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Channel geometry of mountain streams in New Zealand

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Abstract

A dataset of 21 study reaches in the Porter and Kowai rivers (eastern side of the South Island), and 13 study reaches in Camp Creek and adjacent catchments (western side of the South Island) was used to examine downstream hydraulic geometry of mountain streams in New Zealand. Streams in the eastern and western regions both exhibit well-developed downstream hydraulic geometry, as indicated by strong correlations between channel top width, bankfull depth, mean velocity, and bankfull discharge. Exponents for the hydraulic geometry relations are similar to average values for rivers worldwide. Factors such as colluvial sediment input to the channels, colluvial processes along the channels, tectonic uplift, and discontinuous bedrock exposure along the channels might be expected to complicate adjustment of channel geometry to downstream increases in discharge. The presence of well-developed downstream hydraulic geometry relations despite these complicating factors is interpreted to indicate that the ratio of hydraulic driving forces to substrate resisting forces is sufficiently large to permit channel adjustment to relatively frequent discharges.

Keywords: Mountain streams; Downstream hydraulic geometry; Multiple regression analyses; Channel adjustment

1. Introduction

Downstream hydraulic geometry, as developed by Leopold and Maddock (1953), proposed that downstream changes in channel geometry reflect primarily the influence of increasing discharge. This influence is expressed via consistent correlations between bankfull discharge and channel top width, flow depth, and mean velocity

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

$$d = cQ^f \quad (2)$$

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

where Q is bankfull discharge (m^3/s), w is channel top width (m), d is flow depth (m), v is mean velocity (m/s), $b+f+m=1$, and $ack=1$. A primary assumption of downstream hydraulic geometry is that these channel characteristics respond to changing discharge at a timescale of the 1–2 year recurrence interval commonly postulated for bankfull flow. Numerous studies on rivers in a variety of environments have subsequently established the range of exponents (Park, 1977) and have demonstrated that many rivers have strong correlations between downstream increases in discharge and channel geometry.

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Average values for exponents of the original hydraulic geometry dataset are $b = 0.5$, $f = 0.4$, and $m = 0.1$ (Leopold and Maddock, 1953). Rivers with more erosionally resistant channel boundaries, or with non-fluvial influences such as colluvial processes or glaciation, would not necessarily be expected to have similar correlations, but the downstream hydraulic geometry of such rivers has received relatively little attention (Montgomery and Gran, 2001).

Mountain streams typically have steep, confined valleys with substantial colluvial input from adjacent hillslopes and strong influences from ongoing or recent glaciation, tectonic deformation, and bedrock exposure (Wohl, 2000). Mountain streams might thus be expected to display different patterns of downstream channel geometry than those commonly present on lowland alluvial rivers. Recent studies have focused on the correlations between response variables and potential control variables along mountain streams in order to explore the conditions under which channel geometry along mountain streams does or does not approximate lowland river patterns. Contrasting examples come from the Rio Chagres catchment of Panama, which has downstream hydraulic geometry patterns similar to those described for lowland alluvial rivers (Wohl, 2004), and North St Vrain Creek in Colorado, which has poorly developed downstream hydraulic geometry, and stronger correlations with reach-scale controls such as gradient and grain size (Wohl et al., 2004).

In this paper we continue to explore the influences on mountain channel geometry. We used data collected from two sets of streams on the South Island of New Zealand. The eastern streams occupy a drier (750–1000 mm mean annual precipitation), less tectonically active region (uplift 2.5–3.5 mm/yr), whereas the western streams are in a very wet (5000–7000 mm m.a.p.) area of high uplift rates (5–6 mm/yr). Both sets of streams have abundant, frequent colluvial input in the form of rockfall, debris torrents and landslides from adjacent hillslopes, and probably have debris flows along some portions of the channel network. Under these conditions, we hypothesized that the greater unit discharge of the western streams would produce well-developed downstream hydraulic geometry patterns, whereas the eastern streams would have poorly developed downstream hydraulic geometry. We chose a coefficient of determination (r^2) of 0.50 or greater as indicating well-developed downstream hydraulic geometry. Existing literature provides no definition of what constitutes well-developed downstream hydraulic geometry. Exponent values for downstream hydraulic geometry relations are usually simply compared to the average values originally cited by Leopold and Maddock (1953). Park (1977), however, notes that exponent values cover a wide range. Therefore, we here designate downstream hydraulic geometry as being well-developed where variation in discharge explains at least half of the variation in the response variable.

In addition to examining downstream hydraulic geometry patterns, we explored correlations between response variables and potential control variables at the reach scale. Response variables included bankfull width, bankfull depth, bedform wavelength and amplitude, relative submergence (R/D_{84}), shear stress, stream power per unit area and total stream power, and grain size (D_{50}, D_{84}). Potential control variables included bankfull discharge, reach gradient, and drainage area, as well as some of the response variables (e.g. shear stress used as a potential control variable for bedform wavelength). Many of these variables are interrelated; grain size, for example, could reflect colluvial input, reach gradient, and discharge.

2. Study area

All of the study areas are on the South Island of New Zealand (Fig. 1). The Porter and Kowai rivers lie on the eastern side of the Island, whereas Camp Creek and the other study catchments are on the western side. Mean annual precipitation varies dramatically across the Southern Alps, which trend north–south along the South Island. Mean annual precipitation at the eastern sites is approximately 750–1000 mm (McSaveney et al., 1978; Chinn, 1979), primarily from frontal systems and very occasionally from dissipating tropical cyclones. Precipitation at the western sites is 6000–8000 mm (McSaveney et al., 1978; Chinn, 1979), usually from frontal systems that may be enhanced by orographic effects. Flood hydrology varies accordingly. The regional regression equations for the mean annual flood and the 100-year

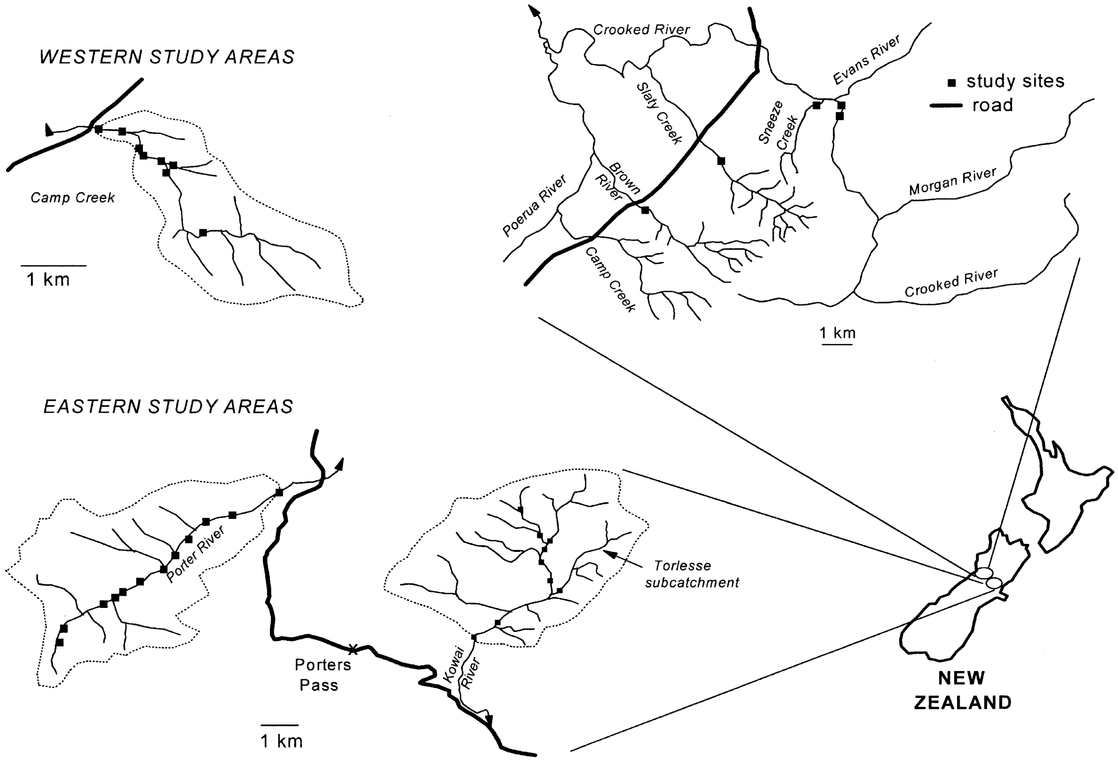

Fig. 1. Location map of the drainage basins discussed in this paper.

