Temporal and spatial variation of sediment yield in the Snowy Mountains region, Australia

BOFU YU
Faculty of Environmental Sciences, Griffith University, Nathan, Queensland 4109, Australia

DAVID NEIL
Department of Geographical Sciences and Planning, University of Queensland, St Lucia, Queensland 4072, Australia

Abstract The relationships between sediment concentration and discharge at 20 streamgauging stations in the Snowy Mountains region were examined to evaluate the temporal and spatial variation of sediment yield. At a given discharge, sediment concentration is generally higher in summer than in winter, although the difference is not sufficient to warrant separate rating curves for different seasons. The slope of the rating curve was found to be positively related to the basin area, and it was also linearly proportional to the correlation coefficient between sediment concentration and discharge. The 1950s was a period of significantly higher sediment yield by comparison with the 1940s and 1960s. Except for two gauging stations affected by construction works upstream, sediment yield of the region depends primarily on runoff and minimum basin elevation, varying from 2.4 to 23 t km^{-2} year^{-1}.

INTRODUCTION

The Snowy Mountains region is unique in that it is the only alpine region in Australia with a significant amount of snowfall in winter. By comparison with many other areas of high elevation, the Snowy Mountains are older, probably Miocene (Ollier & Wyborn, 1989) and many areas have relatively little local relief. According to Costin (1952), four environmental tracts can be identified in the region depending mainly on the elevation. They vary from an alpine tract at the higher elevation ($>$1950 m) through sub-alpine and montane tracts, to a tableland tract below 900 m. The basins included in this study lie mainly in the sub-alpine and montane areas. Land use in these areas from late last century until the period of sediment sampling, was largely sheep grazing with regular burning. The implications of the land utilization practised for land degradation were recognized a century ago (Helms, 1893, 1896) and numerous studies have since confirmed these concerns (e.g. Newman, 1955; Taylor, 1957; Bryant, 1971).

Sediment yields in the Snowy Mountains region are generally low, consistent with the pattern for most of Australia. They are also low by comparison with other high elevation areas. Brown & Millner (1989) tabulated estimates of the denudation rate for 13 basins in the region and showed that their estimates were 2-3 orders of magnitude lower than for other alpine regions in the Northern Hemisphere. Douglas (1966), who analysed Snowy Mountains Hydro-electric Authority (SMHA) data for eight basins, concluded that the Southern Tablelands and Highlands yields were very low by comparison with other areas of 500-1500 mm precipitation. Although the low sediment yield of the region is known, temporal and spatial variation of the sediment yield in relation to streamflow and other basin characteristics has not been examined previously.

Between 1955 and 1970, in connection with the Snowy Mountains Scheme, sediment concentration was regularly measured at numerous streamgauging stations in the Snowy Mountains region. This monitoring program represents one of the most intensive ever undertaken in Australia as far as stream sediment sampling is concerned. These data have been published in print form (SMHA, 1972) along with the streamflow records (SMHA, 1970, 1971).

In this paper, some preliminary results concerning sediment yield for the region are summarized. To estimate sediment yield where significant snowmelt runoff exists and using measurements of sediment concentration at irregular intervals, it is important, first, to determine whether separate rating curves are needed for different seasons. Spatial variation of the sediment concentration-discharge relationship is then examined

Table 1 Reference number, station number, location, basin area, average runoff and sediment yield.

	Station number and location	Area (km^2)	Runoff depth (mm $year^{-1}$)	Sediment yield (t km^{-2} $year^{-1}$)
1	410536 Bald Hill No. 1	0.34	889	3.95
2	410537 Bald Hill No. 2	0.44	856	4.63
3	410538 Bald Hill No. 3	0.54	680	2.35
4	410539 Bald Hill No. 4	0.28	452	3.60
5	410540 Bald Hill No. 5	0.18	527	2.64
6	410508 Eight Mile Creek at T.2 Track	9.06	1191	22.5
7	410534 Happy Jacks R. above Happy Jacks Pondage	109	914	7.36
8	410504 Happy Jacks R. at McKeahnies	46.6	930	7.14
9	410521 Middle Creek at Pinbeyan	10.6	366	12.7
10	410535 Murrumbidgee R. above Tantangara Reservoir	216	713	8.89
11	410509 Tumut River at Cumberland (A)	1098	901	110
12	410533 Tumut River above Happy Jacks Pondage	130	1309	5.57
13	410503 Tumut River at Lobs Hole (A)	885	983	213
14	410513 Tumut River at Sams Diggings	112	1776	19.3
15	410507 Wallaces Creek at Hospital Flat	43.5	556	11.8
16	410506 Yarrangobilly River at Hospital Flat	227	543	17.6
17	222505 Burrungubugge River at Constances Hut	40.4	1257	7.80
18	222511 Crackenback River at Bundilla	122	1574	14.1
19	222502 Crackenback River at the Creel	251	875	11.8
20	222518 Gungarlin River at No. 1 Damsite	171	682	3.69

