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SEDIMENT YIELDS FROM SMALL FORESTED CATCHMENTS NORTH WESTLAND — NELSON, NEW ZEALAND

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ABSTRACT

Sediment yield rates from six small forest catchments in North Westland and from four small forest catchments in Nelson averaged 55 m^3/km^2 p.a. and 5 m^3/km^2 p.a. respectively. Fifty–five percent of the total sediment yield produced from the North Westland catchments over 821 days occurred during one large storm event with a return period of approximateely 20 years. In the Nelson catchments 90 percent of the sediment yield over 608 days occurred during a single storm event with a return period of six months to one year. It is hypothesised that the development of the forested gravel hill country landscapes in North Westland and Nelson have depended closely on infrequent high intensity storms which occur, perhaps once every ten years or less frequently.

INTRODUCTION

Numerous overseas studies have shown that streamflow from undisturbed forest catchments is generally clear and transports negligible sediment except during periods of high discharge resulting from snowmelt or heavy rainfall (Reinhart *et al.* 1963, Dils 1957, Packer 1967, Fredriksen 1970). However, little is known about physical streamwater quality and sediment yields from undisturbed indigenous forest landscapes in New Zealand. Such information not only provides a better understanding of the development of our landscapes bu also helps provide a firm data bank on which the development of our water resources can be based. In an earlier paper Pearce *et al*, (1976) provided some preliminary sediment yield data for six small North Westland beech forest catchments which indicated that the New Zealand sediment yield rates fell within the range of yield rates from comparable intact forest environments overseas. This paper presents the results of a study of sediment yields from six small undisturbed forest catchments in the Maimai experimental area in Tawhai State Forest near Reefton, hereafter referred to as the Maimai catchments, and four similar catchments in Big Bush State Forest near Korere in Nelson, hereafter referred to as the Big Bush catchments. The study is part of a much larger programme aimed at assessing the hydrological behaviour of undisturbed native forest headwater catchments and the hydrological changes which occur when the native forests are cleared and converted to pine plantations.

Catchment Physical Features

The six Maimai catchments selected for study range from 1.63 ha to 4.62 ha in area above the combined gauging station sediment trap structures. The catch-

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ments are topographically similar with narrow ridgetops, V–shaped valley cross–sections, southerly aspects, steep slopes (mean catchment slope 36°), and range in relief from 70 m to 100 m. They drain into Powerline Creek (informal name) a tributary of the Mawheraiti River in the northwest part of Tawhai State Forest. Weathered conglomerates (Old Man Gravels) of early Pleistocene age underlie the catchments. The gravels are firmly compacted and appear to be poorly permeable. Soils are shallow podsolized yellow–brown earths with a stony sandy–loam texture (Blackball Hills Soils in Mew *et al*, 1975). The forest floor forms a more or less continuous fibrous organic mantle of variable thickness (mean depth 17 cm, range 2 cm to 90 cm+; Webster, 1976). The beech–podocarp–hardwood forest cover is dominated by hard beech, kamahi and rimu. Red beech, quintinia, miro and Hall's totara are the more common subdominants while tree ferns, fuschia and pepperwood form a low canopy in the gully bottoms. Annual rainfall averages approximately 2600 mm.

The four catchments in Big Bush State Forest range in area from 4.77 ha to 20.19 ha and are not as steep as the Maimai catchments (mean catchment slope 27°). The catchments have a northwesterly aspect and drain into Donald Creek,

