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Variation of suspended sediment yields around New Zealand: the relative importance of rainfall and geology

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Abstract Data on suspended sediment loads at rural New Zealand River gauging stations have been analysed to asses the average yields of suspended sediment, regional patterns in yields, and the factors controlling spatial variation in yields. Wide ranges of basin rainfall (<1 m to over 11 m year^{-1}), geology, topography, and land use are represented. Average annual yields range over four orders of magnitude, from less than 20 t km^{-2} year^{-1} in low rainfall regions of both North and South Island to almost 30 000 t km^{-2} year^{-1} in a high rainfall schist basin in the Southern Alps. The main factors contributing to spatial variation in annual average yields are rainfall and basin geology. The geological influence encompasses lithology, tectonic activity, and Quaternary history. Mean basin slope and the seasonality and inter-annual variability of rainfall explain some of the variance observed in yields among basins with the same rock type and rainfall.

INTRODUCTION

Previous regional-scale studies of river suspended sediment yields in New Zealand (Adams, 1979, 1980; Griffiths, 1979, 1981, 1982; Thompson & Adams, 1979; see Hicks & Griffiths, 1992, for a review) have shown a wide variation in yields around the country. These range from 30-100 t km^{-2} year^{-1} in intermontane regions of South Island and some low rainfall regions of North Island to 10 000-30 000 t km^{-2} year^{-1} for mountainous schist catchments of western South Island and the mudstone hill country of eastern North Island. This previous work has indicated that the main factors affecting regional variation in sediment yield are basin mean annual rainfall and, to a lesser and more contentious extent, basin geology. Griffiths (1981, 1982) considered that secondary climatic effects, such as differences in the intensity, frequency, and duration of storms, are also important.

Over the 15 years since these earlier studies were conducted, the New Zealand suspended sediment record has been expanded to include more sites and to improve the data at existing sites (Hicks, 1992). This paper presents results from a preliminary analysis of this expanded dataset. The main purpose is to examine further the influence of rainfall and geology on variations in sediment yield around New Zealand.

DATA AND ANALYSIS

Study basins and data

Data are analysed for 203 basins; 116 in North Island and 87 in South Island (these include the 80 sites previously analysed by Griffiths, 1981 and 1982). These cover a wide range of basin physical characteristics: areas range from less than 1 to 6640 km^2; mean annual rainfall ranges from 665 to 11 200 mm; lithology varies widely, for example from soft mudstone and fissile schist to granodiorite and marble; topography ranges from lowland to intensely rugged mountains; and several basins are glaciated to different degrees. All the basins are rural; their land-use/vegetation cover varies extensively in response to their ruggedness and climate, ranging, for example, from the native rain-forests in western South Island, to the retired or extensively grazed semi-arid tussock-lands of the eastern South Island high country, to the partly-forested, partly-grazed hills of the central North Island.

Up until the last five years, suspended sediment was sampled on an almost random basis during flood flows while field teams visited the sites to conduct flow gaugings to define and maintain stage-discharge ratings. In recent years, a more systematic approach has been adopted whereby sediment gaugings are focused on the flow band carrying the bulk of the long-term average sediment yield, and attention is given to sampling over rising and falling stages and different seasons. Standard US Inter-Agency Sediment Project depth-integrating samplers and multi-vertical sampling techniques have been used (as detailed in Edwards & Glysson, 1988).

Analysis methods

The basin sediment yields were estimated using the sediment rating approach. With this, a sediment concentration (C) *vs* water discharge (Q) sediment rating was applied to the flow record compressed into a flow-duration table.

