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REACH-SCALE CHANNEL GEOMETRY OF A MOUNTAIN RIVER

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ABSTRACT

Mountain rivers can be subject to strong constraints imposed by changes in gradient and grain size supplied by processes such as glaciation and rockfall. Nonetheless, adjustments in the channel geometry and hydraulics of mountain rivers at the reach scale can produce discernible patterns analogous to those in fully alluvial rivers. Mountain rivers can differ in that imposed reach-scale gradient is an especially important control on reach-scale channel characteristics, as indicated by examination of North St Vrain Creek in Colorado.

North St Vrain Creek drains 250 km^2 of the Rocky Mountains. We used 25 study reaches within the basin to examine controls on reach-scale channel geometry. Variables measured included channel geometry, large woody debris, grain size, and mean velocity. Drainage area at the study reaches ranged from 2·2 to 245 km^2, and gradient from 0·013 to 0·147 m m^{-1}.

We examined correlations among (1) potential reach-scale response variables describing channel bankfull dimension and shape, hydraulics, bedform wavelength and amplitude, grain size, flow resistance, standard deviation of hydraulic radius, and volume of large woody debris, and (2) potential control variables that change progressively downstream (drainage area, discharge) or that are likely to reflect a reach-specific control (bed gradient). We tested the hypothesis that response variables correlate most strongly with local bed gradient because of the segmented nature of mountain channels.

Results from simple linear regression analyses indicate that most response variables correlate best with gradient, although channel width and width/depth ratio correlate best with discharge. Multiple regression analyses using Mallow's C_p selection criterion and log-transformation of all variables produced similar results in that most response variables correlate strongly with gradient. These results suggest that the hypothesis is partially supported: channel bed gradient is likely to be a good predictor for many reach-scale response variables along mountain rivers, but discharge is also an important predictor for some response variables. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: mountain river; downstream hydraulic geometry; channel adjustment

INTRODUCTION

Downstream hydraulic geometry is based on the assumption that the geometric and hydraulic properties of a river channel will adjust in response to increasing discharge such that a regular downstream trend develops in variables such as hydraulic radius, channel width at the water surface, and mean flow velocity. In the original development of downstream hydraulic geometry, Leopold and Maddock (1953) proposed that rivers develop a morphology in approximate equilibrium with the flow of water and sediment through the channel. This approximate equilibrium is often expressed via equations relating discharge to mean depth, width and velocity; $w = aQ^b$, $d = cQ^f$, and $v = kQ^m$, where w is water-surface width, d is mean depth, v is mean velocity, Q is discharge, and a, c, k, b, f, and m are constants. Substituting these expressions into the continuity equation, $Q = wdv$, it follows that $b + f + m = 1$ and $ack = 1$. Although Leopold and Maddock (1953) found a range of values for the individual rivers in their dataset, the average exponent values of 0·5 for width, 0·4 for depth, and 0·1 for velocity are commonly cited. Leopold and Maddock (1953) noted that this approximate equilibrium seems to be present even in headward ungraded tributaries.

Subsequent studies of the downstream hydraulic geometry of river systems around the world have expanded the range of values reported for each exponent. Park (1977) cites the ranges 0·3 to 0·89 for width, 0·09 to 0·70 for depth, and −0·51 to 0·75 for velocity. Park notes that some of the variability may result from use of different

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flow levels in different studies, differences between gauging station and field data, and different methods of fitting lines to data.

Regardless of the details of obtaining the downstream hydraulic geometry coefficients, the technique rests on the assumption that discharge controls channel characteristics along a river formed in alluvial materials. This assumption may not apply to river systems in which channels are either strongly influenced by non-fluvial processes such as debris flows or valley glaciers, or influenced by longitudinally discontinuous tectonic uplift, changes in substrate resistance, sediment supply from adjacent hillslopes, or loading by large woody debris. All of these characteristics describe mountain rivers, which commonly have portions of the drainage basin heavily influenced by faulting and tilting, mass movements or glaciation, as well as abrupt downstream changes in bedrock type and exposure along the channel, coarse sediment input, and wood loading. Although mountain rivers certainly have the potential to set their own downstream gradient through bedrock erosion, lag times of at least as much as several thousand years between glaciation and bedrock slope adjustment can create a condition in which reach-scale gradient is an independent channel variable at shorter time scales.

Relatively few studies have investigated the downstream hydraulic geometry of mountain rivers. Caine and Mool (1981) found that the hydraulic geometry relations from two drainage basins in the Middle Hills of Nepal were generally similar to those reported from other regions of the world. Although the channels of those two basins are influenced by bedrock structure and contain large boulders beyond the competence of contemporary flows, the channels had strong correlations between discharge and the hydraulic geometry variables (Caine and Mool, 1981). In contrast, Ponton's (1972) investigation of two drainages in the Canadian Rockies indicated that the channels did not follow the expected downstream hydraulic geometry trends because of gradient changes related to glaciation. Phillips and Harlin (1984) described a mountain river in Colorado that did not follow predictable downstream changes in hydraulic geometry because of substantial changes in alluvial substrate. Although Abrahams (1985) noted errors in the Phillips and Harlin analysis, he agreed with their interpretation that the downstream hydraulic geometry exponents varied appreciably over short distances in association with changes in substrate. More recently, Molnar and Ramirez (2002) analysed downstream hydraulic geometry along a pair of gravel-bed mountain rivers in New Zealand. These rivers had fairly strong correlations between hydraulic geometry variables and discharge, as well as hydraulic geometry coefficients well within the expected range for alluvial rivers. Similarly, a study of the mountainous Rio Chagres drainage basin of Panama (Wohl, in press) revealed strong correlations and expected values for hydraulic geometry coefficients. Analysis of five mountain channel networks in the western United States showed that bedrock rivers shared the expected width scaling, with deviations from the expected relations imposed by downstream changes in lithology (Montgomery and Gran, 2001).

