Bedrock rivers are steep but not narrow: Hydrological and lithological controls on river geometry across the USA

James Buckley[1], Rebecca A. Hodge[1] and Louise J. Slater[2]

[1] *Department of Geography, Durham University, Durham, DH1 3LE, UK*

[2] *School of Geography and the Environment, University of Oxford, Oxford, OX1 3QY, UK*

ABSTRACT

Bedrock rivers are often expected to have steeper and narrower channels than alluvial rivers. However, understanding of bedrock river characteristics has largely been based on small samples of sites in specific climates and upland locations. We provide the first systematic assessment of bedrock and alluvial river channel characteristics for 1274 sites across a broad climatic gradient. We assess whether the width, width-to-depth-ratio and slope of bedrock channels differ from those of alluvial channels, and the extent to which these differences are correlated with drainage area, mean annual flow (Q_{MAF}), grain size and lithology. We find that bedrock channels occur at all drainage areas. For the same drainage area, bedrock rivers are wider and steeper than alluvial channels. They also have a higher mean annual precipitation and hence Q_{MAF}, which likely causes the increased width. After accounting for differences in Q_{MAF}, both bedrock and alluvial channels have similar hydraulic scaling. Lithology affects both types of channels in a similar way, with channels on sedimentary lithologies being wider and less steep compared to those on igneous-metamorphic lithologies. Overall, our findings raise new questions about the evolution of bedrock river channels and pave the way for more accurate landscape evolution modelling.

INTRODUCTION

River incision into bedrock is a key process by which landscapes respond to tectonics and climate. Turowski et al. (2008) define a bedrock river as one that "cannot substantially widen, lower, or shift its bed without eroding bedrock". The geometric properties of bedrock rivers, specifically how width (w), width to depth ratio (w/d), and slope (S) scale with discharge (Q) and drainage area (A), are important predictors of channel incision rates. This is because w, w/d and S affect the shear stress (τ) produced by the supplied discharge, determining the rate at which sediment grains are transported and can erode the bed (Sklar and Dietrich, 2004). Robust predictions of bedrock river geometry are therefore necessary to improve landscape evolution modelling, given that almost all models include an implicit or explicit prediction of how w changes with Q (e.g. Attal et al., 2008; Yanites, 2018). Predictions are also necessary for managing these channels, such as planning restoration schemes and flood modelling.

Despite the importance of bedrock rivers, we still do not fully understand how hydraulic geometry differs between bedrock and alluvial channels. Estimates have largely been based on relatively small sample sizes, in specific climatic zones and small catchment areas (e.g. (Montgomery and Gran, 2001; Wohl and David, 2008; Turowski et al., 2008; Allen et al., 2013; Spotila et al., 2015; Whitbread et al., 2015; Ferguson and Rennie, 2017). These studies are sometimes contradictory, and it is difficult to assess the relative importance of different controlling factors. Furthermore, many of these studies use A as a substitute for Q, meaning that any systematic variation in Q for the same A is not accounted for, potentially making the findings location-specific (Ferguson and Rennie, 2017).

Bedrock rivers are commonly thought to be narrower than alluvial rivers (e.g. Wohl and Merritt, 2001; Whitbread et al., 2015; Whipple et al., 2022; Wright et al., 2022). Narrowing has been explained as a mechanism to maintain incision rates in both bedrock and alluvial channels under increased uplift (e.g. Duvall et al., 2004; Finnegan et al., 2005; Whittaker et al., 2007; Pan et al., 2015). However, some field studies found no difference in the width of bedrock channels (Montgomery and Gran, 2001; Wohl and David, 2008) or that bedrock rivers could be wider (Spotila et al., 2015; Ferguson and Rennie, 2017). *w*/*d* is not commonly reported, but Wohl and David (2008) found that *w*/*d* was neither constant along bedrock rivers (*c.f.* Finnegan et al., 2005; Wobus et al., 2006), nor did it scale systematically with *A* (*c.f.* Turowski et al., 2007; Whitbread et al., 2015). Bedrock rivers appear to be steeper than alluvial rivers, both in areas with and without tectonic uplift (e.g. Howard and Kerby, 1983; Wohl and David, 2008; Whitbread et al., 2015), although some studies found no difference (Ferguson and Rennie, 2017). Lithology has been observed to affect bedrock river geometry, with changes in *S* and *w* at lithological boundaries, and narrower, steeper channels in more resistant rocks (Duvall et al., 2004; Jansen et al., 2010; Allen et al., 2013; Spotila et al., 2015; Ferguson and Rennie, 2017; Eidmann and Gallen, 2023). But, in contrast, DiBiase et al. (2010) found lithology had a minor influence.

