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A regionally applicable suspended sediment rating for the schist terrain in Otago

D. Murray Hicks
National Institute of Water and Atmospheric Research Ltd, PO Box 8602, Christchurch

Abstract
Suspended sediment ratings from basins in the schist terrain of Otago collapse into a single regionally-applicable relationship when water discharge is normalised by mean annual flood flow and sediment concentration is normalised by a reference value that indexes sediment availability and depends on basin mean slope, mean elevation, and schist grade. A slightly improved regional relationship results when a quickflow estimator is substituted for total water discharge. The regional sediment ratings so-obtained are useful for estimating statistics of sediment concentration in basins with a flow record but lacking suspended sediment measurements. Mean annual yields computed with the best regional rating agreed with the yields computed using sediment ratings from twelve study sites to within a factor of 1.8, a significant improvement over yield estimates based only on basin characteristics.

Introduction
Suspended sediment ratings represent the relationship between suspended sediment concentration and water discharge in a river. They are typically used to simulate time series of sediment concentration or load from a discharge record. This can then be integrated to obtain an estimate of the average annual sediment yield over the period of the discharge record. Sediment yields so estimated for basins within a region can often be related to various physical and hydrological parameters, leading to a regional model for predicting sediment yields from basins for which there is no sediment information (e.g. Thompson and Adams, 1979; Griffiths, 1981a, 1982). This approach is convenient for estimating the time-averaged sediment yield from an un-sampled basin. However, these days estimates of the average suspended sediment concentration at a given value of water discharge are also needed. One application, for example, is to estimate the proportion of time that the sediment concentration exceeds a value suitable for fish habitat;

another example is to estimate the concentration in diverted river flows. In these situations, a regionally applicable and suitably accurate sediment rating would be useful.

In this paper, two alternative dimensionless models for a regional sediment rating are developed, and these are calibrated and evaluated using suspended sediment gauging data from basins in the schist terrain of Otago. This region was chosen because of its reasonably uniform lithology and good spread of sediment gauging sites.

Model development

The suspended sediment load of a river in flood is derived from two sources: the river's channel and the slopes of its drainage basin. These are often termed the "suspended part of the bed-material load" and the "wash load", respectively.

Suspended fraction of the bed-material load

Fractions of the bed material that are fine enough become suspended by turbulence when the bed becomes mobile. As a flood wanes, this material returns to the bed. Typically, this load is sand-sized, and if the availability of sediment is unlimited a relationship between the sediment concentration (C, in mgl^{-1}) and the discharge (Q, in ls^{-1}) may be derived from hydraulic considerations. Griffiths (1982), for example, combined the bed-material load formula of Engelund and Hansen (1967) with the flow resistance formula of Griffiths (1981b) to derive the semi-empirical relationship

$$C \propto Q^{0.7} S_0^{1.7} / B^{0.7} d_{50}^{1.1} \qquad (1)$$

where S_0 is channel slope, B is channel width, and d_{50} is the bed material median size. At-a-station hydraulic geometry relationships for natural river channels show that width is related to discharge by a power function $B \propto Q^m$. While the exponent m varies, it averages about 0.25 (Leopold and Maddock, 1953). Thus assuming m = 0.25, equation (1) becomes

$$C \propto Q^{0.52} S_0^{1.7} / d_{50}^{1.1} \qquad (2)$$

Equations (1) and (2) represent the theoretical capacity concentration, when unlimited sediment is available from the bed. In gravel-bed channels, the availability of sand for suspension will depend on the proportion of sand in the bed material, the flow at which the bed surface material is mobilised, and the depth to which the bed is disturbed. While the latter two relate to the flow hydraulics, the proportion of sand in the bed material should reflect basin geology, as this influences both the original supply of sand-sized material to the channel and the amount and grade of sand produced during abrasion of coarser bed material. The bed-material size should reflect basin geology as well, although bed material is also modified downstream by abrasion and sorting. Indeed, rivers generally, in the process of regulating the capacity of their discharge to transport their bed material, tend to show a feedback relationship between channel slope and bed material size, with bed material fining as slope decreases (Richards, 1982). Thus it might be expected, at least among sites in the same geologic terrain, that variations in S_0 and d_{50} are interrelated and their effects on bed material concentration, to a fair degree, tend to cancel each other. Based on these considerations, for gravel-bed channels the functional relationship for suspended bed-material concentration might then largely reduce to

$$C = f(Q, \text{Basin geology}) \qquad (3)$$

Wash load

The wash load consists of fine sediment that is derived mainly from erosion sites on the basin slopes (Vanoni, 1975). Typically considered to be sediment finer than 63 microns, its settling velocity is sufficiently low that it remains in suspension while it moves through the drainage network, and it occurs in only trace concentrations in the bed material. Because its predominant source is outside the channel, there is no direct link between wash load concentration and flow hydraulic parameters. Moreover, the capacity of a river in flood to carry wash load is essentially unlimited – at extremely high concentrations, such as described by Beverage and Culbertson (1964), the river becomes a hyperconcentrated flow and the sediment begins to carry the water. Thus for wash load, the C versus Q relationship depends upon the relative supplies of water and sediment.

