Limits of downstream hydraulic geometry

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ABSTRACT

Adjustments to flow width, depth, and velocity in response to changes in discharge are commonly characterized by using downstream hydraulic geometry relationships. The spatial limits of these relationships within a drainage basin have not been systematically quantified. Where the erosional resistance of the channel substrate is sufficiently large, hydraulic driving forces presumably will be unable to adjust channel form. Data sets from 10 mountain rivers in the United States, Panama, Nepal, and New Zealand are used in this study to explore the limits of downstream hydraulic geometry relationships. Where the ratio of stream power to sediment size (Ω/D_{84}) exceeds 10,000 kg/s^3, downstream hydraulic geometry is well developed; where the ratio falls below 10,000 kg/s^3, downstream hydraulic geometry relationships are poorly developed. These limitations on downstream hydraulic geometry have important implications for channel engineering and simulations of landscape change.

Keywords: downstream hydraulic geometry, mountain rivers, channel geometry, channel change, hydraulics.

INTRODUCTION

Downstream hydraulic geometry (DHG) characterizes downstream changes in river channel geometry and flow hydraulics in response to changes in discharge. As originally proposed (Leopold and Maddock, 1953), use of DHG is based on the assumption that river channels formed in alluvium are readily adjustable to changes in the magnitude of fairly frequent flows at or exceeding bankfull stage. Data from alluvial rivers across the continental United States were used to demonstrate that width (w), depth (d), and mean velocity (v) can be related to discharge in the form of simple power functions (Leopold and Maddock, 1953):

$$w = aQ^b, \quad (1)$$

$$d = cQ^f, \quad \text{and} \quad (2)$$

$$v = kQ^m, \quad (3)$$

where, on average, $b = 0.5$, $f = 0.4$, and $m = 0.1$. Subsequent studies have confirmed that these average values adequately describe alluvial rivers around the world and thus provide insight into how a river will respond to changes in discharge (Park, 1977). These power functions are now widely used to describe river response in the context of channel engineering and numerical simulations of landscape evolution (Ibbitt, 1997; Ibbitt et al., 1999; Molnar and Ramirez, 2002).

Because DHG calculations presume that channel parameters are adjusted to changes in discharges that occur on average every 1–2 yr (hereafter referred to as average annual flow), the common assumption has been that DHG models may not adequately describe channels formed in more resistant materials such as bedrock or very coarse grained alluvium (Tinkler and Wohl, 1998; Montgomery and Gran, 2001). Existing studies of mountain rivers provide mixed results: some catchments demonstrate good correlations between hydraulic geometry variables and discharge (Osterkamp and Hedman, 1977; Caine and Mool, 1981; Molnar and Ramirez, 2002; Wohl, 2004), whereas others do not exhibit the expected DHG trends (Ponton, 1972; Phillips and Harlin, 1984; Wohl et al., 2004).

Mountain rivers commonly have more resistant channel boundaries than lower-gradient alluvial channels. Mountain rivers can also be influenced by inherited glacial topography, differential tectonic uplift across the drainage basin, mass movements from adjacent hillslopes, and differing lithologies and associated rock resistance along the course of the river channel (Wohl, 2000). These controls all have the potential to interfere with the adjustment of channel geometry to changes in average annual flows. The upper reaches of mountain channel networks grade upstream from channels dominated by fluvial processes into channels dominated by colluvial processes such as debris flows and rockfalls (Montgomery and Buffington, 1997). Somewhere along this gradation the adjustments quantified by downstream hydraulic geometry presumably no longer describe channel form and process. But what conditions determine where this transition occurs? This study was designed to (1) test whether the concept of downstream hydraulic geometry adequately describes mountain rivers and (2) determine whether a numerical threshold can be used to describe the limits beyond which the concept of downstream hydraulic geometry no longer applies.

FIELD METHODS AND DATA SET

Mountain rivers are here defined as having an average downstream gradient of at least 0.002 m/m. Mountain rivers are also here defined to have a well-developed DHG when the coefficient of determination (r^2) between discharge and at least two of the three response variables (w, d, v) is 0.5 or greater. Rivers that do not meet this latter criterion are designated as having poorly developed DHG.