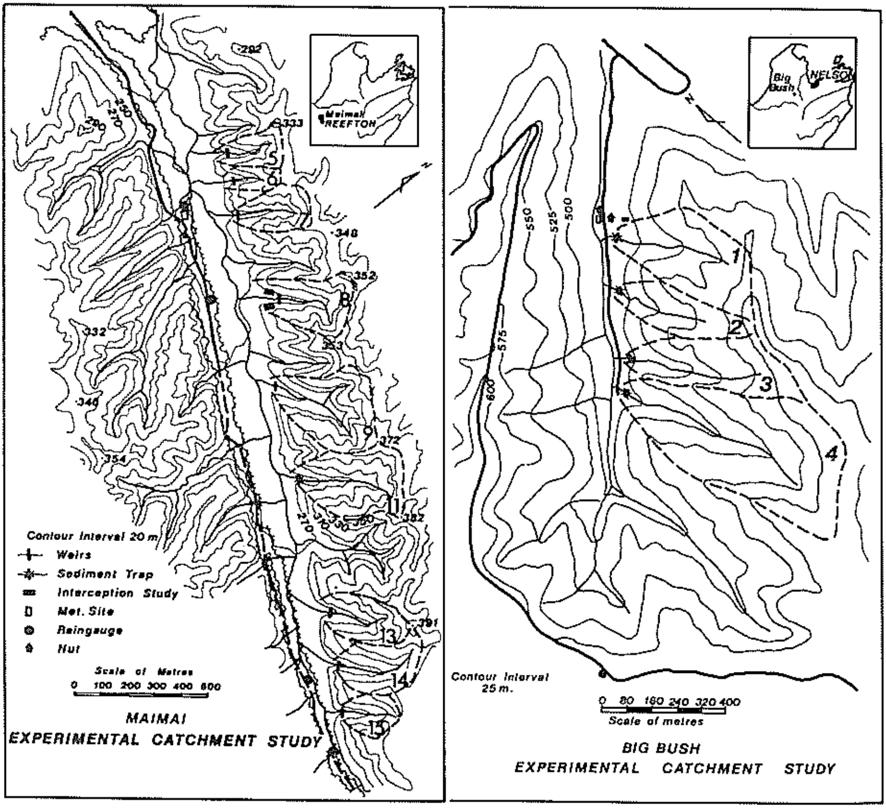

FIG.1 — Locations of Maimai and Big Bush experimental catchments.

a tributary of the Tadmor River. The geology consists of early Pleistocene Moutere Gravels which are genetically, and in most physical respects, equivalent to the Old Man Gravels. However, they are less weathered and appear to contain less fine sand–silt–clay matrix than Old Man Gravels. Red beech and hard beech are the dominant forest species with kamahi, miro, rimu and silver beech sub–dominant. Soils are shallow stony podsolized yellow–brown earths (Hope hill soils) with an overlying forest floor organic mantle which averages 9 cm in depth (Webster 1976). Average annual rainfall approximates 1700 mm.

The locations of the two sets of catchments are shown in Fig. 1 and a summary of the catchment characteristics is presented in Table 1.

Stream Channel Characteristics

A survey of the channels and the forest debris within the streambed region in the Maimai catchments showed that the gross channel form is largely influenced by the surrounding forest vegetation. Living tree roots cross the narrow channels in many places while, occasionally, small living trees are located in the channels.

FIG.2 — Channel conditions in Maimai experimental catchment M13. The cobble bed contains much forest debris including large moss–covered logs.

TABLE 1 – Physical characteristics of experimental catchments.

Catchment	*Geology*[1]	*Area (ha)*	*Mean Elevation (m)*	*Aspect*	*Relief (m)*	*Mean Slope*	*Drainage Density (km/km²)*	*Eroding*[2] *Area (m²)*	*Rc*[3]	*Rf*[4]	*Re*[5]
M5	OMG	2.31	290	S	74	36	16.9	210	0.79	0.64	0.90
M6	OMG	1.63	285	S	85	36	16.0	70	0.66	0.32	0.64
M8	OMG	3.84	305	S	81	36	15.6	40	0.73	0.74	0.97
M13	OMG	4.25	340	S	101	37	14.1	<20	0.78	0.50	0.80
M14	OMG	4.62	340	S	97	36	12.5	<20	0.74	0.53	0.82
M15	OMG	2.64	335	S	75	34	11.7	<20	0.88	0.58	0.86
BB1	MG	8.57	540	NW	133	27		<20	0.70	0.38	0.70
BB2	MG	4.77	555	NW	116	27		<20	0.59	0.28	0.60
BB3	MG	7.84	560	NW	135	28	8.8	<20	0.52	0.23	0.54
BB4	MG	20.19	560	NW	143	27	6.9	<20	0.61	0.31	0.63

1 OMG = Old Man Gravels, MG = Moutere Gravel
2 Eroding area = total area in catchment of landslide scars or eroding exposed soil
3 Rc = circularity ratio = catchment area/area of circle with same perimeter
4 Rf = form factor = catchment area/catchment length^2
5 Re = elongation ratio = diameter of circle of catchment area/catchment length

TABLE 2 — Physical characteristics of the Maimai catchment streambeds.