A careful but subjective approach, employing specialized software, was followed to derive the rating curves and to ensure that they best represented the C-Q relationship over the flow range that carried the bulk of the sediment load. The curves were initially fitted using linear least-squares to the log-transformed data. The curves, with and without bias de-transformation, were then overlaid on the data on both logarithmic and linear scales, and their representativeness judged by comparison with the data lying within the mean-flow to mean-annual-flood band. Often, it was found that the least-squares lines were excessively weighted by data from lower flows and poorly represented the higher flow data. In such cases, the curve was re-drawn manually. Usually, sites with too few data-points or where there were too few gaugings at flood flows were rejected. Separation of the data by rising or falling stage and by season showed, with a few exceptions, no grounds for using separate rising/falling-stage or seasonal ratings. Following this approach, and by comparison with independent estimates of yields at some sites and bearing in mind the work of Walling & Webb (1981, 1988) on the pitfalls associated with the rating method, we have reasonable confidence that our yields are accurate to within a factor of 2.

Information on basin physical and climatic characteristics was extracted for this study by overlaying the basin boundaries on two GIS-based databases: the New Zealand Land Resource Inventory (NZLRI) and the Climate Database (CLIDB). To further pursue the influence of rainfall, four rainfall parameters were extracted: the mean annual rainfall, the coefficient-of-variation of annual rainfall, the ratio of the average rainfall in the wettest month to the annual average rainfall, and the 5-year return period 24-h intensity. The second and third parameters index seasonal and inter-annual variation of rainfall. The last parameter emphasizes the effects of extreme rainstorms. Multiple regression was used to explore the influence of these parameters

RESULTS AND DISCUSSION

Regional variations and patterns in yield: the main controls

The specific suspended sediment yield estimates, plotted in Fig. 1, confirm the earlier findings of Adams (1979, 1980) and Griffiths (1981, 1982) of a wide range in sediment yields around New Zealand. In both islands, the yields range over 3-4 orders of magnitude: in South Island, from 1.7 t km^{-2} $year^{-1}$ at the low rainfall intermontane Maryburn basin to 29 600 t km^{-2} $year^{-1}$ in the alpine Cropp basin in the high rainfall, fissile schist zone of the Southern Alps; in North Island, from 13 t km^{-2} $year^{-1}$ at the forested Purukohukohu basin on the central volcanic plateau to 20 000 t km^{-2} $year^{-1}$ in the Waiapu basin in the dissected, soft Tertiary sediment terrain of the East Cape region.

Comparing the distribution of specific yields with the mean annual rainfall patterns on Fig. 1 suggests that rainfall may be an important control on yields in South Island, where the highest yields generally coincide with the crest of the orographic rainfall distribution along the western flanks of the Southern Alps. In North Island, however, where rainfall variations are generally small relative to those in South Island, the effect of rainfall is not obvious and much of the variation appears to relate to geological factors, either by way of basement rock lithology, rate of tectonic activity, or both. For example, in eastern North Island, which is undergoing compression and uplift associated with the subduction of the Pacific tectonic plate to the east, yields in the range 10 000-20 000 t km^{-2} $year^{-1}$ occur in the soft Tertiary marine mudstones and siltstones of the East Cape region, while yields from one to several thousand t km^{-2} $year^{-1}$ occur in the southern ranges formed from greywacke and argillite basement rocks. Indeed, in both North and South Islands the highest yields tend to cluster along or juxtapose the boundary between the Pacific and Indian tectonic plates (Fig. 1). In South Island, high yields occur in the Southern Alps on the up-thrust eastern side of the Alpine Fault (a dominant feature marking the Indian-Pacific plate boundary), while yields are much lower on the western side of the fault.

The geology factor

The relative importance of rock type and rainfall is clarified on Fig. 2, which plots data from both North and South Island basins in relation to selected lithologies. This shows that both variables induce a very wide range in sediment yield: for a given rainfall,