flood at each site are as follows (McKerchar and Pearson, 1989):

Western sites	Kowai River	Porter River
$Q = 20A^{0.808}$	$Q = 1.5A^{0.808}$	$Q = 2A^{0.808}$
$Q_{100} = 1.8Q$	$Q_{100} = 3Q$	$Q_{100} = 3Q$

where Q is the mean annual flood (m^3/s), A is drainage area (km^2), and Q_{100} is the flood with a 100-year recurrence interval (m^3/s). Most of the study sites are ungauged, but conversations with local people who have lived in the area for many years suggest that the Porter study area had a large flood in the mid-1980s and the upper Kowai had the largest flood of the past few decades in 2002.

The Porter River study area includes the upper 30 km^2 (2030–700 m elevation) of the Porter catchment, which lies within the Craigieburn Range. The Kowai River study area includes the upper 25 km^2 (2000–600 m elevation) of the catchment, which drains the Torlesse Range. Both catchments are underlain by late Carboniferous–early Cretaceous greywacke, with occasional interbedded limestone, chert and mudstone (Riddles, 1987). The two catchments lie adjacent to the Porters Pass fault zone, where uplift rate is estimated at 2.5–3.5 mm/yr (Cowan, 1992). Mean annual temperature is 10–11 °C, and the catchments are covered in tussock grasslands grazed by sheep. Beech (*Nothofagus* spp) forest covered the hillslopes up to 1400 m elevation prior to the arrival of Maori people ca. 1000 years ago, but the upper elevations have been grasslands throughout the Holocene (Hayward, 1980). Valley glaciers were present in headwater tributaries down to approximately 900 m elevation during the Pleistocene, early Holocene and neoglacial periods, but the main valleys remained unglaciated (Chinn, 1975).

The upper Porter valley is relatively broad and the streams are not incised into the valley bottoms. Relict gravel deposits indicate that the sinuous streams are highly laterally mobile. Continuing downstream, the Porter River incises into glacial outwash terraces, and is locally laterally confined by bedrock outcrops.

The streams through much of the study area have step-pool morphology (Montgomery and Buffington, 1997), with some plane-bed reaches just upstream from the braided portion of the river. We limited our study sites to those that are single-thread channels at bankfull flow.

The Kowai River is steeper and more laterally confined than the Porter River in most of the study area. Some of the study reaches have cascade morphology, but most are step-pool channels. Close to the junction with the Torlesse subcatchment, the valley rapidly grows broader and takes on a braided planform that is locally confined by bedrock outcrops or incised terraces. Study reaches in the lower catchment have plane-bed morphology.

The Kowai River study area includes the catchment of Torlesse Creek, which was extensively studied by Hayward (1980). Hayward documented the presence of sediment waves along the steep channels, for which suspended sediment constitutes less than 10% of the total sediment yield of 30 tonnes/km^2 per yr. Hayward examined step-pool sequences and estimated a 50–100 year recurrence interval for step-forming floods.

The Kowai River was gauged by National Institute of Water and Atmospheric Research (NIWA) investigators at State Highway 73 (drainage area 34.9 km^2) from 31 May 1994 to 14 February 1997. The median flow during this period was 0.97 m^3/s; the mean flow was 1.12 m^3/s (Duncan and Biggs, 1998). Floods capable of moving the D_{84} grain size (139 mm) at the gauging site occurred on average 51 times a year. Floods greater than three times the median flow occurred an average of 10 times a year (Duncan and Biggs, 1998). Maximum daily discharge during the period of record was 5.7 m^3/s on 6 February 1997 (M.J. Duncan, pers. comm., 2003).

Camp Creek drains 6 km^2 (1800–140 m elevation) of the Alexander Range, and the other western sites are adjacent to Camp Creek (Fig. 1). The Alexander Range is composed of Cretaceous–Permian biotite schist (Riddles, 1987), and the Alpine Fault runs along the base of the range. Uplift rates in the region are estimated at 5.7 mm/yr (Harrison, 1985). The catchments of the Alexander Range are covered in dense temperate rainforest. In addition to high annual rainfall volumes, rainfall intensities can reach 88 mm in 2 h (Harrison, 1985). Slope failure is widespread, resulting in debris avalanches that induce flooding along Camp Creek every 1–2 years (I. Payne, pers. comm., 2003). One of these debris-induced floods occurred during our study period, producing local bank erosion and deposition of large woody debris, as well as widespread mobilization of clasts present on the channel bed (Fig. 2). The total sediment yield for Camp Creek has been estimated at 10,000 tonnes/km^2 per yr (Harrison, 1985).

Camp Creek and the adjacent catchments were completely occupied by glaciers during the Pleistocene. Both Camp Creek and the adjacent Brown River have irregular longitudinal profiles (Fig. 3), which have been interpreted as post-glacial adjustment to lowered base level following retreat of the large glacier at the base of the Alexander Range (Harrison, 1985). The profile irregularities could also represent steepening associated with continuing uplift along the Alpine Fault.

The majority of Camp Creek and the other western study sites are closely confined, steep valleys with cascade or step-pool channels. Gradient and lateral confinement decrease as each river leaves the Alexander Range, and plane-bed channels are present in the lower portion of the western study area.

NIWA investigators gauged Camp Creek (drainage area 6.92 km^2) from 14 December 1993 to 29 August 1997. The median flow during this period was 0.59 m^3/s; the mean flow was 0.97 m^3/s (Duncan and Biggs, 1998). Floods capable of moving the D_{84} grain size (113 mm) at the gauging site occurred on average 52 times a year. Floods greater than three times the median flow occurred an average of 49 times a year (Duncan and Biggs, 1998). Maximum daily discharge during the period of record was 9.0 m^3/s on 11 February 1997 (M.J. Duncan, pers. comm., 2003).

3. Methods

For each catchment, study reaches were chosen both to represent incremental increases in drainage area and discharge, and to characterize the most commonly observed types of channel morphology. We define a channel reach as a length of channel having consistent bed gradient and bedform type. Each reach was several times the average channel width (range 30–110 m in length). Within each reach, we (1) surveyed channel bed, water-surface, and high water mark gradients; (2) measured the grain-size distribution using a random walk (Wolman, 1954);

