

Compiling and Analysing Bedrock River Data Across the USA to Unpick Bedrock River Geomorphology

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Abstract

Active incision of bedrock rivers exerts a vital control on landscape evolution in upland areas. Previous research found that bedrock rivers were typically steeper and sometimes narrower than alluvial rivers. However, most of the literature on partially exposed bedrock rivers has employed small samples mostly from mountainous regions, so their geomorphological properties remain poorly understood. In contrast with the existing literature, a large-sample analysis of bedrock river channel properties would allow the controls on bedrock river width and slope to be unpicked and reveal whether the existing literature is biased towards pristine, mountainous bedrock rivers. Overall, such an analysis could improve the reliability of upland landscape evolution models.

Here we present an analysis of 1,924 river sites from the EPA National Rivers and Streams Assessment to assess the geomorphological differences between bedrock and alluvial rivers. The influences of lithology and uplift on bedrock channel properties are examined using external datasets. We find bedrock rivers to be significantly steeper and wider than alluvial rivers. Sedimentary bedrock rivers were significantly wider than igneous/ metamorphic bedrock rivers, consistent with findings from Ferguson *et al.* (2017). We estimated shear stress and critical shear stress for each river site and assessed correlation with bedrock exposure. We found that exposed bedrock could not always be explained by local sediment transport exceeding local sediment supply, indicating that bedrock exposure may be controlled by other factors in bedrock rivers. Currently, uplift data are being compiled for further analysis.

Introduction

A bedrock river can be defined as having no alluvial cover on the bed, however more commonly they will have intermittent sections of sediment cover (Whipple *et al.*, 2013). Bedrock rivers are common in mountainous and upland areas where they play a vital role in landscape evolution by actively incising into the in-place rock (Whipple, 2004). Therefore, bedrock rivers control the landscape response to tectonic uplift, base-level changes and climate change in these upland areas (Whipple *et al.*, 2013; Ouimet *et al.*, 2009).

Bedrock exposure is thought to occur in riverbeds due to a combination of sediment-starved conditions and active incision into the surrounding rock over long periods of time (Montgomery *et al.*, 1996). Sediment starved conditions are caused by local sediment transport capacity (Q_c) exceeding local sediment supply (Q_s) (Montgomery *et al.*, 1996). The influence of these two factors on bedrock exposure is thought to vary at different locations due to differences in uplift rates, lithology and climate (Montgomery *et al.*, 1996; Whipple *et al.*, 2013).

Over the past few decades, studies have looked at the geomorphological characteristics of bedrock rivers in different field settings to help improve landscape evolution models. The key characteristics which influence landscape evolution models are bedrock channel slope and width (Whipple *et al.*, 2013). Bedrock rivers have been shown to be steeper than alluvial rivers due to higher rates of bedrock incision (Whipple *et al.*, 2013). Bedrock channel width is expected to be narrower than alluvial channel width as predicted by many bedrock incision models (Finnegan *et al.*, 2005; Whittaker *et al.*, 2007). However, analyses of field data do not always find narrowing in bedrock sections, so the controls on channel width need further study (Whipple *et al.*, 2013). The effects of lithology on bedrock channel width and slope are uncertain, mainly due to small sample sizes used in most studies. Uplift data is difficult to obtain for many river sites and few large-scale uplift datasets are available. Therefore, the effects of uplift on bedrock river slope and width have never been looked at on a large scale.

In this study we present a novel large-scale analysis of the shape and geomorphology of bedrock and alluvial rivers across the USA. We also conduct analysis to determine the controls of lithology and uplift rates on bedrock river shape. This study will help to unpick and interpret the conflicting literature on the effects of lithology and uplift, to help calibrate landscape evolution models to field data.

We present plots of channel slope, bankfull width and bankfull width to depth ratio against drainage area to compare bedrock and alluvial reaches. Comparisons of shear stress and critical shear stress at the river sites are then made to test whether bedrock exposure is due to $Q_c > Q_s$. Lithology and uplift data are then incorporated to help unravel the conflicting literature on the influences of these two factors on bedrock river shape.

Methodology

Before conducting the analyses we checked for human influences at the river sites using the Human Influence Index and the number of dams within 10 km of each river site. All figures and analyses were produced within R using the ggplot2 package. We took any river with percent bedrock exposure greater than zero to be a bedrock river.

First, we examined differences in bedrock river geomorphology across the whole dataset by producing log-log plots of width, slope and width to depth ratio against drainage area and Strahler order.

To further examine whether Q_c exceeding Q_s determines bedrock exposure, we calculated shear stress and critical shear stress for the river sites using Eq1 and Eq2. A plot was produced of shear stress against critical shear stress, with a one-to-one line added to help visualise the ratio of the two variables. To display these trends more clearly, density plots of shear stress and critical shear stress were also produced.

$$\tau = \rho g d S \quad (1)$$

τ = shear stress of river bed
 ρ = water density
 g = gravitational acceleration
 d = bankfull depth
 S = water surface slope