The supply of wash load depends on the intensity of hillslope erosion processes, the erodibility and mobility of slope material, and the availability of erodible material on the slopes. The erosion processes, which include the mobilisation and transport of sediment, are strongly related to rainfall. Since rainfall influences the discharge in the river, then we expect an indirect relationship between wash load concentration and discharge. Elevation (Z) should also affect this relationship since it determines how much precipitation falls as rain or snow. The erosion rate is also related to the average basin slope angle (S). The erodibility and mobility of the slope material depends upon the physical characteristics of the underlying bedrock, its type of weathering product, and rate of weathering. The availability of this material is influenced by the vegetation cover, which is commonly related to elevation.

Allowing that gravitational acceleration and the basic physical properties of water (i.e. density and viscosity) and sediment (density) are constant, then a relationship for the wash load concentration is

$$C = f(Q, S, Z, \text{Basin geology}) \qquad (4)$$

Total suspended load
Particle size information for New Zealand rivers (Hicks and Griffiths, 1992; Jowett and Hicks, 1981; the author, unpublished data) shows that wash load is often the dominant component of their suspended loads. Thus we expect a C versus Q relationship of the form of equation (4) to prevail for the total suspended load, particularly since equation (4) encapsulates equation (3).

A regional sediment rating model
The variables in equation (4) might be formalised into dimensionless variables using the Buckingham Pi Theorem, as followed, for example, by Griffiths and McSaveney (1986) or Rao *et al.* (1997). However, to derive a regionally consistent at-a-station relationship where the only dynamic variables are C and Q, a simpler approach is to convert C and Q to dimensionless variables using reference values. Given that a power law relationship between C and Q is expected (on the basis of measurements in numerous rivers, e.g. Griffiths, 1981a, 1982; Richards, 1982), a suggested model for a regional sediment rating is

$$C/C^* = (Q/Q^*)^{b'} \qquad (5)$$

where Q^* is a reference discharge, C^* is the concentration at that reference discharge, and b' is a dimensionless coefficient. C^* encapsulates the factors influencing sediment availability discussed above, thus $C^* = f(S, Z, \text{Basin geology})$. Normalising the discharge by a reference value helps remove the effect of basin size. The need for this is illustrated by comparing two physiographically similar basins, one large and the other small, both yielding the same storm outflow. In the small basin, the outflow will have been collected over a smaller area and so must be associated with a higher rainfall intensity, which in turn would suggest a higher concentration of sediment. Appropriate reference discharges could be the mean flow or the mean annual flood, since both correlate well with basin area (Pearson, 1998; McKerchar and Pearson, 1989). Ideally, the reference discharge should also be one that is important for transporting sediment in the long term.

The model in equation (5) may be refined by assuming that the suspended load is associated with storm runoff, not with base flows (since sediment availability is curtailed during periods of low flow). Thus the concentration can be expected to be negligibly small during base flows (i.e. when $Q < Q_b$, where Q_b is some simple separator between baseflow and storm flow) and should increase as a function of the quickflow $(Q-Q_b)$ during floods. An alternative model is then

$$C/C^* = [(Q-Q_b)/Q^*]^{b''} \quad (6)$$

These models will be calibrated and evaluated using sediment gauging data from basins in the schist terrain of Otago.

The Otago schist basins

Suspended sediment gaugings are used from 12 sites in the Otago region (Fig. 1, Table 1). All have predominantly schist basins and their runoff and sediment loads are unaffected by lakes. Physical and hydrological features

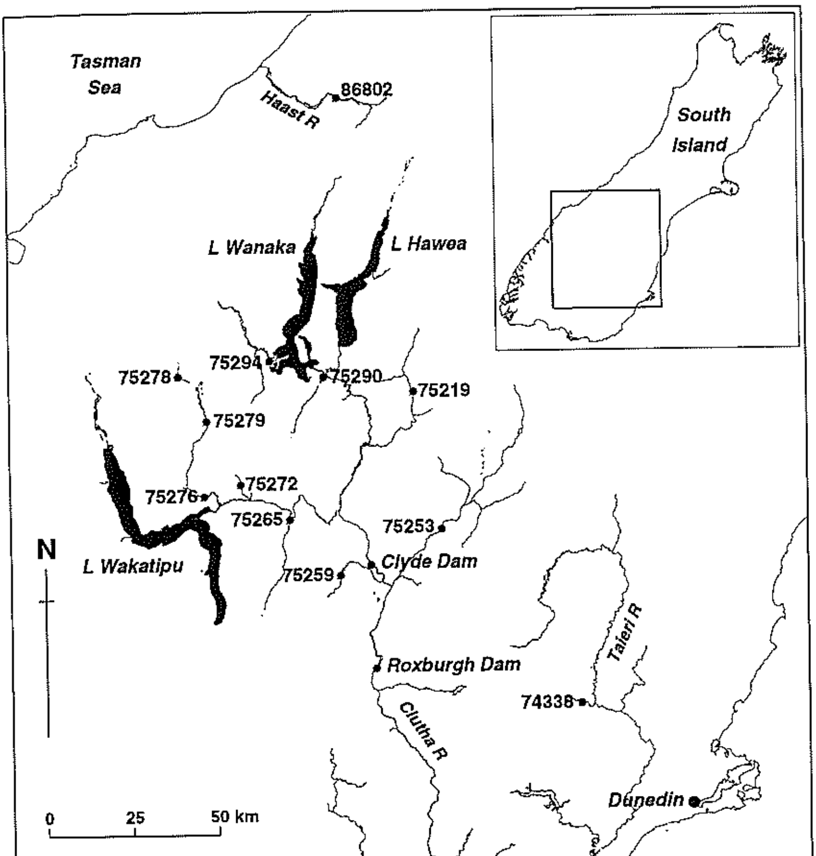

Figure 1 – Map locating the 12 study sites in Otago.