The mixed results for studies of downstream hydraulic geometry along mountain rivers suggest that drainage basin geologic and geomorphic history, and the ability of contemporary discharges to adjust channel geometry, determine whether or not an individual mountain drainage basin has strong systematic downstream hydraulic geometry patterns. We decided to further explore downstream hydraulic geometry and channel characteristics by examining the reach-scale channel geometry of North St Vrain Creek in the Front Range of Colorado. In addition to exploring the usual downstream hydraulic geometry relations, we tested two hypotheses regarding potential controls on reach-scale channel geometry:

H_o, response variables correlate most strongly with local channel-bed gradient because of the segmented nature of mountain channels;

H_a, response variables correlate most strongly with control variables that change progressively downstream (discharge, drainage area).

The reasoning behind the null hypothesis is that many mountain rivers are segmented in a downstream direction by changes in valley geometry associated with tectonic regime, glacial history, mass movements, and changes in lithology and structure that influence the erodibility of the channel substrate. These non-fluvial controls on channel segmentation could prevent the channel from exhibiting the continuous downstream changes in geometry and hydraulics that characterize strongly developed downstream hydraulic geometry typical of alluvial rivers, and produce strong correlations between bed gradient and channel response variables such as width or

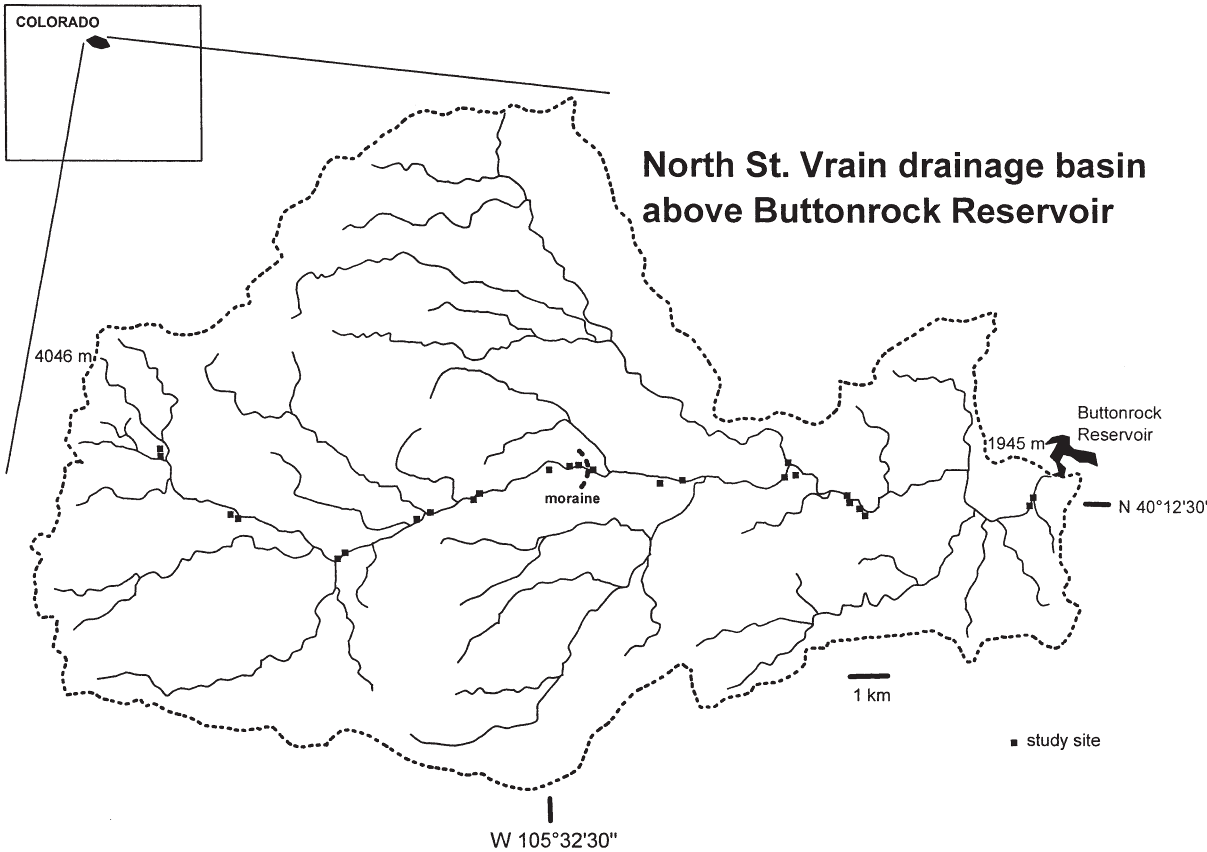

Figure 1. Location map of the study area

depth. Under the alternative hypothesis, the downstream segmentation may exist, but the channel is nonetheless adjusted to downstream changes in discharge such that strongly developed downstream hydraulic geometry relations exist, and discharge correlates strongly with channel response variables.

STUDY AREA

The mountain portion of North St Vrain Creek drains 250 km^2 of the Colorado Front Range (Figure 1). Elevation in the basin ranges from 4046 m at the Continental Divide, to 1945 m at the base of the range, where North St Vrain Creek enters Buttonrock Reservoir. Vegetation and precipitation in the basin are strongly controlled by elevation. Alpine vegetation above approximately 3230 m gives way to subalpine spruce–fir forest, which in turn gives way to montane pine forest below approximately 2500 m elevation. Mean annual precipitation varies from 71 cm in the upper basin to 36 cm in the lower basin, and the contribution of snow relative to rain decreases with elevation. Flow in the basin is dominated by snowmelt, which produces an annual hydrograph with a sustained May–June peak. Thunderstorm-generated flash floods are possible in the lower third of the basin. A gauging station has been maintained discontinuously at the downstream end of the basin since 1926. Mean annual peak flow for the period of record is 20 m^3 s^{-1}, with a maximum peak discharge of 46 m^3 s^{-1} in June 1941. Discharge has also been discontinuously gauged at five other sites in the mountain portion of the St Vrain drainage basin, which includes North, South and Middle St Vrain creeks. These gauge records were used to estimate regression lines between various measures of flow and drainage area. The increase in discharge with drainage area is strongly linear; the linear regression equation of annual peak flow (in ft^3 s^{-1}) and drainage area (in mi^2) is