$$\tau_c = \tau^* (\rho_s - \rho_w) D_i g \quad (2)$$

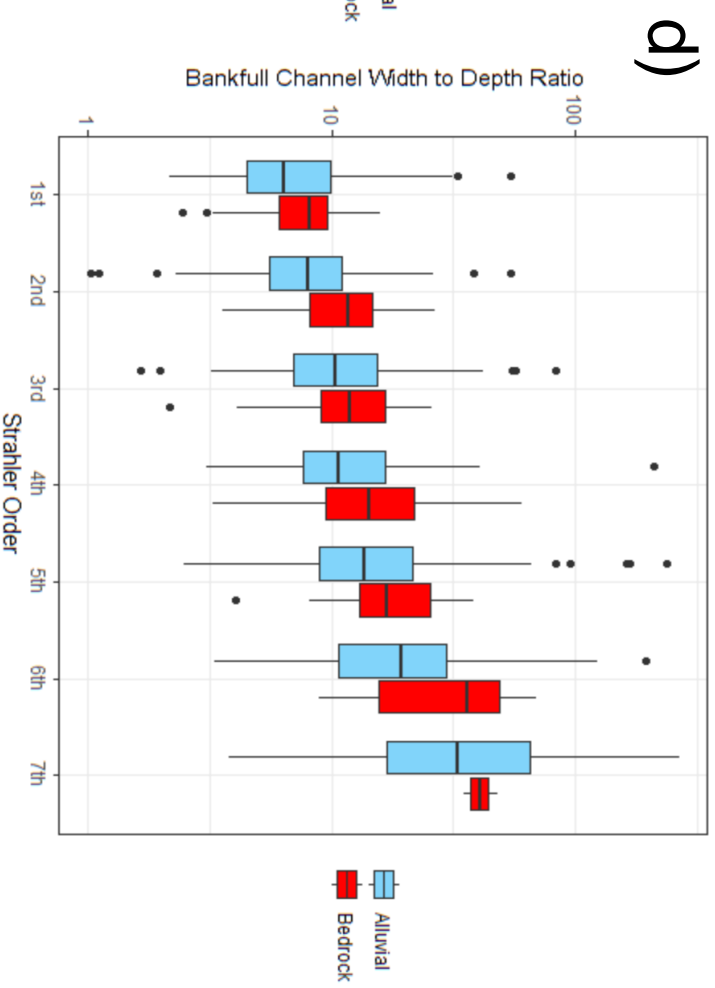
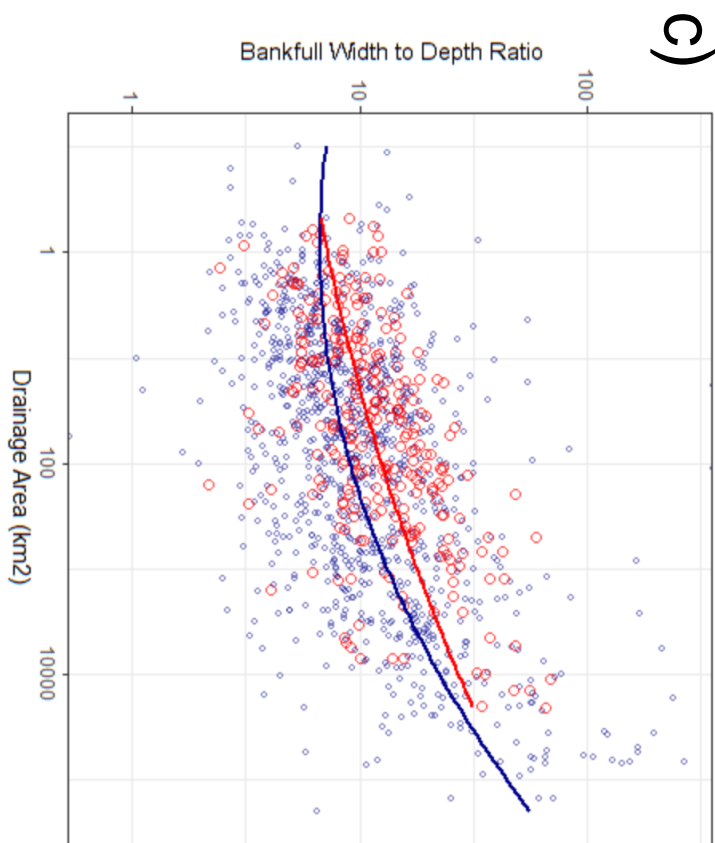
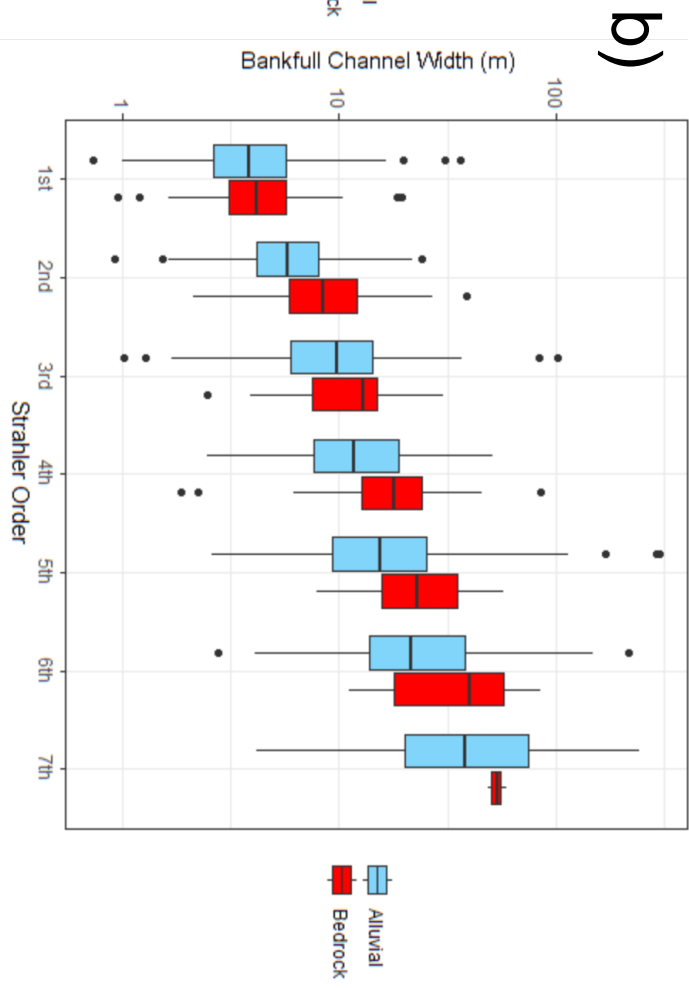
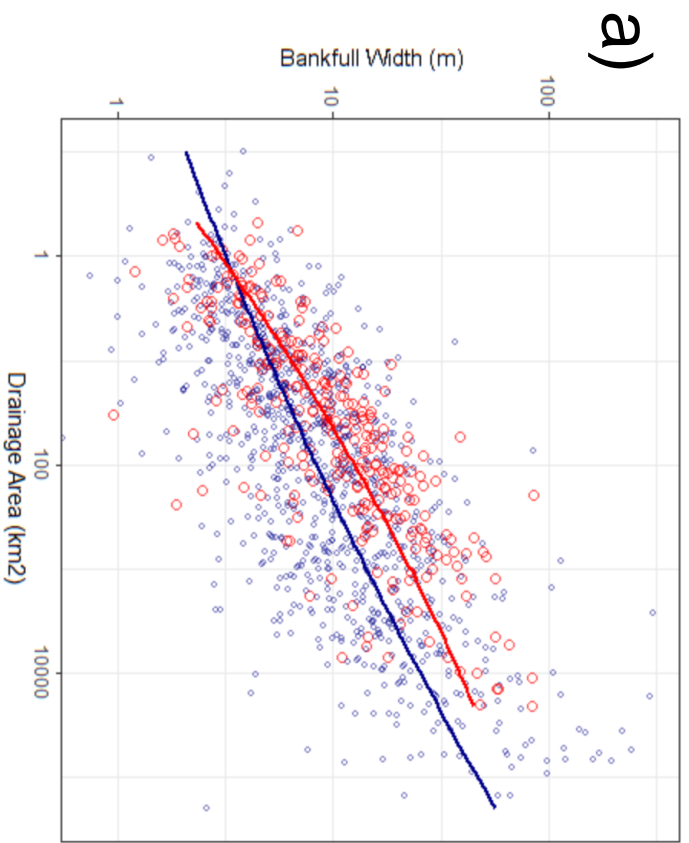
τ_c = critical shear stress of river bed
 τ^* = dimensionless shear stress
 ρ_s = density of sediment
 ρ_w = density of water
 D_i = sediment grain size as D50
 g = gravitational acceleration

