditure (Langbein and Leopold, 1962; Yang, 1971; Cherkauer, 1973; Wohl et al., 1999). For bed profiles, Yang (1971) and Cherkauer (1973) showed that undulating bed relief is a preferred configuration of alluvial channels that minimize the time rate of potential energy expenditure. Using field, flume, and numerical methods Wohl et al. (1999) showed that valley wall oscillations also act to regulate flow energy analogous to bedforms. In analyzing reach scale energy constraints on river behavior Huang et al. (2004) quantitatively showed that wide~~ and ~~/shallow sections and deep~~ and ~~/narrow ~~channels~~sections are two end member cross sectional configurations necessary for efficiently expending excess energy for rivers, so these two types of cross sections imply covarying bed and width undulations as a means of expending excess energy. Therefore the above studies suggest that both bed and width oscillations are a means to optimize channel geometry for the dissipation of excess flow energy. The question now is the extent to which this well-developed theory plays out in real rivers, especially now that meter-scale river DEMs are available.

~~Many of the studies discussed above have shown the presence and geomorphic role of positively covarying bed and width undulations for a limited range of discharges, rarely above bankfull discharge.~~Flows that drive channel maintenance in Western U.S. rivers, such as the test river (described in detail in Section 3 below), are thought to typically have annual recurrence intervals ranging from 1.2 to 5 years (Williams,1978; Andrews, 1980; Nolan et al., 1987). Most of the literature investigating riffle-pool maintenance discussed above report bedform sustaining flow reversals occurring at or near bankfull, often with no specificity to the frequency of these events (Lisle, 1979; Wilkinson et al., 2004). Studies that do report recurrence intervals have ranged from the 1.2 to 7.7 year recurrence flows (Keller, 1971; Sawyer et al., 2010). However, many rivers exhibit multiple scales of freely formed and forced landscape heterogeneity that should influence fluvial geomorphology when the flow interacts with them, no matter the magnitude (Church, 2006; Gangodagamage et al., 2007). For example, Strom and Pasternack (2016) showed that the geomorphic setting can influence the stage at which reversals in peak velocity occur. In their study an unconfined anastomizing reach experienced velocity reversals at flows ranging from 1.5 to 2.5 year recurrence flows, compared to 2.5 to 4.7 year recurrence flows for a valley-confined reach. Given that ~~positive bed and width undulations can control channel maintenance at and near bankfull discharge, it is hypothesized that it could also do so at other discharges, as other~~ river geometry can record memory from past floods (Yu and Wolman, 1987), and the presence of multiple layers of topographic ~~features are activated with increasing~~

~~discharge~~variability (Brown and Pasternack, 2014~~). However, in river corridors a more complete understanding of form, and ultimately process, can ~~), it is hypothesized that covarying bed and width undulations could also be ~~gleamed from considering how landforms steer water at different flows (Brown and Pasternack, 2014). Traditional geomorphometry relies on analyzing landform topography in the absence of water flow (Pike et al., 2008). The coupling of meter-scale topography with commensurate hydraulic models (see the Supplemental Materials) is thought of as advancement to geomorphometry. Given the increasing abundance of remotely sensed data for alluvial rivers, and the ability to model large segments of entire river corridors, this could be an important tool for land managers to understand the topographic structure of river corridors.~~present at discharges other than bankfull.

1.2 Study Objectives

This study sought to evaluate the longitudinal geomorphic covariance structure of bed ~~and~~elevation and flow-dependent width undulations in a river valley for a wide range of discharges above and below the bankfull discharge– a breadth never evaluated before. The primary goal of this study was to determine if there are covarying bed and width oscillations in an incising gravel/cobble river, if they exhibit any periodicity, and ~~whether they vary with discharge.~~ how they vary with discharge. Based on the literature review above, the expectation is that a quasi-oscillatory positive GCSs should exist, with the strongest relationship occurring for a broad range of channel forming flows. A secondary objective is to demonstrate how geomorphic covariance structures for bed and wetted width can be generated from high-resolution topography and hydraulic models. Note that neither objective involves a direct or indirect test of whether GCSs in fact explain past morphodynamic change that formed the current pattern or predict future changes driven by the current GCS. Before a study like that is attempted for a natural alluvial river, it is first necessary to evaluate if such a river even has coherent, self-organized GCSs. Thus, this study investigates the spatial structure of topographic variance in a river from base flow through large flood flows in its own right as the sensible first step.

The study site was a 6.4-km section of the lower Yuba River (LYR), an incising and partially confined self-formed gravel-cobble bedded river (Figure 1; described in Section 3). Several statistical tests were used on the serial ~~covariance~~correlation of minimum bed elevation, Z, channel top width, W^j,and their geomorphic covariance structure, $C(Z,W^j$~~) ,~~), where ~~i~~j indexes the ~~spatial position and j notes the~~ flow discharge. The novelty of this study is that it provides the first assessment of ~~flow-dependent bed and width covariance~~ $C(Z,W^j)$ in a partially confined, self-maintained alluvial river across a wide array of flows. The broader impact is that it provides a framework for analyzing the flow dependent topographic variability of river corridors, without differentiating between discrete landforms such as riffles and pools. Further, an understanding of the flow dependent spatial structure of bed and width GCS would be useful in assessing their utility in applied river corridor analysis and synthesis for river engineering, management and restoration.

2. Experimental Design

~~To evaluate covarying bed and width undulations~~This study aimed to deconstruct and reveal the coherent topographic structure of a heterogeneous river valley as it existed at the moment of its mapping. This understanding ought to inform both how the river arrived at this condition as well as how it might change into the future, but this study does not involve analysis of morphodynamic change to directly seek such linkages. To evaluate co-varying bed and width undulations, the concepts and methods of geomorphic covariance structures (GCSs) were used (Brown, 2014; Brown and Pasternack, 2014).~~ GCSs are univariate and/or bivariate spatial relationships amongst or between variables along a pathway in a river corridor. Variables assessed can be flow independent measures of topography (e.g., bed elevation, centerline curvature, and cross section asymmetry) and sediment size as well as flow dependent hydraulics (e.g., top width, depth, velocity, and shear stress; Brown, 2014), topographic change, and biotic variables (e.g., biomass and habitat utilization). Calculation of a GCS from paired series is relatively~~ Calculation of a GCS from paired spatial series is straightforward by the cross product $x_{std,i} * y_{std,i,}$ where the subscript std refers to standardized and possibly detrended values of two variables x and y at location i along the centerline, creating the serial data set ~~of covariance,~~ $C(X,Y)$. Since this study is concerned with bed and flow dependent top width undulations, the GCS at each flow j is denoted as $C(Z,W^{j})$. More information on GCS theory is provided in section 4.2 below.

GCS series were generated for eight flows ranging from 8.50 to 3,126 m^3/s, spanning a broad range of flow frequency (**Error! Reference source not found.**). The range of selected flows spans a low flow condition up to the flow of the last large flood in the river.-These flows were selected to provide enough resolution to glean flow-dependent effects, while not producing redundant results.

The first question this study sought to answer was if there was a preferencetendency for $C(Z, W^j)$ to positively covary and how it changed with discharge. To analyze this a histogram was generated for each flow dependent series of $C(Z, W^j)$ that was stratified by the signs of bed elevation, Z, and wetted width, W^j to see if there was a preferencetendency for positive $C(Z, W^j$).), and how that changed with flow The second question was whether $C(Z, W^j)$ was random, constant, periodic or quasi-periodic. Quasi-periodicity in this setting is defined as a series with periodic and random components, as opposed to purely random or purely periodic (Richards, 1976a). Quasi-periodicity differs from periodic series in that the there are elements of randomness blended in (Newland, 1993). To answer this question autocorrelation function (ACF) and power spectral density (PSD) analyses of each $C(Z, W^j)$ series were used to. These determine if there were quasi-periodic length scales thatat which $C(Z, W^j)$ covary and how that changes with discharge.

Based on the studies listed above (Section 1.1), we hypothesize that theregravel-cobble bedded rivers capable of rejuvenating their riffle-pool relief should beexhibit a preferencetopography (at any instant in time) with a tendency for positively covarying residuals of positivel $C(Z, W^j)$ for discharges with annual recurrence intervals from 1.25-5 years (Williams, 1978; Andrews, 1980; Nolan et al., 1987), but other complex responses are possible. GCS. The basis for quasi-periodic and positive $C(Z, W^j)$ is founded on the idea that, on average, channel geometry is maintained during bankfull (e.g. geometric bankfull) discharge (Williams, 1978) and that locally channels are shaped by riffle-pool maintenance mechanisms (Wilkinson et al. 2004; MacWilliams et al., 2006; Caamano et al., 2009; Thompson, 2010). Thus, with changesBased on the

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literature reviewed in ~~flow~~Section 1.1 we hypothesize that the ~~residuals of the~~ $C(Z,W^j)$ GCS will, on average, become more positive with increasing flow until approximately the bankfull discharge, where the channel overtops its banks and non-alluvial floodplain features exert control on cross-sectional mean hydraulics. At that point there may not be a ~~preference for positive or negative residuals. With this logic, it's hypothesized that the $C(Z,W^j)$ GCS will be quasi-periodic for flows at and below~~tendency for positive or negative residuals, if the topographic controls at that flood stage are not important enough to control channel morphology. For example, smaller events might occur frequently enough to erase the in-channel effects of the large infrequent events, especially in a temperate climate (Wolman and Gerson, 1978). On the other hand, if a system is dominated by the legacy of a massive historical flood and lacks the capability to recover under more frequent floods, then the $C(Z,W^j)$ GCS will continue to increase until the discharge that carved out the existent covarying bed and width oscillations for the current topography is revealed. Note that we do not expect a clear threshold where organization in the $C(Z,W^j)$ GCS is a maximum, but rather a range of flows near the bankfull discharge. Given that the effect of a particular flow on a channel is dependent not just on that flow, but the history of flow conditions that led to the channel's condition (Yu and Wolman, 1987). Therefore, it should not be expected that the observed patterns will be associated with a singular flow value. Also, this study looked at a river in a Mediterranean climate, and thus it may be more prone to exhibiting a wider range of positive $C(Z,W^j)$ GCS than a temperate or tropical river, as the number and frequency of recovery processes is reduced (Wolman and Gerson, 1978). With this logic, it's hypothesized that the $C(Z,W^j)$ GCS will be quasi-periodic for flows near the bankfull discharge, due to the presence of bar and pool topography, and that the ACF and PSD will yield length scales commensurate with the average spacing of these topographic features. For flows above the bankfull discharge~~ it is unknown how length scales will change, necessitating this study.~~, a river corridor has many local alluvial landforms, bedrock outcrops and artificial structures on its floodplain and terraces. These features influence bed adjustment during floods that engage them, and hence impact the GCS. It is unknown how GCS length scales will change in response to the topographic steering these features induce causing changes to bed elevation, but investigating that is a novel and important aspect of this study. In addition to performing these tests we also present two ~ 1.4-km sections of the $C(Z, W^j)$ GCS, Z, W ~~andthe~~and the detrended topography for three representative flows to discuss specific examples of how these patterns change with landforms in the river corridor across a wide array of discharges.