in detail. Annual time series of two representative basins are presented, and finally, a regression equation between long-term sediment yield and basin characteristics is derived for basins in the region.

DATA

Out of a total of 91 streamgauging stations where some sediment concentration data were available only 20 stations were selected (Table 1). A number of factors were considered in the selection process. They included whether long-term daily streamflow data were available; when impoundment, thus streamflow regulation, commenced; and whether recent bushfires had destroyed the vegetation cover, and modified runoff and sediment transport processes (Brown, 1972). The sediment sampling period was from the mid 1950s to the early 1960s and the sample size varied from 31 to 238. Streamflow record length in general was slightly longer than sediment records, and for some of the gauging stations, streamflow records dated back to the mid 1940s. For each station, data were screened to ensure that there was no more than one sediment concentration reading per day and only the first data entry was retained if multiple data entries were recorded for any given day. Data entries with zero concentration readings were also excluded from this analysis. These 20 stations were spread across the Great Dividing Range with basin areas varying from 0.18 to 1098 km^2 (Fig. 1).

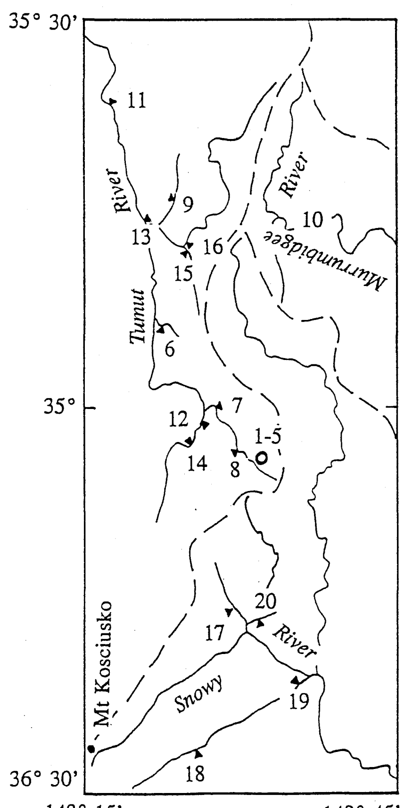

Fig. 1 Location map of the 20 stations (see Table 1 for reference numbers).

METHOD

A log-linear model between sediment concentration, C, and discharge, Q, i.e.

$$C = a\,Q^b \tag{1}$$

was used as a starting point to examine the C-Q relationships. The exponent, b, is the ratio of the percentage change of C to that of Q, representing the sediment concentration response to discharge variations. To use the log-linear model for sediment yield estimation, a correction factor is needed to remove the bias introduced when the log-linear model is retransformed (Ferguson, 1986; Koch & Smillie, 1986). For this analysis, the smearing estimate (Duan, 1983) was used to correct the bias in sediment yield estimates.

To evaluate the seasonal effects on the C-Q relationship, the log-linear model was developed for summer (November-April) and winter (May-October) separately. The difference in sediment concentration can be quantified by:

$$\log(C_s/C_w) \tag{2}$$

with its variance as:

$$\mathrm{var}[\log(C_s/C_w)] = \mathrm{var}[\log(C_s)] + \mathrm{var}[\log(C_w)] \tag{3}$$

where $\log(C_s)$ and $\log(C_w)$ are expected logarithms of sediment concentration for the average measured discharge for summer and winter, respectively, and $\mathrm{var}[\log(C_s)]$ and $\mathrm{var}[\log(C_w)]$ can be determined using classical linear regression theory.