For the geology data (Schruben *et al.*, 1994), we manually examined the 152 rock descriptions and determined whether they defined the area specified as mostly sedimentary, metamorphic or igneous rock types. We then extracted these values at each river site. Faceted plots were produced for the three rock types examining drainage area against width to depth ratio and slope.

For the uplift data we ran multiple linear regression models including variables such as: slope, width, lithology and percent bedrock exposure.

Results

The first hypothesis we tested was whether bedrock exposure affects the geometry of bedrock rivers. Figure 1a indicates that bedrock rivers are similar in width to alluvial rivers at low drainage areas but become wider at drainage areas greater than 100km². Additionally, the width to depth ratio of bedrock rivers is higher than alluvial rivers at drainage areas ~100km², as seen in figure 1c. Figure 1e indicates that bedrock rivers are steeper than alluvial rivers at all drainage areas.



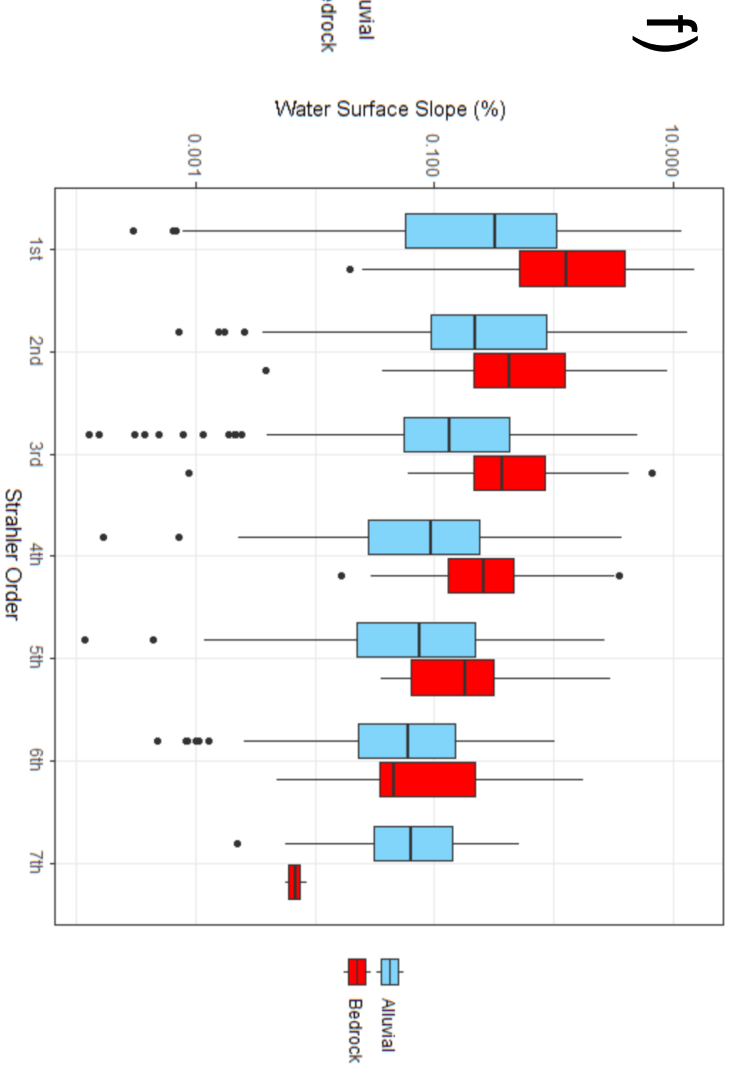
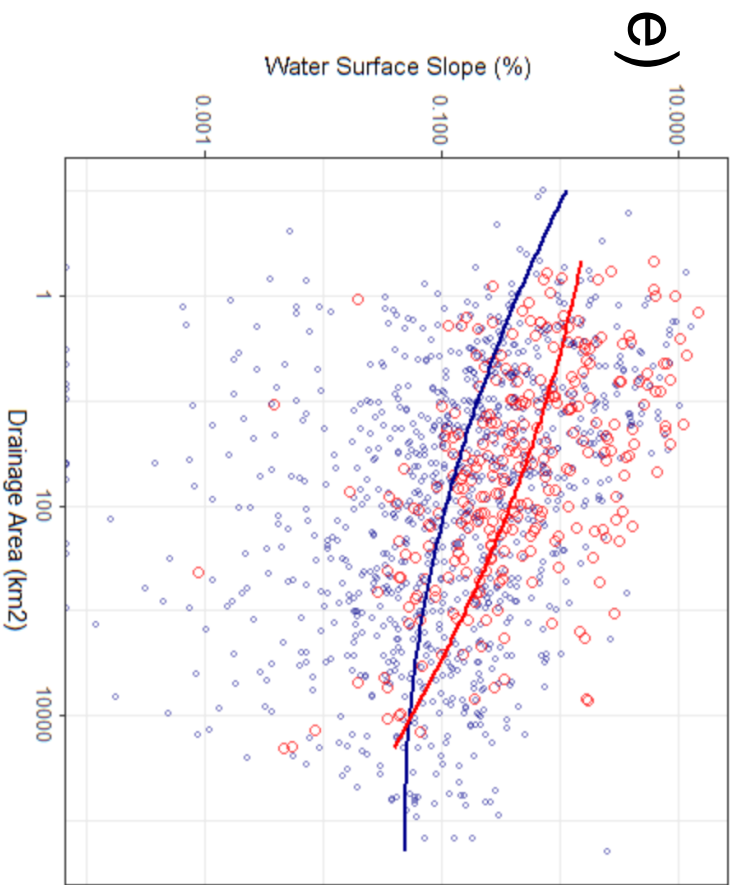