Limitations to this study (but not the GCS approach) for worldwide generalization include not considering other variables relevant to how alluvial ~~river~~rivers adjust their shape, such as grain size, channel curvature and vegetation, to name a few. Some of these limitations were not study oversights, but reflected the reality that the study reach used had relatively homogenous sediments (Jackson et al., 2013), low sinuosity, and limited vegetation (Abu-Aly et al., 2014). This yielded an ideal setting to determine how much order was present for just bed elevation and channel width, but does not disregard the importance of these other controls, which can be addressed in future studies at suitable sites. Also, this study is not a direct test of the response to or drivers of morphodynamic change. The extent to which GCS can be used as an indicator of change to greatly simply geomorphic analysis instead of doing morphodynamic

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modeling remains unknown, but finding metrics that link landforms, the agent that shape them, and the responses they induce has always been the goal of geomorphology (Davis, 1909).

3. Study Area

3.1 River context

The study sitearea was the 6.4-km reach of the Timbuctoo Bend located onReach of the Lowerlower Yuba River (LYR) in northeastern California, USA. (The LYR The reach begins at the outlet of a bedrock canyon that is an incisingdammed ~ 3-km upstream, and partiallythe watershed above the dam drains 3480 km^2 of dry summer subtropical mountains. Little is known about the pre-European Yuba River, but the alluvial river in this reach is confined gravel-cobble bedded river by valley hillsides and bedrock outcrops, and these are evident in some photos from early European settlers panning the river for gold in the late 1840s. During the mid to late 19th century there was a period of extensive hydraulic gold mining of hillside alluvial deposits in the upper Yuba watershed that delivered an overwhelming load of heterogeneous sediment to the lowland river valley (James et al., 2009). Geomorphologist G. K. Gilbert photo documented the LYR around the time of its worst condition in the early 20th century and provided foundational thinking related to how the river would evolve in time (Gilbert, 1917). In 1941 Englebright Dam was built to hold back further sediment export from the mountains, and that allowed the river valley to begin a process of natural recovery, which was reviewed by Adler (1980) and more recently by Ghoshal et al. (2010). However, this process was interfered with a mixture of alluvial channel patterns ranging from weakly anabranching to meandering. Forby widespread dredger mining in the early to mid 20th century. In two locations of the study area the average slope,reach there are wide relict dredger tailings piles on the inside of the two uppermost meander bends that the river has been gradually eroding.

The hydrology of the regulated LYR is complex and quite different from the usual story of significantly curtailed flows below a large dam. Englebright Dam primarily serves as a sediment barrier and it is kept nearly full. As a result, it is operated to overtop when outflow is > 127.4 m^3/s long enough to fill its small remaining capacity, so flood hydrology is still seasonal and driven by rainfall and snowmelt in the watershed. Two of three sub catchments do not have large dams, so winter floods and spring snowmelt commonly cause spill over Englebright sufficient to exceed the bankfull width to depth ratio at bankfull, sinuosity, and mean grain size were 2%, 82,channel in Timbuctoo Bend. The one regulated sub catchment does have a large dam, New Bullards Bar (closed in 1970), and this reduces the frequency and duration of floodplain inundation compared to the pre-dam record (Escobar-Arias and Pasternack, 2011; Cienciala and Pasternack, in press), but not like other rivers where the entire upstream watershed is regulated. Sawyer et al. (2010) reported the 1.1, and 164 mm, respectively (5 year recurrence interval for the post Englebright, pre New Bullards Bar period as 328.5 m^3/s and then for post New Bullards Bar as 159.2 m^3/s. California has long been known to exhibit a roughly decadal return period for societally important major floods that change river courses (Guinn, 1890), though the magnitude of those floods is not necessarily a 10-year recurrence interval scientifically. Since major flow regulation in 1970, the three largest peak annual daily floods came roughly 10 years apart, in the

1986, 1997, and 2006 water years. The flood of 1997 was the largest of the post-dam record. The 2006 peak flood event had a recorded peak 15-minute discharge of 3126.2 m^3/s entering the study reach.

Wyrick and Pasternack~~, ~~ (2012~~). Vegetated cover of the river corridor ranged from 0.8-8.1% of the total wetted area at each flow, with more inundated vegetation at higher flows.The flows~~) analyzed ~~in this study ranged from 8.50 to 3,126 m^3/s, and their recurrence intervals are shown in . Wyrick and Pasternack (2012) analyzed~~LYR inundation patterns in a high-resolution DEM of the river ~~corridor as~~produced after the 2006 wet season, and they considered how channel and floodplain shapes change dramatically through the study reach. Their findings apply to the Timbuctoo Bend Reach. Different locations ~~exhibit~~exhibited spillage out of the channel into low-lying peripheral swales and onto lateral and point bars at flows from ~ ~~28.32~~84.95-141.6 m^3/s. When the water stage rises to 141.6 m^3/s, relatively flat active bar tops become inundated and ~~it lines~~the wetted extents line up with the base of willows along steeper banks flanking the channel~~ where it is well defined~~. These and other field indicators led to the consideration of 141.6 m^3/s as representative of the bankfull discharge adjusted to the modern regulated flow regime since 1970. By a flow of 198.2 m^3/s, banks are all submerged and water is spilling out to various degrees onto the floodplain. The floodplain is considered fully inundated when the discharge reaches 597.5 m^3/s. Above that flow stage exist some terraces, bedrock outcrops, and soil-mantled hillsides that become inundated. ~~In~~For the two ~~locations there are wide ~~relict dredger tailings piles ~~on the inside of the two uppermost meander bends that the river has been gradually eroding and that~~mentioned earlier, they interact with the flows ranging from 597.5-1,195

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m^3/s. Apart from these piles, the flow width interacts predominately with the valley walls for discharges at 1,195 m^3/s and above. Given the estimate of bankfull discharge for the LYR, the instantaneous peak flow during the 2006 flood was ~ 23 times that, so quite substantial compared to those commonly investigated in modern geomorphic studies.

Historically the LYR was impacted by hydraulic gold mining in the late 1800's and dam construction in the mid 1900's. Mining sediments initially overwhelmed the river corridor (James, 2009), but dam construction to retain sediment blocked further upstream input and lessened this impact over time as the river gradually has incised into these deposits (Adler, 1980; Carley et al., 2010). Despite these impacts the LYR still experiences significant channel changing flood flows (Carley et al., 2010; Brown and Pasternack, 2014), as two of three sub catchments do not have large dams. Englebright Dam, located approximately 3 km upstream of the study area is kept nearly full and overtops when outflow is > 127.4 m^3/s, so flood hydrology is still seasonal and driven by rainfall and snowmelt.

Several existing studies can help put the study section into its hydrogeomorphic context. White et al. (2010) used aerial photography and a qualitative analysis of repeat long profiles and valley width series in a valley confined reach to conclude that valley width oscillations controlled longitudinal riffle locations for several decades even as the reach incised dramatically. Sawyer et al. (2010) found that one of the riffles in this reach experienced flow convergence routing between baseflow, bankfull flow, and a flow of ~8 times bankfull discharge that maintained riffle relief. More recently the entire LYR was studied with ~0.5-5 m resolution for geomorphic change detection (Carley et al, 2010), morphological unit mapping (Wyrick and Pasternack, 2012, 2014), and the role of spatially distributed vegetative roughness on flood hydraulics, as simulated using a two-dimensional (2D) hydrodynamic model (Abu-Aly et al., 2013). This study builds on these in several ways. First, this study directly evaluates the relationship between bed elevation and flow width for a range of discharges, which furthers and improves upon the study by White et al (2010) that did not assess stage dependence nor perform rigorous quantitative tests. Second, this study uses 2D-model-derived wetted width outputs from the LYR 2D model of Abu-Aly et al. (2013) and thus advances what one can gleam from such data sets. Further, morphological unit mapping by Wyrick and Pasternack (2012, 2014) is used to contextualize length scales (and thus frequency) associated with pool, riffle, and point bars. Not all morphological units are associated with only lateral and vertical undulations of channel topography, but pool, riffle, and point bar spacing's were thought to be useful in contextualizing length scales for the ACF and PSD analysis. Finally, this study evaluates the organization of channel geometry in light of a study that quantified the magnitude and extent of statistically significant channel change for the entire lower Yuba River (Carley et al., 2012). The overall response was dictated by knickpoint migration, bank erosion and overbank deposition processes. They found there was a decreasing trend of mean vertical incision rates, ranging from approximately -15 cm/yr at the upper limit of this study to almost none at the lower limit, showing that upstream knickpoint migration is driving channel change (e.g. Fig. 11 in Carley et al., 2010). Overall these studies show that the river corridor is still adjusting to upstream sediment regulation (Carley et al., 2010), yet sites have achieved self-maintenance of persistent topographic forms (Saywer et al., 2010; White et al., 2010) and exhibit a highly diverse assemblage of fluvial landforms

(Wyrick and Pasternack, 2014).