To test the controls on bedrock river geometry, we analyse a large-sample dataset (1274 sites) of alluvial and bedrock river geometry, sampled across the broad climatic gradient of the conterminous United States. We compare hydraulic scaling relationships between *Q* or *A* and *w*, *w*/*d*, and *S* for bedrock and alluvial channels, and we evaluate the impact of lithology on these relationships.

METHODS

We used the National Rivers and Streams Assessment 2008-2009 dataset (U.S. Environmental Protection Agency, 2016) of river channel properties across the conterminous USA, collected using standardised collection protocols (Fig. 1, Table S1). We focus on 1274 sites where the presence/absence of exposed bedrock was recorded at over 100 locations across the channel bed. For each site we also extracted: bankfull channel width (*w*, m), water surface slope (*S*, %), bankfull width to depth ratio (*w*/*d*), mean annual flow (Q_{MAF}, $m^3\ s^{-1}$, predicted using unit runoff method), drainage area (*A*, km^2), and geometric mean grain size

(D_{gm}, mm). The lithology at each site was obtained from the Geology of the Conterminous United States dataset (Schruben et al., 1994), and categorised as sedimentary (Sed) or igneous/metamorphic (I/M).

We analysed variations in channel geometry between bedrock and alluvial sites, and by lithology. To identify if a controlling factor was statistically significant, e.g. whether the relationship between w and A differed between bedrock/alluvial groups, we calculated the difference between w and a reference width ($\log(w) - \log(\hat{w})$) for each site, where the reference width $\hat{w}$ was calculated from a linear fit to the entire logged dataset. We then used ANOVA to test for differences in the distributions of $\log(w) - \log(\hat{w})$ between groups.

We define bedrock channels as those with any recorded exposed bedrock. To apply the definition of Turowski et al. (2008), this bedrock should control changes in channel geometry, which we have not been able to verify. A conservative approach might use a higher threshold of exposed bedrock, but Turowski et al. (2008) note that many bedrock controlled channels still contain substantial sediment cover. Furthermore, using a higher threshold does not alter our findings (Fig. S1). Due to data availability, we use Q_{MAF} to compare Q between channels. Although Q_{MAF} is likely to be too small to drive morphological changes we assume that it scales with larger flow percentiles. In alluvial channels, channel geometry adjusts to bankfull conditions (Parker, 1978), and so we focus on bankfull geometry, although in bedrock channels it is unclear what size of flood most controls channel geometry (Wohl and David, 2008). Channel geometry was not affected by the Human Development Index (an indication of human disturbances to the river site, including dams, paved areas, pipes, landfill, agricultural practices, logging and mining), suggesting limited direct influence of such factors (Fig. S2).

RESULTS

Channel Geometry

Bedrock rivers comprise 23% of 1274 sites (Fig. 1), and occur across the range of A though less frequently when $A > \sim 10^3$ km^2. Contrary to much literature, bedrock rivers are, on average, wider than alluvial rivers at all A, with greater difference at larger A (Fig. 2a). Distributions of $\log(w) - \log(\hat{w})$ are significantly different for bedrock and alluvial channels ($p < 0.001$). However, using Q_{MAF} instead of A removes this difference in w (Fig. 2b), with no significant difference in $\log(w) - \log(\hat{w})$ ($p = 0.86$). This similarity in w when we consider Q_{MAF} instead of A is because bedrock channels have a higher Q_{MAF} than alluvial channels for the same A (comparing distributions of $\log(Q_{MAF}) - \log(\widehat{Q_{MAF}})$, $p < 0.001$; Fig. 2e). The higher Q_{MAF} for bedrock channels is correlated with higher catchment-weighted mean annual precipitation (MAP) (Fig. S3). We therefore use Q_{MAF} in subsequent analysis to isolate the additional impact of other factors. Bedrock channels have significantly higher w/d values than alluvial channels (Fig. 2c, $p<0.05$). They are highly significantly steeper (Fig. 2d, $p<0.001$), though the difference in S decreases with increasing Q_{MAF}. D_{gm} is highly significantly different, with larger D_{gm} for bedrock rivers across all Q_{MAF} (Fig. 2f, $p < 0.001$). Most bedrock channels have substantial sediment cover (median bedrock exposure of 7%), but we find no relationship between channel geometry and percentage bedrock exposure (Fig. S1). Channel geometry is not affected by the presence or absence of laterally constraining bedrock features (Fig S4).

Lithology

Most channels are on sedimentary rocks, with 25% of bedrock and 17% of alluvial channels on the more resistant I/M lithology. Both channel types are significantly wider on Sed lithologies ($p \leq 0.01$, Fig. 3a and b). Alluvial rivers show no significant differences in w/d. But, for bedrock rivers, Sed lithologies have a significantly higher w/d than I/M ones (Fig. 3c and d, $p< 0.01$). For both channel types, rivers on I/M rocks are significantly steeper (Fig. 3e and f, $p < 0.001$). D_{gm} also varies with lithology in both channel types, with significantly coarser sediment on I/M lithologies (Fig. 4).