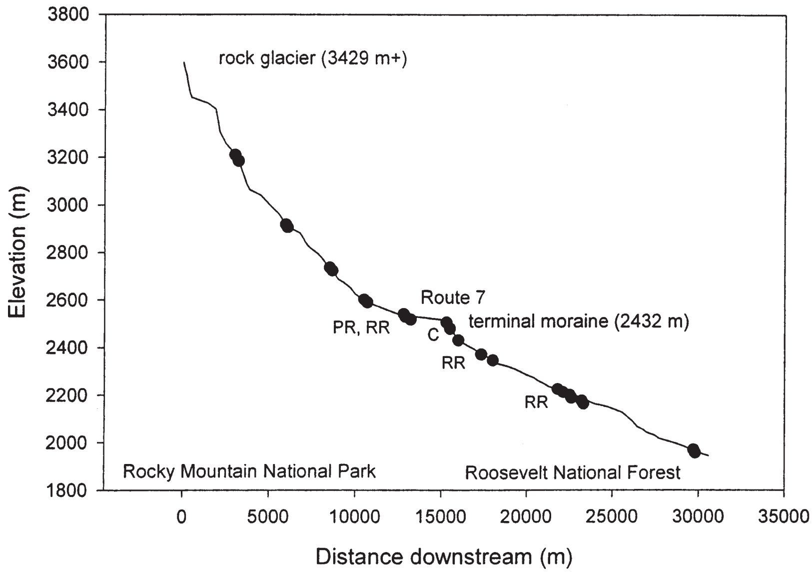

Figure 2. Longitudinal profile of North St Vrain Creek above Buttonrock Reservoir, showing location of study reaches (solid circles), terminal moraine, and land ownership. Reaches labelled PR have pool–riffle morphology, RR indicates plane-bed morphology, and C indicates cascade morphology. All other reaches have step–pool morphology

$$Q = 5{\cdot}5\ A + 197.$$

The entire basin is underlain by Precambrian-age granitic rocks. Although bedrock lithology does not vary substantially throughout the basin, valley geometry is quite variable. The upper half of the basin (above 2490 m) was glaciated during the Bull Lake and Pinedale glacial advances, and the terminal moraine is associated with a pronounced steepening of the creek's longitudinal profile (Figure 2). In relatively wide portions of the valley, boulder terraces occupy most of the valley floor, and contemporary rockfall does not reach the active channel. In narrower portions of the valley, rockfall introduces coarse clasts to the active channel.

The creek has bedrock discontinuously exposed along its bed and banks, but is primarily formed in coarse, bouldery alluvium with a well-formed coarse surface layer underlain by a mixture of boulder- to sand-sized sediment. The coarse surface layer is likely not mobilized during an average flow year. Channel types include cascade, step–pool, plane-bed and pool–riffle segments, as classified using Montgomery and Buffington's (1997) classification system. Large woody debris is locally abundant, but wood loading varies substantially throughout the basin.

We chose North St Vrain Creek for this study of reach-scale channel geometry because the basin has no flow diversion or flow regulation above Buttonrock Reservoir. The basin above the reservoir also has very little development or land-use impacts. The portion of the basin above the terminal moraine is in Rocky Mountain National Park, and has one paved road, one unpaved road and a small network of foot trails. The portion of the basin between the terminal moraine and the reservoir is in the Roosevelt National Forest and has only very limited access by foot trails. Reach-scale channel geometry of North St Vrain Creek is thus largely free of human influences.

METHODS

We designated 25 study reaches throughout the drainage basin of North St Vrain Creek (Figure 1). Field characterization of each 50 to 100 m long reach was undertaken during April–October 2002, a period of drought characterized by discharges of 0·6–3·4 $m^3\ s^{-1}$. Within each reach we measured channel geometry (bankfull width and depth; bed gradient; water-surface gradient during the survey; bankfull water-surface gradient; and