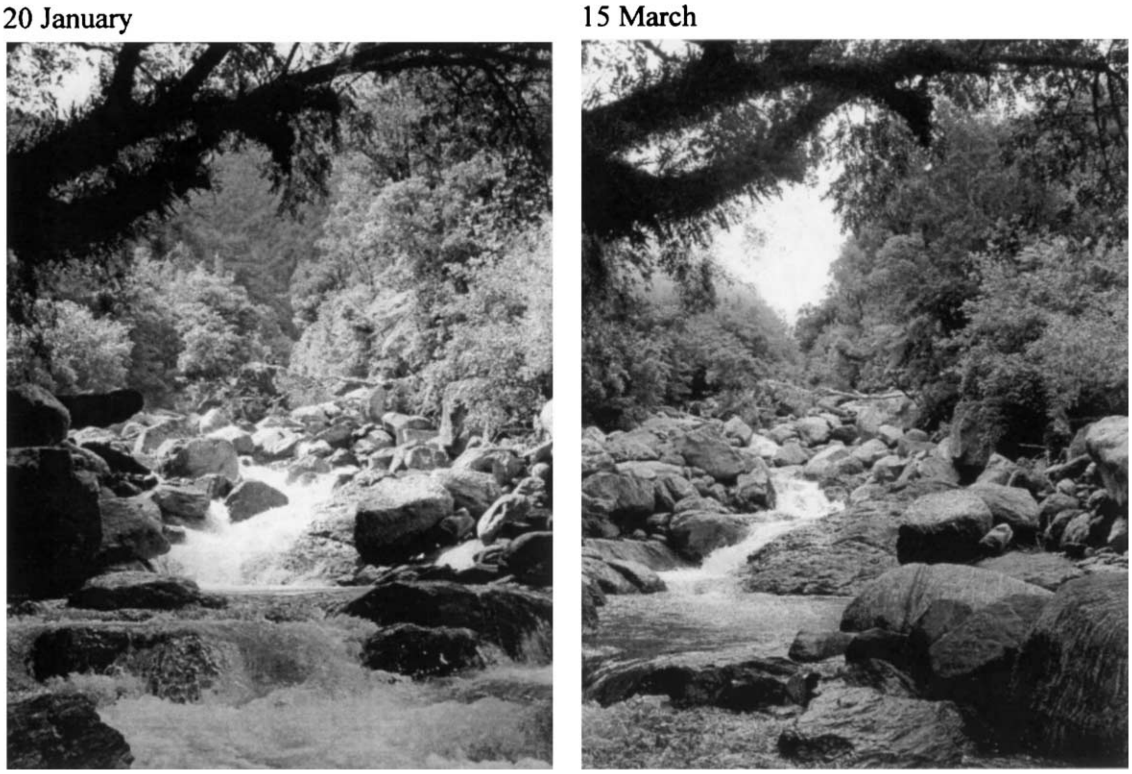

Fig. 2. View of Camp Creek reach 5 before (20 Jan. 03) and after (15 Mar. 03) a flood probably initiated by hillslope instability. Bankfull channel width is approximately 17 m.

(3) measured the average flow velocity at the time of the survey using a salt tracer and conductivity probe to determine time to peak concentration (Spence and McPhie, 1997); (4) surveyed the downstream spacing and height of bed steps where present; and (5) measured the rock-mass strength (Selby, 1980) of bedrock where exposed along the channel bed or banks. A theodolite and stadia rod were used for the channel surveys.

The field data were used to calculate several variables. We used the surveyed channel geometry and high water marks to estimate 'bankfull' values for channel top width, flow depth, hydraulic radius, wetted perimeter, and cross-sectional area. Bankfull in this paper refers to a flow that fills the channel to the top of the banks, where this break in slope is present. We used channel morphology, changes in vegetation, and flow-deposited organic debris to define the bankfull level in the field. Hydraulic radius was calculated by dividing cross-sectional area by measured wetted perimeter, and is thus dependent on the detail with which wetted perimeter was surveyed. We chose survey points at breaks in slope where clasts were finer than 0.5 m in diameter; coarser clasts were outlined with survey points.

We used channel surveys and mean velocity estimates obtained with the salt tracers to calculate Manning's n value for each study reach at the time of field work. These low-flow n values were then used with Hicks and Mason's (1991) text on roughness characteristics of New Zealand rivers to estimate n values for bankfull flow conditions. The n values were used in the Manning equation to estimate bankfull discharge for each reach. The n values for several reaches were subsequently adjusted to ensure that bankfull discharge generally increased with drainage area within each study catchment. We cannot compare these discharge estimates to discharge based on recurrence interval because none of the study catchments are gauged. For all reaches

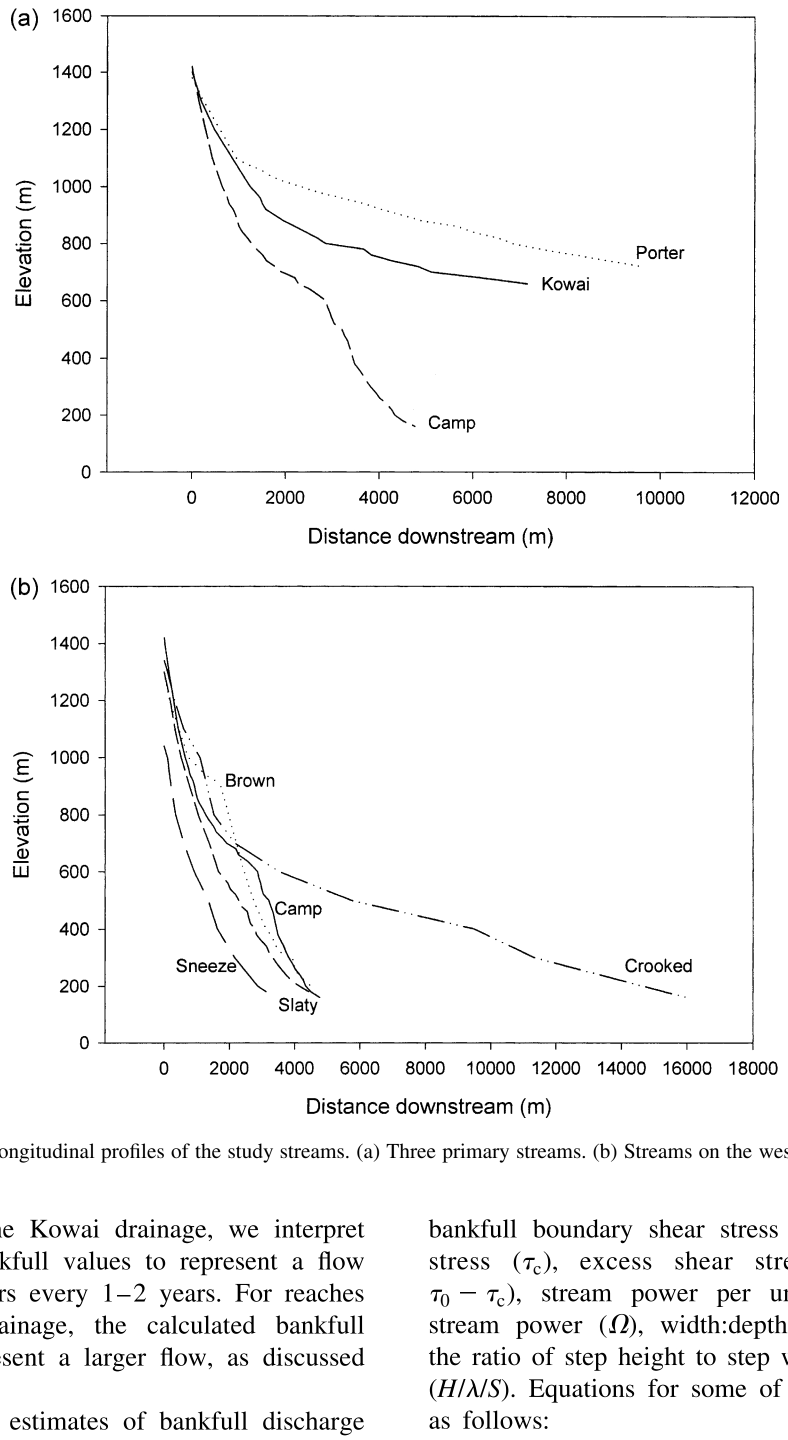

Fig. 3. Longitudinal profiles of the study streams. (a) Three primary streams. (b) Streams on the western side.

except those in the Kowai drainage, we interpret the calculated bankfull values to represent a flow that probably recurs every 1–2 years. For reaches in the Kowai drainage, the calculated bankfull values likely represent a larger flow, as discussed below.