DISCUSSION

Channel Geometry

A surprising finding from our data is that, for a given A, bedrock rivers are on average wider than alluvial rivers. For the same A, bedrock rivers also have higher Q_{MAF} (Fig. 2e), which is correlated with higher MAP, and so their larger w is likely an adjustment to higher Q. In contrast, relationships between w and Q_{MAF} are not significantly different between bedrock and alluvial channels, as also found by Wohl and David (2008) and Turowski et al. (2008). Our finding that bedrock channels are steeper than alluvial ones is consistent with previous work (Wohl and David, 2008; Whitbread et al., 2015).

Phillips and Jerolmack (2016) found that both bedrock and alluvial channels appeared to adjust w and hence τ so that bankfull Q just exceeded the critical τ (τ_c) for bedload transport. The similarity in w-Q_{MAF} scaling across both channel types (Fig. 2) may appear to suggest that w has adjusted in both in similar ways. One caveat to our analysis is that Q_{MAF} will not necessarily have the same scaling with bankfull Q across all locations due to differences in flow regimes, and this may explain some of the scatter in Fig. 2b. Another caveat is that bankfull bedload also depends on channel adjustment to S and D_{gm}, with the higher S but coarser D_{gm} of bedrock channels respectively increasing and decreasing sediment mobility. However, once Q_{MAF} is accounted for, there is overlap between the geometry of bedrock channels and the steep and coarse subset of alluvial channels, and so our results not do not disprove Phillips and Jerolmack (2016). Further analysis would require bedload data from more bedrock channels, or predictions of τ_c, which are complicated by the effects of exposed bedrock on entrainment (Hodge et al., 2011). However, the substantial sediment cover in most of the bedrock channels suggests that adjustment in order to transport the supplied sediment load is an important component of bedrock channel evolution (Turowski et al., 2008).

Lithology

Accounting for variation in Q_{MAF}, we then find that *w*, *w*/*d* and *S* depend on lithology, with Sed channels being wider and less steep than I/M ones. The difference between our data and the common finding of narrower bedrock channels can potentially be reconciled, as we find that bedrock channels are narrower in I/M rocks, which is consistent with where such narrowing has been identified previously (e.g. Montgomery and Gran, 2001; Wohl and David, 2008; Jansen et al., 2010). Such behaviour may therefore not be representative of bedrock rivers more generally. Weaker lithologies have been correlated with wider river valleys (Schanz and Montgomery, 2016), but previous findings that bedrock channels might be wider in Sed rocks are limited by small sample size (Ferguson and Rennie, 2017), or a single location (Spotila et al., 2015; Eidmann and Gallen, 2023; Chen and Byun, 2023). The occurrence of wide Sed bedrock channels has been attributed to differences in erosional processes. Sed lithologies can potentially be more quickly laterally eroded through plucking and slaking, whereas lateral erosion is slower in more resistant I/M lithologies which instead erode vertically through abrasion (Montgomery and Gran, 2001; Spotila et al., 2015; Ferguson and Rennie, 2017). We also observe a difference in grain size between Sed and I/M lithologies, and so differences in channel geometry may also reflect sediment calibre, especially in alluvial channels.

A potential alternative, or additional, control on *w* is sediment supply. Ferguson and Rennie (2017) found that wider bedrock channels in sedimentary rocks had no sediment cover. But, channel widening is more commonly attributed to higher sediment supply (Whitbread et al., 2015; Inoue et al., 2016; Yanites, 2018; Baynes et al., 2020), with sediment cover distributing erosion across the channel and deflecting saltating grains into the banks (Turowski, 2018; Li et al., 2020). However, our data show no correlation between percentage bedrock and *w*, or with log(*w*) - log($\hat{w}$) (Fig. S1). Identifying the role of sediment supply is complicated by its temporal variability (Lague, 2010), and by comparing a snapshot of cover with morphology that evolves over multiple floods. Consequently, the measured alluvial cover may not represent long-term average sediment supply. Uplift rate is another factor that will also affect channel geometry (Turowski, 2018), but which cannot easily be measured across the timescales that are relevant to channel morphological development.

SUMMARY

Bedrock channels occur at all drainage areas. For a given drainage area, bedrock channels are on average wider than alluvial channels, which is explained by bedrock channels responding to their typically higher discharge for the same drainage area. Once discharge has been accounted for, we find that bedrock and alluvial channels show similar channel geometries, although bedrock channels are more likely to be found at higher slopes. Lithology also affects channel properties, but in similar ways for bedrock and alluvial channels. Our results highlight the importance of considering channel geometry relative to discharge rather than drainage area. These findings have implications for modelling and managing the processes in these systems.