TABLE 1 – Basin characteristics, sediment gauging information, sediment rating characteristics, and parameters estimated from sediment ratings.

Site		Basin characteristics										
River and Site	Site No.	Area (km²)	Precipitation (mma⁻¹)	Mean flow (m³s⁻¹)	Mean annual flood (m³s⁻¹)	Base flow (m³s⁻¹)	Most-effective flow (m³s⁻¹)	50%-load flow (m³s⁻¹)	Mean slope (degrees)	Mean elevation (m a.s.l.)	Schist textural zone	Fissility grade
Sutton at SH87	74338	152	710	1.444	104	0.27	21	85	14.35	633	IIIB	4
Lindis at Lindis Peak	75219	546	780	6.5	86	1.58	33	42	26.32	890	IIA-IIIA	3
Manuherikia at Ophir	75253	2091	569	14.9	184	2.1	73	108	17.48	769	I-IIIB	3
Fraser at Old Man Range	75259	118	1020	2.26	36.1	0.28	81	64	14.19	1338	IIIA-IIIB	4
Nevis at Wentworth Stn	75265	693	1098	15.8	256	5.3	226	199	21.69	1203	IIIA	4
Arrow at Beetham Creek	75272	201	1019	3.44	59.1	1.6	80	47	27.82	1139	IV	4
Shotover at Bowens Peak	75276	1088	2007	41.1	452	11.2	130	126	29.72	1163	IV	4
Shotover at 16 Mile	75278	107	2793	11.9	143	4.4	137	68	31.61	1385	IV	4
Shotover at Strohles	75279	564	2479	31.7	438	11	83	145	29.62	1292	IV	4
Cardrona at Albertown	75290	346	716	2.76	48.6	0.29	14	35	22.24	842	IV	4
Matukituki at West Wanaka	75294	732	2458	65.1	633	17.4	185	256	29.2	1106	IV	4
Haast at Roaring Billy	86802	928	7412	191	3713	43	1148	1584	32.27	1039	II-IV, biotite, garnet, oligoclase	3

TABLE 1 - continued

Site	Sediment gaugings						Sediment ratings					Estimates from ratings		
River and site	Number of gaugings	Date span (month/year)	Flow range (m³s⁻¹)	Maximum gauged concentration (mgl⁻¹)	Number of particle-size analyses	d_{50} range (μm)	% silt-clay	$\log_{10}a$	b	r	Factorial standard error	Bias correction factor	Yield (bias corrected) (tha⁻¹)	C* (mgl⁻¹)	Flow when C=120 mgl⁻¹ (m³s⁻¹)
Sutton at SH87	6	8/92 - 6/96	4.9 - 138	596	4	15 - 60	51 - 94	-2.38	1.03	0.83	1.83	1.20	4.15	153	25.6
Lindis at Lindis Peak	32	5/77 - 11/94	5.2 - 108	3839	3	27 - 31	67 - 74	-5.12	1.72	0.85	2.46	1.50	64.20	359	23.1
Manuherikia at Ophir	48	7/71 - 12/95	5.1 - 333	2007	3	24 - 32	80 - 87	-5.82	1.72	0.9	2.27	1.40	130.00	198	54.7
Fraser at Old Man Range	18	8/71 - 8/91	0.36 - 56	1694	..	..	..	-2.73	1.06	0.88	3.24	2.00	3.50	30	68.5
Nevis at Wentworth Stn	30	6/77 - 6/90	8.6 - 331	10903	..	..	..	-7.95	2.21	0.89	2.41	1.47	262	1089	50.6
Arrow at Beetham Creek	9	10/81 - 6/93	3.5 - 48	10064	..	..	..	-6.30	2.24	0.95	1.67	1.14	120	1407	6.26
Shotover at Bowens Peak	124	2/65 - 10/91	16 - 789	11336	9	40 - 195	13 - 79	-4.99	1.6	0.91	2.04	1.29	1538	1817	34
Shotover at 16 Mile	14	12/77 - 6/80	4.0 - 157	7680	1	63	49	-7.51	2.27	0.98	1.93	1.24	222	1532	20.9
Shotover at Strohles	7	6/80 - 12/86	23 - 245	4254	..	..	..	-6.30	1.84	0.97	1.64	1.13	638	1532	40.3
Cardrona at Albertown	24	1/79 - 12/95	2.6 - 69	5284	..	..	..	-5.69	2.06	0.9	2.42	1.48	107	1089	8.74
Matukituki at West Wanaka	11	10/79 - 10/96	50 - 840	2513	5	90 - 190	10 - 39	-4.78	1.41	0.9	2.02	1.28	983	600	93.3
Haast at Roaring Billy	39	8/67 - 12/95	54 - 3745	6234	8	31 - 176	32 - 68	-8.21	1.87	0.91	2.72	1.65	7679	1407	523

of the basins are listed in Table 1. Mean elevation and mean slope were extracted from the NZ Land Resource Inventory (Newsome, 1992) by weighting the values assigned to individually-mapped surface elements within each basin by element area. Basin mean precipitation was determined by overlaying the basin boundaries on a kriged model of the isohyetal surface. The basins are vegetated mainly by tussock, except for the Haast and Matukituki. The Haast is mainly forested, while the Matukituki is partly forested and has glaciers along its western margin.