Catchment	*Main Channel length (m)*	*Total length of channels (m)*	*Mean slope of main channel (m)*	*Mean width of main channel (m)*	*Mean distance between obstructions (m)*
M 5	160	390	0.213	0.96	16
M 6	195	260	0.266	0.63	14
M 8	210	600	0.228	0.70	23
M13	250	600	0.265	0.81	16
M14	300	575	0.211	–	20
M15	150	310	0.197	0.72	13
BB1	345		0.185		
BB2	295		0.215		
BB3	425		0.185		
BB4	765		0.126		

The forest vegetation also causes many dams of organic debris, particularly logs over 10 cm diameter, to accumulate in the channels. These dams obstruct coarse sediment movement and impart a stair–step form to the streambed longitudinal profile. Most of the larger log dams appear to remain as stable obstructions for long periods (years and possibly decades) as the storm streamflows do not attain sufficient energy to move them.

Stream channel form is extremely variable. For much of their length the channels possess a cobble bed with occasional sand and fine gravel bars and levees in the mid and lower reaches (Fig. 2). Channels average approximately 0.7 m wide. In places the channels are ill–defined and streamflow occurs over a tree root mat. In other locations the streams disappear underground for short distances through shallow natural pipes. The mean streambed slope for the Maimai catchments is 0.23, (Table 2). Obstructions, mainly log dams, occur on average once every 17 m along the main channels of the Maimai catchment streambeds. The survey also revealed that, on average, 1.5 m^3 of organic debris, mainly logs, are accumulated within the bed region per 10 m of streambed.

The Big Bush stream channels are less steep (mean slope = 0.18) but are similar in form and obstructions appear to occur at approximately the same frequency. Surveys of the Big Bush catchment channels are not yet complete.

Experimental Methods

The methods employed to obtain hydrologic sediment yield data in the Maimai catchments have been briefly outlined by Pearce *et al*, (1976). A 90° sharpcrested V–notch weir equipped with an automatic water level recorder, and a concrete lined sediment trap was constructed on the lower reaches of each stream. The sediment traps have a capacity of approximately 3 m^3 to 4 m^3 and for materials larger than medium sand, have a high trapping efficiency. Estimates of the weight and volume of materials retained in the traps were made, on average, once every 5 months. During each trap cleanout a representative 10 kg sample was taken for particle size and sediment quality analyses. After splitting, approximately 4 kg to 5 kg subsamples were subjected to dry sieve analyses. Organic constituents were separated manually from the mineral fraction of the sediment retained on sieves >1 phi.

One litre samples of streamwater have been manually collected at the weir notch for characterising the suspended sediment outflow during stormflow and low flow periods throughout the duration of the study. Suspended sediment concentrations were determined using the filtration method (Guy 1969). Logarithmic sediment rating curves were prepared for each catchment. The total volumes of suspended sediment lost over the weirs in the Maimai catchments were calculated by applying the suspended sediment rating curves to hourly streamflow duration data. The total outflow of suspended sediment from the Big Bush catchments was estimated by applying suspended sediment data collected at approximately 2 hour intervals through storms to the streamflow hydrographs for individual storms. Only one stormflow event has moved significant quantities of suspended sediment out of these catchments. In addition to manual sampling a limited amount of water sampling by battery–operated automatic samplers was carried out.

RESULTS

Sediment Yields

Sediment yields (m^3) and yield rates (m^3/km^2 p.a.) from the Maimai catchments were calculated for the period 1.12.74 to 28.2.77 (821 days) and from the Big Bush catchments for the period 1.11.75 to 30.6.77 (608 days). During the study period the Maimai catchments experienced 31 to 47 separate streamflow events when the peak specific discharge exceeded 3 l/sec.ha (Table 3). The sediment rating curves prepared for the Maimai catchments indicated that discharges approximating or exceeding 3 l/sec.ha usually caused measurable suspended sediment transport. In contrast, the Big Bush catchments recorded only 3 to 5 streamflow events when discharges exceeded 3 l/sec.ha and only one event when streamflow transported significant quantities of sediment during the 608 day study period.

The rainfall records, particularly the larger storm records from the Maimai catchments and the Big Bush catchments during the study period, were compared with the longer term records from Reefton and Golden Downs respectively. In general terms, the first half of the study period was probably stormier in the Maimai catchments than the average condition over the preceding decade while the second half of the study period was less stormy. On the other hand, the period of study at the Big Bush catchments was tranquil and was less stormy than the average condition during the preceding 10 years.

Sediment yield rates from the Maimai catchments averaged 55 m^3/km^2 p.a. and ranged from 22 m^3/km^2 p.a. to 113 m^3/km^2 p.a. (Table 4). On the basis of their sediment yields the Maimai catchments can be partitioned into a group of relatively high sediment producers (M5 and M6) and a group of relatively low sediment producers (M8, M13, M14 and M15). The mean yield rate for the first group (104 m^3/km^2 p.a.) is more than three times the mean yield rate from the second group of catchments (32 m^3/km^2 p.a.). The principal reason for this difference is presumably related to the higher incidence of slope failures in M5 and M6 compared to the other catchments as shown in Table 1.