Figure 1. Plots a, c and e show bankfull width, bankfull width to depth ratio and water surface slope against drainage area respectively, split for bedrock and alluvial rivers. Plots b, d and f show box plots of the same metrics against Strahler order..

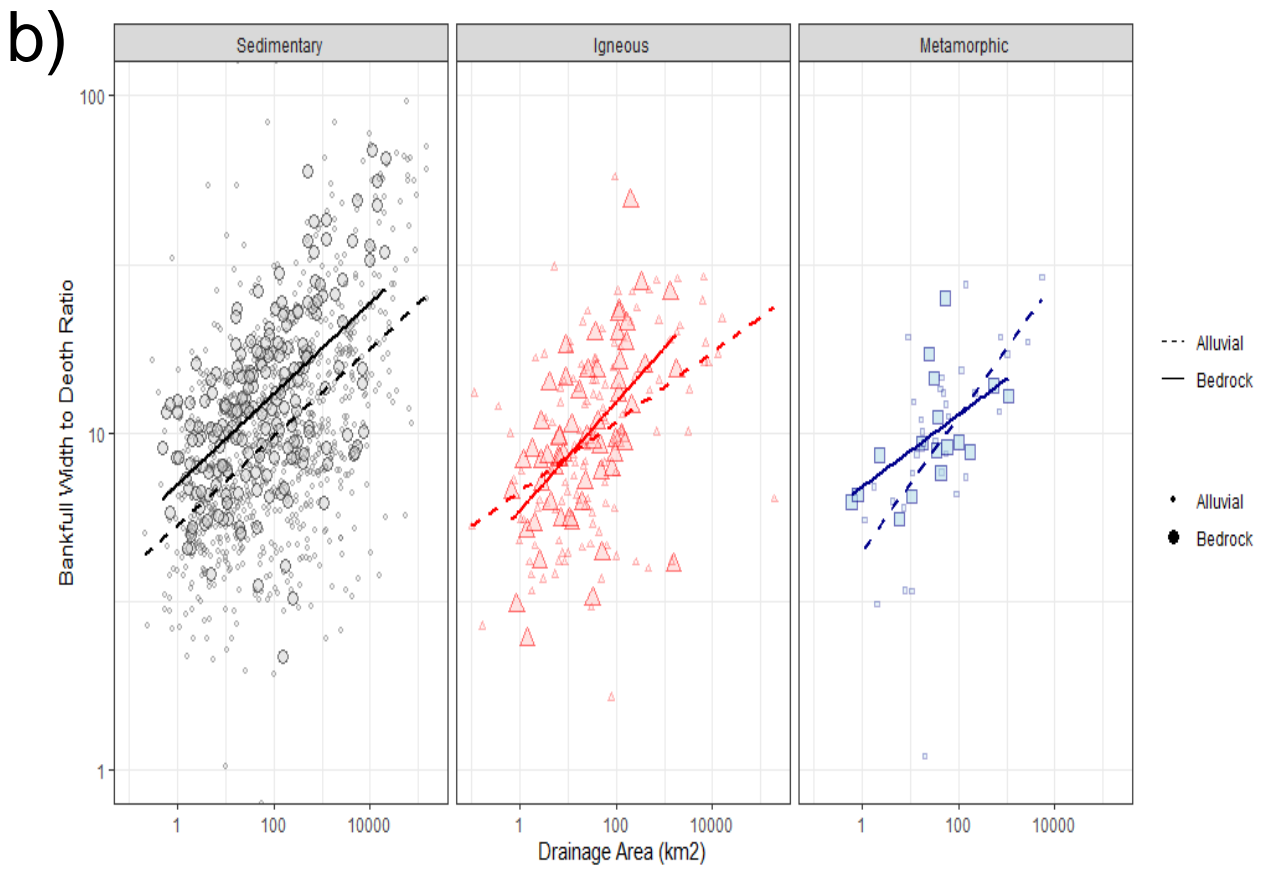
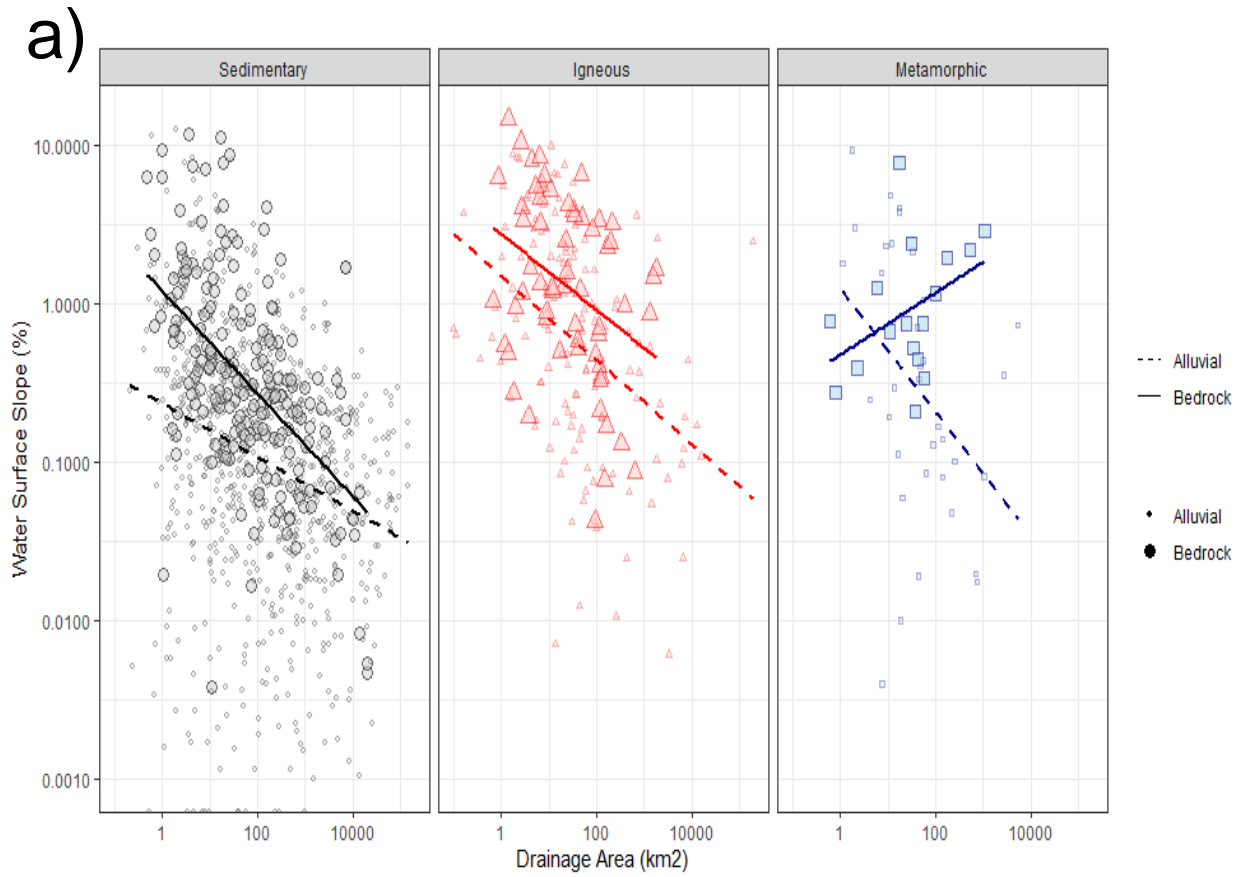