The field-based estimates of bankfull discharge and channel parameters formed the basis for calculating the following hydraulic variables: unit discharge (Q_{bf}/DA), relative submergence (R_{bf}/D_{84}), bankfull boundary shear stress (τ_0), critical shear stress (τ_c), excess shear stress (τ_*, equal to $\tau_0 - \tau_c$), stream power per unit area (ω), total stream power (Ω), width:depth ratio ($w:d$), and the ratio of step height to step wavelength to slope ($H/\lambda/S$). Equations for some of these variables are as follows:

$$\tau_0 = \gamma RS \tag{4}$$

where τ_0 is bankfull boundary shear stress (N/m^2), γ is specific weight of water (9810 N/m^3 for clear water), and S is slope

$$\tau_c = \tau_c^*(\rho_s - \rho_w)gD_{50} \quad (5)$$

where τ_c^* is critical shear stress at initiation of bedload transport (N/m^2), τ_c^* is a dimensionless critical shear stress parameter (assumed to equal 0.047, a value suggested by Meyer-Peter and Muller (1948) and intermediate between values suggested by Miller et al. (1977) and Yalin (1972)), ρ_s is sediment density (assumed to equal 2650 kg/m^3), ρ_w is water density (1000 kg/m^3), g is gravitational acceleration, and D_{50} is median grain size

$$\Omega = \gamma QS \quad (6)$$

where Ω is total stream power (kg m per s^3)

$$\omega = \tau_0 v \quad (7)$$

where ω is unit stream power (W/m^2), τ_0 is as in Eq. (4), and v is bankfull velocity.

Hydraulic geometry patterns were evaluated by plotting the logarithm of bankfull discharge (Q_{bf}) versus the logarithm of bankfull width (w_{bf}), depth (d_{bf}), and velocity (v_{bf}), respectively, to produce power-law relations, as in Eqs. (1)–(3). Values for b, f, and m (from Eqs. (1)–(3)) represent the slope of log–log regressions between Q_{bf} and w_{bf}, d_{bf}, and v_{bf}, respectively. For the hydraulic geometry analysis, reaches in the Porter and Kowai drainage were combined, representing eastern rivers, and reaches in the Camp Creek basin were combined with reaches in adjacent drainages, representing western rivers. If two of the three downstream hydraulic geometry variables (w_{bf}, d_{bf}, v_{bf}) had r^2 values of >0.50 with Q_{bf} for a given basin or group of basins, we identified these areas as having 'well developed' downstream hydraulic geometry. In order to test the hypothesis that the greater unit discharge of western rivers would produce well-developed downstream hydraulic geometry, whereas eastern rivers would have poorly developed hydraulic geometry, t-tests were used to evaluate whether hydraulic geometry relations were statistically different between eastern and western rivers.

In order to explore controls on reach-scale morphology, we identified a set of control and response variables, with some of the response variables also potentially acting as control variables for other response variables. The three primary control variables were drainage area, (DA), slope (S_0), and bankfull discharge (Q_{bf}). Twelve response variables of interest were identified: bankfull top width (w_{bf}), bankfull depth (d_{bf}), grain size (D_{50} and D_{84}), relative submergence (R_{bf}/D_{84}), boundary shear stress (τ_0), excess shear stress (τ*), unit stream, power, (ω), total stream power (Ω), width:depth ratio ($w:d$) and, for step-pool reaches, step wavelength (λ) and step height (H).

The first stage of the analysis of reach-scale morphology involved simple linear regression analyses between all potential control and response variables. We elaborated on this using multiple regression to determine which suites of variables were most responsible for observed morphologic characteristics. In the multiple regressions, various combinations of five control variables were regressed against each of six primary response variables: $w_{bf}, d_{bf}, D_{50}, D_{84}$, and, for step-pool reaches, step wavelength (λ) and step height (H). In these regressions, control variables included drainage area (DA) and slope (S), as well as some combination of other variables hypothesized to potentially exert some control on the response variable of interest. Bankfull discharge was not used as a control variable because of its high collinearity with drainage area. Selection of the best model for describing each response variable was based on Mallow's C_p. For both linear and multiple regressions, all variables were log transformed to homogenize the variance.

4. Results

Measured and calculated variables for each study reach are summarized in Table 1. Downstream hydraulic geometry relations are well developed for both the eastern and western rivers (Fig. 4). Both regions have hydraulic geometry exponents that are similar to the average values reported by Leopold and Maddock (1953): the width, depth, and velocity exponents (b, f, and m in Eqs. (1)–(3)) are 0.50, 0.33, 0.17, respectively, for eastern streams, and 0.52, 0.43, 0.07, respectively, for western streams. Comparison of these values between the eastern and

Table 1
Summary of measured and calculated variables for the study reaches

Reach	DA (km^2)	S (m/m)	n_{bf}	Q_{bf} (m^3/s)	w_{bf} (m)	d_{bf} (m)	v_{bf} (m/s)	D_{50} (mm)	D_{84} (mm)	R/D_{84}	τ_0, τ_c (N/m^2)	ω (W/m^2)	Ω (W)	H (m)	λ (m)	Channel type
Porter 1	1.7	0.08	0.12	1.3	2.2	0.4	1.3	38	235	1.7	310, 29	400	1000	0.39	3.9	Step-pool
Porter 2	2.6	0.05	0.10	1.5	3.6	0.3	1.0	65	140	2.1	150, 49	150	740	0.22	4.0	Step-pool
Porter 3	5.5	0.046	0.05	1.9	2.6	0.3	1.9	120	214	1.4	140, 91	260	870	0.26	4.6	Step-pool
Porter 4	9.0	0.02	0.05	2.8	2.7	0.5	1.8	142	235	2.1	100, 108	170	560	0.22	7.0	Step-pool
Porter 5	10.3	0.04	0.05	5.0	3.6	0.5	2.5	112	315	2.0	200, 85	490	1980	0.30	5.1	Step-pool
Porter 6	14.2	0.047	0.06	9.0	5.6	0.6	2.6	155	410	1.9	280, 118	710	4150	0.24	4.2	Step-pool
Porter 7	19.6	0.05	0.04	9.1	5.8	0.4	3.0	198	222	1.0	200, 151	590	4460	0.36	5.4	Step-pool
Porter 8	19.9	0.043	0.06	12.8	9.3	0.7	2.7	109	245	3.2	300, 83	800	5400	0.22	4.2	Step-pool
Porter 9	21.5	0.034	0.08	12.9	8.1	0.8	2.0	60	207	3.3	270, 46	530	4310	0.22	4.8	Step-pool
Porter 10	23.0	0.022	0.03	8.0	4.8	0.4	2.7	128	258	1.9	90, 97	230	1740	0.27	10.5	Step-pool
Porter 11	25.6	0.016	0.03	7.8	7.2	0.4	2.3	150	164	1.6	60, 114	140	1220	–	–	Plane-bed
Porter 12	29.5	0.02	0.03	15.9	13.0	0.4	2.6	96	535	2.4	80, 73	200	3110	–	–	Plane-bed
Kowai 1	0.7	0.17	0.20	7.1	10.3	0.5	1.3	240	535	0.9	830, 183	1080	11,910	0.37	2.2	Step-pool
Kowai 2	3.0	0.15	0.20	22.4	11.4	0.9	1.8	275	695	1.3	1320, 209	2400	32,930	0.60	3.5	Step-pool
Kowai 3	3.6	0.06	0.07	19.6	5.0	0.8	3.0	170	330	2.4	470, 129	1420	11,540	0.21	3.0	Step-pool
Kowai 4	3.9	0.07	0.08	21.1	7.4	0.7	2.6	200	610	1.2	480, 152	1250	14,500	–	–	Cascade
Kowai 5	7.5	0.05	0.14	43.2	14.7	1.3	1.9	210	680	1.9	640, 160	1210	21,180	0.39	5.7	Step-pool
Kowai 6	10.7	0.045	0.15	47.5	23.5	1.1	1.5	210	520	2.1	480, 160	730	20,960	0.42	4.2	Step-pool
Kowai 7	11.7	0.054	0.06	27.4	7.8	0.9	3.6	170	435	2.1	480, 129	1720	14,540	0.28	4.6	Step-pool
Kowai 8	24.0	0.026	0.05	54.7	16.5	1.1	3.0	60	180	5.0	230, 46	690	13,950	–	–	Plane-bed
Kowai 9	24.9	0.026	0.05	62.2	12.9	0.5	3.4	95	155	7.1	280, 72	960	15,860	–	–	Plane-bed
Camp 1	0.5	0.19	0.20	3.2	3.5	0.5	1.4	280	590	0.8	930, 213	1280	5890	0.64	3.4	Step-pool
Camp 2	2.9	0.14	0.15	14.6	11.8	0.6	1.8	300	1000	0.6	820, 228	1460	19,980	0.64	4.8	Step-pool
Camp 3	4.4	0.24	0.35	43.3	18.5	1.2	1.6	550	1120	1.1	2820, 418	4460	10,1970	–	–	Cascade
Camp 4	5.0	0.17	0.15	47.7	26.3	0.7	2.2	650	1260	0.6	1170, 494	2530	79,500	0.95	5.0	Step-pool
Camp 5	5.1	0.20	0.28	47.9	16.7	1.3	1.9	450	1350	1.0	2550, 342	4840	94,060	–	–	Cascade
Camp 6	5.1	0.15	0.1	48.5	23.0	0.6	2.8	640	1190	0.5	880, 487	2430	71,350	0.73	5.0	Step-pool
Camp 7	5.8	0.10	0.17	49.4	13.0	1.4	2.3	430	910	1.5	1370, 327	3200	48,410	0.52	4.7	Step-pool
Camp 8	6.0	0.05	0.08	50.6	11.5	1.1	3.0	190	580	1.9	540, 145	1610	24,830	0.35	5.7	Step-pool
Crooked 1	70.2	0.029	0.10	178.5	38.0	1.7	2.4	490	1020	1.7	480, 373	1170	50,790	0.56	17.0	Step-pool
Crooked 2	70.3	0.003	0.03	193.8	35.7	1.9	2.8	190	390	4.9	60, 145	160	5700	–	–	Plane-bed
Brown 1	5.9	0.05	0.06	32.3	14.4	0.7	2.9	270	680	1.0	340, 205	1010	15,850	0.46	7.8	Step-pool
Slaty 1	5.3	0.036	0.05	18.8	8.8	0.7	3.0	250	530	1.3	250, 190	740	6660	0.25	4.4	Step-pool
Sneeze 1	1.8	0.07	0.03	4.8	7.0	0.2	3.0	138	300	0.7	140, 105	410	3320	0.25	3.7	Step-pool