The mean sediment yield rate for the drier Big Bush catchments was 5 m^3/km^2 p.a.: approximately an order of magnitude lower than the mean rate for the

TABLE 3 – Summary of storm period streamflow events for Maimai and Big Bush experimental catchments

Catchment	*No. of events with peaks >3 l/sec.ha*	*No. of events with peaks >20 l/sec*	*No. of events with peaks >40 l/sec*
M 5	47	16	5
M 6	47	9	3
M 8	47	28	13
M13	42	31	15
M14	43	32	16
M15	31	12	4
BB1	5	5	2
BB2	4	2	2
BB3	3	3	2
BB4	3	3	3

TABLE 4 – Summary of sediment yield data for Maimai and Big Bush experimental catchments.

	M5	*M6*	*M8*	*M13*	*M14*	*M15*	*BB1*	*BB2*	*BB3*	*BB4*
Catchment area (ha)	2.31	1.63	3.84	4.25	4.62	2.64	8.57	4.77	7.84	20.19
Study period (days)	821	821	821	821	821	821	608	608	608	608
Suspended sediment yield (m^3)	1.69	1.47	2.18	1.78	2.22	2.35	0.41	0.16	0.47	1.59
Trapped sediment yield (m^3)	3.17	2.69	0.21	0.33	0.59	0.49	0.04	0.09	0.29	0.40
Total sediment yield (m^3)	4.86	4.16	2.39	2.11	2.81	2.84	0.45	0.25	0.76	1.99
Sediment yield rate (m^3/km^2 p.a.)	94	113	28	22	27	48	3	3	6	6
*% Total sediment yield produced by major storm	64%	68%	39%	41%	66%	52%	95%	78%	89%	97%

* For Maimai catchments storm on 29.3.75 to 1.4.75
For Big Bush catchments storm on 28.6.77

Maimai catchments. The low rates are partly attributed to the lack of storms during the study period and partly attributed to the high degree of slope stability which limits the sediment supply to the streambeds.

The types of streamflow event which accounted for transport of sediment in the catchments were investigated in some detail. On average, 55 percent of the total sedimment yield from the six Maimai catchments was produced during one large storm period, while on average, 90 percent of the total sediment yield from the four Big Bush catchments occurred during a single shortlived storm period. The percentage of the total sediment yield from each catchment which occurred during the large storms is shown in Table 4.

The important sediment producing storm in the Maimai catchments occurred between 29th March 1975 and 1st April 1975. The storm hydrographs for this event (an example for catchment M13 is presented in Fig. 3) were essentially double-peaked with peak discharges ranging between 70 l/s (M6) and 270 l/s (M13). The event occupied only 0.2 percent of the total study period time and accounted, on average, for 6 percent of the total volume of streamflow during the period. A comparison of the storm's intensity characteristics with rainfall depth-duration-frequency data for Reefton (Robertson, 1964) shows that the storm was one which could be expected to occur about once every 20 years. During this storm 2.8 m^3 and 2.5 m^3 of mainly gravel and coarse sand were deposited in the sediment traps of catchments M5 and M6 respectively. It was these large volumes of trapped material which primarily caused the high mean sediment yield rates from M5 and M6.

The storm which caused sediment transport in the Big Bush catchments occurred on 28th June, 1977. The streamflow hydrographs were single peaked and attained peak discharges between 68 l/s (BB2) and 256 l/s (BB4). This storm was one which could be expected once or twice each year.

Sediment Sources

The source areas of stream transported sediment were studied in catchments M5 and M6 by Maplesden (1976). Using erosion pins driven into stream banks and debris slide surfaces, Maplesden showed that the most actively retreating

TABLE 5 — Comparison of sediment yield rates from small undisturbed forest catchments, USA and NZ.