Data sets from 10 mountain rivers are used in the analysis (Table 1). These rivers together represent a broad range of climatic, tectonic, and geologic conditions. For example, study sites in the Grey River basin of western New Zealand receive as much as 7 m of precipitation annually, whereas rivers in the Agua Fria River basin of Arizona are ephemeral. The part of a given drainage network represented by each data set varies as a function of the area drained by channels with gradients sufficiently steep to meet the criterion used here for mountain rivers. The data set from Arizona, for example, includes channels draining as much as 3000 km^2, whereas the data sets from eastern New Zealand and the Arkansas River basin in Colorado include only the uppermost-channel segments with drainages of 30 km^2 or less (Table 1).

Numerous individual study reaches were characterized within each river basin (Table 1). On-site measurements included channel geometry, gradient, and grain-size distribution. Channel geometry (w, d) was surveyed to include field indicators judged to represent the average annual high-water mark. Indicators included changes in bank geometry, changes in vegetation, organic debris lines, and water stains on clasts or bedrock along the channel. Most of the study reaches had well-defined bankfull geometry. Indirect estimation of discharge by using various types of field indicators creates the possibility that the estimated flow does not represent the same frequency of event at different sites or that the estimate might be unduly influenced by the most recent large flow along a channel at a given point. Most of the basins had at least discontinuous gage records from more than one location in the basin (Table 1). These records were used to estimate discharge-drainage area relationships for average annual high flow that in turn were used to constrain field estimates of discharge.

Field measurements were used to calculate velocity and discharge of average annual high flow by using the Manning equation. Study sites were chosen such that channel parameters appeared to reflect

TABLE 1. CHARACTERISTICS OF RIVERS USED IN THIS ANALYSIS

River basin (no. of reaches)*	Area† (km^2)	Discharge§ (m^3/s)	r^2 for Q vs. w (DHG exp)††	r^2 for Q vs. d (DHG exp)††	r^2 for Q vs. v (DHG exp)††	Ω/D_{84} mean (std. dev.)##	Data source§§
Chagres, Panama (40)	0.5–410	10–2620#	0.76 (0.43)	0.62 (0.36)	0.42 (0.24)	174,334 (210,956)	Wohl (2004)
Dudh Kosi, Nepal (18)	20–1150	7–200	0.68 (0.27)	0.95 (0.47)	0.80 (0.26)	88,182 (38,234)	Cenderelli (1998)
Grey, New Zealand (13)	0.5–70	3.2–190#	0.53 (0.48)	0.79 (0.40)	0.64 (0.14)	40,044 (26,604)	Wohl and Wilcox (2004)
Waimakariri, New Zealand (20)	0.7–30	1.3–60#	0.77 (0.49)	0.83 (0.32)	0.74 (0.18)	25,448 (25,347)	Wohl and Wilcox (2004)
Chena, Alaska (14)	10–3100	3–130#	0.48 (0.34)	0.83 (0.33)	0.30 (0.22)	26,462 (28,318)	This study
South Platte, Colorado (24)	*2–240*	*5–20#*	*0.17 (0.21)*	*0.08 (0.37)*	*0.01 (0.09)*	*9634 (3610)*	Wohl et al. (2004)
Arkansas, Colorado (95)	*1.5–30*	*0.1–6#*	*0.26 (0.25)*	*0.64 (0.46)*	*0.27 (0.32)*	*2214 (2502)*	Wasserman (1990)
Agua Fria, Arizona (15)	0.7–3000	0.7–360#	0.84 (0.59)	0.95 (0.39)	0.48 (0.16)	52,283 (124,979)	This study
Shoshone, Wyoming (20)	17–60	2–10#	0.68 (0.39)	0.63 (0.51)	0.03 (0.05)	15,464 (16,727)	Zelt (2002)
Columbia, Montana (89)	*1–40*	*0.2–11#*	*0.21 (0.14)*	*0.15 (0.23)*	*0.88 (0.27)*	*5267 (4570)*	Madsen (1995)

