XXIV SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

FLOW RESISTANCE IN A MIXED BEDROCK–ALLUVIAL STREAM

Guilherme Kruger Bartels [1]*; George Marino Soares Gonçalves* [2]*; Pedro Loguercio de Ávila* [3] *Nilza Maria dos Reis Castro* [4] *; Gilberto Loguercio Collares* [5]*& Fernando Mainardi Fan* [6]

Palavras-Chave – macro-roughness; flow resistance; bedrock

ABSTRACT

The term mixed bedrock–alluvial characterize streams with patches of exposed bedrock associated with some degree of alluvial cover. In these environments, the presence of large elements (e.g., cobbles, boulders, and bedrock protrusion) are common and cause an increase in resistance to flow due to additional roughness. In the absence of data collected in mixed bedrock -alluvial streams have generally adopted standard flow resistance equations developed for alluvial channels. Thus, we evaluated whether we can apply the empirical flow resistance equations developed for alluvial channels satisfactorily in a mixed bedrock–alluvial stream in Southern Brazil. Our results indicate that the energy loss considered in standard flow resistance equations is underestimated for the flow characteristics of mixed bedrock–alluvial channels. Therefore, in future studies, it is suggested to review the use of standard flow resistance equation, such as investigating different methods to estimate the bed roughness height.

RESUMO

O termo leito misto rochoso-aluvial caracteriza rios com manchas de rocha exposta associadas a algum grau de cobertura aluvial em seu leito. Nesses ambientes, a presença de grandes elementos (por exemplo, blocos, matacões e protuberâncias rochosas) são comuns e causam um aumento na resistência ao fluxo devido à rugosidade adicional. Na ausência de dados coletados em riachos com leito misto, geralmente adotam-se equações padrões de resistência do fluxo desenvolvidas para canais aluviais. Assim, avaliamos se podemos aplicar as equações empíricas de resistência ao fluxo desenvolvidas para canais aluviais de forma satisfatória em um riacho com características de leito misto no sul do Brasil. Nossos resultados indicam que a perda de energia considerada nas equações padrões de resistência do fluxo é subestimada para as características de fluxo em canais com leito mistos rochoso-aluvial. Portanto, em estudos futuros, sugere-se revisar o uso de equações padrões de

---

[1]) Universidade Federal do Rio Grande do Sul, Instituto de Pesquisas Hidráulicas. Rua Bento Gonçalves, 9500. Bairro Agronomia, Campus do Vale, CEP: 91509-900, guilhermebartels@gmail.com

[2]) Universidade Federal de Pelotas, Centro de Desenvolvimento Tecnológico. Rua Gomes Carneiro, 01. Bairro Centro, Campus Anglo, CEP: 96010-610, Pelotas/RS, george.marino.goncalves@gmail.com

[3]) Universidade Federal de Pelotas, Centro de Desenvolvimento Tecnológico. Rua Gomes Carneiro, 01. Bairro Centro, Campus Anglo, CEP: 96010-610, Pelotas/RS, pedrologuercio1@gmail.com

[4]) Universidade Federal do Rio Grande do Sul, Instituto de Pesquisas Hidráulicas. Rua Bento Gonçalves, 9500. Bairro Agronomia, Campus do Vale, CEP: 91509-900, nilza@iph.ufrgs.br

[5]) Universidade Federal de Pelotas, Centro de Desenvolvimento Tecnológico. Rua Gomes Carneiro, 01. Bairro Centro, Campus Anglo, CEP: 96010-610, Pelotas/RS, gilbertocollares@gmail.com

[6]) Universidade Federal do Rio Grande do Sul, Instituto de Pesquisas Hidráulicas. Rua Bento Gonçalves, 9500. Bairro Agronomia, Campus do Vale, CEP: 91509-900, fernando.fan@ufrgs.br

resistência ao fluxo, como a investigação de diferentes métodos para estimar a altura da rugosidade do leito.

INTRODUCTION

In mountain regions are common the presence of streams with patches of exposed bedrock associated with some degree of alluvial cover. The term mixed bedrock–alluvial can be used to characterize the bed of these channels, where the balance between sediment supply and transport capacity defines either the level of the exposure of rock and alluvial cover in a riverbed (Ferguson *et al.*, 2017).