Location	*Source of Information*	*Sediment Yield Rate m^3/km^2 p.a.*
Sleepers R. Vermont	Kunkle and Comer (1972)	20
Fernow, West Virginia	Patric (1976)	0.3
H. J. Andrews Forest, Oregon	Fredriksen (1970)	20 to 40
Silver Ck, Idaho	Megahan (1976)	5 to 20
Northern Mississippi	Ursic and Dendy (1963)	5 to 30
Maimai catchments, NZ		20 to 110
Big Bush catchments, NZ		3 to 6

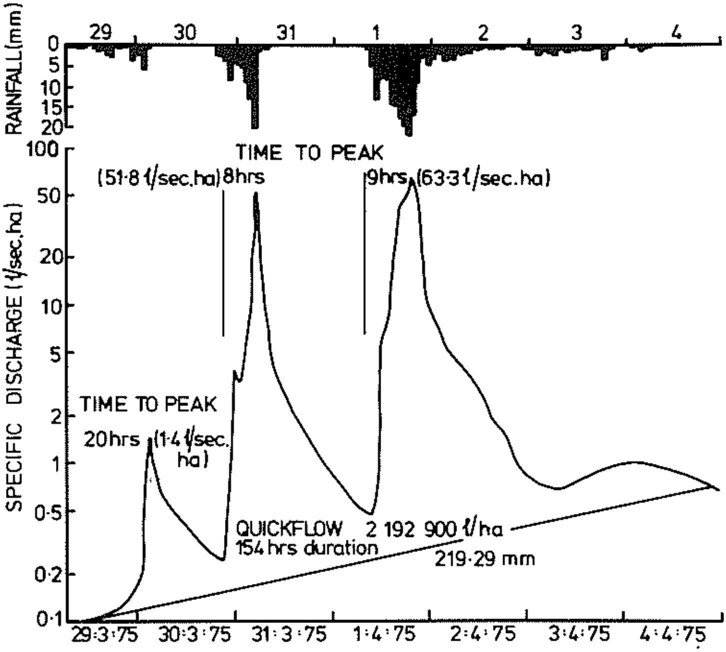

FIG.3 — Storm rainfall and runoff for catchment M13 29.3.75 – 4.4.75.

sites in both catchments were stream banks. During the 78 day period of measurement there was a strong indication that erosion within the catchments was producing more material to the streambed than was being transported out of the catchments. Presumably sediment remains temporarily trapped behind logs and obstructions until infrequent large stormflow events cause downstream transport of channel fill deposits. It was evident that during the March–April 1975 storm a large volume of material was supplied to the streambeds of catchment M5, M6 and M8 from small debris slides. However, since the storm the slide surfaces have partly stabilised under a developing grass and seedling vegetation cover.

Nature of Trapped Sediments

No attempt was made to distinguish bed load from suspended load during the study. The proportion of the total sediment volume which was deposited in the traps averaged 65 percent for the two high sediment yielding catchments (M5 and M6), 16 percent for the remaining Maimai catchments (M8, M13, M14, M15) and 26 percent for the Big Bush catchments.

Figs. 4 and 5 show the particle size distributions, mean size and the percentage of organic material of trapped sediment deposited during large storms (samples 1, 2, 3, 4, 9, 10, 11 and 12) and during small storms (samples 5, 6, 7, 8, 15 and 16). The nature of the sediments transported depended upon the size of the stormflow event; large events transporting much coarser material than small events. For instance, the large April 1975 stormflow in the Maimai catchments deposited