Notes: DA is the drainage area, S is reach gradient, n_{bf} is estimated Manning n value at bankfull flow, Q_{bf} is bankfull discharge, w_{bf} is bankfull channel top-width, d_{bf} is bankfull depth, v_{bf} is bankfull mean velocity, D_{50} is median grain size of streambed, D_{84} represents size at which 84% of the distribution is finer-grained, R/D_{84} is relative submergence, τ_0 is bankfull boundary shear stress, ω is stream power per unit area, Ω is total stream power, H is bedform amplitude (step height), λ is bedform wavelength (step spacing).

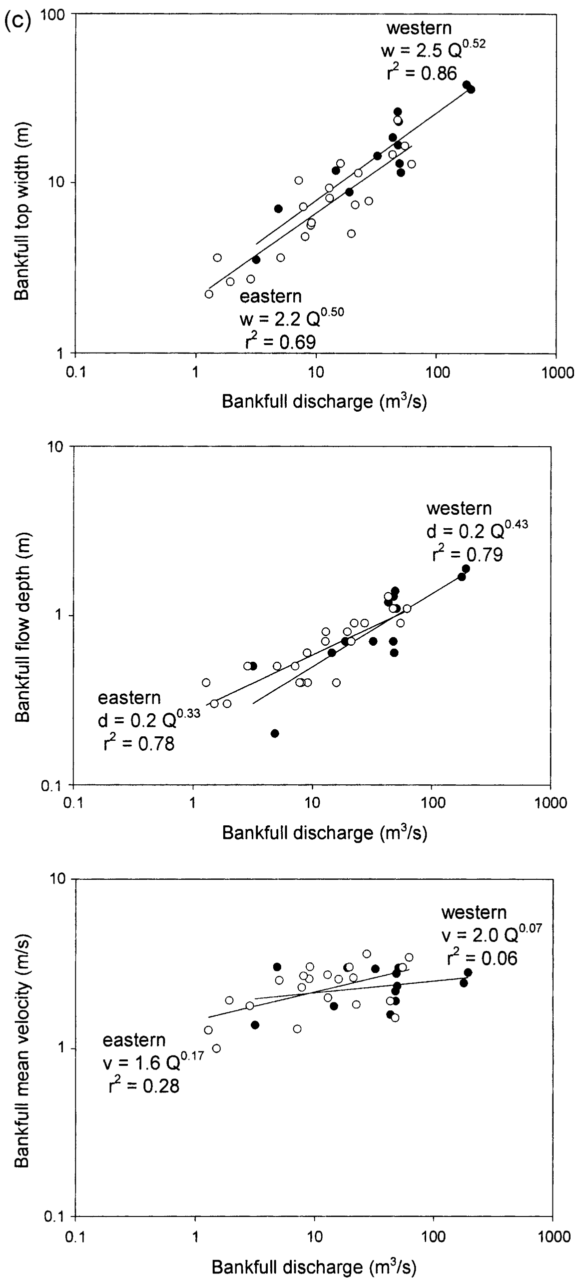

Fig. 4. Downstream hydraulic geometry relations for the study area.

western streams indicates that hydraulic geometry relations are not significantly different between regions.

Average unit bankfull discharges are highest in the Camp Creek basin (8 m^3/s per km^2) and lowest in the Porter River basin (0.5 m^3/s per km^2). Despite the proximity of the Porter and Kowai basins, average unit discharges in the Kowai basin are an order of magnitude higher than in the Porter River basin, reflecting the effects of the 2002 flood in the Kowai. In basins other than the Kowai, values of bankfull discharge are 25–55% as large as values of discharge for the mean annual flood calculated from the regional regression equations in McKerchar and Pearson (1989). Field-estimated bankfull discharge values from the Kowai River are 3–6 times higher than regional values for mean annual flood and are similar in magnitude to the regional regression-based estimate of the 100-year flood. Field-based estimates of bankfull discharge for the Kowai River and Camp Creek sites are much higher than discharges measured during approximately three years of stream gauging in the mid-1990s on the Kowai River and Camp Creek. This suggests that the field-calculated discharge values may not represent a flow that occurs approximately annually. However, the trend of the regressions is not likely to be altered as a result: Ibbitt (1997) demonstrated that regression lines for width, depth or velocity versus discharge plots showed little variation in slope with flow at exceedances of 70, 50 and 30% for the mean annual flow.

Linear regression analyses for individual variables (Tables 2 and 3) indicate that drainage area and discharge, which are highly correlated with each other, are the variables most likely to be correlated with response variables. On the Kowai River, grain size correlates with reach gradient; step height correlates with grain size, shear stress, and total stream power; and step wavelength correlates with discharge, drainage area, and flow depth. Step wavelength correlates with both reach gradient and with shear stress on the Porter. Some of the correlations between individual variables result from the use of one of the variables in the formula for the other variable (e.g. S is used to calculate τ_0, resulting in a high correlation between these variables).