Within the Otago schists, the grade of schistosity, reflecting the increasing fissility (or foliation) and amount and thickness of quartz segregation banding in metasandstones, generally increases from east to west (Mortimer, 1993). The friability of the schists – and hence their propensity to erode on hillslopes and to break up into suspended load during stream transport – depends significantly on the grade of fissility but is also affected by the degree of weathering and the parent rock (e.g. sandstone, mudstone, or lava) prior to metamorphism (N. Mortimer, Institute of Geological & Nuclear Sciences Ltd, Dunedin, pers. comm.). Most of the 12 study basins are formed in schists of Textural Zone IIIB-IV, which are characterised by strongly fissile metasandstones with 'sweats' of quartz >2 mm thick (Mortimer, 1993). The schists in the Lindis Basin range from weakly to strongly fissile (Textural Zones IIA-IIIA), while in the Manuherikia Basin the basement lithology ranges from unfoliated metasandstone (Textural Zone I) through to strongly fissile schist with quartz 'sweats' < 10 mm thick (Textural Zone IIIB). The Haast Basin lithology ranges from weakly fissile semi-schist (Textural Zone IIA) to garnet schist (NZ Geological Survey, 1972). Geomorphological features of the Otago region are reviewed by McSaveney and Stirling (1992).

Suspended sediment gaugings and characteristics

All suspended sediment gaugings at the study sites were made with depth-integrating samplers at multiple verticals (refer to Hicks and Fenwick, 1994, for method details) and so the concentration represents the discharge-weighted cross-section mean concentration. The sediment gaugings were made immediately after matching discharge gaugings (refer to Arnold *et al.*, 1988, for methods used to measure discharge). The time span of sediment gaugings varies among sites, ranging from 26 years for the Shotover at Bowens Peak to three years for the Shotover at 16 Mile (Table 1). Generally, most gaugings were conducted from the 1970s to mid 1980s in conjunction with hydro-electric power planning. The number of gaugings per site varies from six at Sutton Stream to 124 at Shotover at Bowens Peak (Table 1). Typically, more gaugings were conducted during spring and summer (September-January), reflecting the incidence of flood flows. The maximum concentration measured was 11336 mgl^{-1} in the Shotover River at Bowens Peak (Table 1).

Suspended sediment particle-size information from depth-integrated samples is available for seven sites (Table 1). The silt-clay (i.e. wash load) proportion varies considerably among sites and often at a site, ranging from 10% to 94%. The median sizes (d_{50}) lie either in the fine to very-fine sand range (typically 90-195 mm) or in the medium-coarse silt range (typically 15-63 mm). When the sand fraction is significant, the size distribution is often bimodal, with fine sand and coarse silt modes that presumably reflect bed material and wash load origins, respectively. In the Shotover River, the silt mode was present in all samples analysed for particle size, while the sand mode was sampled only sometimes, possibly when waves of bed material passed through the gauging reach.

The original C-Q suspended sediment ratings for these sites are plotted in Figure 2. Power model rating equations of the form

$$C = a\,Q^{b} \qquad (7)$$

were fitted by least-squares regression of the logarithms of the data. Listed in Table 1 are values for coefficients a and b, the regression coefficient r, the factorial standard-error-of-the-estimate (equal to 10^{s}, where s is the standard-error-of-the-estimate in base 10 log units), and a factor to correct for the bias induced by the logarithmic transformation. This factor was estimated as $\exp(2.651s^{2})$ (after Ferguson, 1987); its use is appropriate where

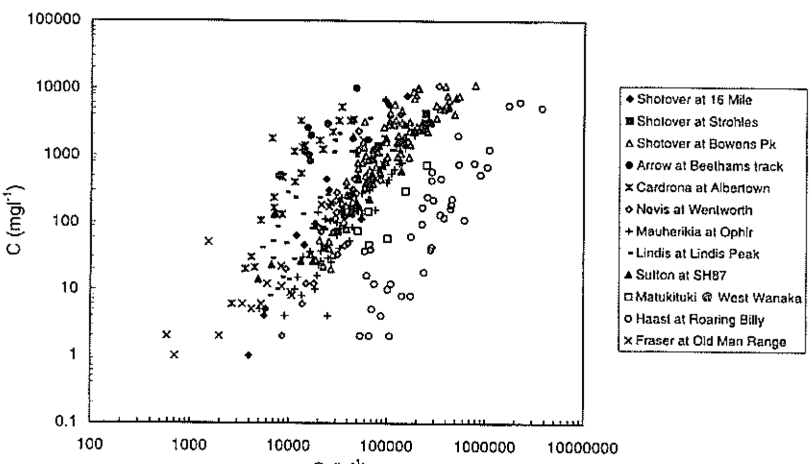

Figure 2 – Suspended sediment concentration vs. water discharge data for study sites.

the log-log model is a good fit to the data and where the residuals are normally distributed, conditions that were reasonably met within the dataset. The values of the exponent b ranged from 1.03 to 2.27, averaging 1.75 for the 12 sites.