3.2 Timbuctoo Bend details

A lot is known about the geomorphology of Timbuctoo Bend, and this information helps inform this study to substantiate the possibility that the river's topography is organized in response to differential topographic steering as a function of flow stage. According to Wyrick and Pasternack (2012), the reach has a mean bed slope of 0.2%, a thalweg length of 6337 m, a mean bankfull width of 84 m, a mean floodway width of 134 m, an entrenchment ratio of 2.1 (defined per Rosgen, 1996), and a weighted mean substrate size of 164 mm. Using the system of Rosgen (1996), it classifies as a B3c stream, indicating moderate entrenchment and bed slope with cobble channel material. A study of morphological units revealed that its base flow channel area consists of 20% pool, 18% riffle, and then a mix of six other landform types. More than half of the area of the riverbank ecotone inundated between base flow and bankfull flow is composed of lateral bars, with the remaining area containing roughly similar areas of point bars, medial bars, and swales (Wyrick and Pasternack, 2012). A study of bankfull channel substrates found that they are differentiated by morphological unit type, but the median size of all units is in the cobble range (Jackson et al., 2013)– even depositional bars, which are often thought of as relatively fine in other contexts. Vegetated cover of the river corridor ranged from 0.8 to 8.1% of the total wetted area at each flow, with more inundated vegetation at higher flows.

White et al. (2010) used a sequence of historical aerial photos, wetted channel polygons, repeat long profiles from 1999 and 2006, and a valley width series to conclude that even though Timbuctoo Bend has incised significantly since 1942 in response to many floods, there are several riffles and pools that persist in the same wide valley locations, suggesting that valley width oscillations maintain those positions and drive morphodynamic response. This suggests that it wouldn't matter exactly which instant's topography one might analyze to look at the effect of topographic variability in controlling or responding to large flood processes, as they all should reflect the same topographic steering regime induced by the valley walls.

Two studies have been done to look at the hydraulic processes associated with different flood stages in Timbuctoo Bend. Sawyer et al. (2010) found that one of the pool-riffle-run units in this reach experienced flow convergence routing between baseflow, bankfull flow, and a flow of roughly eight times bankfull discharge that maintained riffle relief. Strom et al. (2016) assessed the hydraulics of the whole reach over the same range of flows in this study, and they reported that the reach exhibits a diversity of stage-dependent shifts in the locations and sizes of patches of peak velocity. The spatial persistence of such patches decreased with discharge until flows exceeded ~ 1000 m^3/s, at which point valley walls sustained their location for flows up to the peak of 3,126 m^3/s. Also, peak-velocity patches resided preferentially over chute and riffle landforms at within-bank flows, several morphological unit types landforms for small floods, and pools for floods > 1000 m^3/s. These studies corroborate the process inferences made by White et al. (2010) in that hydraulics were found to be stage-dependent in ways that were consistent with the mechanism of flow convergence routing.

Finally, Carley et al. (2012), Wyrick and Pasternack (2015), and Pasternack and

Wyrick (in press) used DEM differencing, uncertainty analysis, scale-stratified sediment budgeting, and topographic change classification to analyze how the LYR changed from 1999-2008, including Timbuctoo Bend. These studies took advantage of the repeated mapping of the LYR in 1999 and 2006-2008, with Timbuctoo Bend mapped entirely in 2006. They found large amounts of erosion and deposition, strong differential rates of change among different landforms at three spatial scales, and topographic changes driven by 19 different geomorphic processes. For Timbuctoo Bend, the dominant topographic change processes found were in-channel downcutting (including knickpoint migration) and overbank (i.e., floodplain) scour, with noncohesive bank migration a distant third. Thus, the river appears to change through adjustments to its bed elevation far more than changes to its width in this reach. This finding will come into play in interpreting the results of this study later on.

In summary, even with modern technology it is impossible to monitor the hydrogeomorphic mechanics of fluvial change in a large river for flows up to 22 times bankfull discharge, so recent studies have tried to get at the mechanisms during such events with a range of strategies. Historical river analysis, hydrodynamic modeling, and topographic change detection and analysis have been used together to reveal a picture of a river that is changing in response to multiple scales of landform heterogeneity that drive topographic steering. Even though the river has changed through time, there has been a persistence of nested landforms, and thus it would be useful to understand how topographic features are organized purely through an analysis of the DEM per the methods developed in this study. This study exclusively uses the 2006 map made during the dry season that followed the dramatic 2006 wet season, which included the large flood, two other notable peaks, and a total of 18 days of floodplain filling flow Thus it addresses the topography as it existed after that river-altering wet season and how it will in turn influence the dynamics of the next one.

4. Methods

To test the study hypotheses regarding the potential existence of geomorphic covariance structures, Z~~,~~ and ~~W_i^j~~W^j series were extracted from the meter-scale topographic map of ~~the Lower Yuba River~~Timbuctoo Bend produced from ~~airborne LiDAR,~~ echosounder~~,~~ and robotic total station ground surveys (Carley et al., 2012; see Supplemental Materials). A meter-scale 2D hydrodynamic model was used to generate data sets for wetted width for each discharge. Details about the 2D model are documented in the Supplemental Materials and previous publications (Abu-Aly et al., 2013; Wyrick and Pasternack, 2014; Pasternack et al., 2014); it was thoroughly validated for velocity vector and water surface elevation metrics, yielding outcomes on par or better than other publications using 2D models.

4.1 Data Extraction

A first step was to extract minimum bed elevation and top width spatial series from the digital elevation model and 2D model outputs. This required having a sample pathway along which bed elevation could be extracted from the DEM and top width from the wetted extents from the 2D model. Sampling river widths was done using cross sections~~ that are~~ generated at even intervals perpendicular to the sample pathway and then clipped to the 2D model derived wetted ~~extents~~extent for each flow. Because of this, the pathway selected can have a significant bearing on whether or not sample sections represent downstream oriented flow or overlap where pathway curvature is high. There are several options in developing an appropriate pathway for sampling the river corridor. The thalweg is commonly used in flow-independent geomorphic studies, but ~~since there are sub-channel-width forced scour holes adjacent to local bedrock outcrops,~~ the thalweg is too tortuous within the channel to adhere to a reasonable definition of top width. Further, as flow increases, central flow ~~path~~pathway deviates from the deepest part of the channel due to higher flow momentum and topographic steering from submerged and partially submerged topography (Abu-Aly et al., 2014). Therefore, in this study we manually developed flow-dependent sample pathways using 2D model hydraulic outputs of depth, velocity and wetted area. The effect of having different sample pathways for each flow is that it accounts for flow steering by topographic features in the river corridor. ~~Some sample pathways were similar, as inundation extents were governed by similar topographic features. Namely, 283.2 and 597.5 m^3/s were very similar, as were 2,390 and 3,126 m^3/s. Since each sample pathway was flow dependent, the lengths decreased with discharge, as features that steer flow at lower discharges can be submerged at higher discharges. This is in line with theories of maximum flow efficiency in rivers (Huang et al., 2004), and broader concepts such as constructal theory for the design of natural systems (Bejan and Lorente,2010).~~

For each flow a ~~conveyance~~ grid of flow momentum $(d_i * v_i^2)$ was generated in ARCGIS®, where d_i is the depth and v_i is the velocity at node i in the 2D model hydraulics rasters. Then a sample pathway was manually digitized using the

~~conveyance~~momentum grid, following the path of greatest ~~conveyance~~momentum. For flow splits around islands, if the magnitude of ~~conveyance~~momentum in one channel was more than twice as great as the other it was chosen as the main pathway. If they were approximately equal then the pathway was centered between the split. Once a sample pathway was developed it was then smoothed using a Bezier curve approach over a range of 100 m, or approximately a bankfull channel width to help further minimize section overlaps. ~~Still there are some~~ For each sample pathway cross sections were generated at 5 m intervals and clipped to the wetted extent of each flow, with any partially disconnected backwater or non downstream oriented areas manually removed.

Despite smoothing there were areas of the river where the river has relatively high curvature in the sample pathway causing sample section overlaps to occur. These were manually edited by visually comparing the sample sections with the ~~conveyance~~momentum grid and removing overlapped sections that did not follow the downstream flow of water. This was more prevalent at the lower discharges than the higher ones due to the effects topographic steering creating more variable sample pathways. ~~After overlaps were removed, the data was linearly interpolated between the remaining sections to match the original sampling frequency. Before sections were clipped to the wetted extents, any backwater or non downstream oriented areas were removed.~~

To provide a constant frame of spatial reference for comparison of results between flows, while preserving flow-dependent widths, sections were mapped to the lowest flow's sample pathway using the spatial join function in ARCGIS®. The lowest flow was used, because that had the longest path. This insures no multiple-to-one averaging of data would happen, as that would otherwise occur if data were mapped from longer paths to shorter ones. To create evenly spaced spatial series the data was linearly interpolated to match the original sampling frequency of 5 m. For bed elevation, Z, the minimum value along each section was sampled from the DEM using the same sections for measuring width for each flow. All data were sampled at intervals of 5 m (~ 6% of the average bankfull width), giving a sampling frequency of 0.2 cycles per meter and cutoff frequency of 0.1 cycles per meter.the lowest flow sample pathway..