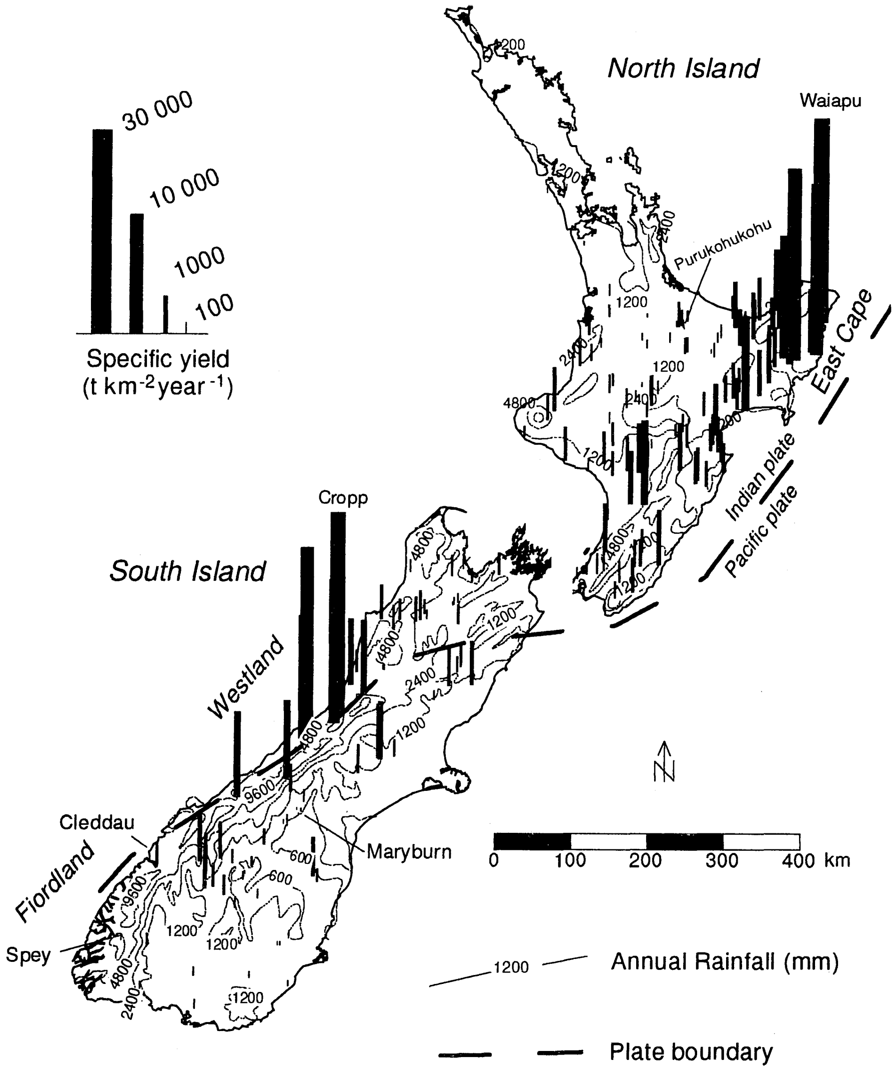

Fig. 1 Map of New Zealand showing suspended sediment yields at gauging stations and mean annual rainfall isohyets. Bar areas are proportional to sediment yield.

sediment yields from Tertiary marine mudstone terrain are some 1000 times larger than yields from crystalline igneous and metamorphic terrain, while for a given lithology (e.g. schist and semi-schist), sediment yields range over a factor of 4000 when the rainfall varies from 700-11 000 mm. Assuming a power-law relationship between sediment yield (S) and rainfall (P) of the form $S = aP^{2.3}$ (the exponent 2.3 was obtained by least-squares analysis of the schist/semi-schist subset) for each of the four lithological groups plotted on Fig. 2, then Table 1 shows the range of the coefficient a for each group. The average values of a indicate relative yields (for a given rainfall) in the ratios 1:15:25:900 for gneiss/granite/marble, greywacke and argillite, schist and semi-schist, and soft marine sedimentary basins respectively.