Table I. Summary of variable values for each study reach

	A	Q	S	R	w	w/d	v	λ	a	D_{50}	D_{84}	τ	ff	R/D_{84}	Ω	R_{sd}	LWD
SP18	2·2	5·4	·059	0·3	3·6	12	0·9	3·2	0·35	90	300	174	1·7	1·0	3122	0·15	0·86
SP17	2·3	5·4	·103	0·35	3·8	10·9	1·6	4·8	0·54	150	520	353	1·1	0·67	5451	0·13	4·11
SP11	18·6	6·4	·056	0·26	9·1	35	1·4	3·5	0·36	160	450	143	0·6	0·58	3512	0·16	1·80
SP12	18·7	6·4	·031	0·54	10·2	18·9	1·7	5·5	0·73	160	300	164	0·4	1·8	1944	0·26	3·13
SP13	55·7	8·5	·086	0·49	12·4	25·3	1·0	5·4	0·48	230	790	413	3·3	0·62	7164	0·24	3·09
SP14	55·8	8·5	·085	0·5	21·5	43	1·0	6·7	0·94	350	1050	416	3·3	0·48	7080	0·29	7·73
SP15	64·6	9·0	·079	0·55	8·2	14·9	1·0	11·6	1·06	400	975	426	3·4	0·56	6968	0·22	0·28
SP16	77·5	9·7	·022	0·63	7·4	11·8	2·7	9·1	0·35	220	500	136	0·2	1·26	2091	0·14	0·59
PR1	82·1	10·0	·021	0·49	8·7	17·8	2·3	58	0·4	108	180	101	0·2	2·72	2058	0·12	0
PR2	82	10·0	·01	0·38	10·3	27·1	1·3	58	0·2	110	188	37	0·2	2·02	980	0·18	0
RR3	83	10·1	·013	0·37	15·3	41·4	2·0	–	–	60	170	47	0·1	2·18	1287	0·11	0
C1	84·7	10·2	·147	0·72	14·0	19·4	1·6	–	–	450	960	1037	3·2	0·75	14694	0·29	1·72
SP8	84·9	10·2	·056	0·64	18·3	28·6	1·6	6·4	0·74	280	1060	351	1·1	0·6	5598	0·31	0·87
SP7	85	10·2	·074	0·56	13·2	23·6	1·2	7·9	0·81	250	640	406	2·3	0·88	7397	0·38	1·83
SP9	135·8	13·1	·041	0·54	11·0	20·4	1·9	8·8	0·66	150	450	217	0·5	1·2	5264	0·3	18·98
RR2	136	13·1	·015	0·56	16·8	30	1·7	–	–	90	310	82	0·2	1·81	1926	0·1	1·72
SP5	138·8	13·3	·023	0·62	12·4	20	2·2	7	0·5	190	370	140	0·2	1·68	2998	0·16	0
SP6	57·4	8·6	·061	0·32	5·4	16·9	1·6	5·2	0·34	135	320	191	0·6	1·0	5141	0·11	1·69
SP4	196·3	16·6	·032	0·73	12·2	16·7	2·1	12·1	0·62	200	580	229	0·4	1·26	5206	0·29	0·44
SP3	202·1	16·9	·03	0·2	12·7	63·5	0·8	8·1	0·46	190	370	59	0·7	0·54	4969	0·18	0·23
SP2	202·3	16·9	·028	0·4	15·0	37·5	1·3	5·9	0·42	180	330	110	0·5	1·21	4637	0·23	2·03
RR1	202·4	16·9	·018	0·69	15·7	22·8	1·5	–	–	110	210	122	0·4	3·29	2981	0·13	9·82
SP1	202·6	16·9	·027	0·64	10·2	15·9	1·7	9·2	0·31	160	280	169	0·5	2·29	4472	0·14	0
SP10	244·2	19·3	·034	0·66	12·7	19·2	2·0	9·8	0·6	300	975	220	0·4	0·68	6431	0·35	0
SP19	244·8	19·4	·025	0·26	11·2	43·1	0·9	10·7	0·5	320	690	64	0·6	0·38	4753	0·23	0

SP, step–pool reach; PR, pool–riffle reach; RR, plane-bed reach; C, cascade reach.
A, drainage area (km^2); *Q*, bankfull discharge ($m^3 s^{-1}$); *S*, reach gradient ($m m^{-1}$); *R*, hydraulic radius (m); *w*, channel top width (m); *w/d*, ratio of width to depth ($m m^{-1}$); *v* is mean velocity ($m s^{-1}$); λ is bedform wavelength (m); *a* is bedform amplitude (m); D_{50} is median grain size (mm); D_{84} is coarse grain size (mm); τ is bed shear stress ($N m^{-2}$); *ff* is Darcy-Weisbach friction factor; R/D_{84} is ratio of hydraulic radius (m) to D_{84} (m); Ω is total stream power (W); R_{sd} is standard deviation of hydraulic radius (m); *LWD* is volume of large woody debris (m^3)

wavelength and amplitude of bedforms, where present). Bankfull in this study was defined in the field based on high-water marks such as changes in grain size, vegetation, and bank gradient, as well as fluvially deposited organic debris. These features are interpreted to mark the average high-water level, or a discharge equivalent to the mean annual peak flow. For each reach we also measured size and orientation of large woody debris within the bankfull channel, grain-size distribution of the channel bed, and reach-averaged velocity under low-flow conditions. Surveying was conducted using a total station laser theodolite. Grain-size distributions were measured using a random-walk procedure (Wolman, 1954). Reach-averaged velocity was measured with conductivity probes placed midway across the channel, at approximately 0·6 of the flow depth, at the upstream and downstream end of each reach, and a salt tracer. Drainage area at each study reach was measured using 7·5 minute quadrangle topographic maps.

We used the field and map measurements, and the discharge records for the basin, to calculate 17 variables for each reach (Table I). These variables are: (1) drainage area A; (2) peak discharge during bankfull conditions Q; (3) bed gradient S; (4) bankfull hydraulic radius R; (5) bankfull top width w; (6) bankfull width/depth ratio w/R; (7) mean velocity v; (8) bedform wavelength λ; (9) bedform amplitude a; (10) median grain size D_{50}; (11) coarse grain size D_{84}; (12) boundary shear stress τ; (13) Darcy-Weisbach friction factor ff; (14) Manning's n; (15) relative submergence R/D_{84}; (16) total stream power Ω; (17) standard deviation of hydraulic radius at the time of the field survey R_{sd}; and (18) volume of large woody debris within the bankfull channel *LWD*.

In order to test the hypotheses stated previously, we distinguished between reach-scale response variables (R, w, v, ff, λ, a, D_{50}, D_{84}, τ, ff, n, R/D_{84}, Ω) and potential control variables that change progressively downstream (A, Q) or that are reach-specific (S). We used linear regression analyses as well as multiple regression analyses

Table II. Summary of multiple regression analyses

		Gradient			Channel geometry			Channel resistance to flow									Hydraulics		
Dependent variable	Q	S_{th}	S_{bf}	S_w	R	w	w/R	λ	a	LWD	D_{50}	D_{84}	R_{sd}	ff	n	R/D_{84}	v	τ	Ω
S_{bf}				**x**	0		0		x	0		0				0			
S_w		**x**	**x**				0			x	x	x							
S_{bf}					0				x			**0**			x	0	x		
S_w					0				x			0			x	0	**x**		
R		0										0	0					**x**	
w	x							**0**	x										
w/R	x	x						0	x								**0**	**0**	
λ	x		0			0	**0**		**x**						0			0	
a			**x**	**x**			x	x					x						0
D_{50}		x	0				x	x	**x**	0				x			**x**		
D_{84}		**x**	0						x	0									
R_{sd}						x	x	x	**x**										
ff	0										**x**	**x**							
n		**0x**			**0**	x	0			0			x					x	
R/D_{84}		**0**	x								0							x	

x indicates log (variable) entered model with a positive parameter value; 0 indicates log (variable) entered model with a negative parameter value.