ACKNOWLEDGEMENTS

This work was initiated when JB was a Laidlaw Scholar. Thanks also to Durham University Geography Department's Research Development Fund. Data are available at 10.5281/zenodo.8210986. Thanks to five anonymous reviewers and Jens Turowski whose comments helped to improve earlier versions of this work. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

FIGURES

Figure 1. All sites across the conterminous United States. 977 (77%) sites are alluvial, and 297 (23%) are bedrock.

Figure 2. Bedrock (orange) and alluvial (blue) river channel geometries by drainage area (A) or mean annual flow (Q_{MAF}). Dashed lines show linear regression fits and shaded areas show corresponding 95% confidence bands. Box plots show distributions of differences between the y value and a reference $\hat{y}$ value calculated from a linear fit to the entire logged dataset, with p values calculated using ANOVA.

Figure 3. The influence of lithology on channel geometry. Data are split by channel type, and lithology (sedimentary: yellow; igneous and metamorphic; purple). Linear fits and boxplots as in Fig. 2.

Figure 4. The influence of lithology on D_{gm}. Data are split by channel type, and lithology (sedimentary: yellow; igneous and metamorphic; purple). Linear fits and boxplots as in Fig. 2.

REFERENCES CITED

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, v. 118, p. 1806–1825, doi:10.1002/jgrf.20113.

Attal, M., Tucker, G.E., Whittaker, A.C., Cowie, P.A., and Roberts, G.P., 2008, Modeling fluvial incision and transient landscape evolution: Influence of dynamic channel adjustment: Journal of Geophysical Research: Earth Surface, v. 113, doi:10.1029/2007JF000893.

Baynes, E.R.C., Lague, D., Steer, P., Bonnet, S., and Illien, L., 2020, Sediment flux-driven channel geometry adjustment of bedrock and mixed gravel–bedrock rivers: Earth Surface Processes and Landforms, p. esp.4996, doi:10.1002/esp.4996.

Chen, H., and Byun, J., 2023, Effects of erosional resistance on bedrock channel occurrence and morphology: Examination of the Seo River catchment in South Korea: Geomorphology, p. 108810, doi:10.1016/j.geomorph.2023.108810.

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, v. 289, p. 134–144, doi:10.1016/j.epsl.2009.10.036.

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, v. 109, doi:10.1029/2003JF000086.

Eidmann, J.S., and Gallen, S., 2023, New remote method to systematically extract bedrock channel width of small catchments across large spatial scales using high-resolution digital elevation models: Earth Surface Processes and Landforms, p. esp.5560, doi:10.1002/esp.5560.

Ferguson, S.P., and Rennie, C.D., 2017, Influence of alluvial cover and lithology on the adjustment characteristics of semi-alluvial bedrock channels: Geomorphology, v. 285, p. 260–271, doi:10.1016/j.geomorph.2017.01.040.

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, v. 33, p. 229–232, doi:10.1130/G21171.1.

Hodge, R.A., Hoey, T.B., and Sklar, L.S., 2011, Bedload transport in bedrock rivers: the role of sediment cover in grain entrainment, translation and deposition: Journal of Geophysical Research-Earth Surface, v. 116, p. F04028, doi:10.1029/2011JF002032.

Howard, A., and Kerby, G., 1983, Channel changes in badlands: Geological Society of America Bulletin, v. 94, p. 739–752.

Inoue, T., Iwasaki, T., Parker, G., Shimizu, Y., Izumi, N., Stark, C.P., and Funaki, J., 2016, Numerical Simulation of Effects of Sediment Supply on Bedrock Channel Morphology: Journal of Hydraulic Engineering, v. 142, p. 04016014, doi:10.1061/(ASCE)HY.1943-7900.0001124.

Jansen, J.D., Codilean, A.T., Bishop, P., and Hoey, T.B., 2010, Scale Dependence of Lithological Control on Topography: Bedrock Channel Geometry and Catchment Morphometry in Western Scotland: The Journal of Geology, v. 118, p. 223–246, doi:10.1086/651273.

Lague, D., 2010, Reduction of long-term bedrock incision efficiency by short-term alluvial cover intermittency: Journal of Geophysical Research-Earth Surface, v. 115, doi:10.1029/2008JF001210.

Li, T., Fuller, T.K., Sklar, L.S., Gran, K.B., and Venditti, J.G., 2020, A Mechanistic Model for Lateral Erosion of Bedrock Channel Banks by Bedload Particle Impacts: Journal of Geophysical Research: Earth Surface, v. 125, doi:10.1029/2019JF005509.

Montgomery, D.R., and Gran, K.B., 2001, Downstream variations in the width of bedrock channels: Water Resources Research, v. 37, p. 1841–1846, doi:10.1029/2000WR900393.