Several characteristics present in these streams increase the resistance to flow due to additional roughness, including large boulders that remain immobile even during high flows (Nitsche *et al.*, 2011), bed material with a wide grain-size distribution (GSD) (Monsalve *et al.*, 2016; Yager *et al.*, 2012a), and reduced relative flow depth (Comiti and Mao, 2012).

Flow resistance relations may be used to predict the mean flow velocity (v) when direct measurements are not possible or available (Schneider *et al.*, 2015b). The Darcy-Weisbach flow resistance equation is widely used to predict v and derive flow resistance relations given it is a dimensionless coefficient (Ferguson, 2007; Rickenmann and Recking, 2011):

$$\frac{v}{\sqrt{gdS}} = \sqrt{\frac{8}{f_{tot}}}, \qquad (1)$$

where v is the mean flow velocity, f_{tot} is the Darcy–Weisbach friction factor, d is the flow depth, S is the energy slope (or the channel bed slope), g is the gravity acceleration, and the right side of the equation represents flow resistance. Flow resistance is often described using empirical equations based on the relative flow depth d/R (where R is bed roughness height).

Many studies used grain size as a descriptor of the bed roughness height, such as D_{84} (84th percentile of the GSD) (Rickenmann and Recking, 2011), D_{65} (65th percentile of the GSD) (Wilcock *et al.*, 2009), or used the dimensions/concentrations of boulders and protrusions (Yager *et al.*, 2012a, 2007). There are recent advances in techniques designed to measure channel topography with high spatial resolution that allow more accurate measurement of river-bed geometry, for example the use of laser scan and photogrammetry, and description by a range of statistical metrics (Hodge *et al.*, 2009; Schneider *et al.*, 2015). The standard deviation of bed elevation (σz) has the potential to describe macro roughness of the bed structure at the reach scale (Coleman *et al.*, 2011). As noted by Nikora *et al.* (1998), σz is a parameter capable of describing bed roughness for a fixed gravel bed with a Gaussian bed elevation distribution.

Among other flow resistance equations, the variable power equation (VPE) developed by Ferguson (2007) considers the friction factor (f_{tot}) as the sum of two components (grain friction and form drag) which are both presents in coarse streambeds:

$$\sqrt{\frac{8}{f_{tot}}} = \frac{a_1 a_2 \left(\frac{d}{D_{84}}\right)}{\sqrt{{a_1}^2 + {a_2}^2 \left(\frac{d}{D_{84}}\right)^{5/3}}}, \qquad (2)$$

where we used the empirical constant values a1 = 6.5 and a2 = 2.5, as suggested by Ferguson (2007) and Rickenmann and Recking (2011). Alternative methods regarding approaches that use relative flow depth and ftot have been proposed to represent the flow velocity. Among these, the dimensionless hydraulic geometry relationships provide better estimates of flow velocities in steep streams (Comiti *et al.*, 2007; Rickenmann and Recking, 2011; Schneider *et al.*, 2015b; Zimmermann, 2010). Thus, the flow velocity can be nondimensionalized as follows:

$$v^{**} = kq^{**m}, \tag{3}$$

where v^{**} is the dimensionless velocity $v^{**} = v/(gSD_{84})^{0.5}$, q** is the dimensionless discharge $q^{**} = q/(gSD_{84}{}^{3})^{0.5}$, q is the discharge per unit channel width, and *k* and *m* are empirical constants. Rickenmann and Recking (2011) transformed the original VPE based on relative flow depth (Eq. 2) to an equivalent q-based form as shown in Eq. 4.

$$v^{**} = \frac{v}{\sqrt{gSD_{84}}} = 1.443q^{**0.6}\left[1 + \left(\frac{q^{**}}{43.78}\right)^{0.8214}\right]^{-0.2435} \tag{4}$$