Note: Data highlighted with italics are for river basins that have poorly developed downstream hydraulic geometry (DHG).
*The name of the major drainage in the study area. In most cases, the actual streams studied are very minor tributaries to this larger river.
†Range of smallest and largest drainage areas within the data set; upper number is rounded to the nearest 10 km^2.
§Range of smallest to largest discharge calculated for the study reaches on each river.
#Some systematic gage records exist for the basin.
**The number of individual study sites in each drainage area.
††Coefficient of determination (r^2) values are adjusted, and data used for regressions are log-transformed. DHG exponent is the exponent in the downstream hydraulic geometry regression for this variable.
##Mean and standard deviation of reach values of Ω/D_{84} for each river basin used in Figure 1.
§§Each reference represents the publication that describes the field area, methods, and data in much more detail.

dominantly fluvial processes; i.e., no recent evidence of debris flows was present at the study site. Study sites represent only single-thread, rather than braided, channels. Channel types represented in the data sets include cascade, step-pool, plane-bed, and pool-riffle forms (Montgomery and Buffington, 1997). Discontinuous bedrock outcrops were present along the streambed or banks of many study reaches, but none of the reaches were completely formed in bedrock.

RESULTS AND DISCUSSION

Three of the rivers used for analysis have poorly developed DHG, whereas the remainder meet the criterion for well-developed DHG. Individual river data sets might be expected to fail the criterion of having well-developed DHG, as defined in terms of coefficients of determination of >0.5, if the range of the control variable (discharge) is narrow or if the data set has relatively few individual study reaches. Under these conditions, the range of the response variable (w, d, v) would have to be correspondingly narrower to meet the criterion. However, these limitations do not seem to invalidate the approach used here. Data sets with a similarly narrow range of discharge can have either well-developed DHG (e.g., Nepal, both New Zealand data sets, Alaska, Wyoming) or poorly developed DHG (e.g., both Colorado data sets, Montana) (Table 1). Data sets with <20 study reaches can display well-developed DHG (e.g., Nepal, New Zealand, Alaska, Arizona), whereas data sets with >50 study reaches can display poorly developed DHG (e.g., Montana, Arkansas River, Colorado).

The second step of the analysis focused on distinguishing rivers with poorly developed DHG from those with well-developed DHG. Of the 10 rivers in the full data set, 8 were randomly chosen and used to explore indices that might distinguish between poorly developed and well-developed DHG. The two remaining rivers (Arkansas River, Colorado, and Agua Fria River, Arizona) were then used to test the resulting index.

If well-developed DHG relationships indicate adjustment between discharge and channel parameters, then hydraulic driving forces should be sufficiently large to overcome substrate resistance and alter channel dimensions. Recent literature on bedrock channels expresses driving forces in terms of an excess shear stress above some threshold value or in terms of some function of stream power (Howard and Kerby, 1983; Costa and O'Connor, 1995; Sklar and Dietrich, 1998; Wohl and Merritt, 2001; Dietrich et al., 2003; Snyder et al., 2003).

Several parameters were calculated to determine whether they successfully discriminated between the rivers designated here as having well-developed and poorly developed DHG. These parameters included (1) discharge per unit drainage area, dimensional ratios of driving force to substrate resistance expressed as (2) total stream power relative to the coarse-grain-size fraction of the streambed (Ω/D_{84}), (3) stream power per unit area relative to the coarse-grain-size fraction (Ω/D_{84}), and (4) excess shear stress calculated both as $\tau_b - \tau_c$ and τ_b/τ_c, where τ_b is shear stress at average annual high flow and τ_c is critical shear stress necessary to entrain D_{84} (the grain size for which 84% of the streambed is smaller in size). Only the ratio of Ω/D_{84} proved to be an effective discriminator between rivers with poorly developed and well-developed DHG.

The dimensional ratio of Ω/D_{84} comes from

$$\Omega = \gamma QS, \tag{4}$$

where Ω is total stream power per unit bed length (kg·m/s^3), γ is the specific weight of water (9800 N/m^3, or 9800 kg/[m^2·s^2]), Q is estimated annual high flow for each reach (m^3/s), and S is reach stream gradient (m/m). D_{84} is expressed in meters. The dimensions of the Ω/D_{84} ratio are thus kg/s^3.