RESULTS

Seasonal effect

Both the difference in sediment concentration and its 90% confidence interval are presented as a function of the basin area in Fig. 2. For a given gauging station, if the confidence interval lies entirely above the abscissa, the sediment concentration for that site would then be significantly higher (at 0.1 level) in summer than in winter at the specified discharge. Although the sediment concentration tends to be higher in summer than in winter by about 40% on average, for the majority of the stations (13 out of 20), the difference is not statistically significant. For those stations having significantly higher sediment concentration in summer, the difference is still only marginal given the relatively large confidence intervals. Thus, only a single C-Q relationship is used for the purpose of sediment yield estimation.

Overall concentration-discharge relationship

It is interesting to note, that for streams in the Snowy Mountains region, there is a positive and reasonably good relationship between the exponent and the basin area (Fig. 3):

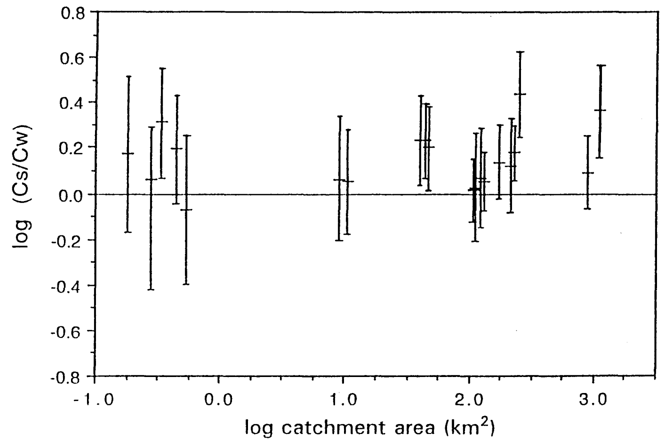

Fig. 2 The difference in sediment concentration in summer and winter at the average measured discharge.

$$b = -0.376 + 0.281 \log A, \qquad r^2 = 0.75 \tag{4}$$

where A is the basin area in km^2. Negative b, or negative slope of the rating curve, is exclusively associated with small basins (< 1 km^2) at the higher elevations (> 1400 m). As basin area increases, so does the exponent, indicating that the sediment concentration is more responsive to variations of streamflow for large basins, probably because the proportion of the basin unaffected by snowfall and snowmelt runoff increases as the basin area increases. It was also noted that the correlation between sediment concentration and discharge is highly variable and the correlation coefficient depends on the exponent (Fig. 4):

$$r_c = 0.81\, b, \qquad r^2 = 0.97 \tag{5}$$

where r_c is the linear correlation coefficient between $\log(C)$ and $\log(Q)$. The implication of this relationship is that the variation of sediment concentration is proportional to that

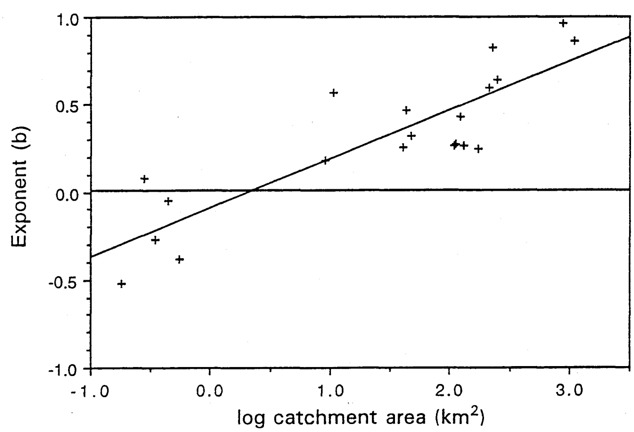

Fig. 3 The relationship between the exponent (b) and basin area.