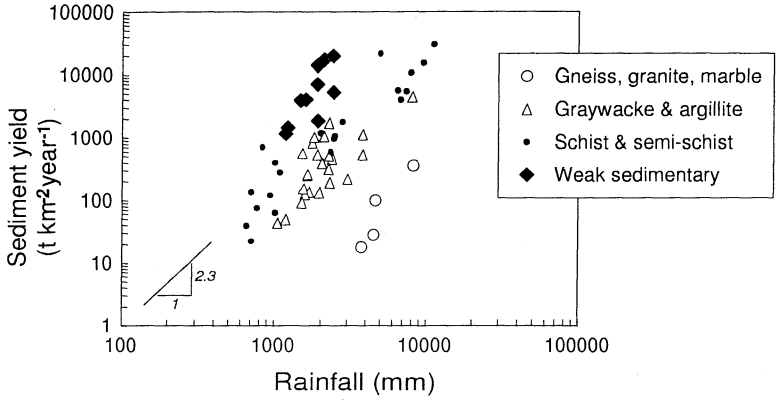

Fig. 2 Sediment yield plotted against mean annual rainfall for basins on selected rock types.

The influence of basin geology on New Zealand sediment yields has been a point of dissension in previous studies. Griffiths (1981) concluded from his study of South Island yields that geology had little apparent influence; the main controlling factor was mean annual rainfall. He suggested that differences among regions might reflect variations in rainfall intensity, frequency and duration patterns. In contrast, Adams (1980) argued that lithology, tectonic uplift rates, and Quaternary geological/geomorphological history were also important. Moreover, he observed that uplift rates within the Southern Alps, which peak on the eastern side of the Alpine Fault, were roughly in balance with the erosion rates indicated by the river sediment yields.

A key figure in the debate was the yield estimated for Cleddau basin (mean annual rainfall 8350 mm) in the glacially-carved, rain-forested, resistant, gneissic-granitic terrain of Fiordland in southwest South Island. From much the same dataset and both using the sediment rating approach, Adams (1980) estimated a yield of 275 t km^{-2} year^{-1} while Griffiths' (1979 and 1981) estimate was 13 300 t km^{-2} year^{-1}. Fitting a sediment rating to the data used by Griffiths, we estimate a yield of some 350 t km^{-2} year^{-1}. We regard the uncertainty on our estimate as substantial – perhaps up to a factor of four – since there are only 16 data-points available and the highest concentration (100 mg l^{-1}) was measured at a water discharge of only 170 m^3 s^{-1} which is much less than the mean annual flood flow (693 m^3 s^{-1}) and maximum flood flow (1850 m^3 s^{-1}). This means that the sediment rating had to be extrapolated across the flow range that carried the bulk of

Table 1 Ranges of mean annual rainfall, sediment yield, and coefficient a in $S = aP^{2.3}$ model for selected lithological groups.

Lithological group	Annual rainfall, P (mm)	Sediment yield, S (t km^{-2} year^{-1})	Coefficient a in $S = aP^{2.3}$
Granite, gneiss, marble	3700-8400	17-350	1.0×10^{-7} to 3.5×10^{-7}
Greywacke, argillite	1060-8100	44-1740	2.1×10^{-6} to 3.3×10^{-5}
Schist, semi-schist	660-11 200	22-29 600	6.0×10^{-6} to 6.7×10^{-5}
Weak marine sedimentary	1200-2400	1200-20 000	5.2×10^{-5} to 4.0×10^{-4}

the sediment yield. We could only reproduce Griffiths' figure by drawing a rating curve much steeper than the trend indicated by the data.

Low specific sediment yields in Fiordland, despite the region's high rainfall, have been verified recently by sampling at another river site and by stratigraphic investigation of the sediments accumulating on the floor of several fiords. We have recently commenced sampling in the Spey River (mean annual rainfall 4550 mm); our preliminary estimate of the yield there is 28 t km^{-2} $year^{-1}$. Pickrill's (1993) study of fiord sediments employed seismic reflection profiling, coring, and radiometric dating to estimate sedimentation volumes and rates over the Holocene. For three fiord basins, he derived long-term average sediment yields ranging from 28 to 209 t km^{-2} $year^{-1}$.