The ratio of Ω/D_{84} was calculated for each study reach in each river basin. These values were then used to compare basins. It might be expected that as the ratio of Ω/D_{84} increases, the river will be progressively more capable of adjusting channel parameters in response to downstream changes in discharge. River basins with well-developed DHG clearly had higher values of the Ω/D_{84} ratio than those with poorly developed geometry. The mean values of this ratio for rivers with poorly developed geometry were significantly different (at a level of 0.05) than the values for rivers with well-developed geometry. A visually estimated threshold value of Ω/D_{84} = 10,000 kg/s^3 separates the two groups of rivers (Fig. 1). Subsequent addition of the two remaining data sets from Colorado and Arizona confirmed the existence of the threshold.

It is not readily apparent from the ratio Ω/D_{84} whether a low value results from small stream power, large grain size, or some combination of these factors. Plotting the range of total stream power and D_{84} within each data set (Fig. 2) indicates that neither power nor grain size are consistently different between the data sets with well-developed and poorly developed DHG relationships. The relationship between the two factors, rather than consistent variation in either power or grain size, determines the extent to which a river can develop DHG.

Because of the limited sample size of 10 rivers, DHG trends within a single river basin are also used to explore the proposed threshold. Subsampling the farthest upstream parts of the relatively large data sets from Panama and from eastern New Zealand (Waimakariri River) confirmed that values of Ω/D_{84} that exceed the threshold correspond to

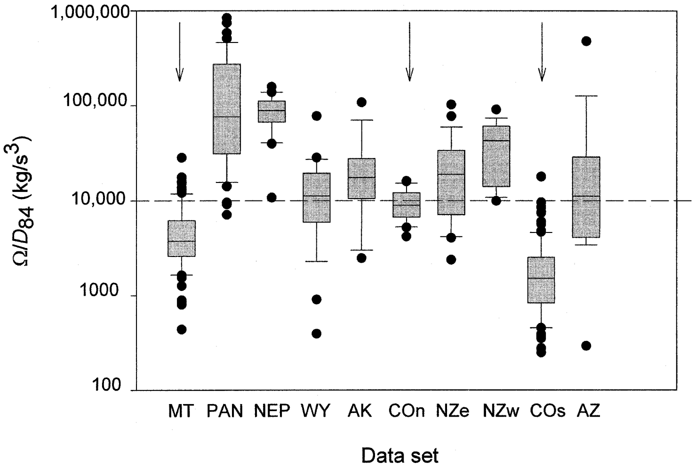

Figure 1. Ratio of Ω/D_{84} (see text) plotted for data sets discussed. Vertical arrows indicate those data sets with poorly developed downstream hydraulic geometry. Threshold ratio of 10,000 is indicated by dashed horizontal line. Abbreviations: MT—Montana; PAN—Panama; NEP—Nepal; WY—Wyoming; AK—Alaska; COn—Colorado north, Platte drainage; NZe—New Zealand east, Waimakariri drainage; NZw—New Zealand west, Grey drainage; COs—Colorado south, Arkansas drainage; AZ—Arizona.

well-developed hydraulic geometry. A subset of 13 study reaches from the Waimakariri data set (drainage area, <20 km^2; discharge range, 1.3–28 m^3/s) had a mean ratio of Ω/D_{84} = 17,977 and met the criterion for well-developed DHG, as did a subset of 14 study reaches from Panama (drainage area, ≤15 km^2; discharge range, 10–228 m^3/s; mean Ω/D_{84} ratio, 63,936).

Upstream reaches within a mountain drainage basin are potentially less adjustable than downstream reaches because of lower discharge, steeper gradients, and greater clast size. Of the 10 rivers in this study, 7 were subsampled to determine whether the upper part of each drainage had a lower Ω/D_{84} ratio and less-well-developed DHG than the lower part of the drainage. Four data sets (Montana, South Platte of Colorado, Panama, and Waimakariri of New Zealand) were chosen for subsampling because each data set contained at least 20 stream reaches. The data sets from Arizona, Alaska, and Nepal were chosen for subsampling because each data set had a large range of drainage area (Table 1). The relative strength of DHG correlations for upper and lower basins did not differ in the subsets from rivers with a small range in drainage area (New Zealand, Montana, Colorado). Of the rivers with a larger drainage range, only Panama had sufficient study reaches to support DHG regression analyses for both upper and lower parts of the drainage. DHG correlations were slightly stronger in the lower part of the basin. This finding suggests that higher values of the ratio correspond to a progressively greater ability to adjust channel geometry proceeding downstream within a single drainage basin, but rigorous testing of this possibility requires much larger data sets from individual drainage basins.