Figure 2. Slope (a) and width to depth ratio (b) against drainage area, split into different rock types and bedrock/ alluvial rivers.

The second hypothesis we tested was how lithology influences bedrock river shape. Figure 2a shows that bedrock rivers could be steeper than alluvial rivers for all rock types. Figure 2b shows sedimentary bedrock channels are wider and shallower at all drainage areas whereas igneous/metamorphic bedrock rivers are similar to alluvial rivers.

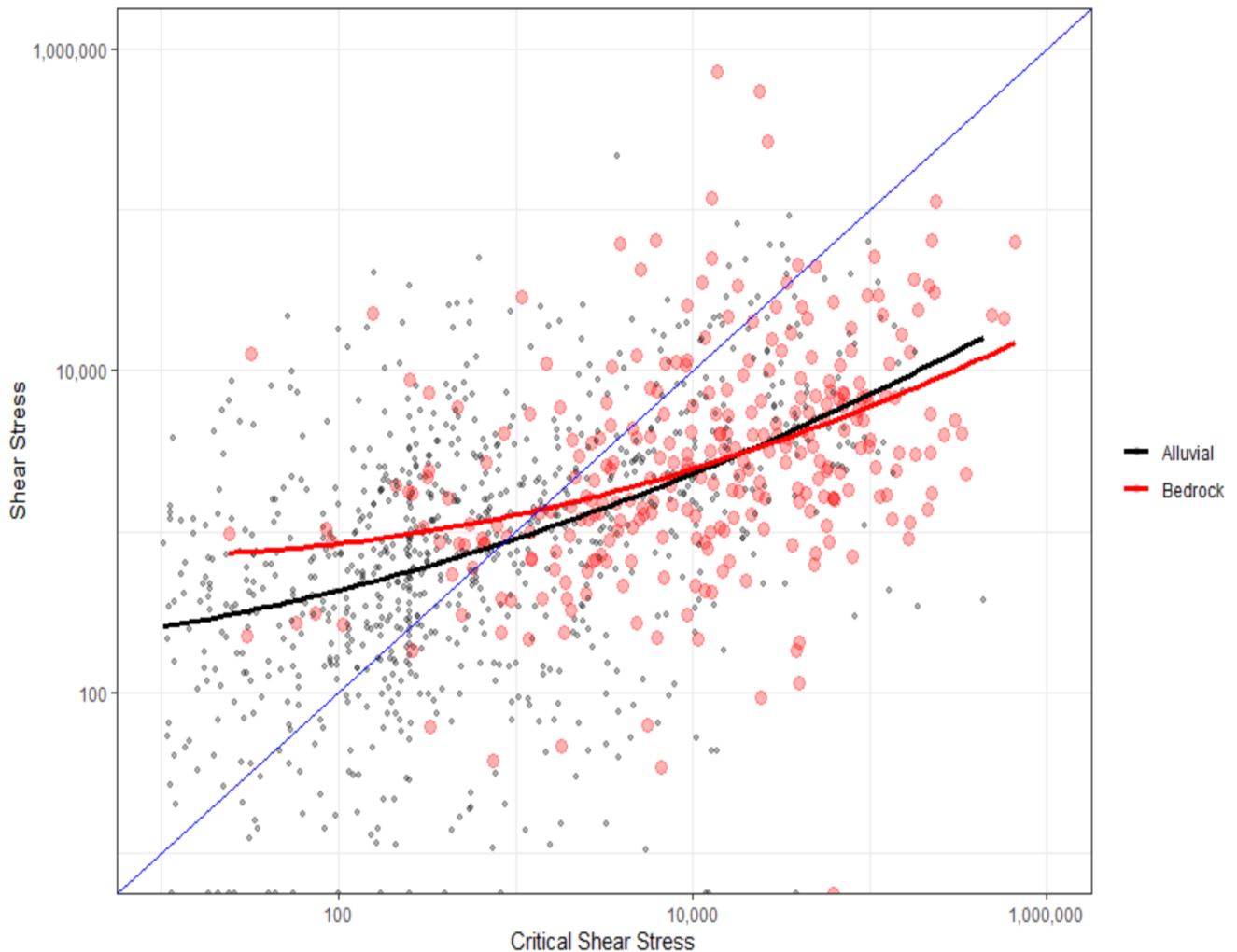


Figure 3. A plot of critical shear stress against shear stress for bedrock and alluvial rivers.