In the North Island, Adams (1979) found no consistent relation between sediment yield and rainfall, nor with basin size or relief, and suggested this was due to large variations in lithology, uplift rate, and perhaps man-accelerated erosion. Griffiths (1982), however, again concluded that, apart from the obviously different soft-rock East Cape region, most of the variation in sediment yield could be explained by rainfall parameters. Our preliminary findings are more supportive of Adams.

Secondary effects of rainfall

Griffiths (1981 and 1982) considered that much of the inter-regional variation in New Zealand sediment yields might reflect secondary climatic effects, such as differences in the intensity, frequency, and duration of storms. We have explored these possibilities for the schist/semi-schist and greywacke/argillite data groups using stepwise multiple regression analysis to test whether a statistically significant (at the 5% level) improvement could be made to the simple $S = aP^b$ power law model. The tested changes included substituting the 5-year return-period, 24-h duration intensity (*I*24) for *P*, and adding the coefficient of variation of annual rainfall (*P*COV) or the ratio of wettest-monthly-rainfall:mean-annual-rainfall (*P*wet:*P*mean) into the model. For the schist basin group, a statistically significant but minor improvement (adjusted r^2 increased from 0.78 to 0.84) resulted from the addition of the *P*wet:*P*mean parameter. This parameter indexes a seasonal intensification of rain, and is thus probably accounting for the increased seasonality of the rainfall experienced to the east of the Southern Alps. Substituting *I*24 for *P* resulted in essentially the same regression performance statistics, as was expected from the high correlation between these two parameters ($r = 0.91$).

For the greywacke/argillite group, a small but significant improvement to the $S = aP^b$ model (adjusted r^2 increased from 0.58 to 0.69) was obtained with the addition of the *P*COV parameter. This indexes inter-annual variability and probably reflects the climatic differences between basins in South and North Island. Again, substituting *I*24 for *P* made no improvement.

The conclusion from this analysis is that secondary climatic parameters may account for statistically significant but relatively minor amounts of the variance observed in sediment yields around New Zealand.

Physiographic controls

The influence of basin physiography was also examined within the schist/semi-schist and greywacke/argillite groups. Four basin physiographic parameters were evaluated from the NZLRI geographic database: mean elevation (Z), mean slope angle (θ), elevation standard deviation (Zsd), and slope standard deviation (θsd). For the schist group, all four parameters were inter-correlated, but the slope induced the greatest improvement in the $S = aP^b$ regression model. The best regression performance was obtained when $P\sin\theta$ was substituted for P (adjusted r^2 increased from 0.78 to 0.86). $P\sin\theta$ is essentially a "rain power" parameter and might be expected to be a reasonable erosivity index. This is because rainfall is directly related to specific runoff, R, and specific stream power, $\gamma R\sin\theta$, is a well known index of stream sediment transport capacity (e.g. Bagnold, 1966). The $S = a(P\sin\theta)^b$ model for the schist/semi-schist group was not improved by the addition of secondary climatic variables. Physiographic parameters made no improvement to the $S = aP^b$ model for the greywacke/argillite group.

CONCLUSIONS

Preliminary conclusions from analysis of suspended sediment loads in New Zealand rivers are:

(a) The main controls on spatial variations in suspended sediment yields are mean annual rainfall and basin geology. Variations in either of these controls can induce yields to range over three orders of magnitude.

(b) Geological control is clearly related to lithology, but also appears to relate to the level of tectonic activity and the Quaternary history. The highest yields are generally clustered near the boundary between the Indian and Pacific lithospheric plates, reflecting the inter-related effects of tectonic activity, erosion susceptible rocks, and high mountains inducing high orographic rainfall.

(c) Mean basin slope and secondary climatic parameters that index the seasonality and inter-annual variability of the rainfall explain some of the spatial variance observed in yields from basins with the same general rock type and annual rainfall.

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