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4.2 Developing geomorphic covariance structures

To generate GCS series for bed and flow--dependent width undulations the two variables, Z and W^j were first detrended and standardized. Detrending is not always needed for width in GCS analysis, but some analyses in this study did require it. Minimum bed elevation data, Z, were detrended using a linear model (Table 2) as is common in many studies that analyze reach scale bed variations (Melton, 1962, Richards, 1976a; McKean et al., 2008). Similarly, each flow dependent width series was linearly detrended, but the trends were relatively lowextremely small, with a consistent slope of just 0.002 (Table 2). Finally, each series was standardized by the mean and variance of the entire detrended series (Salas et al., 1980) to achieve second order stationarity, which is a prerequisite for spectral analysis. Second order stationarity of a series means that the mean and variance across the domain of analysis (Newland, 1983). Removal of the lowest frequency of a signal, which can often be visually assessed, has little impact upon subsequent spectral analyses (Richards,1979). A linear trend was used over other options such as a polynomial, because a linear trend preserves the most amount of information in the bed series, while a polynomial can ~~effectively~~ filter out potential oscillations. ~~It is important to note that standardization by the mean and variance of each series makes each dataset dependent on the length analyzed. This has the effect that the magnitude and potentially the sign of $C(Z,W^j)$ at specific locations are not similar if different lengths of a river are analyzed. Once~~ After detrended and standardized series of Z and W^j were generated, then the GCS between them was ~~created~~computed by taking the ~~cross~~ product of the two at each centerline station, yielding a measure of how the two covary, and thus called the covariance, $C(Z,W^j)$ (Figure 2). The GCS is the whole series of $C(Z,W^j)$ values and not a single metric such as ~~shown in .~~the traditional statistical definition of covariance. Interpretation of a GCS is based on the sign ~~of~~, which in turn is driven by the ~~covariance and that~~signs of contributing terms. For $C(Z,W^j)$, if both Z and W^j are positive or negative then $C(Z,W^j) > 0$, but if only one is negative then $C(Z,W^j) < 0$. For $C(Z,W^j)$ these considerations yield four sub-reach scale landform end members that deviate from normative conditions (Figure 3). ~~Due to the statistical transformation of the raw data to detrended and standardize values, normative~~Normal conditions in this context refer to areas where both variables are ~~those~~ close to ~~zero.~~ the mean and thus $C(Z,W^j) \sim 0$. These landforms are not the same as classic zero-crossing riffles and pools (e.g. Carling and Orr, 2000), because they explicitly account for bed and width variation. Neither are they the same as laterally explicit morphological units (Wyrick and Pasternack, 2014), because they average across the full channel width. Also, both of those types of landforms are flow independent, whereas the landforms identified herein are expressly flow-dependent ~~to ascertain~~, reflecting the ~~combined functionality of flow~~

~~and~~entire cross sectional topography ~~in terms of overall~~at a given flow~~ conveyance~~. Note that the signs of Z and W^j are not only important, but the magnitude ~~of the covariance~~ is, too. Since $C(Z, W^j)$ is generated by multiplication, if either Z or W^j is ~~≤~~ within the range of -1 ~~or >~~ to 1, then it serves to discount the other~~, while if~~. If Z or W^j is > 1 or ~~≤-~~< -1 it amplifies $C(Z, W^j)$. ~~To~~We did not assess the statistical significance of coherent landform patterns ~~we utilize a similar threshold of +/-1 for statistical significance~~, but one could do so following Brown and Pasternack (2014).

4.3 Data Analysis

Before any statistical tests were performed we first visually assessed the data in two approximately 1.4-km long sections to illustrate how $C(Z, W^j)$ is affected by flow responses to landforms. For these two examples only three discharges were selected to illustrate flow dependent changes in Z, W^j, and $C(Z, W^j)$ with fluvial landforms. The lowest and highest flows, e.g. 8.50 and 3,126 m^3/s, were selected to bracket the range of flows investigated. The intermediate flow selected was 283.2 m^3/s based on the shifts in $C(Z, W^j)$ observed in the histogram, ACF and PSD tests as shown below in the results. For these examples the exact magnitudes of $C(Z, W^j)$ are not as important as the patterns and how they relate to visually discernible landforms. ~~However, the term "significant" will be used when any series is >1 or <-1 as in Brown and Pasternack (2014).~~

A Mann-Whitney U-test was performed between each $C(Z, W^j)$ dataset to determine if they were statistically different at the 95% level. Histograms were then computed for each $C(Z, W^j)$ dataset to evaluate whether there was a preferencetendency for the data to be positively covarying and how that changes with discharge. Two histograms were developed, one based on the quadrant classification of $C(Z, W^j)$ for each flow and another showing the magnitudes of covariance.$C(Z, W^j)$ magnitude. This was done so that the distribution of both the type of covariance $C(Z, W^j)$ and magnitudes could be assessed. Additionally, the bivariate Pearson's correlation coefficients (r) were computed between Z and W^j to assess their potential interdependence. Bivariate Pearson's correlation coefficients were also computed each series of W^j. Since this analysis requires series of equal length width sections for each W^j were mapped to the bankfull centerline at 141.6 m^3/s using the near function in ARCGIS®. Statistical significance was assessed for (r) using a white noise null hypothesis at the 95% level.

Next, two complimentary tests were used to determine if $C(Z, W^j)$ was quasi-periodic or random. Since, as it was visually evident that it was not constant or strictly periodic. If a series is quasi-periodic this will be reflected in statistically significant periodicity in the ACF (Newland, 1993; Carling and Orr, 2000). While the ACF analysis reveals periodicity in the signal (if present), the PSD analysis presents the associated frequencies. Because the PSD is derived from the ACF the two tests show the same information, but in different domains, with the ACF in the space domain and the PSD in the frequency domain. Both are shown to visually reinforce the results of the PSD analysis. This is helpful because spectral analysis can be very sensitive to the algorithm used and associated parameters such as window type and size. Showing the ACF allows a visual check of dominant length scales that may have quasi-periodicity. The ACF analysis was performed for each flow dependent series of $C(Z, W^j)$ and then these were compared among flows to characterize stage dependent variability and to analyze how spatial structure changed with discharge. This test essentially determines the distances over which $C(Z, W^j)$ are similar. An unbiased estimate of autocorrelation for lags was used:

$$R_k = \frac{\frac{1}{\mathrm{n-k}}\sum_{\mathrm{i=1}}^{\mathrm{n-k}}(x_i - \bar{x})(x_{i+k} - \bar{x})}{\frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n-k}}(x_i - \bar{x})^2} \quad (1)$$

wherewhere x_i is a value of a GCS series at location i, $\bar{x}$ is the mean value of the GCS (zero due to standardization process) and the terms $\frac{1}{\mathrm{n-k}}$ and $\frac{1}{\mathrm{n}}$ account for sample bias (Cox, 1983; Shumway and Stoffer, 2006). Each R_k versus lag series was plotted against discharge for a maximum of 640 lags (3.2 km, or approximately half the study length), creating a surface that shows how ACF evolves with flow. Lag intervals are equal to sample interval for the datasets (e.g. 5 m). Statistical significance was assessed relative to both white and red noise autocorrelations, where the latter. White noise is essential a firstassociated with random processes that are uncorrelated in space, while red noise is associated with data that has properties of 1st order Markov processautocorrelation (Newland, 1993).. The benefit of this approach is that (i) many fluvial geomorphic spatial series display autoregressive properties (Melton, 1962; Rendell and Alexander, 1979; Knighton, 1983; Madej, 2001) and (ii) it provides further context for interpreting results beyond assuming white noise properties. The 95% confidence limits for white noise are given by $-\frac{1}{n} +/- \frac{2}{\sqrt{n}}$ (Salas et al., 1980). For red noise, a first order autoregressive (AR1) model was fit to the standardized residuals for each spatial series of bed elevation and channel width. For comparison, first order autoregressive (AR1) models were produced for 100 random spatial series (each with

Formatted: Tab stops: Not at 3.25" + 6.5" the same number of points as the flow width spatial series) and averaged. Each averaged AR1 flow width series was then multiplied against the AR1 bed elevation series to create an AR1 model for each $C(Z, W^j)$. The red noise estimate was then taken as the average of all AR1 models of $C(Z, W^j)$. The ACF plots were made so that values not exceeding the white noise significance are not shown, along with a reference contour for the AR1 estimate. Frequencies can be gleaned from the ACF analysis by taking the inverse of the lag distance associated repeating peaks following Carling and Orr (2002).

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Power spectral density was estimated for each $C(Z, W^j)$ series using a modified periodogram method as an additional test for periodicity (Carter et al., 1973). The periodogram is the Fourier transform of the biased estimate of the autocorrelation sequence. The periodogram is defined as:

$$P(f) = \frac{\Delta x}{N} \left| \sum_{n=0}^{N-1} h_n x_n e^{-i2\pi f n} \right|^2 \quad (2)$$

where $P(f)$ is the power spectral density of x, h_n is the window, Δ~~$x$is~~x is the sample rate, and ~~$N$is~~N is the number of data data points~~.~~ (Trauth et al., 2006). While the raw periodogram can exhibit spectral leakage, a window can reduce this effect. A hamming window was used with a length equal to each data set. Since samples were taken every ~~5m~~5 m, this resulted in a sampling frequency of 0.2 cycles/m, and a Nyquist frequency, or cutoff of 0.1 cycles/m. The number of data points used for the analysis was roughly half the largest data set, resulting in a bandwidth of 0.00016 cycles/m. For PSD estimates a modified Lomb-Scargle confidence limit for white noise at the 95% level was used as recommended by Hernandez (1996). Since this study was concerned with changes in PSD with flow, estimates were plotted relative to the standard deviation of all

PSD results for all series. This was done instead of using the standard deviation of each series, because that erroneously inflates power within a series without context for the variance of adjacent flows.

~~It's important to note that the sample pathway, and thus stationing, changes with each flow, due to having flow dependent sample pathways to account for topographic steering. This has no effect on the statistical tests applied, except for the correlation comparison between stage dependent wetted widths. For example, all of the tests employed herein were initially performed using a single sample pathway at the bankfull flow and statistical results were consistent across both static and dynamic sample pathways. This approach does create some difficulty in directly comparing similar locations with changes in flow. To visually assess interflow comparisons significant bed profile features were used to line up each spatial series. In discussing these features a focus will be placed on geomorphic features, but when stations are referenced they will be associated with the flow that is being discussed.~~

5. Results

5.1 Relating $C(Z, W^j)$ patterns to landforms

The first example ~~section~~ is located at the lower end of the study area and transitions from a valley meander to a straighter valley section with several valley corridor oscillations (Figure 4). Starting upstream there is a large point bar on river left with a ~~constricted~~ pool (i.e., $-Z$) that transitions to a broad riffle ~~that~~with a 200 m long zone with $Z > 1$. Downstream the river channel impinges on the valley walls creating two forced pools with localized negative spikes in Z (Figure 4~~.~~A,B). Downstream of this the low flow channel is steered to the left of the valley, being bounded by two ~~point bars.~~bars. Relative bed elevations in this zone have positive Z values near 1. Past this there is an inset anabranch that transitions to a constricted pool with a broad terrace on river left. Relative bed elevations in this lower zone fluctuate between 0 and -1.