The rating plots were examined for differences between rising stage and falling stage data and among data from different seasons. The difference test involved fitting ratings of the form of equation (7) to the rising/falling or seasonal data subsets using the same b coefficient as obtained for the undivided dataset, then testing for significant differences in the coefficient a derived for each subset. No significant seasonal differences were observed. Significant rising/falling stage differences were noted only for the Manuherikia at Ophir site. The Manuherikia data were still represented by a single regression model, however, since the distribution of gaugings between rising and falling stages matched reasonably the relative durations of rising- and falling-stage flood flows, thus giving an unbiased weighting of rising and falling stage data in the regression procedure (which aims to model the conditional mean concentration for the period of record). If, say, there were relatively fewer rising stage data points, then the rating would have been biased by the falling stage data.

Reference values for Q and C**

The reference discharge Q* was selected on the basis of several criteria: (i) it should be easily determined, (ii) there should be sufficient sediment gaugings around that flow value at the study sites for the matching C* to be adequately defined, and (iii) it should be a flow that makes an important contribution to sediment transport in the long term.

The power-law ratings listed in Table 1 were integrated with the discharge records for each site to estimate the long-term average suspended sediment yields, the 'most-effective discharges' (i.e. the discharge that transports the most sediment load in the long term), and the '50%-of-load discharges' (i.e. the discharge at which half the sediment load is carried by higher discharges and half by lower discharges). Overall for the 12 study sites, the latter two indices correlated best with the mean annual flood (r^2=0.97 for the most-effective discharge; r^2=0.98 for the 50%-of-load discharge). A zero-intercept regression model indicated that the most-effective discharge equalled 0.3 times the mean annual flood (Q_{maf}). Since the mean annual flood is easily determined and all sites were well sampled at discharges around $0.3Q_{maf}$, this was selected as the reference discharge Q*. The matching reference concentration, C*, was computed from the site sediment rating equations for the case Q=Q*. These reference values and sediment yield parameters are listed in Table 1.

Thompson and Adams (1979) used a reference discharge equal to 5 times the mean discharge to normalise sediment rating curves for basins on the eastern slopes of the Southern Alps, including some of the basins included in the present study. Adams (1980) justified the use of this flow statistic by noting that it represents flood flows that transport most of the suspended load, although he presented no information to confirm this. In fact, a zero-intercept linear regression model of the relationship between mean annual flood and mean discharge (Q_{mean}) for the basins in this study yields $Q_{maf} = 18\ Q_{mean}$ (r^2=0.96), hence $0.3Q_{maf} = 5.4\ Q_{mean}$. Thus there is effectively little difference in normalising by 0.3 Q_{maf} or by 5 Q_{mean}.

Baseflow estimator

The baseflows (Q_h) used in equation (6) were selected from flow frequency data for the study sites using an arbitrary procedure. The flow frequency distribution was plotted, smoothed by hand, and Q_h taken as the discharge below which the frequency fell away rapidly (i.e. at the 'low flow shoulder' of the modal discharge band). Figure 3 demonstrates the derivation of Q_h = 4.40 m^3s^{-1} for the Shotover River at 16 Mile. This approach was preferable to setting Q_h equal to the smoothed modal discharge or to the discharge at a given percentile of exceedance (e.g. 95%) for several reasons. Firstly, the modal band was typically quite broad, thus choosing a single modal value would have involved greater uncertainty. Secondly, the exceedance percentile at the beginning of the modal band varied among the sites from 82% to 99%. Finally, a Q_h value towards the lower end of the modal range was required to ensure that the (Q-Q_h) term remained positive for the gaugings in the dataset.

Results and discussion

Rating models

In Figures 4a and 4b the pooled data are plotted in terms of the dimensionless variables in equations (5) and (6). All show the data falling within a single band. The reference values C* and Q* translate the data, while in equation (6) and Figure 4b the (Q-Q_h) term effects a clockwise pivoting of the slopes of the data trends. Notice, for example, how subtraction of the baseflow from the Shotover at 16 Mile flattens its rating, bringing it more in line with the ratings for the Strohles and Bowens Peak sites, further downstream (the shift in the data at lower discharges is most noticeable).

Log-transformed linear regression results for the pooled data plotted in Figures 2 and 4 are compared in Table 2. In terms of the regression coefficient, F-ratio, and standard-error-of-the-estimate, there was no significant difference (at the 5% level) between equations (5)and (6), al-

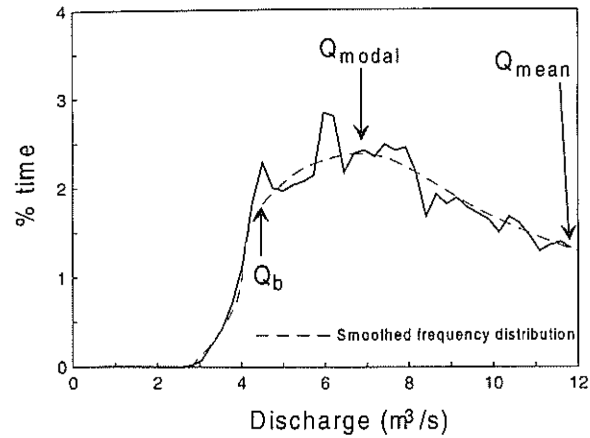

Figure 3 – Low flow distribution for Shotover River at 16 Mile. Base flow estimator Q_b is chosen as the point where flow frequency begins to decline rapidly.