Pan, B., Li, Q., Hu, X., Geng, H., and Gao, H., 2015, Bedrock channels response to differential rock uplift in eastern Qilian Mountain along the northeastern margin of the Tibetan Plateau: Journal of Asian Earth Sciences, v. 100, p. 1–19, doi:10.1016/j.jseaes.2014.12.009.

Parker, G., 1978, Self-formed straight rivers with equilibrium banks and mobile bed. Part 2. The gravel river: Journal of Fluid Mechanics, v. 89, p. 127–146, doi:10.1017/S0022112078002505.

Phillips, C.B., and Jerolmack, D.J., 2016, Self-organization of river channels as a critical filter on climate signals: Science, v. 352, p. 694–697, doi:10.1126/science.aad3348.

Schanz, S.A., and Montgomery, D.R., 2016, Lithologic controls on valley width and strath terrace formation: Geomorphology, v. 258, p. 58–68, doi:10.1016/j.geomorph.2016.01.015.

Schruben, P.G., Arndt, R.E., Bawiec, W.J., and Ambroziak, R.A., 1994, Geology of the Conterminous United States at 1: 2,500,000 Scale–A Digital Representation of the 1974 PB King and HM Beikman Map: US Geological Survey: Digital Data Series, DDS-11, scale, v. 1, p. 2500000.

Sklar, L.S., and Dietrich, W.E., 2004, A mechanistic model for river incision into bedrock by saltating bed load: Water Resources Research, v. 40, p. W06301, doi:10.1029/2003WR002496.

Spotila, J.A., Moskey, K.A., and Prince, P.S., 2015, Geologic controls on bedrock channel width in large, slowly-eroding catchments: Case study of the New River in eastern North America: Geomorphology, v. 230, p. 51–63, doi:10.1016/j.geomorph.2014.11.004.

Turowski, J.M., 2018, Alluvial cover controlling the width, slope and sinuosity of bedrock channels: Earth Surface Dynamics, v. 6, p. 29–48, doi:https://doi.org/10.5194/esurf-6-29-2018.

Turowski, J.M., Hovius, N., Wilson, A., and Horng, M.-J., 2008, Hydraulic geometry, river sediment and the definition of bedrock channels: Geomorphology, v. 99, p. 26–38, doi:10.1016/j.geomorph.2007.10.001.

Turowski, J.M., Lague, D., and Hovius, N., 2007, Cover effect in bedrock abrasion: A new derivation and its implications for the modeling of bedrock channel morphology: Journal of Geophysical Research-Earth Surface, v. 112, doi:10.1029/2006JF000697.

U.S. Environmental Protection Agency, 2016, National Rivers and Streams Assessment 2008-2009:, https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys (accessed September 2021).

Whipple, K.X., DiBiase, R.A., Crosby, B., and Johnson, J.P.L., 2022, Bedrock Rivers, *in* Treatise on Geomorphology, Elsevier, p. 865–903, doi:10.1016/B978-0-12-818234-5.00101-2.

Whitbread, K., Jansen, J., Bishop, P., and Attal, M., 2015, Substrate, sediment, and slope controls on bedrock channel geometry in postglacial streams: Journal of Geophysical Research: Earth Surface, v. 120, p. 2014JF003295, doi:10.1002/2014JF003295.

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, v. 35, p. 103–106, doi:10.1130/G23106A.1.

Wobus, C.W., Tucker, G.E., and Anderson, R.S., 2006, Self-formed bedrock channels: Geophysical Research Letters, v. 33, p. L18408, doi:10.1029/2006GL027182.