Given that bed elevation is held fixed for this type of analysis changes in relative flow width with discharge act to modulate the sign and magnitude of the $C(Z, W^j)$ GCS with increasing flow. In particular, when Z is near a value of 1, the relative flow W modulates the GCS signal, with several possible changes including persistence, shifting, reversal, and emergence. For example, a persistent positive W oscillation occurs above the broad riffle near station 1300, where this zone is always relatively wide regardless of flow. The anabranch zone however, shows the positive peak in W shift downstream from station 900 to 600 from 8.5 to 283.2 m^3/s. Two reversals in relative flow width occur from low to high flow near stations 350 and 1100, which also create reversals in the GCS, but with different signs. Near station 350 Z and W are negative at 8.5 and 283.2 m^3/s creating a positive GCS. However, W increases with flow discharge with an emergent positive peak in W at 3,126 m^3/s, creating a negative GCS.

At 8.5 m^3/s zones of high relative flow width are located above zones of positive Z, such as near stations 800 and 1300. As flow increases to 283.2 m^3/s these areas continue to amplify in magnitude becoming relatively wider, however the patterns are slightly different. Relative flow widths at the broad riffle near station 1300 increase upstream of the zone of positive Z, whereas for the anabranch near station 800 the peak in relative width shifts downstream ~200 m. At 3126 m^3/s the valley walls are fully engaged in this location and there are three oscillations in W with positive peaks centered near 300, 1100 and 1500 (Figure 4At 8.50 m^3/s the pool has a zone of significant low Z, but since W is positive and less than 1, the $C(Z,W^{j})$ GCS is also negative and not significant (A). The head of the broad riffle has a significant section of high Z and W, creating a zone of positive $C(Z,W^{j})$. Immediately downstream the forced pools have significant low Z, but as with the other pool W is positive, but in this case > 1, making the $C(Z,W^{j})$ GCS also significant. Through the alternate bar section Z was relatively high at ~ 1 for 600 m, but W oscillates through the section from negative to positive, creating a $C(Z,W^{j})$ GCS that oscillates from negative to positive. Through the anabranch Z and W were not significant so the $C(Z,W^{j})$ GCS was relatively incoherent. The downstream pool had significantly low Z and W, creating a small positive peak in the GCS.

At 283.2 m^3/s in the upstream pool both Z and W are synchronous and negative, creating a positive peak in $C(Z,W^{j})$ that is nearly at 1 (B). The width expands over the downstream riffle along with Z, creating another positive peak in $C(Z,W^{j})$ over the head of the riffle. Thus, from 8.50 to 283.2 m^3/s W and $C(Z,W^{j})$ phase downstream from over the broad riffle. Since the width expansion also occurs over the two forced pools the sign of $C(Z,W^{j})$ is still negative. The width oscillation through the alternate bar section amplifies and shifts downstream ~ 200 m (~2 average bankfull widths), which translates the oscillating peaks in $C(Z,W^{j})$ downstream. The positive width expansion is now over the tail of the riffle, forced pool and head of the anabranch. This creates a distinct negative peak in $C(Z,W^{j})$ over the forced pool. Similar to the upstream pool the negative W cycle is in phase with the negative W elevation cycle, creating a positive peak in $C(Z,W^{j})$.

At 3,126 m^3/s the valley walls are engaged and there are three negative oscillations in W for the first 1000 m (C). This creates significant positive peaks in $C(Z,W^{i})$ over the pool, the upper section of the broad riffle and forced pool. The sign of W, and thus $C(Z,W^{i})$, reverses over the broad riffle, shifting the zone of positive $C(Z,W^{i})$ upstream. Over the anabranch both W and Z are of relatively low magnitude, so $C(Z,W^{i})$ is not significant. The downstream section continues to widen, so the combination of low Z and W create a significant negative spike in $C(Z,W^{i})$.

The other exampleD).

The other example area occurs at a transition from a valley bend to a straighter section where the river transitions from a broad point bar on river left and eventually crosses over between two smaller inset point bars (

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Figure 5).A,B). Starting at the upstream extent the channel morphology is characterized by a large point bar and valley meander,is located on river left with two forced pools in the channel at approximately 3500 and 3600 that have highly significantwith the strongest negative spikes in Z (

Figure 5.C,D). Downstream where the point bar ends the bed profile increases with a significanthigh magnitude peak (e.g. Z >1) over a broad riffle that anabranches at flows greater than baseflowlocated above 3000. As mentioned above in Section 3, this pool-riffle-run sequence was studied in great detail by Sawyer et al. (2010), who confirmed the occurrence of naturally rejuvenating riffle-pool topography. Immediately downstream ofbelow the broad riffle there is a localized forced pool where flow impinges on zone adjacent to a small bedrock outcrop creating an area of low $ZZ < 1$. Within the alternate bars the bed profile dampens somewhat but there isis between 0 and 1 for ~

300 m, followed by a non significantlocalized negative peak in Z around station 2500 (using the 8.50 m^3/s stationing), centered at approximately the midpoint of the path of the meandering low flow channel.2300.

For the first 200 m W is < 0 for all three flows, but gradually increases downstream with increasing flow (

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Figure 5At 8.50 m^3/s W is relatively muted along the point bar on river left except for two areas of W ≈ -1 at stations 3600 and 3700 where the combination of low Z and W create two peaks in positive $C(Z,W^{i})$ (A). Flow width increases and reaches a maximum at the head of the riffle, where the significant peaks in Z and W create a positive peak in $C(Z,W^{i})$. Beyond the riffle W decreases which creates a significant peak in positive $C(Z,W^{i})$ at the forced pool. However, Z and W are both non significant and opposite in sign in the alternate bar zone, creating a negative and non significant$C(Z,W^{i})$.

At 283.2 m^3/s W is oscillatory with significant minimas at the upstream and downstream extents and a significant maxima centered over the broad riffle, which now has an anabranching flow split (B). The two significant zones of low Z centered on 3500 and 3600 have relatively lower W, than the prior flow, enhancing the positive peaks in $C(Z,W^{i})$. The peak in W has now shifted downstream over the head of the riffle and the forced pool. This has the effect of shifting the significant positive peak in $C(Z,W^{i})$ downstream, and also creating a significant negative spike in $C(Z,W^{i})$ associated with the forced pool. In the alternate bar zone downstream $C(Z,W^{i})$ is non significant despite decreases in W since the Z profile is relatively low.

At 3,126 m^3/s the flow fully engages with valley walls and the tailings on river right at the upstream extent (C). The valley width in the upper half of this area is relatively low due to the tailings, so localized areas of low Z have the effect of maintaining positive peaks in $C(Z, W^j)$, albeit slightly lower magnitudes. Therefore, the tailings on river left suppress W, and thus $C(Z, W^j)$. The upstream section of the broad riffle has a non significant negative $C(Z, W^j)$, from having high Z, but low W. However, the lower extent of the broad riffle at station 2750 still has a significantly high Z and W preserving the positive peak in $C(Z, W^j)$, but reducing its magnitude from 2.6 to 0.8 from 283.2 m^3/s flow. As flow fully overtops the alternate bars the sign of the oscillatory pattern of W for the alternate bar section reverses from the pattern at 283.2 m^3/s, but $C(Z, W^j)$ is still low since Z is close to zero.

Is there a preferencec). The two deep pools in this initial zone have $Z < 1$, so the GCS is >1 for all flows but reaches a maximum magnitude of 6 at 283.2 m^3/s. Beyond this area W increases for all flows, but the relative peak broadens and shifts downstream with increasing discharge. At 8.5 m^3/s the peak is centered near station ~ 3000 where it appears a backwater increases flow widths upstream of station 2900. For 283.2 m^3/s the peak shifts downstream ~ 150 m as the anabranch becomes activated and begins to spread water out. At 3126 m^3/s the peak is shifted another ~ 300 m downstream as the bounding point bars are inundated. These shifts in relative W act with the bed profile to create a sharper positive peak in $C(Z, W^j)$ near the riffle at low flows, but then this peak dampens and shifts downstream with increasing flow. Given that the lower ~ 500 m of this example area have Z ~ 0 the $C(Z, W^j)$, GCS is also ~ 0.

Overall both examples show that zones where Z was either > 1 or < -1 were associated with large pools and riffles in the study area, and were characterized by strong peaks (e.g. >1) in $C(Z, W^j)$. An interesting result is that most of the locations where Z <1 were short in length, whereas areas where $Z > 1$ tended to be broader in length.

5.2 Is there a tendency for positively covarying bed and width oscillations?

The histogram of $C(Z, W^j)$ showed that regardless of discharge, there was a ~~preference~~tendency for positive values, and that this ~~uniquely~~ changed with stage (Figure 6A). At least 55% of the data always had $C(Z, W^j) > 0$, increasing to ~~69~~68% at 283.2 m^3/s, and then slightly declining beyond this flow and stabilizing around 60% (Figure 6). There were at most 5% of values < -1, with an average and standard deviation of 3% and ~~1~~2%, respectively. Contrasting this, values > 1 peaked at ~~21~~35% at ~~both 283.2 and 597.5~~141.6 m^3/s and declined with increasing discharge. So out of the two extremes, the data exhibited a ~~preference~~tendency for positive values, with negative values ~~<-~~< -1 being very rare.

The Mann Whitney U-test showed interesting flow dependent aspects of the $C(Z, W^j)$ data sets, where some ranges of flows were significantly different from each other, and others being similar (Table 3). For example, the 8.50 m^3/s $C(Z, W^j)$ had p values that were all significant at the 95% level for each other flow, indicating differences in their distributions. For flows between 28.3-597.5 m^3/s, the p values indicated that the series were statistically similar, but not for higher ~~flow~~flows. The p values for 1,195, 2,390, and 3,126 m^3/s were statistically similar at the 95% level, but not for lower flows.

The quadrant~~-~~based histogram reveals further insight into the distribution of river geometry with flow (Figure 6B). The average percentage of $C(Z, W^j)$ for each quadrant across all flows was ~~31~~30% $\{+W, +Z\}$, ~~13~~14% $\{+W, -Z\}$, ~~24%~~ 25% $\{-W, +Z\}$, and ~~32~~31% $\{-W, -Z\}$, with standard deviations ranging from 2-3%. Percentages of positive $C(Z, W^j)$ was relatively evenly distributed between $\{+W, +Z\}$ and $\{-W, -Z\}$, although the latter was slightly more prevalent. The percent of the data in the ~~-~~$\{+W, +Z\}$ quadrant increased from 26% at 8.50 m^3/s, peaked at ~~35~~34% at ~~598~~597.5 m^3/s, decreased to 30% at 1195 m^3/s and stabilized near this value for higher flows. Meanwhile, the percent of the data in the $\{-W, -Z\}$ quadrant increased from 29% at 8.50 m^3/s and peaked at 35~~%, but~~% at ~~the~~141.6 - 283.2 m^3/s flow, and then decreased to 30% at 597.5 m^3/s. After that it increased to ~~32~~33% and stabilized at and beyond 1,195 m^3/s. Both the $\{+W, -Z\}$ and $\{+W, -Z\}$ quadrants followed a similar but opposite trend, reaching a minimum at 283.2 m^3/s.