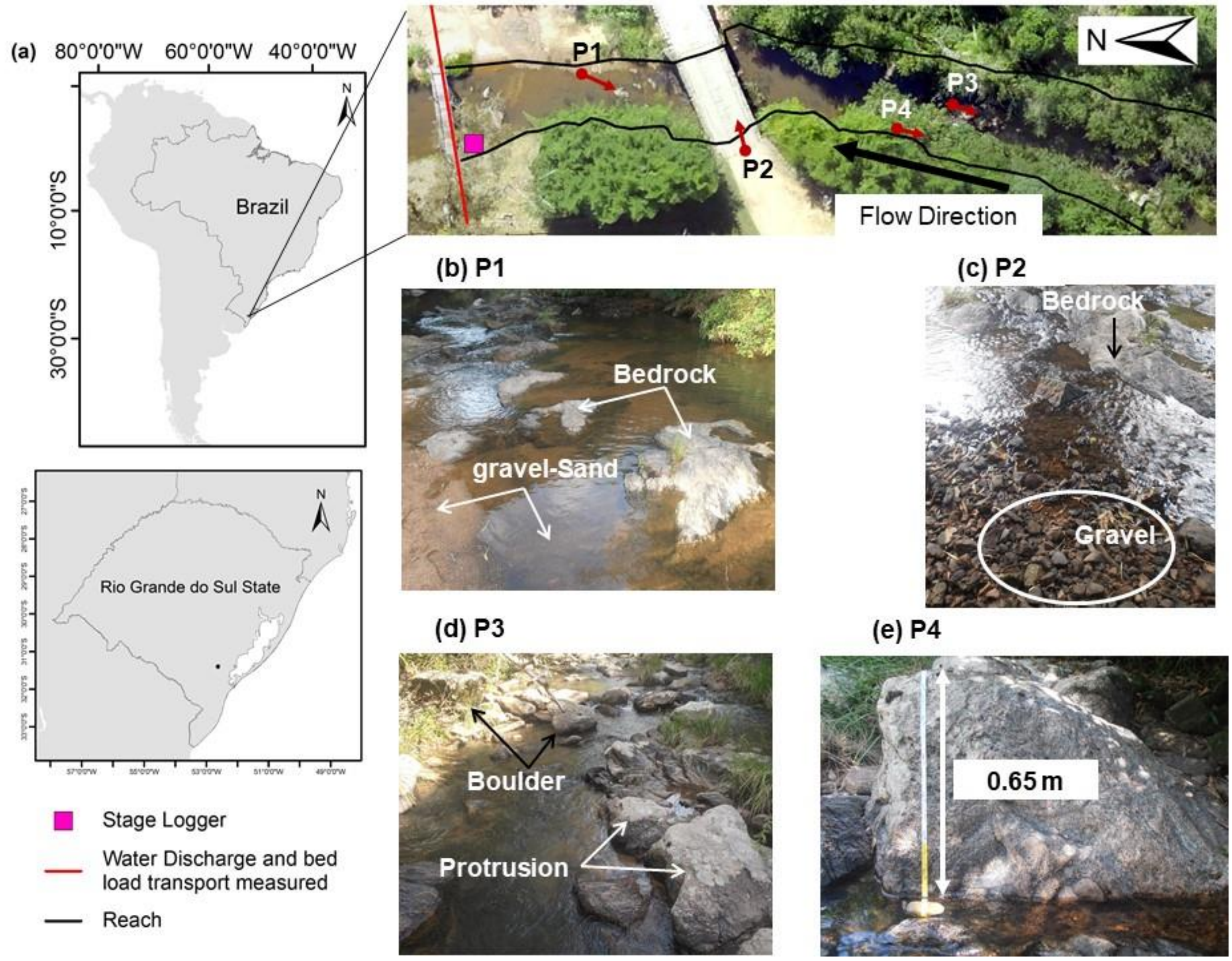
However, flow resistance equations were developed for alluvial channels and are more reliable for streams with low roughness (Rickenmann and Recking, 2011). Although bedrock streams have characteristics in common with coarse bed alluvial channels, the conditions in the reach analyzed (presence of cobbles, boulders, and bedrock protrusion) contrast with those applied initially in flow resistance equations. Thus, we motivated to assess whether we can apply the empirical flow resistance equations developed for alluvial channels satisfactorily in a mixed bedrock–alluvial stream in Southern Brazil. The results of this study were originally published in Bartels *et al.* (2021), being used for a more detailed analysis of bedload transport equations. We consider that the findings on resistance to flow in the mixed bedrock – alluvial channel are relevant for dissemination in a national event, as XXIV SBRH.