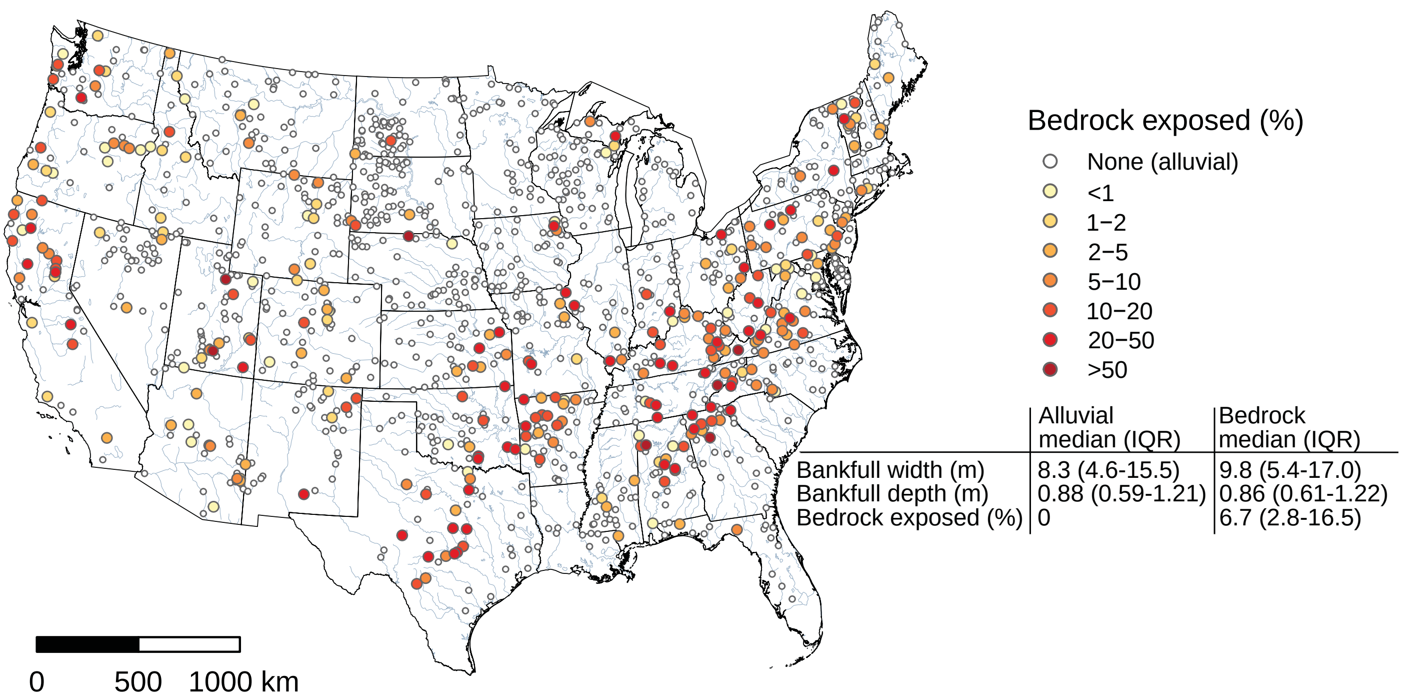
Wohl, E., and David, G.C.L., 2008, Consistency of scaling relations among bedrock and alluvial channels: Journal of Geophysical Research: Earth Surface, v. 113, doi:10.1029/2008JF000989.

Wohl, E.E., and Merritt, D.M., 2001, Bedrock channel morphology: Geological Society of America Bulletin, v. 113, p. 1205–1212.

Wright, M., Venditti, J.G., Li, T., Hurson, M., Chartrand, S., Rennie, C., and Church, M., 2022, Covariation in width and depth in bedrock rivers: Earth Surface Processes and Landforms, p. esp.5335, doi:10.1002/esp.5335.

Yanites, B.J., 2018, The Dynamics of Channel Slope, Width, and Sediment in Actively Eroding Bedrock River Systems: Journal of Geophysical Research: Earth Surface, v. 123, p. 1504–1527, doi:10.1029/2017JF004405.