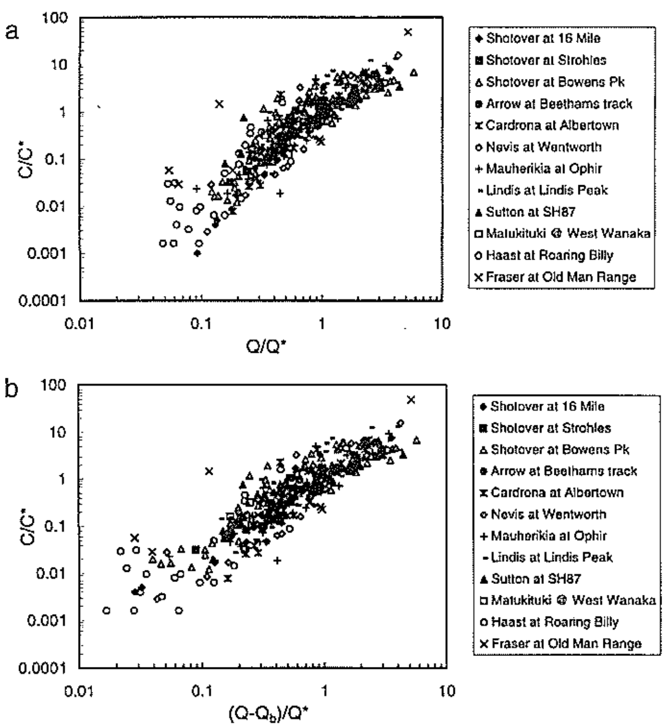

Figure 4 – Dimensionless sediment concentration vs. dimensionless water discharge: **a** as defined in equation (5), **b** as in equation (6).

TABLE 2 – Results of linear regression analysis of sediment rating models. Variables were transformed to logarithms. 95% confidence intervals are given for coefficients a and b. The confidence interval on a is expressed as a factor.

Model	Eqn.	a	b	r^2_{adj}	Factorial standard error	Bias correction factor	F-ratio	n
$C/C^* = a'(Q/Q^*)^{b'}$	(5)	0.96 ×/÷1.1	1.75 ±0.10	0.79	2.38	1.45	1372	362
$C/C^* = a''[(Q-Q_b)/Q^*]^{b''}$	(6)	1.09 ×/÷1.1	1.49 ±0.08	0.80	2.32	1.42	1429	362
$C = aQ^b$	(7)	0.013 ×/÷5	0.92 ±0.15	0.32	5.4	4.1	162	362

though the statistics for equation (6) were marginally better. Both performed significantly better than the un-normalised equation (7). The factorial standard-error-of-the-estimate for equation (6), at ×/÷ 2.32, was similar to those for the study site sediment ratings, which ranged between 1.64 and 3.24 and averaged 2.22 (Table 1). Factorial errors, requiring the result to be multiplied or divided by the error factor to get the upper and lower confidence limits, are used here because the data residuals are log-normally distributed. While a ± percentage error, %E, can be approximated from the factorial error, f, as %E = 100(f-1), the lower confidence limit becomes increasingly incorrect as f increases from 1; indeed, when f > 2 a negative lower limit results, which is nonsense in terms of sediment concentration or load. The coefficients a′ and a″ for equations (5) and (6) were not significantly different from 1, as expected from the normalisation procedure. The exponent b′ (i.e. the slope of the log-log plot) in equation (5) was significantly larger than b″ in equation (6). This is due to the pivoting effect of the ($Q-Q_h$) term, as discussed above. Both b values are significantly less than the value of 2.3 that was assumed by Thompson and Adams (1979) to be representative of basins draining the eastern slopes of the Southern Alps (including schist, greywacke, and other lithologies). While the b values in this analysis are strongly influenced by data for the Shotover at Bowens Peak, which represents a third of the total data, the b value for the individual site ratings averaged 1.75 – the same as determined for equation (5).

*Controls on C**

Multiple regression analysis was used to explain the variance in the reference concentration C*. The independent variables included in the analysis (Table 1) were basin area, rainfall, mean annual flood, distance south-eastward from the Alpine Fault (as an index of tectonic activity), mean elevation, slope (expressed as the tangent of the mean slope angle), and schist grade. For this analysis, the schist grade was defined solely on the basis of fissility, assigning a value of 1 to non-fissile metasandstone (Textural Zone I), 2 to weakly fissile semi-schist (Textural Zone IIA), 3 to well foliated semi-schist (Textural Zone IIB), and 4 to strongly fissile schists (Textural Zones III-IV). Where this fissility grade varied within a basin, an area-weighted average was used, rounded to the nearest integer. For the Haast basin, where the schist ranges from Textural Zone II semi-schist to garnet schist, an average value of 3 was assumed. All variables were log-transformed. Most of the variance in C* (67%) was accounted for by the basin mean slope (S); apart from slope, only mean elevation (Z, in m) and schist grade (G) made any significant improvements to the regression model.