MATERIAL AND METHODS

Study área

The study was performed in the Arroio do Ouro watershed, with an area of 17.17 km^2, in the state of Rio Grande do Sul, Brazil (Fig. 1). The elevation ranges from 76 to 326 m above sea level; the mean slope is 7.4°, reaching up to 30°. The climate in the region is Cfa (Köppen classification), characterized by a humid subtropical climate with hot summers and well-distributed rain throughout the year (Peel *et al.*, 2007). The selected river reach is considered representative of existing natural streams in the region.

Figure 1 - (a) Location of the study area. Locations of photographs (P1, P2, P3, and P4): (b) P1 bed with fine sediments (gravel–Sand) and bedrock; (c) P2 showing a gravel-bed and bedrock; (d) P3 showing a coarser bed and bedrock protrusion; (e) P4, an example of a bedrock protrusion measurement. Source: Adapted from Bartels *et al.* (2021).



Mapped reach and flow measurements

We mapped a reach area that was 66 m long, approximately 5.5 m wide, and bed gradient of 2.3%, directly upstream from the cross-section where water discharge measurements were taken. All the procedures adopted to determine the GSD of the bed can be consulted in Bartels et al. (2021). The bed grain size showed a substantial difference between the D50 (16 mm) and the D84 (333 mm), due to the wide range of grain sizes present in the bed (Bartels et al., 2021), from large boulders to sand and gravel (See Fig. 1). A total of 55 discharges were measured between the period of July 2013 to June 2015 using a traditional current meter (Turnipseed and Sauer, 2010). Flow velocity was measured in the cross-section in verticals spaced 0.5 m or 1.0 m, and the water discharge (Q), flow area (A), flow width (W), and wetted perimeter (P) were quantified. From these, we calculated hydraulic radius (R = A/P), average flow depth (d = A/w), and average flow velocity (v = Q/A).

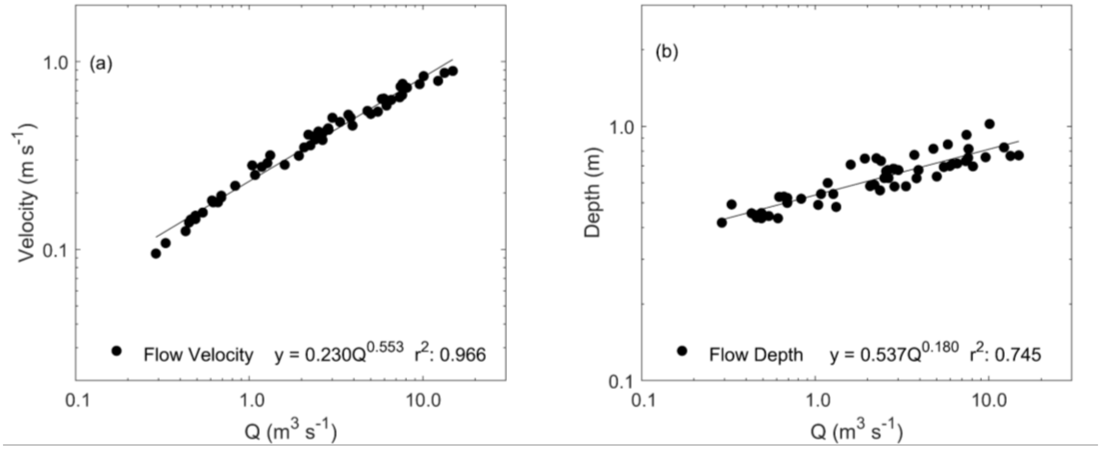
RESULTS AND DISCUSSION

Hydraulic Geometry

Discharge measurements ranged from 0.12 to 14.84 $m^3 s^{-1}$, with a stage range between 0.29 to 1.45 m. Figure 2 shows the tendencies to increase the flow velocity and flow depth with the discharge. It is observed that the flow velocity has a greater increase with discharge than that flow depth. The power function fitted by ordinary least squares had exponents of 0.55 for flow velocity and 0.18 for flow depth. In practical terms, this characterizes the flow resistance decrease with increased discharge because sources of grain and form roughness occupy a progressively smaller portion of the flow

(David *et al.*, 2010a). These results are consistent with other studies of bedrock channels (Ferguson *et al.*, 2017) and steep alluvial streams (Comiti *et al.*, 2007; David *et al.*, 2010a).

Figure 2 - Hydraulic relationships between discharge and: (a) mean flow velocity, (b) mean flow depth.