The variability in the minimum drainage area at which well-developed DHG relationships exist suggests that there is no specific drainage area or unit discharge threshold beyond which the concept of DHG applies. Rather, the threshold for well-developed DHG is most effectively defined in terms of both discharge (or its surrogate—drainage area) and grain size in the stream channels. Grain size depends in part on local controls such as rock type, climate and weathering regime, and hillslope stability.

The degree to which DHG relationships are developed also does not seem to directly reflect the distribution of bedrock along the channel margins. Study reaches in Panama, New Zealand, and Colorado (South Platte River) had approximately equivalent percentages of bedrock exposure, yet the Panama and New Zealand sites had well-developed DHG and the Colorado site did not.

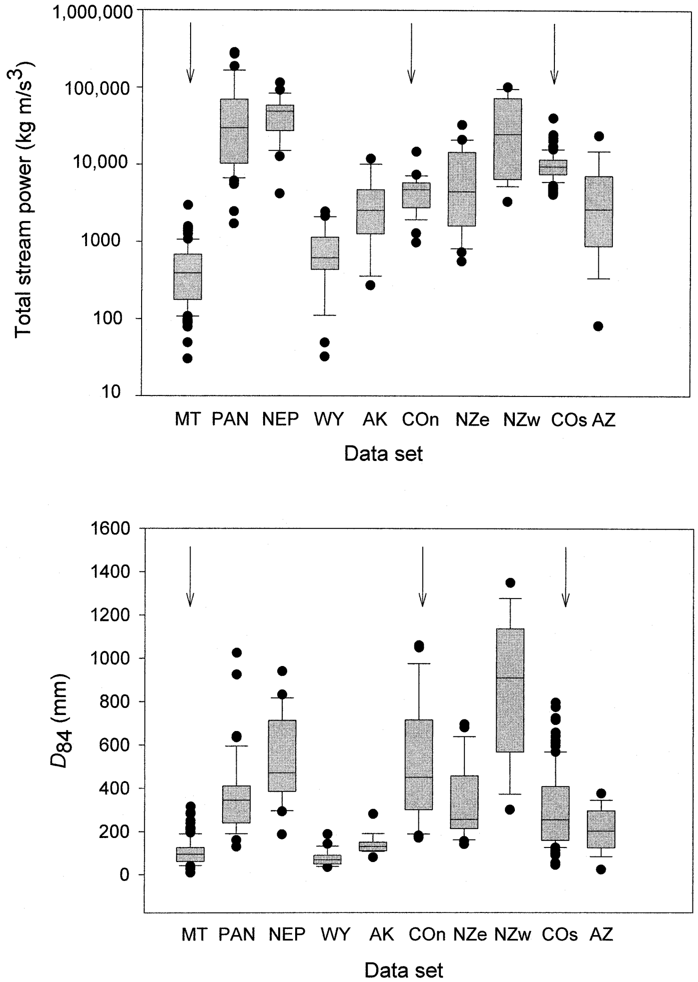

Figure 2. Plots of total stream power and D_{84} (see text) for each data set discussed. Vertical arrows indicate those data sets with poorly developed downstream hydraulic geometry. Abbreviations: MT—Montana; PAN—Panama; NEP—Nepal; WY—Wyoming; AK—Alaska; COn—Colorado north, Platte drainage; NZe—New Zealand east, Waimakariri drainage; NZw—New Zealand west, Grey drainage; COs—Colorado south, Arkansas drainage; AZ—Arizona.

