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COARSE SEDIMENT YIELDS FROM THE UPPER WAIPAWA RIVER BASIN, RUAHINE RANGE

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ABSTRACT

From North Branch, in the Upper Waipawa River basin, having a sediment supply area of 0.354 km^2 and a drainage area of 1.6 km^2, the resulting floods during cyclone Alison, March 1975, transported more than 44,400 m^3 of coarse sediment, representing a specific yield of 28,000 m^3/km^2.

The flood level produced by cyclone Alison on the upper Waipawa River has an estimated recurrence interval of about 7.5 years leading to a minimum average annual sediment yield of 3700 m^3 km^{-2} a^{-1} from this storm alone. When other floods are taken into account a more realistic average annual sediment yield of North Branch is estimated to be c 4500 m^3 km^{-2} a^{-1}, but this also is conservative.

From this specific yield other approximate specific yields were derived for the headwater areas of: Middle Stream, 2100 m^3 km^{-2} a^{-1}; Smith Stream, 3200 m^3 km^{-2} a^{-1} and Mangataura Stream, 1400 m^3 km^{-2} a^{-1}.

Compared with available values of annual erosion rate and sediment yield for geologically and physiographically similar regions in New Zealand, the coarse sediment yield from the upper Waipawa branches of >4500 m^3 km^{-2} a^{-1} may be one of the highest, if not the highest, in New Zealand.

INTRODUCTION

Recent aggradation of the channels of Waipawa and Tukituki rivers in the Ruataniwha Plains area of North Island, New Zealand (Fig 1), has seriously reduced the protection now given by the Upper Tukituki Flood Control Scheme, completed in 1969 by the Hawkes Bay Catchment Board. The problems caused by aggradation include: increased risk of flooding of about 190 km^2 of agricultural land, loss of land due to channel widening and impeded drainage, reduction of clearance under bridges and increased structural damage to them during floods, and increased difficulties in the control of water supplies (Cunningham and Stribling, 1978).

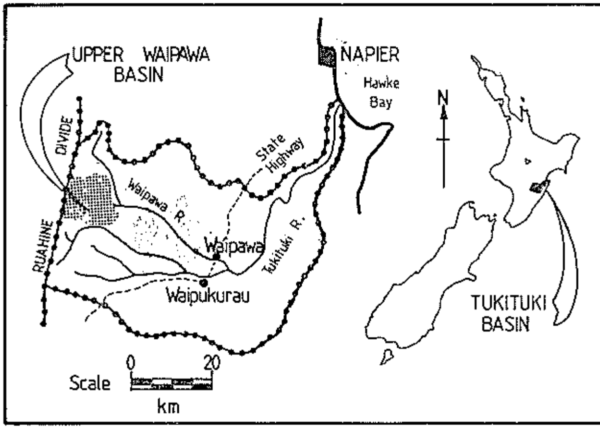

FIG. 1—Location of the Tukituki and Upper Waipawa basins, North Island, New Zealand. The Ruataniwha Plains area is shown lightly stippled.

Throughout the Ruahine Range, the source region of Waipawa and Tukituki rivers, the current trend of change appears to be one of increased erosion and sediment transport. The pattern of change since 1920 has been determined for the upper Waipawa River basin by Grant (1977); in the late 1940s the average coarse sediment transport rate increased and during the 1960s and 1970s it further increased.

The Hawkes Bay Catchment Board is now planning for upper Tukituki Catchment Control Scheme No. 2. There is thus a need to:

1. Map and classify source areas of coarse alluvial sediment
2. Determine sediment yield and patterns of downstream transport
3. Identify the factors responsible for the recently increased rates of change
4. Decide what can be reasonably done to retard erosion and transport on slopes and in channels
5. Derive reliable predictions for downstream planning and design.

This paper is a small contribution towards the above needs.

UPPER WAIPAWA BASIN

Waipawa River, on the eastern side of the Ruahine Range, is a major tributary of Tukituki River which flows into Hawkes Bay (Fig. 1). This study is based on only one small tributary, North Branch (Fig. 2) of the upper Waipawa River. However the findings of this work may be translated to Centre Branch and South Branch; and also to three major tributaries, Mangataura, Middle and Smith streams (Fig. 2).

The upper Waipawa Basin, and the Ruahine Range in general, is composed chiefly of Upper Jurassic alternating sandstones and argillites (Kingma, 1962; Te Punga, 1978) which are complexly folded and faulted.