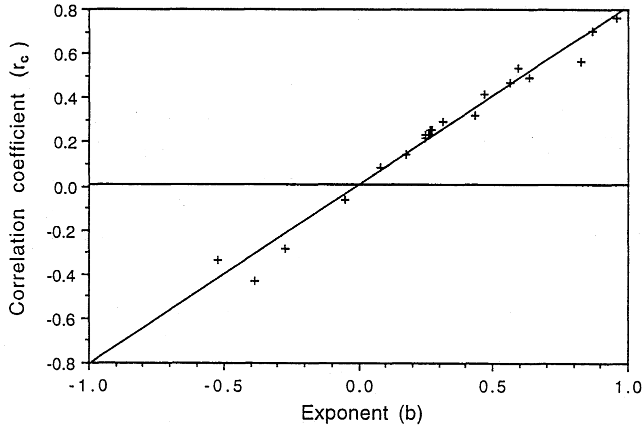

Fig. 4 The relationship between the correlation coefficient (r_c) and the exponent (b).

of discharge irrespective of the basin area and the overall concentration-discharge relationships. These relationships between the exponent, correlation coefficient and basin area may be used to estimate sediment rating curves for ungauged basins in the region, an approach that has been developed for other regions in the world (e.g. Rannie, 1978; Mimikou, 1982).

Examples of these diverse concentration-discharge relationships are illustrated in Fig. 5. At Bald Hill No. 3, with a basin area of 0.54 km^2, the sediment concentration is inversely related to discharge, and the concentration tends to be higher in winter than in summer (Fig. 5(a)). On the other hand, for larger basins like the Tumut River at Lobs Hole with a basin area of 885 km^2 (Fig. 5(b)), the sediment concentration is slightly higher in summer than in winter, and the slope of the rating curve is close to 1.0.

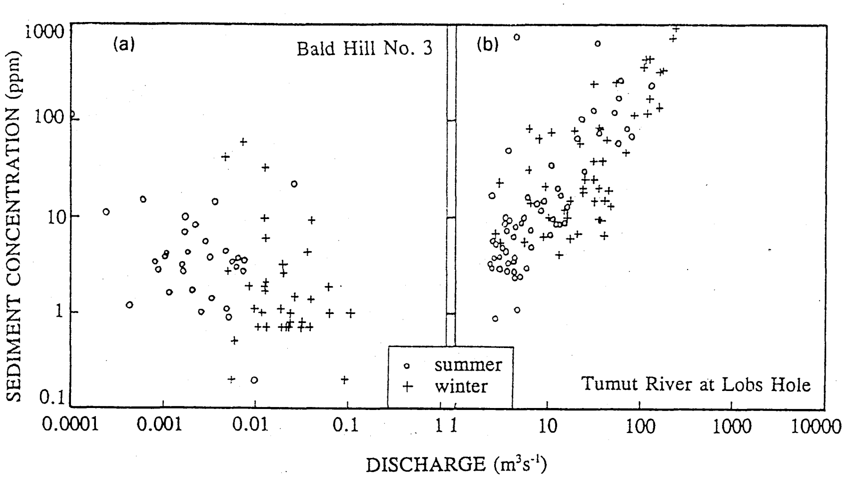

Fig. 5 Plots of sediment concentration *vs.* discharge for (a) Bald Hill No. 3, and (b) Tumut River at Lobs Hole (A).

Temporal variation of the sediment yield

Time series of sediment yield for the two basins with the longest record length are shown in Fig. 6. Yarrangobilly River is a tributary of the Tumut River to the north and the Crackenback River is a tributary of the Snowy River to the south. It can be seen that for the overlapping period of 1953 to 1964, the sediment yield for the two basins is well correlated ($r = 0.90$), and the 1950s, especially the years 1952 and 1956, was a period of greater sediment yield. For the Crackenback River, the average sediment yield for 1950-1959 was 14 t km^{-2} year^{-1}, which was significantly (at 0.02 level) greater than the average sediment yield of 9.9 t km^{-2} year^{-1} for the combined period of 1945-1949 and 1960-1966. The above-average sediment yield for the 1950s was related to the higher streamflow for that period, a pattern that has been recognized for most of southeastern Australia (e.g. Bell & Erskine, 1981; Riley, 1988).