The regression model is

$$C^* = 2.91 \times 10^7 \, S^{3.55} \, G^{2.72} \, Z^{-1.67} \qquad (8)$$

with $r^2 = 0.72$, and the factorial standard-error-of-the-estimate is ×/÷ 1.83. In Figure 5 the observed C* is plotted against C* predicted from equation (8). The observed Matukituki C* value is less than one third the predicted value, possibly because half of the Matukituki basin has native forest cover and part of its steepest, western margin has a permanent snow and glacier cover. Both of these factors are liable to limit the availability of sediment to the drainage network. Removing the Matukituki outlier from the data results in the improved model

$$C^* = 9.6 \times 10^7 \, S^{3.9} \, G^{3.44} \, Z^{-1.93} \qquad (9)$$

with $r^2 = 0.84$; the factorial standard-error-of-the-estimate is ×/÷ 1.61.

Equations (8) and (9) are in agreement with the earlier theoretical considerations on how basin characteristics should affect sediment supply (i.e. sediment availability increases with more fissile schist grades, steeper slopes, and lower elevation – which allows a greater proportion of precipitation to fall as rain).

Sediment yield estimates

A common use of sediment rating curves is to estimate the average sediment yield over a period of flow record. The true accuracy of the regional sediment rating models in equations (5) and (6) for estimating sediment yields cannot be established, since there are no continuous records of sediment load available for any of the study sites. However, their yield estimates can at least be compared with yields estimated from the study site sediment ratings. This comparison was conducted by integrating the rating equations (as defined by the parameters in Table 2) with the flow records for the 12 study sites. The integrations spanned up to 20 years, depending on the length of flow record. C* was estimated using equation (9), and all rating coefficients were corrected for log-transformation bias, as previously discussed. For consistency, concentration was always assumed equal to 0 for $Q<Q_b$. Figure 6 shows the results of this comparison, while the factorial standard errors of the predicted yields (i.e. using the modelled ratings) over the 'observed' yields (i.e. using the study site sediment ratings) are listed in Table 3. Equation (6) performed best, with a factorial error of ×/÷ 1.80.

It is useful to compare these results with yield estimates predicted solely from basin variables. Using multiple regression, the bias-corrected yields (Y, in ta^{-1}) obtained with the site sediment ratings were related to the same

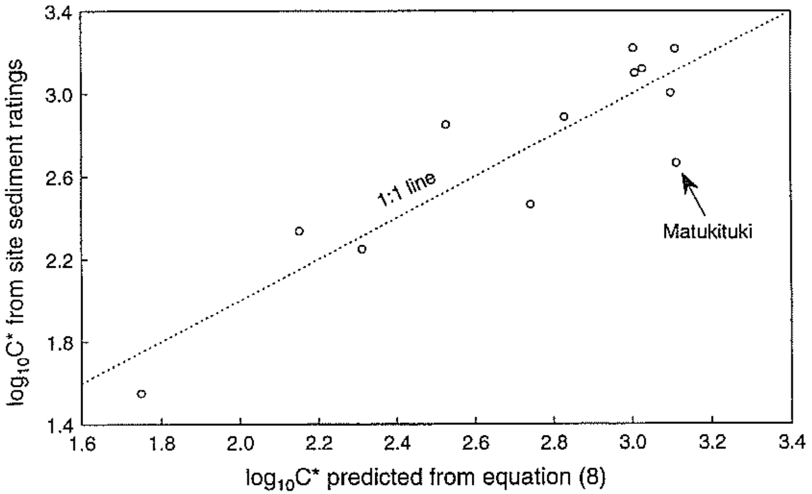

Figure 5 – C* predicted from basin characteristics with equation (8) compared with C* estimated from sediment ratings for study sites.

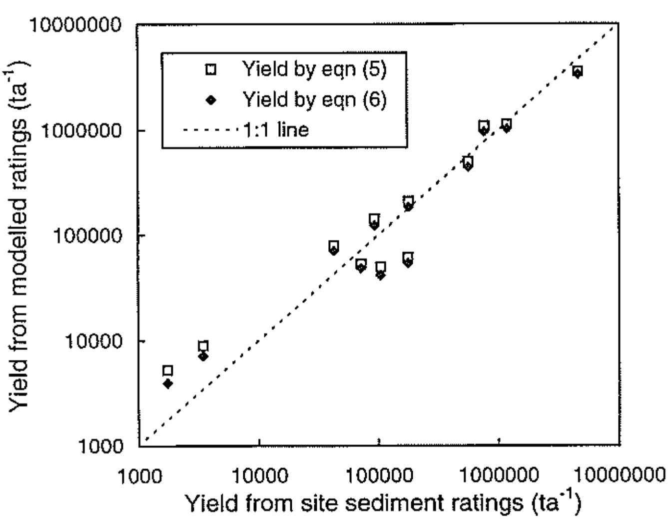

Figure 6 – Suspended sediment yield estimated with regional sediment rating models compared with yields estimated using sediment ratings for study sites.

basin variables considered in the above analysis of C*. The best regression model was

$$Y = 27430\, Q_{maf}^{0.91}\, S^{3.64} \qquad (10)$$

with $r^2 = 0.88$; the factorial standard-error-of-the-estimate is ×/÷ 2.14. Thus by virtue of their smaller factorial standard error, equations (5) and (6) produce a more accurate sediment yield estimate than does equation (10). This is expected, given that yield computations using equations (5) and (6) utilise the flow record, not just basin characteristics.