Both x and 0 indicate log (variable) that entered the model with different signs in the two models summarized in the table; x and 0 in bold indicate variables with the strongest effect in at least one of the two best regressions

with Mallow's C_p selection criterion to examine correlations among these control and response variables. We also examined relations among response variables. For example, we tested bedform wavelength and amplitude for correlations with grain size, width/depth ratio, R/D_{84}, and shear stress, as well as with the control variables.

The multiple regressions were run without any *a priori* assumption that some variables were not response variables. In other words, each variable was tested as if it were a response variable against all other appropriate variables. Appropriate variables were limited to variables that were not used to calculate the response variable, and did not contain factors that were used to calculate the response variable. This made it essentially impossible to model variations in velocity or stream power, and no correlations for predicting these variables are presented. Also, D_{50} was excluded as an independent variable in modelling D_{84}, and vice versa. The regressions were conducted using data from the 19 step-pool reaches and the statistics program SAS (SAS Institute, 1985). Only step–pool reaches were used in order to keep bedform parameters consistent throughout the analyses and reduce the likelihood of undocumented influences on reach characteristics. Model size was limited to a maximum of five independent variables. The best eight models selected using Mallow's C_p were evaluated, and the best two models were selected. The two best models were assumed to be those with the lowest C_p that also had all parameters significant at the 0·10 level. The variables in the two best models were then recorded, and are shown in Table II.

In modelling width and total stream power, it was particularly difficult to find a significant model. For these variables only one model was found that had all parameters significant at the 0·10 level, and the variables in this model are shown in Table II. In contrast, many different sets of variables could have been used to model variables such as width/depth ratio.

RESULTS

Single-variable downstream hydraulic geometry relations indicate that only the relation between discharge and bankfull width is statistically significant (Figure 3). Where significance is reported for downstream hydraulic geometry relations, streams judged to display well-developed relations have correlations between discharge and response variables that are significant at the 0·10 or 0·05 levels (e.g. Caine and Mool, 1981; Ibbitt *et al*., 1998;

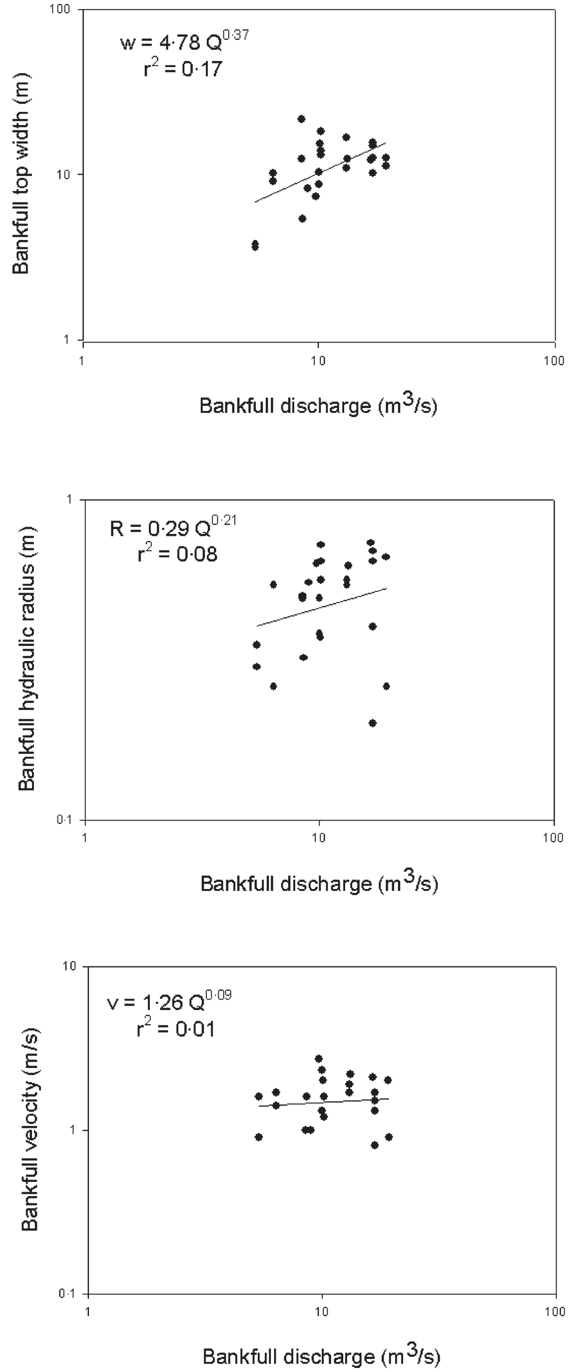

Figure 3. Log–log plots of downstream hydraulic geometry variables

Molnar and Ramirez, 2002), whereas streams that do not display predictable downstream changes in hydraulic geometry have low correlation values (e.g. Phillips and Harlin, 1984). The hydraulic geometry exponents for North St Vrain Creek are 0·37 for width, 0·21 for depth, and 0·09 for velocity. These values sum to 0·67. These results suggest that downstream hydraulic geometry trends are not well developed along North St Vrain Creek.

Table III. Summary of linear correlations among reach-scale response variables and potential control variables

	R	w	w/d	v	λ	a	D_{50}	D_{84}	τ	ff	R/D_{84}	Ω	R_{sd}	LWD
Q		**x**	x		**x**					x				
A		**x**	**x**		**x**							**x**		
S					x		**x**	**x**	**x**	**x**	**x**	**x**	**x**	

x is significant at $\alpha = 0{\cdot}10$, **x** is significant at $\alpha = 0{\cdot}05$.