The third hypothesis we tested was could sediment supply be causing bedrock exposure. To test this, we looked at the ratio of shear stress to critical shear stress. Figure 3 shows bedrock rivers to possibly have shear stress exceeding critical shear stress when the grain size is small. However, at higher critical shear stress, bedrock rivers are observed to have a lower ratio of shear stress to critical shear stress than alluvial rivers. As bedrock exposure increases, critical shear stress increases at a faster rate than shear stress (figure 4).

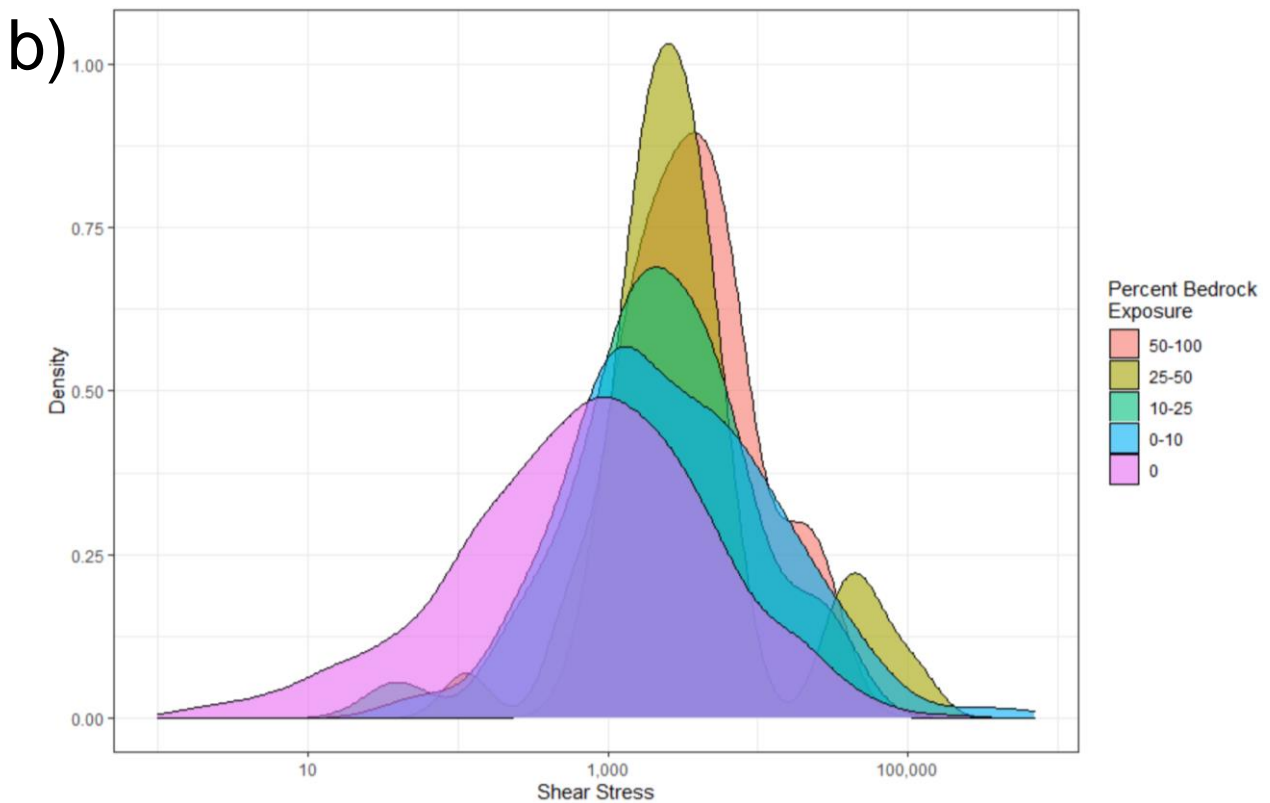
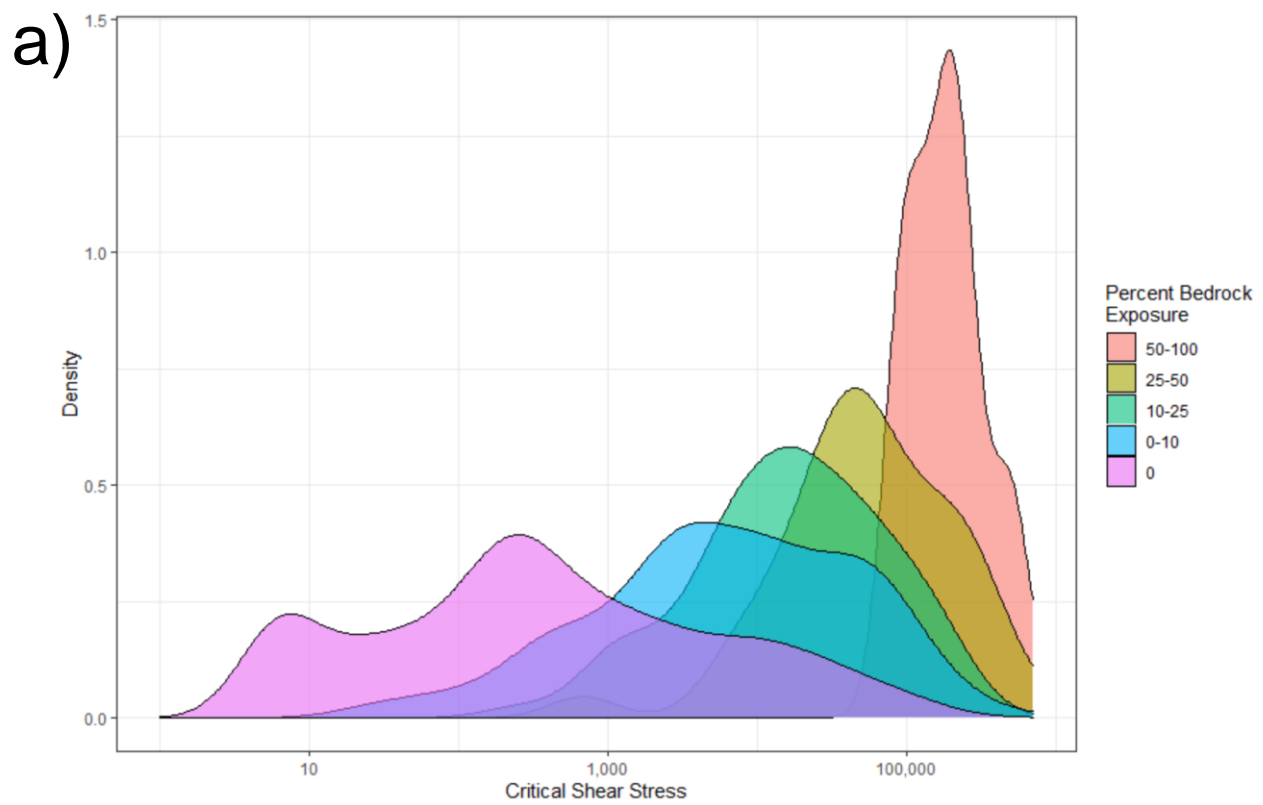