Multiple regression analyses (Table 4) also indicate that variation in response variables is most often explained by drainage area and, to a lesser extent, slope. Drainage area appears in models for channel width and step wavelength in all study basins. Models for grain size include slope and channel width in both the Porter basin and Camp Creek; shear stress is

Table 2
Coefficients of determination (r^2) for simple linear regressions between primary control variables (DA, Q_{bf}, S) and reach-scale response variables, based on log transformation of values in Table 1

Control variable	Basin	Q_{bf}	S	w	d	v	D_{50}	D_{84}	R/D_{84}	w/d	τ	τ^*	ω	Ω	H	λ
DA	All	0.22	**0.58**	0.14	0.13	0.29	0.03	0.08	0.37	0.03	0.24	0.15	0.11	0.00	0.05	**0.52**
	Porter	**0.89**	0.44	**0.67**	0.20	**0.73**	0.37	0.09	0.03	0.39	0.11	0.14	0.02	**0.42**	0.08	0.23
	Kowai	**0.90**	**0.86**	0.17	**0.57**	0.40	**0.54**	0.41	**0.74**	0.00	**0.58**	**0.56**	0.17	0.01	0.01	**0.78**
	Camp	**0.96**	0.11	**0.74**	0.41	**0.52**	0.11	0.26	0.04	0.20	0.03	0.01	0.33	**0.67**	0.03	**0.87**
Q_{bf}	All	–	0.02	**0.84**	**0.74**	0.21	0.28	0.27	0.03	0.18	0.12	0.10	0.25	**0.63**	0.21	0.15
	Porter	–	0.21	**0.83**	0.36	0.67	0.18	0.08	0.09	0.41	0.00	0.07	0.14	**0.70**	0.05	0.06
	Kowai	–	**0.77**	0.31	**0.78**	0.19	0.36	0.25	**0.63**	0.00	0.39	0.38	0.18	0.09	0.02	**0.82**
	Camp	–	0.07	**0.77**	0.44	0.49	0.18	0.29	0.04	0.19	0.06	0.02	0.43	**0.77**	0.01	**0.80**
S	All	0.02	–	0.00	0.00	0.15	0.23	0.36	**0.51**	0.00	**0.73**	**0.55**	**0.57**	0.26	0.49	0.33
	Porter	0.21	–	0.18	0.00	0.12	0.19	0.03	0.03	0.20	**0.71**	0.49	0.32	0.01	0.28	**0.68**
	Kowai	**0.77**	–	0.11	0.41	0.40	**0.66**	**0.54**	**0.79**	0.00	**0.83**	**0.82**	0.38	0.04	0.20	**0.54**
	Camp	0.07	–	0.01	0.05	**0.54**	0.41	0.33	0.35	0.05	**0.51**	0.37	0.17	0.06	**0.80**	0.43

Correlations >0.50 are shown in bold.

the only significant variable in models for grain size in the Kowai River. Step height is explained by models including drainage area and/or D_{84}, Models for flow depth include slope and excess shear stress in all three basins; D_{50} and total stream power also appear in models for some of the basins. In models where drainage area appears as a significant control variable, substitution of bankfull discharge for drainage area results in significant correlations between Q_{bf} and the response variable. For many of the response variables (w, D_{50}, D_{84}, H, λ), certain control variables that were not significant in any individual basins did appear as significant in models for all basins, because of the larger number of degrees of freedom afforded by the combined data set.

The distributions of grain size, unit stream power, and total stream power reach a peak value at some intermediate distance downstream, but this distance is not consistent among the three rivers (Figs. 5 and 6).

For step-pool reaches, the ratio of step height to step wavelength to slope ($H/\lambda/S$) was calculated to determine whether these values were between 1 and 2, a range that Abrahams et al. (1995) suggested was indicative of maximization of flow resistance in step-pool channels. The $H/\lambda/S$ values for individual reaches ranged from 0.95 to 2.2. Overall averages for streams within each basin were similar, ranging from 1.1 (Camp Creek) to 1.3 (Kowai and Porter). No significant difference in $H/\lambda/S$ values was observed between basins, although values were slightly higher in eastern rivers. Nearly all values of $H/\lambda/S$ in our study reaches were within the range suggested by Abrahams et al. (1995) as indicating maximization of flow resistance in step-pool channels. Most values clustered toward the low side of this range, however, and $H/\lambda/S$ values were all close to 1 in Camp Creek.

5. Discussion and conclusions

The study streams, especially those on the west side of the South Island, are located in a remarkably dynamic geomorphic setting, with high uplift rates (2.5–6 mm/yr), high annual precipitation (750–6000 mm/yr), and large sediment yields (10,000 tonnes/km^2 per yr for Camp Creek). The dynamic setting results in high unit discharges, high excess shear stresses, and a rapid transition from single-thread to braided channels (i.e. the onset of braiding occurs at relatively small drainage areas). Excess shear stress values ($\tau_0 - \tau_c$) calculate here, which suggest that sediment mobilization occurs frequently in these channels, are indicative of the dynamic nature of the study streams. In particular, very large excess shear stress value were calculated for the Kowai (average of 500 N/m^2) and the Camp (average of 1200 N/m^2) basins. For the Kowai, this result reflects the likelihood that our estimates of 'bankfull' stage (and therefore bankfull boundary

Table 3
Results of simple linear regressions between reach-scale response variables and potential control variables, based on log transformation of values in Table 1

Basin	w v D_{50}	w v D_{84}	w v R/D_{84}	w v τ	w v Ω	w v H	w v λ	d v D_{50}	d v D_{84}	d v τ^*	d v Ω	d v H	d v λ	D_{50} v τ_0	D_{50} v τ^*	D_{50} v ω	D_{50} v Ω
All	0.33	0.32	0.00	0.12	**0.61**	0.35	0.08	0.17	0.24	0.34	0.49	0.11	0.09	0.42	0.24	**0.47**	**0.57**
Porter	0.05	0.00	0.16	0.02	**0.57**	0.14	0.00	0.00	0.12	0.22	0.41	0.12	0.00	0.15	0.12	0.00	0.04
Kowai	0.04	0.01	0.08	0.02	0.23	0.49	0.15	0.05	0.02	0.07	0.28	0.03	**0.88**	**0.81**	**0.70**	0.35	0.15
Camp	0.49	**0.64**	0.07	0.09	**0.85**	0.12	**0.60**	0.00	0.03	0.36	0.31	0.37	0.27	0.33	0.11	0.42	**0.56**
	D_{50} v H	D_{50} v λ	D_{84} v τ_0	D_{84} v τ^*	D_{84} v ω	D_{84} v Ω	D_{84} v H	D_{84} v λ	H v R/D_{84}	H v τ_0	H v ω	H v Ω	H v λ	λ v R/D_{84}	λ v τ_0	λ v ω	λ v .Ω
All	**0.55**	0.04	**0.63**	0.40	**0.63**	**0.67**	**0.73**	0.02	0.48	**0.58**	0.46	**0.51**	0.01	0.01	0.04	0.01	0.06
Porter	0.01	0.19	0.11	0.07	0.36	0.18	0.22	0.00	0.49	0.04	0.05	0.00	0.00	0.02	0.19	0.00	**0.31**
Kowai	**0.82**	0.07	**0.70**	**0.61**	0.26	0.19	**0.83**	0.09	0.30	**0.60**	0.02	**0.74**	0.01	0.21	0.07	0.04	0.10
Camp	**0.66**	0.00	0.39	0.19	**0.51**	**0.69**	**0.56**	0.10	**0.79**	0.36	0.06	0.10	0.08	**0.50**	0.00	0.22	0.24

Values shown are coefficients of determination (r^2); r^2 values >0.50 are shown in bold.