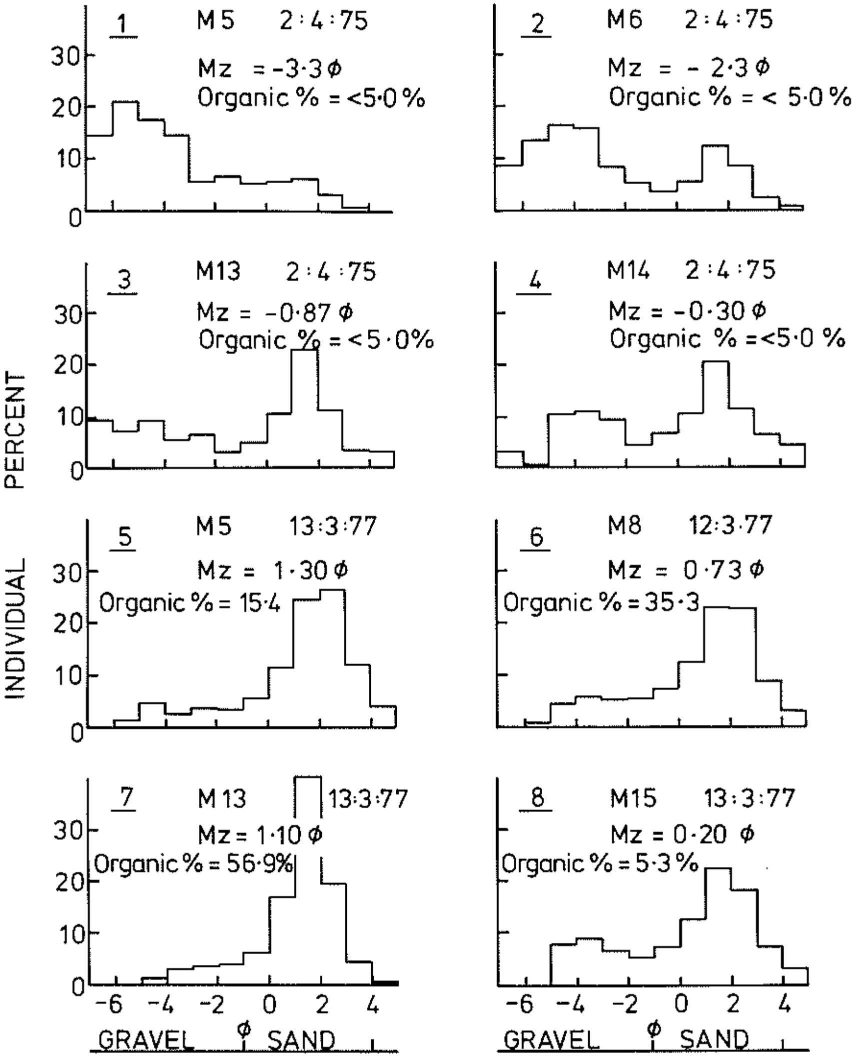

FIG.4 — Histograms showing particle size distributions of trapped sediment. Mz = graphic mean size (Folk 1965). Organic % = % organic material in range -0.6Ø to 1.0Ø.

coarse sediments with particle size distributions showing modes in the medium gravel (-3*5* to -6*5*) and medium sand (1*5* to 3*5*) ranges. Mean size ranged from -0.3*5* to -3.3*5*. In contrast, the smaller stormflows deposited sediment largely consisting of sand grades. Mean diameters ranged from -0.3*5* to 1.5*5*. The large June 1977 stormflows in the Big Bush catchments also produced sediment with modes in the medium gravel and medium sand range except in the smallest catchment (sample 10) which generated relatively small peak stormflow and transported dominantly sand grades.

It appears that only stormflows exceeding 40 l/s to 50 l/s will transport gravel in the channels of the Maimai and Big Bush catchments. The percentage of organic material in the trapped sediments was relatively small for sediment transported in large events compared to sediment transported in small events.

Suspended Sediment Concentrations and Physical Water Quality

Suspended sediment, dominantly in the fine sand–silt grades, ranged in concentrations from less than 10 mg/l to more than 2000 mg/l at the weir outflows during stormflows. Typically for small catchments, plots of suspended sediment concentrations against stream discharge (Fig. 6) produced a large scatter which is likely to be the major source of error in calculations of sediment yield using sediment rating curve – flow duration methods. Walling (1977) has shown that errors could range up to +280%. During stormflows, sediment concentrations at a given discharge were generally higher on the rising slope than on the falling stage and the occurrence of peak sediment concentrations usually preceded peak discharges. Examples of sediment concentration and streamflow hydrographs for selected storm periods are shown in Fig. 7. These data illustrate that sediment concentrations in small streams fluctuate greatly during storms.