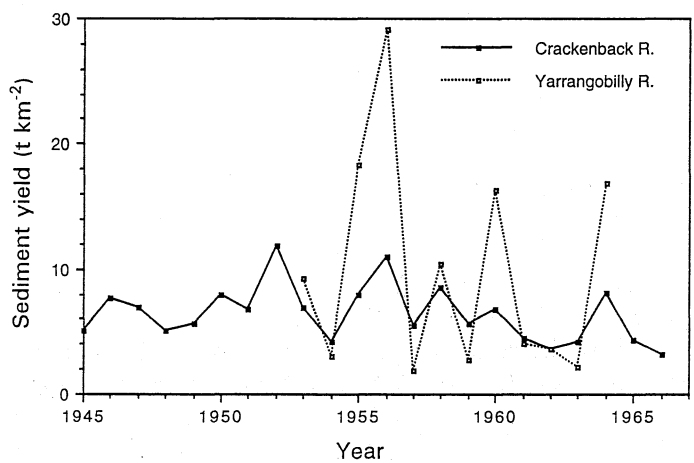

Fig. 6 Time series of annual sediment yield of selected basins: Yarrangobilly River at Hospital Flat and Crackenback River at the Creel.

Spatial variation of the sediment yield

For most of the basins, long-term average sediment yield varies from 2.4 to 23 t km^{-2} year^{-1} with an average of 9.5 t km^{-2} year^{-1}. The sediment yields of the Tumut River at Cumberland and the Tumut River at Lobs Hole are an order of magnitude greater than the sediment yield for other basins (Table 1). Since these are the only two sites downstream of storage reservoirs, it is most likely that this abnormally high sediment yield was related to the heavy construction activities at that time. Except for these two disturbed basins, long-term average sediment yield for the rest of the basins primarily depends on mean annual runoff and the minimum basin elevation, i.e. the elevation of the gauging station. A simple log-linear regression yields:

$$\log S = 1.41 + 0.423\,R - 0.769\,E, \qquad r^2 = 0.80 \qquad (6)$$

where S is average sediment yield in t km^{-2} year^{-1}, R average runoff in m year^{-1} and E the minimum basin elevation in km, and the standard error of the estimates is 0.144.

A plot of predicted and actual sediment yield is shown in Fig. 7. The average runoff for these 18 streamgauging stations varied from 366 to 1776 mm year^{-1} and the minimum basin elevation varies from 585 to 1548 m. The fact that the minimum basin elevation is better correlated with sediment yield than mean basin elevation suggests that the minimum elevation limits the type of vegetation cover, and thus the erodibility of the basin. Other variables, such as basin area, total relief or average slope of the basin, do not contribute significantly to the relationship between sediment yield and basin characteristics in this region.

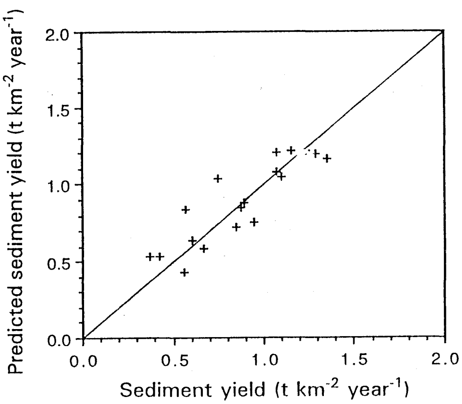

Fig. 7 Predicted and actual sediment yield in the Snowy Mountains regions using average runoff and the minimum basin elevation.

While sediment yields reported here are low, much higher rates apparently occur locally. For example, Costin *et al.* (1959), cited in Bryant (1971), estimated a loss of one million tons of soil from three square miles over a fifty year period, which is equivalent to 2600 t km^{-2} year^{-1}. Similarly, Brown (1972) reported an increase in sediment concentration of three orders of magnitude in response to bush fires.

CONCLUSIONS

As the only alpine region in mainland Australia, the Snowy Mountains region shows considerable spatial variation in terms of seasonal climatic contrast, relief, streamflow and sediment concentration-discharge relationships. The inverse relationship between concentration and discharge was noted for smaller basins at the higher elevations and a greater responsiveness of sediment concentration to discharge variation occurs for larger basins. Despite the seasonal variation in precipitation and temperature, the concentration-discharge relationship in most basins does not change significantly from season to season. With respect to the temporal and spatial variation of sediment yield, the 1950s was a period of above-average sediment yield by comparison with the adjacent decades and the long-term average sediment yield depends mainly on average runoff and the minimum basin elevation except for those basins disturbed by construction of storage reservoirs.