Further insights into the positive nature of $C(Z, W^j)$ can be inferred from bivariate Pearsons correlation coefficients of Z and W^j(Figure 7). Similar to $C(Z, W^j)$ the flow dependent response was that the correlation between Z and W^j increased with flow until 283.2~~-~~ to 597.5 m^3/s and then subsequently declined. To further reinforce these results one can also inspect the plot of Z,W^j and $C(Z, W^j)$ for 283.2 m^3/s, visually showing the synchronous nature of Z and W^j (Figure 2) The correlations between combinations of W^j show that each series is significantly correlated to the next highest flow, but there is an interesting flow dependent ~~-~~pattern (Figure 8). Correlations between series decrease with increasing flow, reaching a minimum between 597.5 and ~~1,195~~1195 m^3/s, and then increasing again.

5.3 Are bed and width oscillations quasi-periodic?

The ACF of $C(Z, W^j)$ also showed similar changes with discharge as the above analyses with increases in the presence and magnitude of autocorrelation from 8.50 to ~~283.2~~597.5 m^3/s and then subsequent decline with increasing flow (Figure 9A). At the lowest discharge there are approximately ~~3~~two broad bands of positive autocorrelation that ~~exceed~~ exceeded both the white noise ~~threshold, spaced roughly 650 m apart. Only one lag exceeded the~~ and AR1 threshold at ~~approximately~~ lag distances of 1400 and 2100 m. At 28.32 m^3/s these three peaks broaden ~~with two peaks exceeding the AR1 threshold, one~~and the highest correlation was found at ~~1400 m and 2100 m~~lag distance 1400 m, which increased from ~0.38 to 0.65. At the bankfull discharge of 141.6 m^3/s the peak at ~~1500m~~1400m diminishes, while the peak ~~at lags 700,1400 and~~near 2100 m ~~increase~~increaseed in strength (e.g. correlation magnitude). At 283.2 m^3/s there are still peaks ~~that~~near 1400 and 2100 mthat exceed both white noise and the AR1 threshold~~ at 700,1400, 2100~~,but two other significant peaks emerge near 700 and 2800 m~~, whith the last one emerging at~~. Similar statistically significant correlations are found at 596.5 m^3/s, albeit narrower bands of correlation. The correlation distances at 283.2 and 596.5 m^3/s average ~700 m, and this ~~discharge. These correlation distances~~ would have a frequency of approximately 0.0014 cycles/m. Beyond ~~283.2~~596.5 m^3/s the ACF diminishes rapidly with no peaks that are statistically significant compared to red noise. Overall, the ACF results show that $C(Z, W^j)$ is quasi-periodic from 8.50 m^3/s to 141.6-~~283.2~~597.5 m^3/s, but then the periodicity decreases in strength as flow increased.

Similar to ACF analysis, PSD analysis showed quasi-periodic components of $C(Z,W^j)$ exhibiting flow ~~dependence~~dependent behavior (Figure 9B). For 8.50-283.2 m^3/s there is a high power band (e.g. PSD/σ ~12) centered on 0.0014 cycles/m, which is confirmed from the ACF analysis above. For ~~this range of discharge~~8.50 -141.6 m^3/s there are also smaller magnitude peaks ~~of approximately 6 at 0.0007, 0.002 and 0.0034 cycles/m, but these are still less than half the magnitide of the 0.0014 band~~ranging from 3-8, spread out over several frequencies. There's also a high magnitide component at the lowest frequency band that emerges at 28.32 and declines by 283.2 m^3/s. These low frequency components are commonly associated with first order auto-regressive behavior in the data (Shumway and Stoffer, 2010). ~~Beyond 597.5 m^3/s~~At 597.5 m^3/s power is still associated on 0.0014 cycles/m, albeit with a ~50% reduction in magnitude. Beyond this flow the frequency range and magnitude of statistically significant values declines with discharge. Overall, both ACF and PSD results show that $C(Z,W^j)$ is quasi-periodic from 8.50 m^3/s to 283.2 m^3/s but then decreased in strength as flow increased. Further, the PSD results show that the $C(Z,W^j)$ GCS is flow dependent and multiscalar ~~and~~, being characterized by a range of statistically significant frequencies.

6. Discussion

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~~*6.1 Relating $C(Z,W^j)$ patterns to landforms*~~

~~The zoomed examples of $C(Z,W^j)$ and the detrended river topography highlight how this type of GCS can be used to characterize the topographic influence on wetted width and bed elevation variability in river corridors. Overall, topographic extremas where Z~~

was either > 1 or < -1 were associated with the largest pools and riffles in the study area, and were characterized by strong peaks (e.g. >1) in $C(Z,W^{i})$. Therefore, the $C(Z,W^{i})$ GCS may be used diagnostically to assess riverine structure and hydraulic function in a continuous manner within a river across an array of flows. While not studied herein, prior work (Brown and Pasternack, 2014) showed that the magnitude of $C(Z,W^{i})$ can also be related to flow velocity, though lagged effects do occur. Since the magnitudes can be linked to both unique landforms and flow velocity they may have utility in assessing topographic and hydraulic controls in river corridors.

The examples also provide information on how fluvial landforms such as anabranches, alternate bars, broad riffles, forced pools and point bars can affect $C(Z,W^{i})$ with stage (,). Overall, positive peaks in $C(Z,W^{i})$ at 8.50 and 283.2 m^3/s were associated with the heads of riffles where alluvial bars are widest and centers of constricted pools. Negative peaks in $C(Z,W^{i})$ where associated with narrow, high hydraulic controls that presumably function as hydraulic nozzles, and also localized forced pools adjacent to alluvial bars created from flow impinging into the bedrock walls, creating zones of relative low bed elevation and high flow width. The increase in flow from 8.50 to 283.2 m^3/s acted to shift the location of these peaks downstream approximately 200 m and broaden their overall shape. In the second example the constricted pools adjacent to the point bar and tailings have positive peaks in $C(Z,W^{i})$ that are persistent across all flows. If the tailings were not present on river left in this area the magnitude of $C(Z,W^{i})$ would likely decrease as the valley width would be wider. The broad riffle creates a peak in $C(Z,W^{i})$ at 8.50 m^3/s, but this broadens and translates downstream by 283.2 m^3/s as the anabranch activates a greater width of flow. The alternate bars channelize flows at 8.50 m^3/s, but even when flow has already spilled well onto the floodplain at 283.2 m^3/s the $C(Z, W^{j})$ is still not significantly positive or negative because despite increases in W the Z profile was of relatively low magnitude. This in particular highlights the effect of the standardization process on Z and W, if either one is of low magnitude (e.g. <1) then it effectively discounts the magnitude of the other, while when the covariate is > 1 it will amplify the other. When flow is contained within the point bars it is relatively constricted, but as flow increased expansions occur near the crossover between bars, causing the relative width expansion to shift. For flood flows point bars, broad riffles and anabranches all occur in valley expansions, as shown by White et al. (2010).

This study quantitatively supports the idea that river morphology in partially confined valleys is hierarchically nested with broader exogenic as well as channel width scale alluvial controls. In this setting, valley width is constrained across fluvial geomorphic timescales from bedrock, and results show that a top-down organization occurs in the river channel as a result. Each series of W^{j} was significantly correlated with the next highest flow, but this was lowest between 597.5 and 1,195 m^3/s, where the valley walls begin to be engaged. Since each series of W^{j} is interdependent on the other (), and bed elevation is highly correlated with width (), this supports the notion that bed elevation adjusts to variations in width and further justifies the positively covarying $C(Z, W^{j})$ GCS (Wilkinson et al. 2004; MacWilliams et al., 2006; Caamano et al., 2009; Thompson, 2010; White et al., 2010). White et al. (2010) also show a non-persistent riffle at one of the widest valley expansions. This suggests that when width oscillations reach a certain magnitude inset point bars develop and steer flow at an angle non parallel to the valley centerline. This has the effect of the topographic high point being located not in the widest part of the valley, but phased to the orientation of the lowest lateral bar relief, driven by topographic steering of the bars. For example, at flows below 141.6 m^3/s the point bars constrict flow but as flow increases to 283.2-597.5 m^3/s the bars steer flow transverse to the valley profile, creating expansions at the head or tail of the alternate bars. When the bars are overtopped at 1,195 m^3/s or greater flow begins to be steered by the valley walls. So this suggests that as large floods deposit valley wide bars in expansions, subsequent more frequent flows erode through these deposits with bed elevation syncing to the self-formed channel width. There's an obvious feedback between the both bed elevation and channel width in this setting, as originally proposed by Richards (1976b) where increased bed elevations presumably deflect flow onto the banks. The exogenous constraint of the bedrock valley walls and large dredger tailings piles also introduce variations in curvature that affect the occurrence of pools, not investigated herein, but this is not consistent throughout. For example, the first valley meander bend at the top of the study reach has several riffles nested within it, while the next one (shown in) has a single large pool. This suggests that at the highest flood flows curvature may not play as an important of a role as variations in flow conveyance.