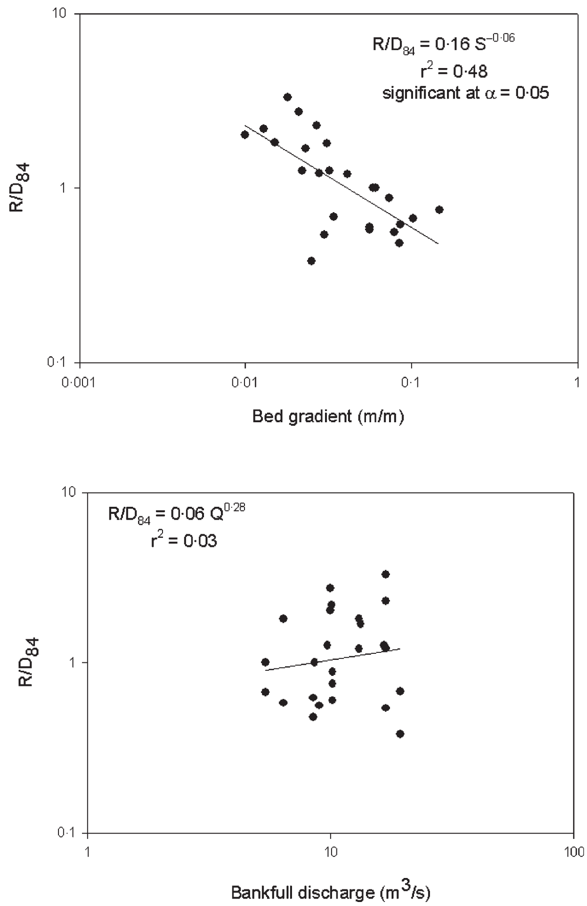

Figure 4. Log–log regression plots of relative roughness versus bed gradient and versus bankfull discharge

Results from simple linear regression analyses indicate that the log-transformed response variables R/D_{84}, D_{50}, D_{84}, ff, τ, Ω, and R_{sd} correlate more strongly with bed gradient than with discharge or drainage area (Table III; Figure 4), whereas the log-transformed response variables w, w/d, and λ correlate more strongly with discharge or drainage area (Figure 5) than with bed gradient.

We used box plots and t-tests to examine potential influences of glaciation on the fluvial variables of S, D_{50}, and D_{84} by comparing populations of these variables above and below the terminal glacial moraine (Figure 6). These tests indicated no significant difference between the populations of D_{50} and D_{84} above and below the moraine. Average bed gradient was higher above the moraine at the 0·05 significance level. Figure 7 shows that neither Ω nor D_{84} at each study site displays a consistent downstream trend, presumably because of the influences of glaciation and rockfall.

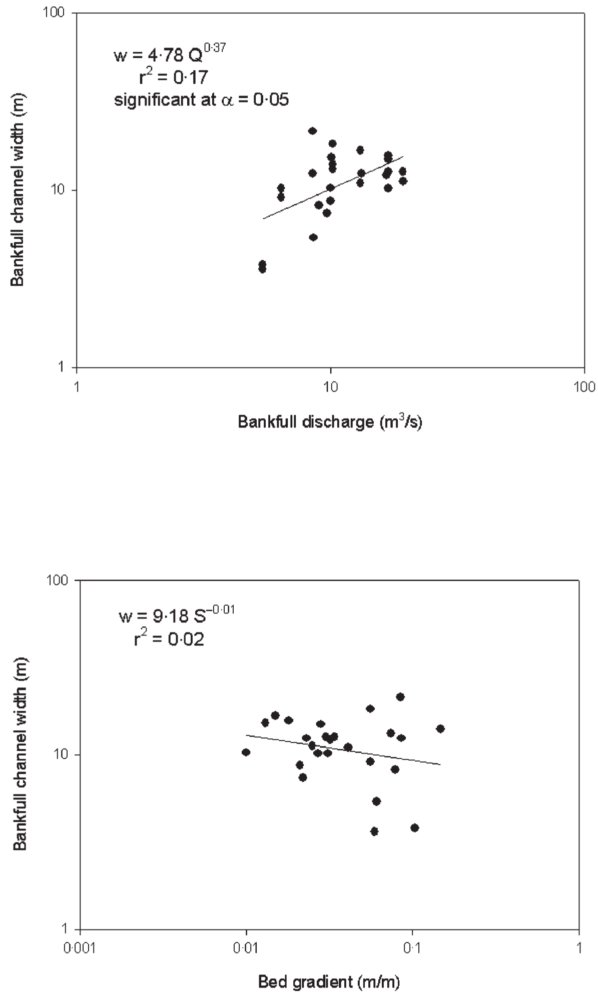

Figure 5. Log–log regression plots of bankfull channel width versus bankfull discharge, and versus bed gradient

Analyses of relations among log-transformed response variables indicate many strong correlations (Table IV). Correlations between a dependent variable and a single control may indicate either a control–response relationship or a mutual adjustment between the variables. Some correlations arise simply because the response variables tested against one another are not independent of one another; for example, w and w/R or v and *ff*. Other correlations provide insight into potential influences on response variables beyond the primary control variables of bed gradient, drainage area and discharge. Bedform wavelength correlates strongly with R and D_{50}. Bedform amplitude correlates strongly with D_{50}, D_{84}, τ, *ff*, R/D_{84}, Ω and R_{sd} (Figure 8). The grain size parameters correlate with each other, and with τ, *ff*, R/D_{84}, Ω and R_{sd}. Darcy-Weisbach friction factor also correlates with τ, R/D_{84}, and Ω. The standard deviation of the hydraulic radius correlates strongly with τ and Ω. The relative roughness correlates with v and Ω. The multitude of linear correlations among these pairs of log-transformed response variables suggests that multiple regression analyses may provide additional insight into the interdependent adjustments within the channel.

Multiple regression analyses with Mallow's C_p selection criterion and log transformation of all variables produced similar results: most response variables correlate strongly with bed gradient, whereas a few correlate well with drainage area. The specific variables differ from those selected in simple linear regressions: R/D_{84}, D_{84} and D_{50} correlate with bed gradient as in the simple linear regressions, and the variables n, S_w, R, and w/R also correlate with bed gradient in multiple regressions. The variables w, w/R, *ff*, and τ correlate best with discharge in multiple regressions.