REFERENCES

Bell, F. C. & Erskine, W. D. (1981) Effects of recent increases in rainfall on floods and runoff in the upper Hunter Valley. *Search* **12**, 82-83.

Brown, J. A. H. (1972) Hydrologic effects of a bushfire in a catchment in south-eastern New South Wales. *J. Hydrol.* **15**, 77-96.

Brown, J. A. H. & Millner, F. C. (1989) Aspects of the meteorology and hydrology of the Australian Alps. In: *The Scientific Significance of the Australian Alps* (ed. by R. Good) (Proc. First Fenner Conf. on the Environment, Canberra), 297-329.

Bryant, W. G. (1971) Deterioration of vegetation and erosion in the Guthega catchment area. *J. Soil Conservation Service of NSW* **27**, 62-81.

Costin, A. B. (1952) Hydrological studies in the Upper Snowy catchment area with special reference to the effects of land utilisation. *J. Soil Conservation Service of NSW* **8**, 5-16.

Costin, A. B., Wimbush, D. J., Kerr, D. & Gay, L. W. (1959) Studies in catchment hydrology in the Australian Alps. I. Trends in soils and vegetation. *Div. of Plant Industry Tech. Pap. 13, CSIRO, Melbourne.*

Douglas, I. (1966) Denudation rates and water chemistry of selected catchments in eastern Australia and their significance for tropical geomorphology. PhD thesis, Australian National Univ., Canberra.

Duan, N. (1983) Smearing estimate: a nonparametric retransformation method. *J. Am. Stat. Assoc.* **78**, 605-610.

Ferguson, R. I. (1986) River loads underestimated by rating curves. *Wat. Resour. Res.* **22**, 74-76.

Helms, R. (1893) Report on the grazing leases of the Mt Kosciusko Plateau. *Agric. Gaz. of NSW* **4**, 530-531.

Helms, R. (1896) The Australian Alps or Snowy Mountains. *J. Roy. Geogr. Soc. Austral.* **6**, 4.

Koch, R. W. & Smillie, G. M. (1986) Bias in hydrologic prediction using log-transformed regression models. *Wat. Resour. Bull.* **22**, 717-723.

Mimikou, M. (1982) An investigation of suspended sediment rating curves in western and northern Greece. *Hydrol. Sci. J.* **27**, 369-383.

Newman, J. C. (1955) Tumut catchment area – survey of vegetation and erosion. *J. Soil Conservation Service of NSW* **10**, 205-213; **11**, 48-61; 95-110; 146-162; 207-222.

Ollier, C. D. & Wyborn, D. (1989) Geology of alpine Australia. In: *The Scientific Significance of the Australian Alps* (ed. by R. Good) (Proc. First Fenner Conf. on the Environment, Canberra), 35-53.

Rannie, W. F. (1978) An approach to the prediction of sediment rating curves. In: *Research in Fluvial Systems* (ed. by R. Davidson-Arnott & W. Nickling), 149-167. Geobooks, Norwich, UK.

Riley, S. J. (1988) Secular change in the annual flows of stream in the NSW section of the Murray-Darling basin. In: *Fluvial Geomorphology of Australia* (ed. by R. F. Warner), 245-266. Academic Press, Sydney.

SMHA (1970) *Streamflow Records of the Snowy Mountains Region Australia to 1965.* Snowy Mountains Hydro-electric Authority, Cooma, NSW.

SMHA (1971) *Streamflow Records of the Snowy Mountains Region Australia 1966 to 1970.* Snowy Mountains Hydro-electric Authority, Cooma, NSW.

SMHA (1972) *Sediment Records of the Snowy Mountains Region Australia.* Snowy Mountains Hydro-electric Authority, Cooma, NSW.

Taylor, A. C. (1957) A soil conservation of the Snowy catchment. *J. Soil Conservation Service of NSW* **13**, 187-197; **14**, 5-23; 104-130.