Table 4
Results of multiple linear regression analyses, showing control variables that appeared in models with the lowest Mallows C_p

Response variable	Basin	Control variable (s)
w	All	$\boldsymbol{S}$, **DA**, $\boldsymbol{\tau}$, R/D_{84}
	Porter	**DA**, D_{50}
	Kowai	DA
	Camp	S, **DA**, τ
d	All	$\boldsymbol{S}$, $\mathbf{D_{50}}$, $\boldsymbol{\tau^*}$, $\boldsymbol{\Omega}$
	Porter	$\boldsymbol{S}$, $\boldsymbol{\tau^*}$, $\boldsymbol{\Omega}$
	Kowai	S, $\boldsymbol{D_{50}}$, τ^*, Ω
	Camp	$\boldsymbol{S}$, $\boldsymbol{D_{50}}$, $\boldsymbol{\tau^*}$
D_{50}	All	$\boldsymbol{\Omega}$
	Porter	S, **DA**, $\boldsymbol{w}$
	Kowai	$\boldsymbol{\tau}$
	Camp	S, w
D_{84}	All	**DA**, $\boldsymbol{\Omega}$
	Porter	S, DA, w
	Kowai	$\boldsymbol{\tau}$
	Camp	$\boldsymbol{S}$, w
H	All	$\boldsymbol{S}$, $\boldsymbol{D_{84}}$
	Porter	DA, D_{84}
	Kowai	$\boldsymbol{D_{84}}$
	Camp	DA, $\boldsymbol{w}$, τ
λ	All	S, **DA**, D_{50}
	Porter	DA, τ
	Kowai	**DA**
	Camp	**DA**, $\boldsymbol{\tau}$

Control variables within the selected models that were also significant at $\alpha = 0.10$ using stepwise model selection are shown in bold.

shear stress) represent a very large event, in which the threshold of sediment motion would have been easily surpassed. In Camp Creek, the large excess shear stress values suggest that sediment transport occurs at well below bankfull stage, even though the bed material in this channel is very large ($D_{50} > 400$ mm). This is consistent with our observations of sediment motion during our field surveys on Camp Creek, and with evidence of substantial reworking of one reach of Camp Creek between our field visits. The steep channel gradient and high unit discharge of Camp Creek create considerable driving forces for transporting sediment which, coupled with the large volumes of sediment delivered to the channel and the effects of uplift along the Alpine Fault, create an active fluvial system. Even the Kowai

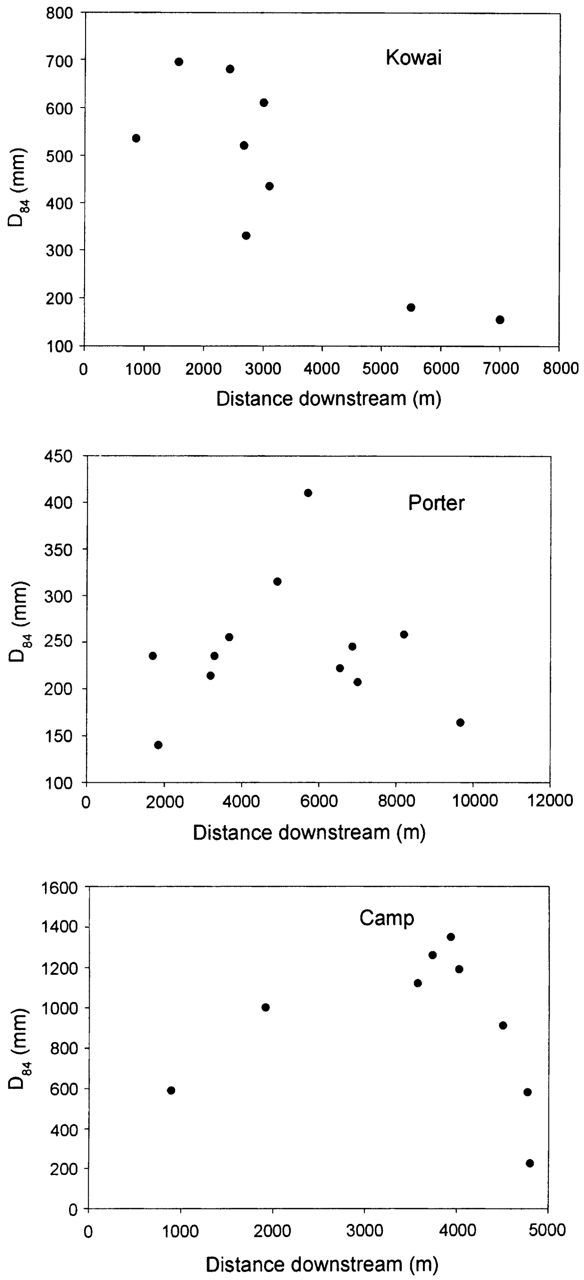

Fig. 5. D_{84} in relation to distance downstream for the three primary study streams.

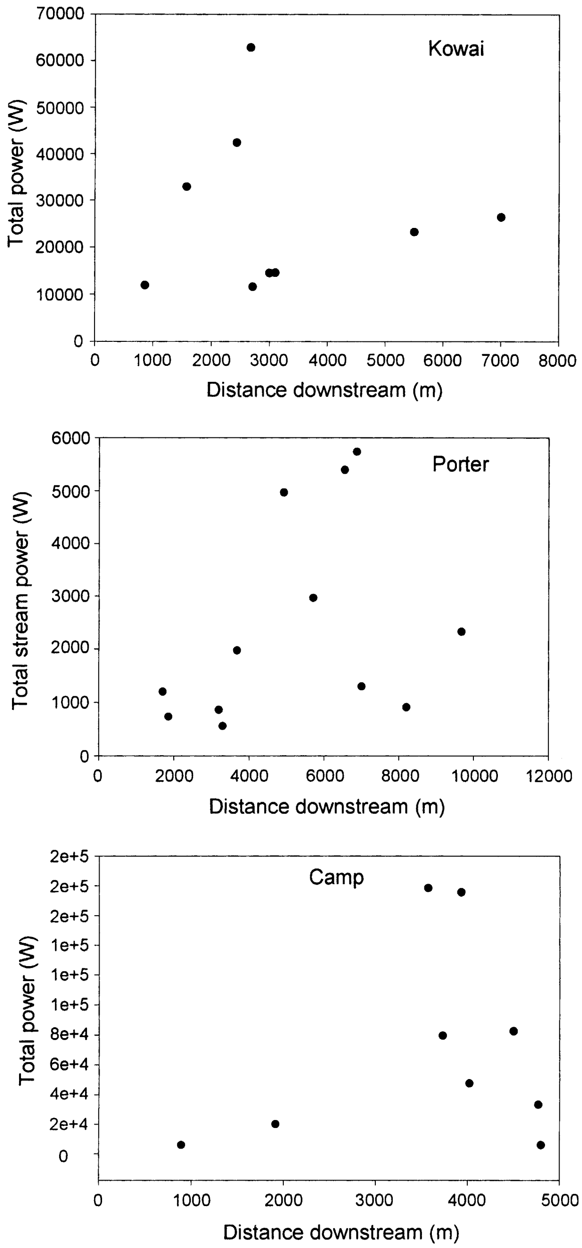

Fig. 6. Total stream power in relation to distance downstream for the three primary study streams.

River, which was originally included in the study as an example of a 'less dynamic' system because of its location on the eastern side of the Southern Alps and its lower mean annual precipitation than the western streams, also proved to be extremely active.

Calculations using regional regression relations suggest that the 2002 flood in the Kowai basin was on the order of a 100-year recurrence interval event. Because our field estimates of bankfull channel dimensions were affected by this event, unit discharges calculated here for the Kowai are an order of magnitude larger than those in the neighboring Porter basin, although the Kowai unit discharges are smaller than those in Camp Creek. Hayward's (1980) study in the Torlesse (a subbasin in the Kowai drainage) indicating that 50–100 year events are necessary in the Torlesse to create steps suggests that step-pool sequences may have been formed by the 2002 flood in the Kowai. Field observations were unable to confirm the age of step-pool sequences in the Kowai, however. Step geometries ($H/\lambda/S$) observed in the Kowai were not significantly different from the other study basins, suggesting that $H/\lambda/S$ data from the Kowai do not contain any evident signature indicating that steps here were recently formed.