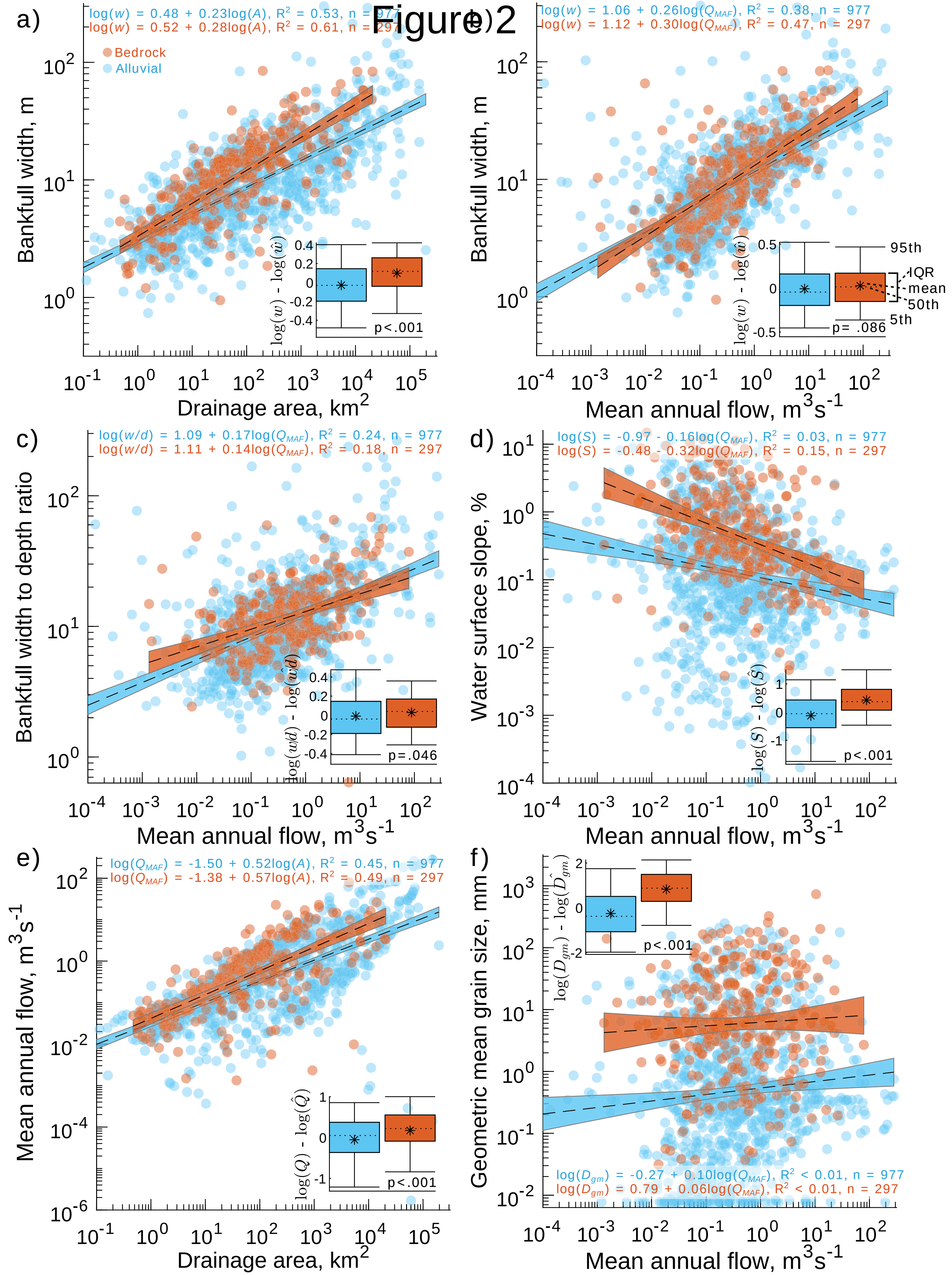
Figure 1



	Alluvial median (IQR)	Bedrock median (IQR)
Bankfull width (m)	8.3 (4.6-15.5)	9.8 (5.4-17.0)
Bankfull depth (m)	0.88 (0.59-1.21)	0.86 (0.61-1.22)
Bedrock exposed (%)	0	6.7 (2.8-16.5)