6.26.1 *Coherent undulations in cobble-gravel bed river topography*

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The resultsprimary result of this study have shownis that in an incising and, partly confined, regulated cobble-gravel river there is a preference for positively covaring $C(Z, W^i)$ that increases in strength from the basewhose flow up until flows with a 1.2-2.5

year return interval, and then decrease and level off at ~ 5-year flow up until the 20-year flow (,). This pattern regime is interpreted as a shift in organization from channel centric processes for flows within banksdynamic enough to broader scale exogenous controls such as floodplain, terrace, mine tailing and valley width undulations when the river spills overafford it the capability to rejuvenate its banks. This gives support to the idea that alluvial, self maintained rivers have a preferencelandforms, there was a tendency for positive bed elevation and wetted width GCS's, especially for discharges associated with channel maintenance and it adds new insight that this even remains true to a large degree for a wide range of floods, indicating that total cross-sectional conveyance matters for landform self-maintenance. Grain scale processes do not seem likely to explain this coherent organization with positive positively covaring $C($$C(Z, W^j)$ and thus covarying Z, W^j) for floods.

and W amongst all flows analyzed. Based on the ACF and PSD analyses the undulations in $C(Z, W^j)$ GCS are non-random and are instead quasi-periodic. The most coherent power was achieved at the 1.5 year recurrence interval, with the most dominant frequency being ~ 0.0014 cycles/m, which equates to a length scale of ~ 700 m (). This length scale can be also visually gleamed from the peaks of $C(Z, W^j)$ in the two examples, which are both ~ 700 m (,). Notably, statistically significant variance was also distributed over several other bands such as 0.0007, 0.002 and 0.0034 cycles/m indicating that the GCS is multiscalar. The results of this study associated channel organization across a range of Three of the morphologic units (MUs) studied by Wyrick and Pasternack (2014) can be used for context including pools, riffles, and point bars. In their results for the Timbuctoo reach, pools, riffles, and point bars had an average frequency of 0.0029, 0.0028, and 0.001 cycles/m. In this study the dominant frequency identified in the PSD analysis was 0.0014 cycles/m, which is half the MU frequency of both pools and riffles reported by Wyrick and Pasternack (2014). Therefore, it appears that the quasi-periodicity of the $C(Z, W^j)$ GCS is related to the pool-riffle oscillation in the river corridor. This is in agreement with studies based on field investigations and numerical models that relate this observation to quasi-periodic bed and width variations associated with bar-pool topography (Richards, 1976b; Repetto and Tubino, 2001; Carling and Orr, 2002).

The results of this study suggest that self-formed gravel-cobble bedded rivers inset into partially confined valleys organize channel geometry into zones of alternating co-varying bed and width oscillations at discharges with modest recurrence intervals frequencies within the range of commonly reported channel forming discharges for Western U.S. rivers (e.g., 1.2-2.5 years).) as well as substantially larger flows. These conclusions are obviously limited to the study reach, but this should not prohibit discussing possible mechanisms that could lead to these observed patterns, as well as the role of variable flows and incision.

Most notably, the test river exhibited a dominance of positively covarying values of $C(Z, W^j)$ across all flows, being characterized by an alternating pattern of wide and shallow or narrow and deep cross sections. This supports the idea that alluvial river reaches have a tendency for adapting wide and shallow and narrow and deep cross sections to convey water flow (Huang et al., 2004). Rather than select a single type of cross section to maximize energy dissipation to create a uniform cross section geometry at a single channel maintaining flow, commonly referred to as bankfull, it appears that alluvial rivers adjust their channel topography to have cross sections that alternate between those that are wide and shallow and narrow and deep (Figure 6~~(~~B; Huang et al., 2004), with some locations having a prismatic channel form indicative of normative conditions, particularly in transition zones. ~~Presumably, the $C(Z, W^j)$ GCS patterns are also linked to flow dependent patterns of acceleration and deceleration,~~ Whether this is attributed to minimizing the time rate of potential energy expenditure per unit mass within a reach (Langbein and Leopold, 1962; Yang, 1971; Cherkauer, 1973; Wohl et al., 1999) or channel unit scale mechanisms associated with riffle-pool maintenance (Wilkinson et al. 2004; MacWilliams et al., 2006; Caamano et al., 2009; Thompson, 2010;) remains to be determined. Given that extremal hypotheses and riffle-pool maintenance act at different, yet interdependent scales, it is likely that both play an intertwined and inseparable role in channel form. That said, extremal theories are limited to predicting mean channel conditions within a reach (Huang et al., 2014), with no models that can yet fully predict sub-reach scale alluvial river topography, so we turn our attention to more tractable hydrogeomorphic processes related to riffle and pool topography.

Presumably, the quasi-oscillatory $C(Z, W^j)$ GCS pattern is also linked to flow dependent patterns of convective acceleration and deceleration zones (Marquis and Roy, 2011; MacVicar and Rennie, 2012), as the length scales of the GCS were aligned with the spacing of erosional and depositional landforms such as bars and pools. This aspect is supported by ACF and PSD results as well as other two studies on the test reach. First, it appears that the quasi-periodicity of the $C(Z, W^j)$ GCS is related to the pool-riffle oscillation in the river corridor. The PSD analysis showed that the dominant frequency of $C(Z,W^j)$ was ~ 0.0014 cycles/m, which equates to a length scale of ~ 700 m (Figure 9). Three of the morphologic units (MUs) studied by Wyrick and Pasternack (2014) can be used for context including pools, riffles, and point bars. In their results for the Timbuctoo Bend Reach, pools, riffles, and point bars had an average frequency of 0.0029, 0.0028, and 0.001 cycles/m. Considering that pools and riffles are defined as two end-members of positive $C(Z,W^j)$, then the frequency of riffles and pools should be twice that of the $C(Z,W^j)$ GCS as found herein. That is, a single oscillation of $C(Z,W^j)$ GCS would include both a narrow and deep (e.g. pool) and a wide and shallow (e.g. riffle) geometries, although transitional forms are possible within a cycle, too (Figure 3). Therefore, it appears that the quasi-periodicity of the $C(Z,W^j)$ GCS is related to the pool-riffle oscillation in the river corridor. This is in agreement with studies based on field investigations and numerical models that relate this observation to quasi-periodic bed and width variations associated with bar-pool topography (Richards, 1976b; Repetto and Tubino, 2001; Carling and Orr, 2002).

~~This aspect is supported by two studies on the LYR. First, Sawyer et al.~~Second, Sawyer et al. (2010) showed that stage dependent flow convergence maintained bed relief by topographically mediated changes in peak velocity and shear stress at the central riffle in second example (

Figure 5~~. Additionally~~). Interestingly, the flow width series phases relative to bed elevations in accordance with theory (Wilkinson et al., 2004) and field and numerical studies (Brown and Pasternack, 2014). This supports an already reported relationship between the $C(Z,W^j)$ GCS and the process of flow convergence routing (Brown and Pasternack, 2014 Brown et al., 2016).

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Lastly, Strom and Pasternack (~~submitted~~2016) showed that peak zones of velocity undergo variable changes in their location with discharge, with most velocity reversals occurring after 597.5 m^3/s. In this case the zones of peak velocity patches underwent complex changes from being associated with narrow topographic high points at base flows~~($-W^j$~~ $(-W^j, +Z)$ to topographic low points where flow width is constricted at high flows $(-W^j, -Z$~~). Further, this study is aligned with prior work that suggests a single frequency or flow does not fully describe~~). Overall, the ~~relationship between $C(Z, W^j)$,~~presence of oscillating wide and ~~presumably channel morphology (Wyrick~~shallow and ~~Pasternack, 2014) but that a continuum of frequencies are present (Chin, 2002).~~narrow and deep cross sections appears to be linked to hydrogeomorphic processes of riffle-pool maintenance.

6.2 Hierarchical nesting, variable flows and the role of incision

This study quantitatively supports the idea that river morphology in partially confined valleys is hierarchically nested with broader exogenic constraints such as the bedrock valley walls, as well as channel width scale alluvial controls such as point bars and islands. Our study quantitatively characterized interesting shifts in the amount of correlation amongst flow width series and in the presence of quasi-periodic oscillations in $C(Z, W^j)$ with changes in flow. Each series of W^j were significantly correlated with the next highest flow, but this was lowest between 597.5 and 1195 m^3/s, where the valley walls begin to be engaged (Figure 7). Further, both the ACF and PSD show that quasi-periodicity in $C(Z, W^j)$ declines after 597.5 m^3/s (Figure 9). In addition, Strom and Pasternack (2016) showed that reversals in peak velocity occur when flows exceed

597.5 m^3/s. While results show that statistically significant correlations between Z and W^j occur for a range of flows, the greatest magnitude is not when the valley walls are inundated, but for the 283.2 m^3/s channel and incipient floodplain. Given that correlations were still significant for the flows that inundate the valley walls, this does not refute the role of valley width oscillations in potentially controlling riffle persistence (White et al., 2010), but rather adds new insight to the morphodynamics of rivers incising in partially confined valleys. This suggests that the incision process may be decoupling the organization of the riverbed away from being controlled by the valley walls and instead phased towards reshaping channel topography within the inset bars that are nested within the valley walls. As the riverbed incises further down through knickpoint migration (Carley et al., 2012) this may act to shift zones of high and low wetted width upstream unless lateral erosion can keep pace.

6.3 Broader Implications

This study quantified relationships between flow width and minimum bed elevation in a partly confined and incising gravel-cobble bedded river, as well as for the first time how they change with stage. ~~The~~While study results are currently limited to rivers similar to the study reach, there are several key results of this study ~~are relevant~~that may have broader relevance to river restoration and management.

First, a key result of this study was that channel geometry was organized into positively covering bed and width undulations across all flows analyzed, alternating between wide and shallow and narrow and deep cross sections. This is a very different view from the classical definition of singular and modal bankfull channel geometry often used to guide river and stream restoration (Shields et al., 2003). Instead, our study found that channel geometry at all flows had a relatively even mixture of wide and shallow and narrow and deep cross sections. Studies that deconstruct the complexity of river channel geometry to modal ranges of channel width and depth have always shown scatter, which has mostly been attributed to measurement uncertainty and/or local conditions (Park, 1977; Philips and Harman, 1984; Harman et al., 2008; Surian et al., 2009). Our study suggests that this variability is a fundamental component of alluvial river geometry. While this concept was proposed by Hey and Thorne (1983) over two decades ago, few studies have integrated these ideas into river engineering and design (e.g. see Simon et al., 2007). Thus, this study further supports a needed shift away from designing rivers with modal conditions to designing rivers with quasi-oscillatory and structured variations in channel topography (Brown et al., 2016).