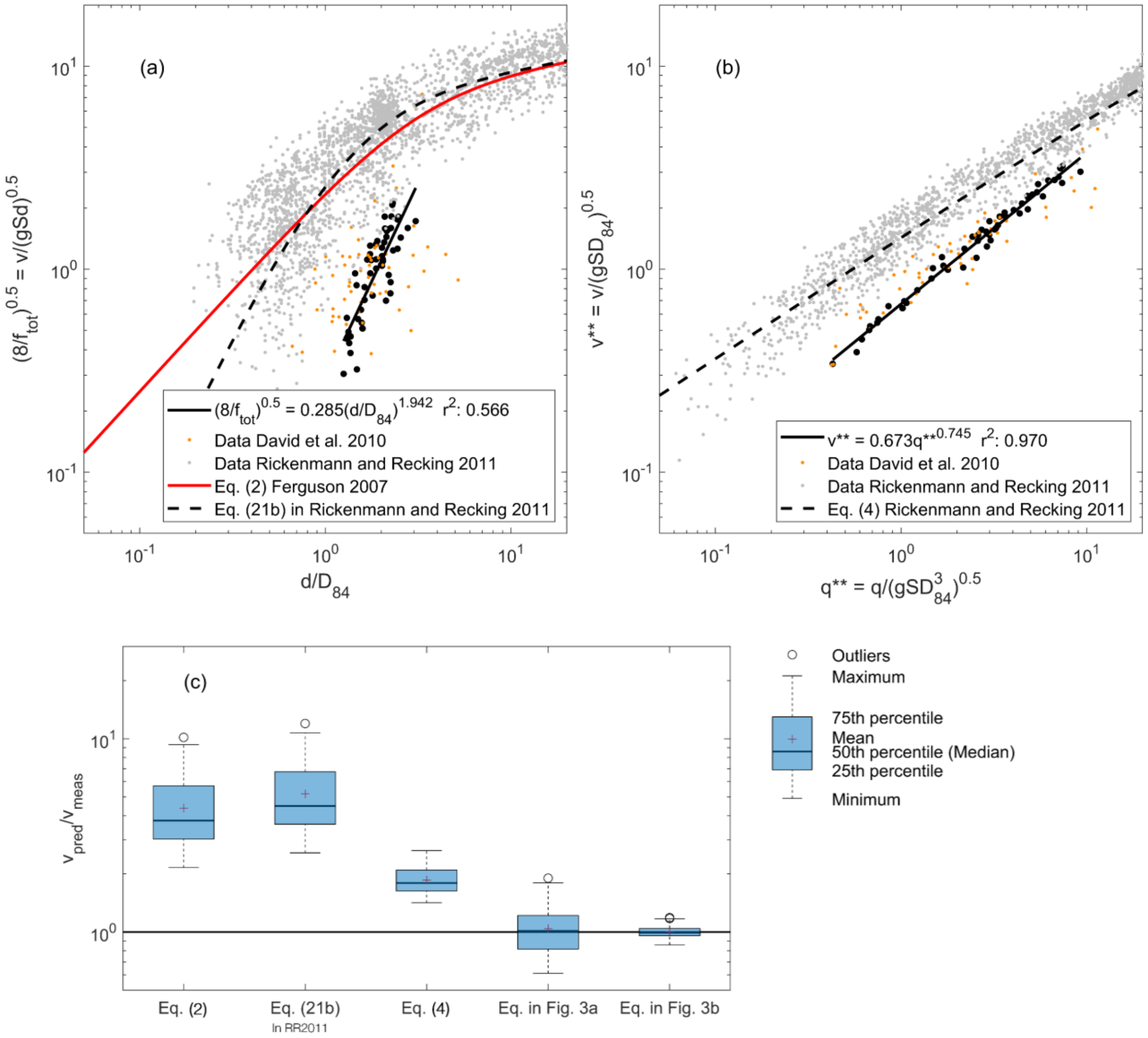


Flow resistence analysis

We analyze our data with those from the study of David *et al.* (2010b) in steep mountain streams and a large data set of alluvial channel grouped by Rickenmann and Recking (2011). In Figure 3, all the analyzed data are presented and the flow resistance laws described in the introduction. It is possible to observe that the data from Arroio do Ouro, have a greater similarity with those presented by David *et al.* (2010b) and these are below the range of alluvial flow resistance. According to Bartels *et al.* (2021), the macro-roughness present in the reach (e.g., boulder, bedrock protrusion) is what conditioned this increased flow resistance, mainly due to the drag that occurs around large boulders (Nitsche *et al.*, 2012). The equations developed for coarse-bed alluvial channels underestimate the measured flow resistance in the reach of Arroio do Ouro. This was also shown in other studies that examined the flow resistance in mixed bedrock–alluvial channel (Ferguson *et al.* 2017).