As a matter of interest, equation (10) provides better estimates of sediment yields from the 12 basins in this study than do the empirical relationships derived by Hicks *et al.* (1990) for schist basins in the Southern Alps (which included four of the basins used in this study). These relationships are

$$Y = 843\, A\, R^{1.44} \qquad (11)$$

and

$$Y = 168\, A\, P^{2.33} \qquad (12)$$

where A is basin area (km^2), R is annual runoff (m), P is annual precipitation (m), and the coefficients in each equation have been multiplied by 0.91 to convert total sediment load to suspended load. As shown in Table 3, the factorial standard errors of the suspended sediment yields estimated from equations (11) and (12) using the basin data in Table 1 were ×/÷ 3.1 and ×/÷ 2.45, respectively – higher than the error of equation (10).

Concentration exceedance estimates

If a flow record is available, the regional sediment ratings can also be used to estimate statistics of the suspended sediment concentration in rivers lacking sediment gaugings. For example, for assessing a stream's suitability as a fish habitat, one may wish to determine the proportion of time that the concentration exceeds a benchmark level. Rowe and Dean (1996) suggest that fish habitat is generally degraded at sediment concentrations above 120 mgl^{-1}. After inverting equations (5) and (6) to obtain the discharge corresponding to this concentration (e.g. from equation 5, $Q_{c=120} = Q^*[120/C^*]^{1/h'}$), the flow duration table can be used to estimate the proportion of time that the $Q_{c=120}$ discharge is exceeded. Figure 7 compares $Q_{c=120}$ values estimated using equations (5) and (6) and using the sediment ratings for the study sites. The factorial standard errors of the comparison (Table 3), at approximately ×/÷ 1.45 for both equations (5) and (6), are substantially less than the factorial standard-errors-of-the-estimate associated with the study site sediment ratings (Table 1). Thus while the uncertainty in estimating

TABLE 3 – Factorial standard errors on sediment yield and flow at which C = 120 mg.ℓ^{-1}, obtained by comparing estimates from regional sediment rating models (equations 5 and 6) with estimates from sediment ratings for study sites. Also, factorial standard errors comparing sediment yields estimated from regional models based on basin characteristics (equations 10 – 12) with yields estimated from study site ratings.

Equation	Sediment yield	$Q_{C=120}$
(5)	1.90	1.45
(6)	1.80	1.49
(10)	2.14	-
(11)	3.10	-
(12)	2.45	-

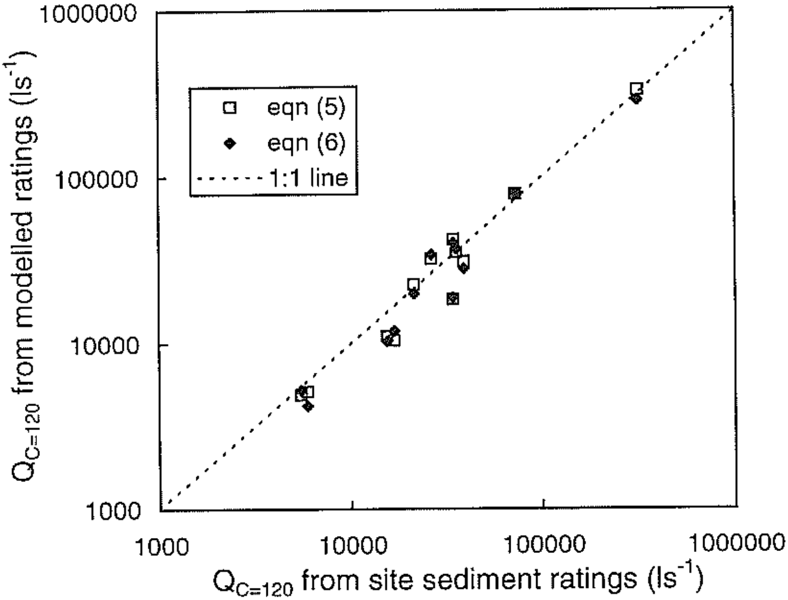

Figure 7 – Water discharge at C = 120 mg.ℓ^{-1} ($Q_{C=120}$) estimated with regional sediment rating models compared with $Q_{C=120}$ estimated using sediment ratings for individual sites.

concentration exceedance times using sediment ratings is high, by virtue of the large scatter in the ratings, this uncertainty is not greatly worsened by using a regional rating.

Conclusions

For the schist region of Otago, a regionally applicable suspended sediment rating relationship results from normalising water discharge by a reference flood discharge and normalising sediment concentration by a reference value that indexes sediment availability. The sediment reference value depends on the basin slope, elevation, and lithology. This relationship improves slightly if a quickflow estimator is substituted for the total water discharge. Either relationship is recommended for estimating suspended sediment concentrations in rivers lacking sediment gaugings but having a flow record. Sediment yields estimated by combining either of these regional ratings with flow records are more accurate than those estimated from empirical models relating sediment yield to basin characteristics only.

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