Second, this study has implications to restoration design and flow reregulation in that a wide array of discharges beyond a single channel forming flow are presumably needed for alluvial channel maintenance (Parker et al., 2003). ~~This is~~Commonly singular values of channel forming discharge, usually either bankfull or effective discharge, are used in stream and river restoration designs (Shields et al., 2007; Doyle et al., 2007). This study refutes this concept for rivers such as studied herein, as supported by the results that show gradual changes in channel organization within a band of discharges with recurrence intervals ranging from 1.2-~~2.5 years, and two fold range in absolute discharges. Further~~5 years, and four fold range in absolute discharges. Instead, stream and river restoration practitioners should analyze ranges of flow discharges and the potential topographic features (existing or designed) that could invoke stage-dependent hydrodynamic and geomorphic processes associated with complex, self maintaining natural rivers.

Third, while the length scales of covarying bed and width undulations are approximate to the spacing of bars and pools in the study area, they are quite complex and lack explicit cutoffs that illustrate power in a singular frequency band. Thus, river restoration efforts that specify modal values of bedforms may overly simplify the physical structure of rivers with unknown consequences to ecological communities and key functions that are the focus of such efforts. ~~Designs~~River restoration designs need to mimic the multiscalar nature of self-formed topography by incorporating GCS into river engineering (Brown et al., 2014) or somehow insure that simpler uniscalar designs will actually evolve into multiscaler ones given available flows and anthropogenic boundary constraints.

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~~This~~Fourth, this study has potential implications for analyzing the effect of flow dependent responses to topography and physical habitat in river corridors. Valley and channel widths have shown to be very predictive in predicting the intrinsic potential of salmon habitat (Burnett et al., 2007). Further, the role of covarying bed and width undulations in modulating velocity signals and topographic change has implications to the maintenance of geomorphic domains used by aquatic organisms. As one example, consider that adult salmonids use positively covarying zones such as riffles (e.g. $+W^j, +Z$) for spawning and pools (e.g. -$W^j, -Z$) for holding (Bjorn and Reiser, 1991). In the study reach Pasternack et al. (2014) showed that 77% of spawning occurred in riffles and chute morphologic units, which are at or adjacent to areas where $C(Z, W^j)$>~~0~~1 (Figure 4,

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Figure 5), supporting this idea. The presence and structure of covarying bed and width undulations is also thought to be important indirectly for juvenile salmonids that require shallow and low velocity zones for refugia during large floods. For example, the expansions that occur at the head of riffles would presumably provide lateral zones of shallow depths and moderate velocities needed for flood refugia. In the absence of positive bed relief, and zones of $+W, +Z$, flow refugia zones would be hydrologically disconnected from overbank areas, impacting the ability of juvenile salmon to utilize these areas as refugia during floods and potentially leading to population level declines (Nickelson et al., 1992). Future work should better constrain the utility of GCS concepts in assessing aquatic habitat.

Lastly, ~~it's~~it is possible that the $C(Z,W^j)$ GCS could be used ~~across rivers~~ as a comparative proxy in remote sensing applications to determine how the topographic structure of rivers change with flow, and how that may also change though time. The zoomed examples of $C(Z,W^j)$ and the detrended river topography highlight how this type of GCS can be used to characterize the topographic influence on wetted width and bed elevation variability in river corridors. ~~.~~ The $C(Z,W^j)$ GCS may be used diagnostically to assess riverine structure and hydraulic function in a continuous manner within a river across an array of flows. While not studied herein, prior work (Brown and Pasternack, 2014) showed that the magnitude of $C(Z,W^j)$ can also be related to flow velocity, though lagged effects do occur. Since the magnitudes can be linked to both unique landforms and flow velocity they may have utility in assessing topographic and hydraulic controls in river corridors.

LiDAR and analytical methods for developing bed topography in rivers has improved considerably (McKean et al, 2009). For example, Gessese et al. (2011) derived an analytical expression for determining bed topography from water surface elevations, which can be obtained from LiDAR (Magirl et al, 2005). Assuming one has an adequate topographic data set, whether numerical flow modeling is needed to generate wetted width data sets places a considerable constraint on performing this type of analysis. This could potentially be relaxed, especially at flows above bankfull, using a constant water slope approximation for various flow stages. At smaller discharges in rivers there are typically defects in the water surface elevation, where the bed topography exerts a strong control on bed elevations (e.g. Brown and Pasternack, 2008). However, many studies suggest that on large alluvial rivers bankfull and flood profiles show that they generally flatten and smoothen once bed forms and large roughness elements such as gravel bars are effectively submerged. In this case, one can then detrend the river corridor and take serial width measurements associated at various heights above the riverbed (Gangodagamage et al., 2007). The height above the river then can then be related to estimates of flow discharge and frequency, so that the change GCS structure can be related to watershed hydrology (Jones, 2006). There's also the obvious option of using paired aerial photography with known river flows by correlating discharge with imagery dates and widths. Future work should constrain whether similar conclusions can be reached using field and model derived estimates of wetted width as opposed to modeled solutions.

7. Conclusions

A key conclusion is that the test river exhibited positively covaring oscillations of bed elevation and channel width ~~that had a unique response to flow discharge as supported by several tests. As discharge increased the amount of positively covarying values of $C(Z,W^j)$ increased up until the 1.5 and 2.5 year annual recurrence flow and then decreased at the 5 year flow before stabilziing for higher~~across all flows~~.~~ analyzed. These covarying oscillations ~~are~~ were found to be quasi-periodic at channel forming flows, scaling with the length scales of pools and riffles. Thus~~,~~ it ~~is thought~~appears that ~~gravel-cobble bedded~~ alluvial rivers organize their topography ~~with a preference for quasi-periodic covarying bed~~to have oscillating shallow and wide and narrow and ~~width undulations at channel forming flows due to both local bar-pool~~deep cross section geometry, even despite ongoing incision. Presumably these covarying oscillations are linked to hydrogeomorphic mechanisms ~~and non~~ associated with alluvial ~~topographic controls.~~ river channel maintenance. As an analytical tool, the GCS concepts in here treat the topography of river corridors as system, which is thought of as an essential view in linking physical and ecological processes in river corridors at multiple scales (Fausch et al., 2002; Carbonneau et al., 2012). While much research is needed to validate the utility of these ideas to these broader concepts and applications in ecology and geomorphology, the idea of GCS's, especially for width and bed elevation, holds promise.

8. Data Availability

Each $C(Z,W^j)$ dataset is available from either author by request.

~~8.~~9. Acknowledgements

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~~10.~~11. List of Figures

Figure 1. Regional and vicinity map of the lower Yuba River (A) and extent of study segment showing inundation extents predicted by the 2D model~~.~~ (B).

Figure 2. Raw bed profile (A) and flow width (B) series for 283.2 m^3/s. After detrending and standardizing ~~both series~~, values of Z (black line in C) and W (blue line in C) are multiplied ~~by each other generating the~~ together to compute $C(Z, W^j)$ ~~GCS~~ (red line in C). The whole series of $C(Z, W^j)$ is the GCS

Figure 3. Conceptual key for interpreting $C(Z, W^j)$ geomorphic covariance structures (A). For quadrant 1 Z and W^j are both relatively high, so that implies wide and shallow areas associated with deposition. Conversely, in quadrant 2 Z is relatively low, but and W^j is relatively high, which implies deep and wide cross areas, which implies that these areas may have been scoured at larger flows. In quadrant 3 Z and W^j are both relatively low, so that implies narrow and deep areas associated with erosion. Finally, in quadrant 4 Z is relatively high and ~~W^j~~ W^j is relatively low, so that implies narrow and topographically high areas. Prototypical channels and GCS with positive (B), and negative (C) $C(Z, W^j)$ colored according to (A).

Figure 4. Example section ~~of detrended bed topography and plots of Z, W, and $C(Z, W^j)$ for 8.50 m^3/s (A), 283.2 m^3/s (B), 3,126 m^3/s (C)~~ in the middle of the study area~~. The detrended topography has been clipped to the wetted~~ showing inundation extents ~~for each~~ (A). Below are plots of minimum bed elevation (B), flow ~~to accentuate relative bed~~

~~features. Flow dependent sample pathways are shown for stationing reference between the~~widths for 8.50 m^3/s, 283.2 m^3/s, and 3,126 m^3/s (C), and $C(Z, W^j)$for the same flows. The aerial image ~~and the plots.~~is for a flow of 21.29 m^3/s on 9/28/2006.

Figure 5. Example section ~~of detrended bed topography and plots of Z, W, and $C(Z, W^j)$ for 8.50 m^3/s (A), 283.2 m^3/s (B), 3,126 m^3/s (C)~~ at the lower extent of the study area~~.~~ ~~The detrended topography has been clipped to the wetted~~ showing inundation extents ~~for each flow to accentuate relative bed features. Flow dependent sample pathways~~(A). Below are ~~shown for stationing reference between the~~plots of minimum bed elevation (B), flow widths for 8.50 m^3/s, 283.2 m^3/s, and 3,126 m^3/s (C), and $C(Z, W^j)$for the same flows. The aerial image ~~and the plots.~~ is for a flow of 21.29 m^3/s on 9/28/2006.

Figure 6. Histogram~~-~~ of $C(Z, W^j)$ classified by positive and negative values as well as > and < 1 (A). Also shown is a histogram classified by quadrant (B). Both illustrate ~~anoverall preference~~an overall tendency for $C(Z, W^j) > 0$ with increasing discharge and also illustrating an increasing ~~preference~~tendency for positive values of $C(Z, W^j) > 1$ up until 283.2 m^3/s after which it declines. Colors represent bin centered values.

Figure 7. Pearson's correlation coefficient for Z and W^j ~~(A)~~ between each flow ~~and an example scatter plot of Z vs W^j at 283.2 m^3/s (B).~~.

Figure 8. Pearson's correlation coefficient for sequential pairs of flow dependent wetted width series.

Figure 9. Autocorrelation (A) and PSD (B) of $C(Z, W^j)$ with increasing flow. For the ACF plot (A), only values exceeding white noise at the 95% level are shown and the red countor demarcates the 95% level for an AR1 process(red noise). For the PSD plot (B) only values exceeding white noise at the 95% level are shown.

Table 1. Flows analyzed and their approximate annual recurrence intervals.

Table 2. Linear trend models and R^2 for Z and W^j used in detrending each series.

Table 3. Mann Whitney U-test p values amongst all combinations of Z and W^j at the 95% level.