The Arroio do Ouro data plot is below the limit of the data compiled by Rickenmann and Recking (2011), both the approach that uses the relative flow depth and f_{tot} and the relations of dimensionless hydraulic geometry (Figure 3). The data of David *et al.* (2010b) behaved similarly to that observed by our set of measurements. In the case of measurements by these authors, we can assume that the high flow resistance was influenced by the increasing wood load present in many reaches measured.

Figure 3. (a) Relationship between flow resistance and relative flow depth; (b) dimensionless velocity related to dimensionless discharge; (c) Measured flow velocity (v_{meas}) compared to velocity predictions (v_{pred}) based on relative flow depth and dimensionless discharge. Source: Adapted from Bartels *et al.* (2021).



The equations of Rickenmann and Recking (2011) and Ferguson (2007) described in the introduction section overestimated the flow velocity. Based on the performance of the equations, the flow velocity predictions are better when using the dimensionless hydraulic geometry approach (Figure 3c). How we can improve these standard equations to be applied satisfactorily in mixed bedrock–alluvial stream is open to question. From some studies, there are indications that the problem can be circumvented by the investigation of different methods to estimate the bed roughness height. Chen *et al.* (2020) obtained better results using the standard deviation of bed elevation (σz) as a roughness descriptor in gravel bed streams. In a small bedrock reach, Ferguson *et al.* (2019), using the same descriptor of roughness, also obtained promising results. However, there remains a gap in studies conducted in conditions that are more irregular beds.

CONCLUSIONS

We analyzed the flow resistance in a mixed bedrock–alluvial stream in Southern Brazil, considering the energy loss effects caused by the macro-roughness of large elements (such as boulders). It is important to highlight that the energy loss considered in standard flow resistance equations is underestimated for the flow characteristics of mixed bedrock–alluvial channels. Therefore, our results provide evidence that energy loss caused by large boulders and bedrock protrusions should be reviewed in flow resistance equations for further studies. A valuable addition may be the investigation of different methods to estimate the bed roughness height.

ACKNOWLEDGMENTS

The authors wish to thank NEPE-HidroSedi at Federal University of Pelotas (UFPel) for offering us its facilities to perform lab analysis and field campaigns. We thank Dieter Rickenmann for providing flow resistance data compiled by Rickenmann and Recking (2011). We thank the National Council for Scientific and Technological Development (CNPq) for financing a PhD fellowship (Grant number 141235/2017-9) for the first author and research productivity fellowship for the fourth and sixth authors (Grant number 305636/2019-7).

REFERENCES

BARTELS, G. K., DOS REIS CASTRO, N. M., COLLARES, G. L., & FAN, F. M. (2021). *"Performance of bedload transport equations in a mixed bedrock–alluvial channel environment"*. CATENA, *199*, 105108.

CHEN, X., HASSAN, M. A., AN, C., & FU, X. (2020). *"Rough Correlations: Meta-Analysis of Roughness Measures in Gravel Bed Rivers"*. Water Resources Research, *56*(8), e2020WR027079.

COLEMAN, S. E., NIKORA, V. I., & ABERLE, J. (2011). *"Interpretation of alluvial beds through bed-elevation distribution moments".* Water Resources Research, 47(11).

COMITI, F., MAO, L., WILCOX, A., WOHL, E. E., & LENZI, M. A. (2007*). "Field-derived relationships for flow velocity and resistance in high-gradient streams"*. Journal of hydrology, *340*(1-2), 48-62.

COMITI, F., MAO, L. *"Recent Advances in the Dynamics of Steep Channels". In*: CHURCH, M.; BIRON, P. M.; ROY, A. G. (org.). *Gravel-Bed Rivers*. Chichester, UK: John Wiley & Sons, Ltd, 2012. p. 351–377.