Figure 4. Density plots of critical shear stress (a) and shear stress (b) for bedrock and alluvial rivers

Discussion

We found bedrock channels to be wider and have a higher width to depth ratio than alluvial channels, which contrasts the majority of current literature (Lavé and Avouac, 2001; Duval *et al.*, 2004; Yanites *et al.*, 2018). These differences in width are less pronounced in smaller drainage areas $>100\text{km}^2$. It is expected that exposed bedrock enables the bed to be incised at a rapid rate. In mountainous areas bedrock rivers tend to incise downwards rather than laterally to oppose the high uplift rates. Hence, bedrock rivers are expected to be narrower and deeper than alluvial rivers. Our findings suggest that other factors are influencing bedrock river width and width to depth ratio which will be further examined later in this discussion section.

The ratio of shear stress to critical shear stress for the bedrock river sites was lower than expected in figure 3 with many bedrock sites having higher critical shear stress than shear stress. At lower critical shear stresses, where the sediment grain size is smaller, the ratio of shear stress to critical shear stress for bedrock rivers is >1 so bedrock exposure may be controlled by $Q_c > Q_s$. At higher critical shear stress the bedrock river sites have a similar ratio of shear stress to critical shear stress as alluvial rivers, indicating other factors influence bedrock exposure when the grain size is larger. However, the methods of measuring grain size in the dataset are not very precise so any conclusions drawn from this data are tentative.

Lithology appears to influence the width to depth ratio of bedrock rivers as shown in figure 2b. Sedimentary bedrock rivers are shown to form a distinct geomorphological subclass compared to igneous and metamorphic bedrock rivers. The width to depth ratios for igneous and metamorphic bedrock rivers align with current literature and show bedrock rivers to be narrower and deeper than alluvial rivers. However, sedimentary bedrock rivers are seen to be wider than igneous/metamorphic bedrock rivers at all drainage areas, consistent with the findings of Ferguson *et al.* (2017). This could be because sedimentary rocks have lower rock strength than igneous and metamorphic rocks (Sklar and Dietrich, 2001), though this may be a generalisation of these rock types.

The plots in figure 2 also show sedimentary bedrock river sections occur at larger drainage areas which could indicate that they make up most of the bedrock river sections not found in upland areas. Therefore, due to most studies focusing on mountainous bedrock rivers, sedimentary bedrock rivers could be underrepresented in the current literature.

Conclusions

This study provides a novel large-scale field analysis of the differences between alluvial and bedrock rivers as suggested by Whipple (2004). We found the analyses of channel slope to be consistent with the current literature, showing bedrock rivers to be steeper than alluvial rivers. However, some bedrock rivers were found to be wider than alluvial rivers which contrasts bedrock incision models and other, smaller sample size field studies. Upon further examination lithology was found to have a major influence on bedrock channel width to depth ratio with sedimentary bedrock rivers forming a distinct geomorphological subclass in comparison to

igneous/metamorphic bedrock rivers. Further research needs to be conducted into the controls of lithology on bedrock river geomorphology by testing specific rock types in different environments.