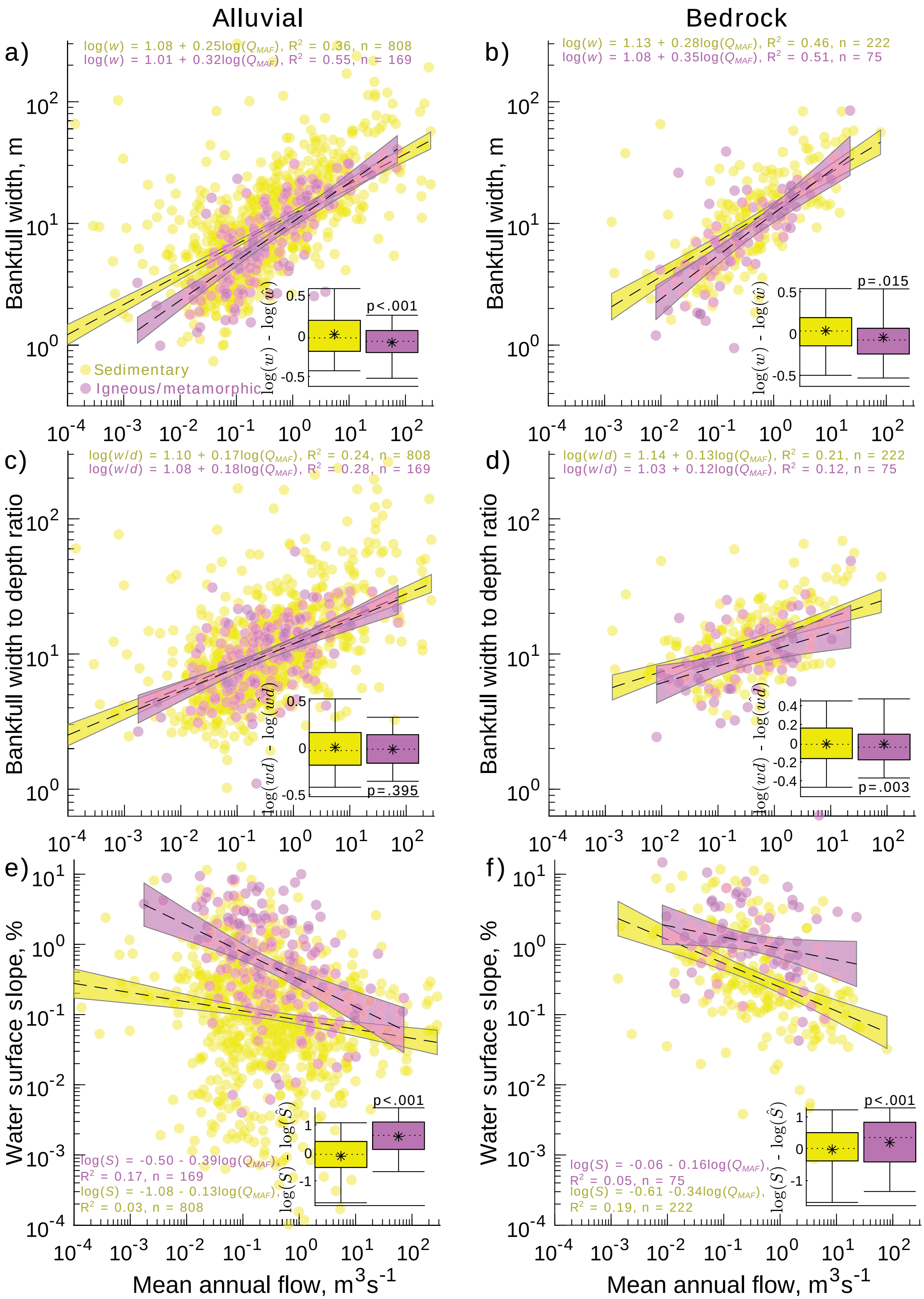
Buckley et al., Fig 1

Figure 2



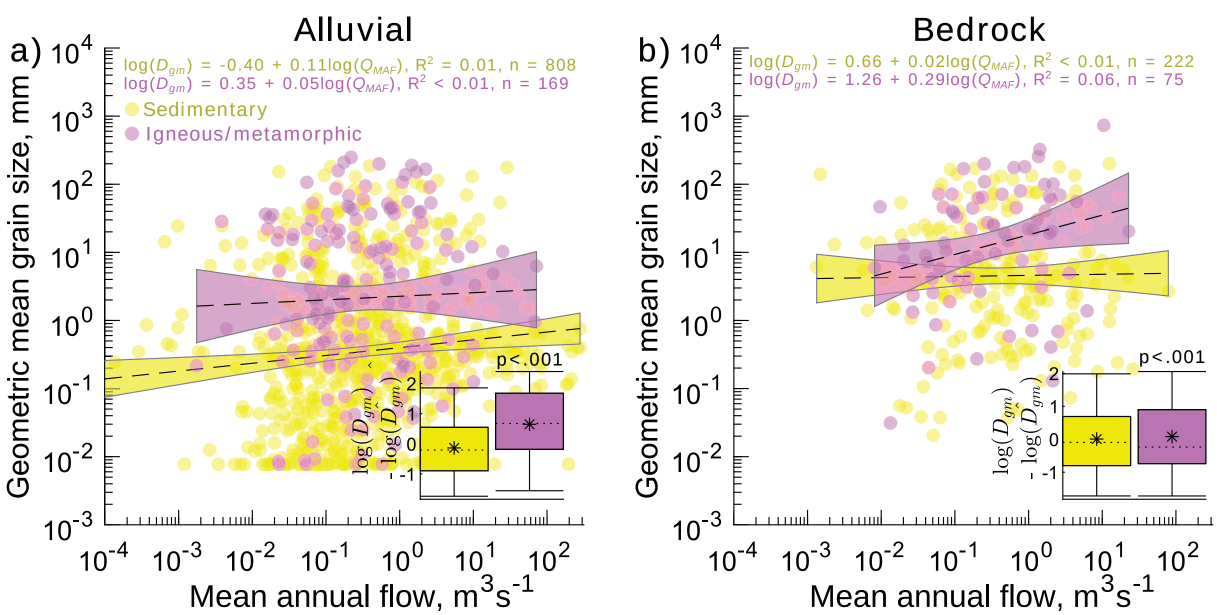
Buckley et al., Fig 2

Figure 3



Buckley et al., Fig 3

Figure 4



a)
Alluvial
log(D_{gm}) = -0.40 + 0.11log(Q_{MAF}), R^2 = 0.01, n = 808
log(D_{gm}) = 0.35 + 0.05log(Q_{MAF}), R^2 < 0.01, n = 169
Sedimentary
Igneous/metamorphic
p<.001
b)
Bedrock
log(D_{gm}) = 0.66 + 0.02log(Q_{MAF}), R^2 < 0.01, n = 222
log(D_{gm}) = 1.26 + 0.29log(Q_{MAF}), R^2 = 0.06, n = 75
p<.001
Geometric mean grain size, mm
Mean annual flow, m^3s^{-1}