DAVID, G. C., WOHL, E., YOCHUM, S. E., & BLEDSOE, B. P. (2010a). *"Controls on spatial variations in flow resistance along steep mountain streams"*. Water Resources Research, 46(3).

DAVID, G. C., WOHL, E., YOCHUM, S. E., & BLEDSOE, B. P. (2010b*). "Controls on at-a-station hydraulic geometry in steep headwater streams, Colorado, USA"*. Earth Surface Processes and Landforms, *35*(15), 1820-1837.

FERGUSON, R. I., SHARMA, B. P., HARDY, R. J., HODGE, R. A., & WARBURTON, J. (2017). *"Flow resistance and hydraulic geometry in contrasting reaches of a bedrock channel"*. Water Resources Research, *53*(3), 2278-2293.

FERGUSON, R. (2007). *"Flow resistance equations for gravel-and boulder-bed streams"*. Water resources research, 43(5).

FERGUSON, R. I., HARDY, R. J., & HODGE, R. A. (2019). *"Flow resistance and hydraulic geometry in bedrock rivers with multiple roughness length scales"*. Earth Surface Processes and Landforms, 44(12), 2437-2449.

HODGE, R., BRASINGTON, J., & RICHARDS, K. (2009). *"In situ characterization of grain-scale fluvial morphology using Terrestrial Laser Scanning"*. Earth Surface Processes and Landforms, 34(7), 954-968.

MONSALVE, A., YAGER, E. M., TUROWSKI, J. M., & RICKENMANN, D. (2016). *"A probabilistic formulation of bed load transport to include spatial variability of flow and surface grain size distributions"*. Water Resources Research, *52*(5), 3579-3598.

NIKORA, V. I., GORING, D. G., & BIGGS, B. J. (1998). *"On gravel-bed roughness characterization".* Water Resources Research, 34(3), 517-527.

NITSCHE, M., RICKENMANN, D., KIRCHNER, J. W., TUROWSKI, J. M., & BADOUX, A. (2012). *"Macroroughness and variations in reach-averaged flow resistance in steep mountain streams"*. Water Resources Research, 48(12).

NITSCHE, M., RICKENMANN, D., TUROWSKI, J. M., BADOUX, A., & KIRCHNER, J. W. (2011). *"Evaluation of bedload transport predictions using flow resistance equations to account for macro-roughness in steep mountain streams"*. Water Resources Research, *47*(8).

PEEL, M. C., FINLAYSON, B. L., & MCMAHON, T. A. (2007). *"Updated world map of the Köppen-Geiger climate classification"*. Hydrology and earth system sciences, *11*(5), 1633-1644.

RICKENMANN, D., & RECKING, A. (2011). *"Evaluation of flow resistance in gravel-bed rivers through a large field data set"*. Water Resources Research, *47*(7).

SCHNEIDER, J. M., RICKENMANN, D., TUROWSKI, J. M., & KIRCHNER, J. W. (2015). *"Self-adjustment of stream bed roughness and flow velocity in a steep mountain channel"*. Water Resources Research, *51*(10), 7838-7859.

TURNIPSEED, D. P., & SAUER, V. B. (2010). "*Discharge measurements at gaging stations* (No. 3-A8)". US Geological Survey.

WILCOCK, P., PITLICK, J., & CUI, Y. (2009). *"Sediment transport primer: estimating bed-material transport in gravel-bed rivers"*. Gen. Tech. Rep. RMRS-GTR-226. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 78 p., 226.

YAGER, E. M., DIETRICH, W. E., KIRCHNER, J. W., & MCARDELL, B. W. (2012a). *"Prediction of sediment transport in step-pool channels"*. Water Resources Research, 48(1).

YAGER, E. M., DIETRICH, W. E., KIRCHNER, J. W., & MCARDELL, B. W. (2012b). *"Patch dynamics and stability in steep, rough streams"*. Journal of Geophysical Research: Earth Surface, 117(F2).

YAGER, E. M., KIRCHNER, J. W., & DIETRICH, W. E. (2007). *"Calculating bed load transport in steep boulder bed channels"*. Water Resources Research, 43(7).

ZIMMERMANN, A. (2010). *"Flow resistance in steep streams: An experimental study"*. Water Resources Research, 46(9).