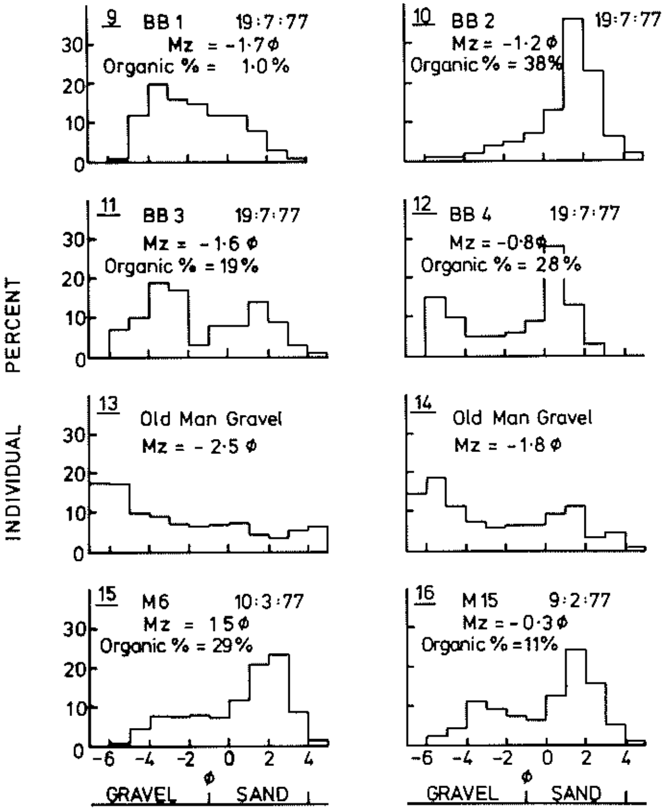

FIG.5 – Histograms showing particle size distributions of trapped sediment. Mz = graphic mean size (Folk 1965). Organic % = % organic material in range -0.6Ø to 1.0Ø.

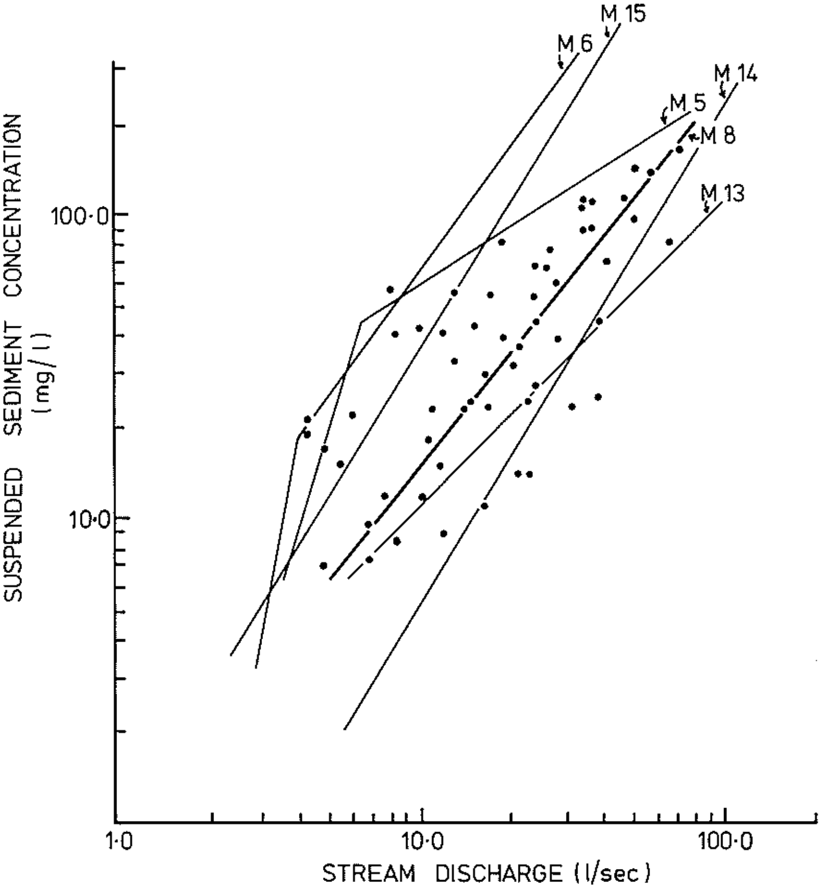

FIG.6 — Suspended sediment ratings for Maimai catchments. Data points for catchment M8.

even under undisturbed conditions. Brown (1972) attributes this characteristic to the fact that small additions of material, which would be rapidly diluted by the flow of a large river, produce great increases in sediment concentration on small streams.

The sediment rating curves for each catchment indicate that flows less than 3 l/s p.ha. generally carry less than 20 mg/l of suspended solids, a level of concentration which does not noticeably discolour streamwater. The hourly flow duration curves (Fig. 8) show that the streamflows from the experimental catchments remain clear and transport negligible sediment during approximately 97 percent of the time in the Maimai catchments and 99.7 percent of the time in the Big Bush catchments.