The dataset examined was one of the first large datasets with percentage bedrock exposure data. Therefore, we were able to look at the ratio of shear stress to critical shear stress at bedrock and alluvial sites in this study. We found that $Q_c > Q_s$ could only explain bedrock exposure when the local grain size was smaller, and at high critical shear stresses the ratio of shear stress to critical shear stress was similar in bedrock and alluvial rivers. This reveals that controls on bedrock exposure may be more complex or governed by different factors in mountainous and non-mountainous areas. Further studies should be carried out on mixed-bedrock rivers in non-mountainous environments. Additionally, a more diverse range of bedrock river sites could be found using spatial data and remote sensing techniques.

These analyses have implications in landscape evolution modelling of upland areas. Bedrock river incision and shape could be predicted more reliably by including lithology and uplift variables in the models. This will help us understand how to better manage anthropogenic changes to rivers in the future.

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References

- Allen, G.H., Barnes, J.B., Pavelsky, T.M. and Kirby, E., 2013. Lithologic and tectonic controls on bedrock channel form at the northwest Himalayan front. *Journal of Geophysical Research: Earth Surface*, 118(3), pp.1806-1825.
- DiBiase, R.A., Whipple, K.X., Heimsath, A.M. and Ouimet, W.B., 2010. Landscape form and millennial erosion rates in the San Gabriel Mountains, CA. *Earth and Planetary Science Letters*, 289(1-2), pp.134-144.
- Duvall, A., Kirby, E. and Burbank, D., 2004. Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California. *Journal of Geophysical Research: Earth Surface*, 109(F3).
- Ferguson, S.P. and Rennie, C.D., 2017. Influence of alluvial cover and lithology on the adjustment characteristics of semi-alluvial bedrock channels. *Geomorphology*, 285, pp.260-271.
- Finnegan, N.J., Roe, G., Montgomery, D.R. and Hallet, B., 2005. Controls on the channel width of rivers: Implications for modeling fluvial incision of bedrock. *Geology*, 33(3), pp.229-232.
- Harkins, N., Kirby, E., Heimsath, A., Robinson, R. and Reiser, U., 2007. Transient fluvial incision in the headwaters of the Yellow River, northeastern Tibet, China. *Journal of Geophysical Research: Earth Surface*, 112(F3).
- Kirby, E. and Whipple, K., 2001. Quantifying differential rock-uplift rates via stream profile analysis. *Geology*, 29(5), pp.415-418.

- Kirby, E., Whipple, K.X., Tang, W. and Chen, Z., 2003. Distribution of active rock uplift along the eastern margin of the Tibetan Plateau: Inferences from bedrock channel longitudinal profiles. *Journal of Geophysical Research: Solid Earth*, 108(B4).
- Kobor, J.S. and Roering, J.J., 2004. Systematic variation of bedrock channel gradients in the central Oregon Coast Range: implications for rock uplift and shallow landsliding. *Geomorphology*, 62(3-4), pp.239-256.
- Lavé, J. and Avouac, J.P., 2001. Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *Journal of Geophysical Research: Solid Earth*, 106(B11), pp.26561-26591.
- Montgomery, D.R. and Gran, K.B., 2001. Downstream variations in the width of bedrock channels. *Water Resources Research*, 37(6), pp.1841-1846.
- Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M. and Stock, J.D., 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature*, 381(6583), pp.587-589.
- Ouimet, W.B., Whipple, K.X. and Granger, D.E., 2009. Beyond threshold hillslopes: Channel adjustment to base-level fall in tectonically active mountain ranges. *Geology*, 37(7), pp.579-582.
- Schruben, Paul G., Arndt, Raymond E., Bawiec, Walter J., King, Philip B., and Beikman, Helen M., 1994, *Geology of the Conterminous United States at 1:2,500,000 Scale -- A Digital Representation of the 1974 P.B. King and H.M. Beikman Map: U.S. Geological Survey Digital Data Series DDS-11*, U.S. Geological Survey, Reston, VA.
- Sklar, L.S. and Dietrich, W.E., 2001. Sediment and rock strength controls on river incision into bedrock. *Geology*, 29(12), pp.1087-1090.
- Snyder, N.P., Whipple, K.X., Tucker, G.E. and Merritts, D.J., 2003. Importance of a stochastic distribution of floods and erosion thresholds in the bedrock river incision problem. *Journal of Geophysical Research: Solid Earth*, 108(B2).
- Turowski, J.M., Lague, D. and Hovius, N., 2009. Response of bedrock channel width to tectonic forcing: Insights from a numerical model, theoretical considerations, and comparison with field data. *Journal of Geophysical Research: Earth Surface*, 114(F3).
- U.S. Environmental Protection Agency. 2016. National Aquatic Resource Surveys. National Rivers and Streams Assessment 2008-2009 (data and metadata files). Available from U.S. EPA web page: <https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys>. Date accessed: 10/09/2020
- Whipple, K.X., 2004. Bedrock rivers and the geomorphology of active orogens. *Annu. Rev. Earth Planet. Sci.*, 32, pp.151-185.
- Whipple, K.X., Dibiase, R.A. and Crosby, B.T., 2013. Bedrock rivers. In *Treatise on geomorphology* (pp. 550-573). Elsevier Inc..
- Whittaker, A.C., Cowie, P.A., Attal, M., Tucker, G.E. and Roberts, G.P., 2007. Bedrock channel adjustment to tectonic forcing: Implications for predicting river incision rates. *Geology*, 35(2), pp.103-106.
- Wohl, E. and David, G.C., 2008. Consistency of scaling relations among bedrock and alluvial channels. *Journal of Geophysical Research: Earth Surface*, 113(F4).
- Yanites, B.J., 2018. The dynamics of channel slope, width, and sediment in actively eroding bedrock river systems. *Journal of Geophysical Research: Earth Surface*, 123(7), pp.1504-1527.
- Yanites, B.J., Tucker, G.E., Mueller, K.J., Chen, Y.G., Wilcox, T., Huang, S.Y. and Shi, K.W., 2010. Incision and channel morphology across active structures along the Peikang River, central Taiwan: Implications for the importance of channel width. *Bulletin*, 122(7-8), pp.1192-1208.