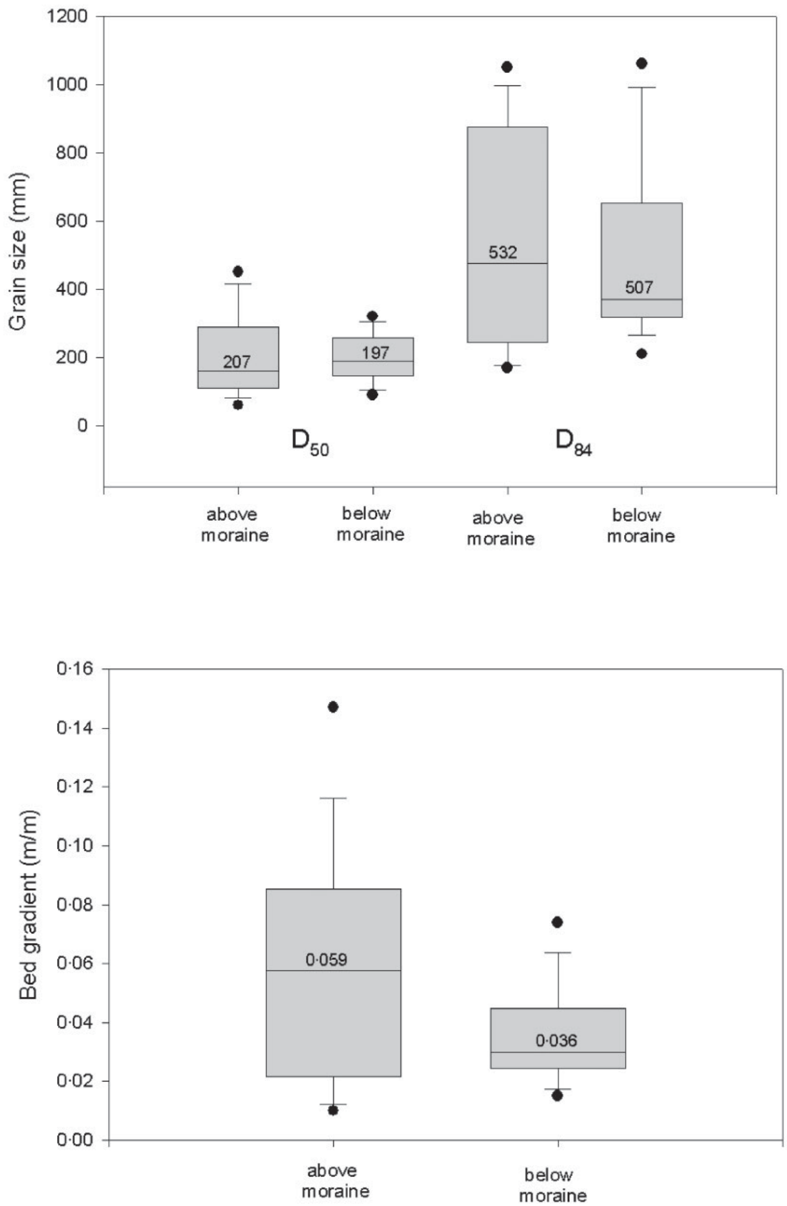

Figure 6. Box plots of populations of D_{50}, D_{84}, and S above and below the terminal glacial moraine. Mean value of each sample is given above the line in the box

In the multiple regressions, w/R is the only response variable that has a significant correlation with both drainage area and bed gradient. It appears likely that this correlation occurs because R varies inversely with bed gradient and w varies with discharge.

DISCUSSION AND CONCLUSIONS

The range of discharge values used in analyses for the North St Vrain Creek drainage basin is less than the range reported in many studies of downstream hydraulic geometry, which decreases the likelihood of finding significant correlations in the North St Vrain data. However, the poor correlations between bankfull discharge and the downstream hydraulic geometry variables of width, depth and velocity along North St Vrain Creek correspond

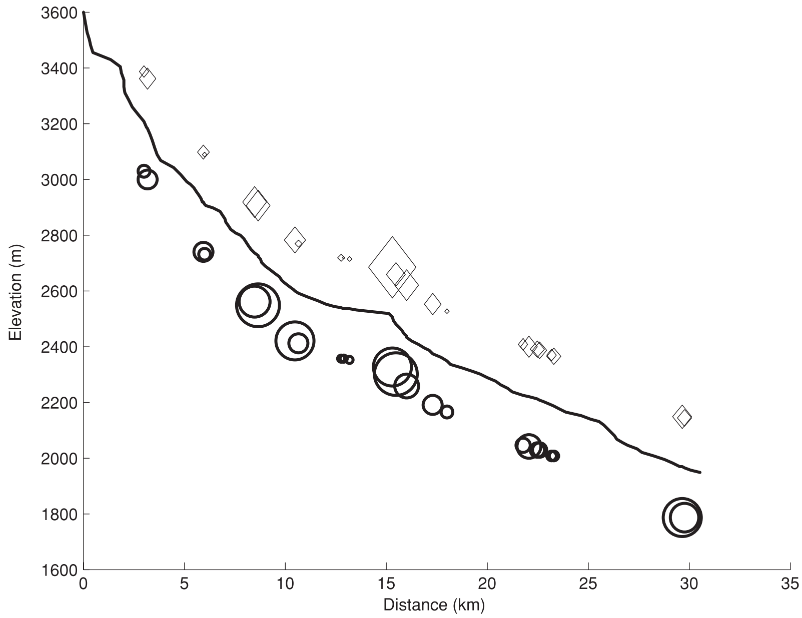

Figure 7. Longitudinal profile of North St Vrain Creek, showing the relative magnitude of total stream power (diamonds) and D_{84} (circles) at each study reach

Table IV. Summary of linear correlations among reach-scale log-transformed response variables