One method to examine whether the Ω/D_{84} ratio has any predictive power relative to the strength of DHG relationships, rather than simply providing a threshold value, is to plot the DHG exponent for each data set against Ω/D_{84} (Fig. 3). Only the width exponent has a marginally significant correlation with Ω/D_{84}, suggesting that width may be the most responsive variable as power increases relative to grain size. The average width and depth exponents are very similar for the entire data set of 10 catchments (width exponent = 0.36, depth exponent = 0.38). However, the width exponent for channels with well-developed DHG (exponent = 0.43) is significantly different from the exponent for channels with poorly developed DHG (exponent = 0.20), as well as being much closer to the average for alluvial channels worldwide (exponent = 0.5) (Park, 1977). The average depth exponents are similar for channels with well-developed (exponent = 0.40) DHG and poorly developed (exponent = 0.35) DHG, and are both similar to the average worldwide value of 0.4 (Park, 1977). These results suggest that, where hydraulic driving forces do not sufficiently exceed substrate resisting forces to produce well-developed DHG, channel width is especially poorly adjusted. A lower width/depth ratio is expected where channel boundaries are resistant to erosion (Wohl and Merritt, 2001), although even channels formed entirely in bedrock

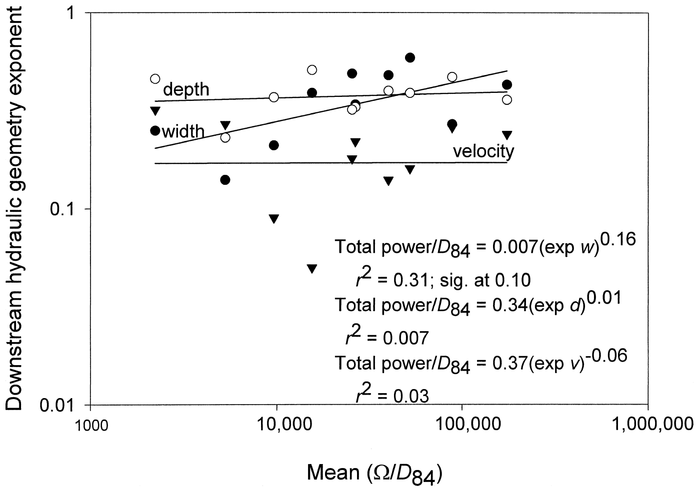

Figure 3. Downstream hydraulic geometry exponent for each data set plotted against Ω/D_{84} ratio (see text) for width (solid circles), depth (open circles), and velocity (triangles) exponents.

can have regular downstream trends in width (Montgomery and Gran, 2001).

The analysis summarized here does not address several complicating factors. The single value of total stream power calculated for each study reach contains no adjustment for the duration and/or frequency of discharges reaching this stream power. The parameter D_{84} contains no adjustment for varying degrees of sorting in the grain-size distribution at each study site or for the influence of bedrock outcrops on substrate resistance. Focusing strictly on the relationship between discharge and channel parameters ignores the influence that nonfluvial processes, such as debris flows, may have in shaping channel geometry.

CONCLUSIONS

The results presented here suggest that, despite the complications introduced by glacial history, bedrock exposure, large woody debris, and tectonic and colluvial influences, mountain rivers with greater hydraulic driving forces relative to substrate resistance are likely to behave as fully alluvial rivers in terms of having well-developed DHG relationships for average annual flow. The threshold described by a Ω/D_{84} ratio of $<10{,}000$ kg/s^3 appears to define the limit below which DHG relationships do not adequately describe river behavior, although further testing of this concept with more extensive data from mountain rivers is necessary. The limit defined by the Ω/D_{84} ratio can be incorporated into (1) quantitative models of landscape evolution that parameterize river adjustment through time, (2) assumptions regarding channel response to changes in discharge resulting from land use or climate change, and (3) attempts to design stable channel geometry when restoring or rehabilitating channels.

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REFERENCES CITED

Caine, N., and Mool, P.K., 1981, Channel geometry and flow estimates for two small mountain streams in the Middle Hills, Nepal: Mountain Research and Development, v. 1, p. 231–243.