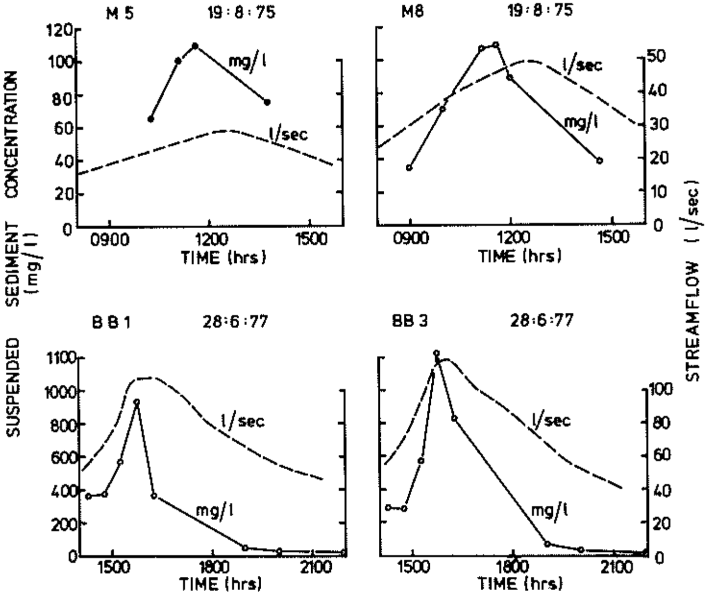

FIG.7 — Storm hydrographs and corresponding suspended sediment concentration curves for selected storms. Maimai and Big Bush experimental catchments.

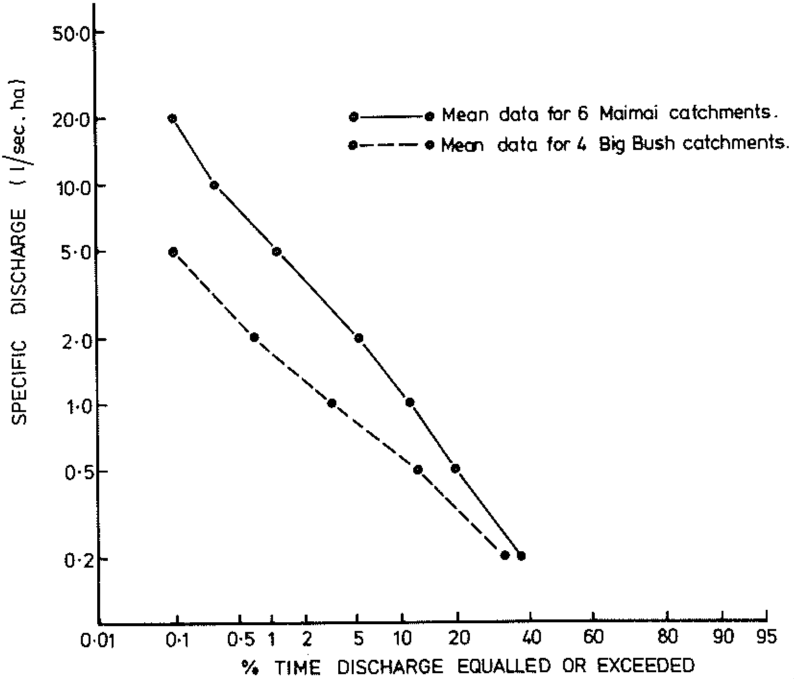

FIG.8 — Flow duration curves for hourly flows. Maimai and Big Bush experimental catchments.

DISCUSSION

The sediment yield rates calculated for the Maimai catchments are high when compared with sediment yield rates measured in temperate climate, forested hill environments in the USA (Table 5). Catchments M5 and M6 averaged approximately 100 m^3/km^2 p.a. while the average for the six catchments was 55 m^3/km^2 p.a. These rates are heavily influenced by the large 1975 storm and are probably higher than the long term average sediment yield rates. Published data for intact forest catchments in the USA show sediment yield rates from small catchments range from approximately 0.3 m^3/km^2 p.a. to about 50 m^3/km^2 p.a. In contrast, the Big Bush catchments have sediment yield rates which lie at the low end of the range of USA data.

The results of this study have important implications from the viewpoint of magnitude–frequency relationships. In both sets of catchments a disproportionate amount of sediment entrainment and transport occurred during intense events which occupied a very small part of the total time of study. It appears that the small area of the catchments which limits storm streamflow quantities, the coarse nature of the debris available for transport, the stable nature of the slopes and streambanks which are reinforced with tree root networks and the numerous stream channel blockages, combine to give infrequent, intense events great geomorphological significance. These factors raise the threshold below which mass wasting, sediment entrainment and sediment transport are largely inhibited. We therefore propose that the sculpturing of the forested gravel hill country landscapes in North Westland and Nelson has depended closely on infrequent high intensity storms which occur perhaps once every ten years or less frequently. Similar conclusions have been reported by Hack and Goodlett (1960), Williams and Guy (1971), Swanston and Swanson (1976) and Renwick (1977) for a range of forested hill and mountain environments.

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