	R	*w*	*w/d*	*v*	*λ*	*a*	D_{50}	D_{84}	*τ*	*ff*	R/D_{84}	Ω	R_{sd}
w													
w/d	**x**	**x**											
v	**x**		x										
λ	**x**	x											
a	x	x											
D_{50}					**x**	**x**							
D_{84}						**x**	**x**						
τ	**x**		x			**x**	**x**	**x**					
ff				**x**		**x**	**x**	**x**	**x**				
R/D_{84}	x			**x**		**x**	**x**	**x**	x	**x**			
Ω						**x**	**x**	**x**	**x**	**x**	**x**		
R_{sd}		x			x	**x**	**x**	**x**	**x**	x	x	**x**	
LWD													

Symbols as in Tables I and III.

to the results from previous studies in the Rocky Mountains (Ponton, 1972; Phillips and Harlin, 1984). The difference in development of downstream hydraulic geometry between rivers of this mountainous region and those described in Nepal, New Zealand and Panama may be related to the greater values of precipitation and unit discharge in the latter regions. Presumably, the greater the unit discharge, or the greater the ratio of hydraulic driving forces to substrate resisting forces, the more effective bankfull discharge would be in shaping downstream channel geometry along mountain rivers. For North St Vrain Creek, the lack of strong downstream hydraulic geometry correlations suggests that bankfull discharge may not be as effective in shaping the channel geometry of this mountain river as is commonly assumed for alluvial rivers. This difference could arise as a result of strong, site-specific influences on channel geometry, such as rockfall or glacial history. Channel-bed gradient is a single variable that can reasonably represent these influences.

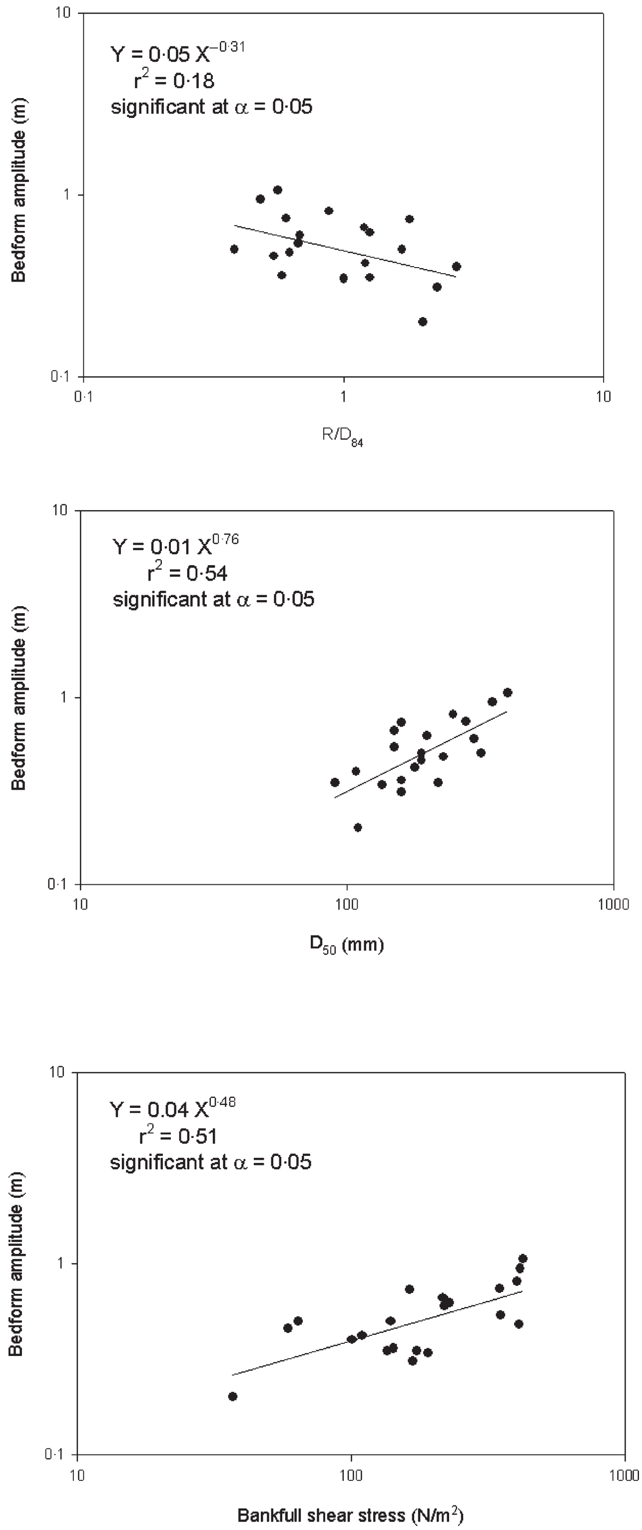

Figure 8. Sample log–log regression plots of relations among dependent variables; in this case, bedform amplitude versus R/D_{84}, D_{50}, and τ, respectively

The results of linear and multiple regression analyses examining correlations among response and control variables suggest that the null hypothesis that channel-bed gradient is likely to be a good predictor for many reach-scale response variables along mountain rivers is partly supported. The alternate hypothesis is also partly supported in that discharge and drainage area are better predictors for some response variables.

The adjustment of mountain rivers is subject to constraints imposed by downstream changes in gradient, the size of grains supplied to the channel by hillslope processes, and boundary resistance. These constraints on channel adjustment may explain both the segmented nature of many mountain drainages, in which adjacent downstream reaches display substantial differences in gradient and channel geometry, and the strong correlations between gradient and such response variables as grain size, hydraulic roughness, and variables that include gradient in their definition (e.g. shear stress and friction factor). The strong correlations between the response variables of width, width/depth ratio and bedform wavelength and the control variables of discharge and drainage area suggest that adjustments in the channel geometry and hydraulics of mountain rivers at the reach-scale produce discernible patterns analogous to those in fully alluvial rivers. Mountain rivers may differ in that imposed reach-scale gradient also exerts an important control on some reach-scale channel characteristics.

In general, channel-bed gradient correlates most strongly with variables reflecting channel-boundary resistance or hydraulics, whereas discharge or its surrogate, drainage area, correlates most strongly with channel-form variables. This suggests that bankfull discharge influences width and width/depth ratio within the constraints imposed by gradient, coarse sediment supply, and channel-boundary frictional resistance.

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