Cenderelli, D.A., 1998, Glacial-lake outburst floods in the Mount Everest region of Nepal: Flow processes, flow hydraulics, and geomorphic effects [Ph.D. thesis]: Fort Collins, Colorado State University, 247 p.

Costa, J.E., and O'Connor, J.E., 1995, Geomorphically effective floods, *in* Costa, J.E., et al., eds., Natural and anthropogenic influences in fluvial geomorphology: American Geophysical Union Geophysical Monograph 89, p. 45–56.

Dietrich, W.E., Bellugi, D.G., Sklar, L.S., Stock, J.D., Heimsath, A.M., and Roering, J.J., 2003, Geomorphic transport laws for predicting landscape form and dynamics, *in* Wilcock, P.R., and Iverson, R.M., eds., Prediction in geomorphology: American Geophysical Union Geophysical Monograph 135, p. 103–132.

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

Ibbitt, R.P., 1997, Evaluation of optimal channel network and river basin heterogeneity concepts using measured flow and channel properties: Journal of Hydrology, v. 196, p. 119–138.

Ibbitt, R.P., Willgoose, G.R., and Duncan, M.J., 1999, Channel network simulation models compared with data from the Ashley River, New Zealand: Water Resources Research, v. 35, p. 3875–3890.

Leopold, L.B., and Maddock, T., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, p. 1–56.

Madsen, S.W., 1995, Channel response associated with predicted water and sediment yield increases in northwest Montana [M.S. thesis]: Fort Collins, Colorado State University, 230 p.

Molnar, P., and Ramirez, J.A., 2002, On downstream hydraulic geometry and optimal energy expenditure: Case study of the Ashley and Taieri Rivers: Journal of Hydrology, v. 259, p. 105–115.

Montgomery, D.R., and Buffington, J.M., 1997, Channel-reach morphology in mountain drainage basins: Geological Society of America Bulletin, v. 109, p. 596–611.

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

Osterkamp, W.R., and Hedman, E.R., 1977, Variation of width and discharge for high-gradient stream channels: Water Resources Research, v. 13, p. 256–258.

Park, C.C., 1977, World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations: Journal of Hydrology, v. 33, p. 133–146.

Phillips, P.J., and Harlin, J.M., 1984, Spatial dependency of hydraulic geometry exponents in a subalpine stream: Journal of Hydrology, v. 71, p. 277–283.

Ponton, J.R., 1972, Hydraulic geometry in the Green and Birkenhead basins, British Columbia, *in* Slaymaker, H.O., and McPherson, H.J., eds., Mountain geomorphology: Geomorphological processes in the Canadian Cordillera: Vancouver, Canada, Tantalus Research, p. 151–160.

Sklar, L., and Dietrich, W., 1998, River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply, *in* Tinkler, K.J., and Wohl, E.E., eds., Rivers over rock: American Geophysical Union Geophysical Monograph 107, p. 237–260.

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, v. 108, no. B12, p. ETG 17-1–17-15, doi: 10.1029/2001JB001655.

Tinkler, K., and Wohl, E., 1998, A primer on bedrock channels, *in* Tinkler, K., and Wohl, E., eds., Rivers over rock: American Geophysical Union Geophysical Monograph 107, p. 1–18.

Wasserman, A.A., 1990, Analysis of downstream hydraulic geometry in the Sangre de Cristo Range, Colorado [Ph.D. thesis]: Denver, Colorado, University of Denver, 207 p.

Wohl, E., 2000, Mountain rivers: American Geophysical Union Water Resources Monograph 14, 320 p.

Wohl, E., 2004, Downstream hydraulic geometry along a tropical mountain river, *in* Harmon, R., ed., The Rio Chagres: A multidisciplinary profile of a tropical watershed: Dordrecht, Kluwer (in press).

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

Wohl, E., and Wilcox, A., 2004, Channel geometry of mountain rivers in New Zealand: Journal of Hydrology (in press).

Wohl, E., Kuzma, J., and Brown, N., 2004, Reach-scale channel geometry of a mountain river: Earth Surface Processes and Landforms (in press).

Zelt, R.B., 2002, Channel characteristics and large organic debris in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming [M.S. thesis]: Fort Collins, Colorado State University, 214 p.

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