The analyses presented here are subject to uncertainties in our estimates of several hydraulic variables. Estimates of Manning's n at bankfull are particularly susceptible to uncertainty, which in turn creates uncertainty in estimates of bankfull velocity and discharge. Calculation of bankfull velocity, boundary shear stress, and several other hydraulic parameters substituted bed slope for friction slope, which is only strictly valid in the case of steady, uniform flow. It is likely, however, that high flows in these channels are unsteady and nonuniform. In addition, bankfull channel dimensions were difficult to identify in some reaches, including reaches along the Kowai affected by the 2002 flood and reaches along the western rivers bordered by abundant vegetation. These type of field-based uncertainties are inherent in studies of many mountain rivers, but we do not believe that these uncertainties invalidate the inferences regarding controls on channel adjustment that we have drawn from the New Zealand field data.

Contrary to our initial hypothesis, streams on both the eastern and western sides of New Zealand have well-developed downstream hydraulic geometry relations with exponents similar to average values for rivers worldwide. These results suggest that despite abundant colluvial input, active tectonic uplift, and Quaternary glaciation—all of which might be expected to interfere with channel adjustment to downstream increases in discharge—the hydraulic geometry of the mountain streams examined in this study is adjusted to contemporary bankfull discharge.

Table 5
Comparison of downstream hydraulic geometry exponents among New Zealand rivers

River (data source)	Width exponent	Depth exponent	Velocity exponent
Western streams (this study)	0.52	0.43	0.07
Eastern streams (this study)	0.50	0.33	0.17
Cropp River (Henderson et al., 1999)	0.47	0.31	0.22
Ashley River (McKerchar et al., 1998)	0.44	0.24	0.32
Taieri River (Ibbitt et al., 1998)	0.52	0.25	0.24
Hutt River (Ibbitt, 1997)	0.52	0.14	0.34
Buller River (Ibbitt, 1997)	0.45	0.39	0.15

The hydraulic geometry exponents for the study streams are very similar to those reported for other rivers in New Zealand (Table 5). The exponent values for New Zealand do not show any consistent differences in relation to mean annual precipitation or unit discharge, and have less internal variability than values from humid temperate drainage basins in other regions of the world (Henderson and Ibbitt, 1996).

The Rio Chagres of Panama and North St Vrain Creek, Colorado were presented in the introduction as contrasting examples of downstream hydraulic geometry along mountain rivers. The strong development of downstream hydraulic geometry along the Rio Chagres was attributed to hydraulic driving forces that sufficiently exceeded substrate resisting forces to override specific lithologic and hillslope influences on channel width and depth when averaged across sub-basin to basin scales (Wohl, 2004). Values of total stream power in the 40 study reaches of the Rio Chagres commonly exceeded 10,000 W (mean 58,300 W), and values of D_{84} were generally under 1000 mm (mean 366 mm). The poor correlation of hydraulic geometry variables with bankfull discharge along North St Vrain Creek may reflect the smaller ratio between hydraulic driving forces (total stream power mean value 4725 W) and substrate resisting forces (D_{84} mean 519 mm) (Wohl et al., 2004). Viewed in this context, the presence of well-developed downstream hydraulic geometry along the New Zealand study streams is expected (mean total stream power 27,380 W, mean D_{84} 520 mm).

At the reach scale, some individual geometric and hydraulic variables for the New Zealand streams appear to reflect primarily gradient (e.g. shear stress). Gradient may be responding to the increased erosive and transport ability of increasing downstream discharge, but may also reflect non-fluvial controls such as bedrock resistance, tectonic uplift, glacial history, and colluvial sediment inputs. The correlations between gradient and response variables suggest that reach-scale channel geometry along the study rivers adjusts to multiple interdependent parameters.

Brummer and Montgomery (2003) found systematic downstream coarsening of median bed-surface grain size (D_{50}) in four mountain drainages in western Washington. Maxima in unit stream power in the four study areas roughly corresponds to both the grain size maxima and an inflection in drainage area–slope relations that Brummer and Montgomery (2003) interpreted to represent the transition from debris flow-dominated headwater channels to fluvially dominated channels. Similar correspondence occurs in the New Zealand study areas; maxima in unit stream power and grain size, and inflections in the slope–area relations, occur at approximately 20 km^2 on the Porter River (Fig. 7), 10 km^2 on the Kowai River, and 5 km^2 on Camp Creek. Field observations of levees and boulder bars along all three channels, and increases in valley width for the Porter and Kowai rivers suggest that these points on the New Zealand rivers may also represent the transition from a mixed colluvial-fluvial channel regime upstream to a solely fluvial regime downstream. This implies that, although the channel top width, flow depth, and mean velocity all increase systematically in relation to discharge, and thus reflect primarily fluvial processes, other channel parameters such as reach gradient and grain-size distribution may reflect colluvial as well as fluvial influences.

In summary, some channel parameters along the mountain streams examined here appear to be influenced by both colluvial and fluvial processes. However, the existence of discharge-based correlations for hydraulic geometry variables in these field areas indicates that mountain streams may have downstream adjustments in channel geometry analogous to those present along lowland alluvial rivers, given a sufficiently large ratio of driving to resisting forces.

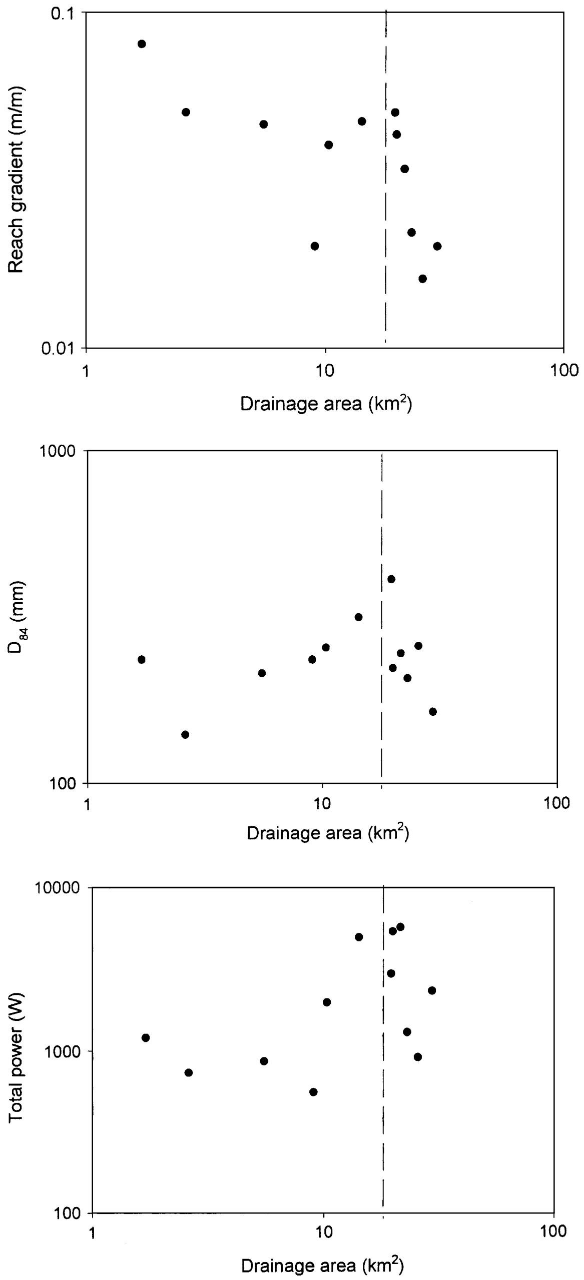

Fig. 7. Reach gradient, D_{84}, and total stream power in relation to drainage area, Porter River.

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