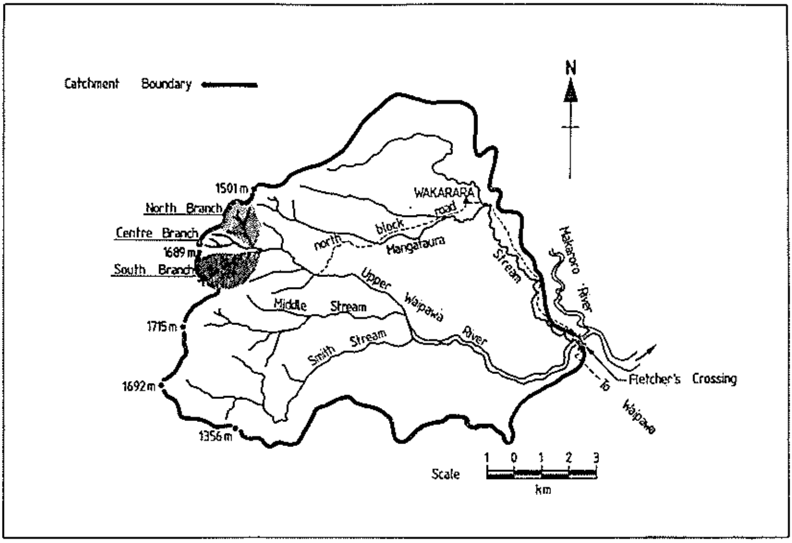

FIG. 2—Upper Waipawa River basin with its major tributaries.

Above an altitude of 1000 m, large areas of eroded rock constitute the main sources for coarse sediment in the channels. Eroded surfaces are classified as either "very active" or "slightly active". Very actively eroding areas are devoid of vegetation and have enlarged or degraded noticeably in recent times. Slightly active areas usually carry some vegetation and they have not changed perceptibly in recent decades. The areas of eroded surfaces are in Table 1 for the entire North Branch basin and for the Armstrong tributary of North Branch (Fig. 3).

At Glenwood raingauge, 640 m, (Fig. 3) the normal (1941-1970) annual rainfall is 2800 mm, at Waipawa Fork, 732 m, it is 3490 mm and at altitudes above 1000 m it is in the range 4000-5000 mm. Flood levels in the

TABLE 1—Areas of eroded surface after cyclone Alison, at May 1975, in the North Branch of the Upper Waipawa River Basin.

	Sediment Supply Area (ha)		Non-Supply Area (ha)		Total Eroded Surface (ha)
	Very active	Slightly active	Very active	Slightly active	
Entire North Branch	26.2	9.2	—	5.5	40.9
Armstrong tributary North Branch	16.3	—	—	—	16.3

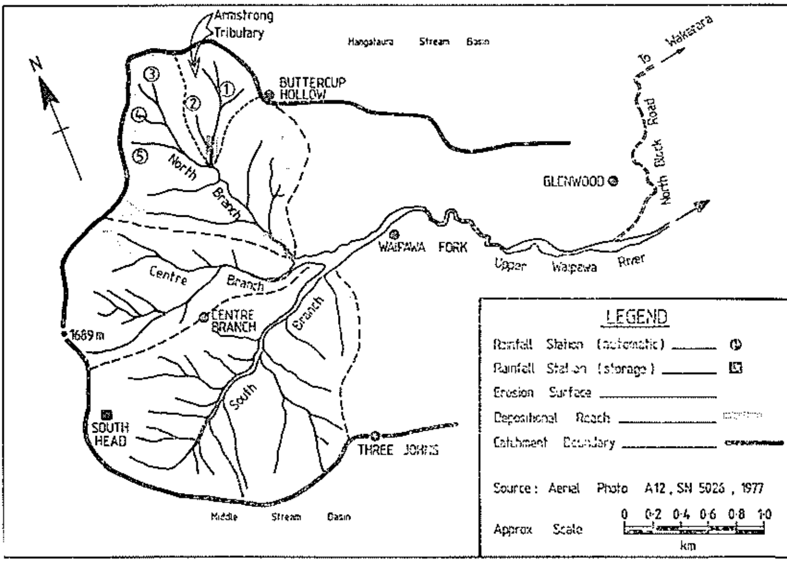

FIG. 3—Erosion surfaces in the three main branches of the Upper Waipawa River, some being numbered in North Branch, the depositional reaches of the main North Branch channel and Armstrong tributary, and rainfall station locations.

upper Waipawa River are measured at Fletcher's Crossing Bridge (Fig. 2.) Information on soils, vegetation, wild animals and channels has been presented by Grant (1977).

CYCLONE ALISON'S IMPACT

Tropical cyclone Alison travelled southwards to the west of New Zealand during 11-14 March 1975. Tomlinson (1975) provided a summary of the weather situation. Grant *et al* (1978) described the effects of Alison on the north-eastern Ruahine Range and included rainfall information for Glenwood and Waipawa Fork, the only raingauges operating in the upper Waipawa Basin (Fig. 3) at the time. By March 1978 automatic raingauges had been installed at Buttercup Hollow, 1310 m, Centre Branch, 1220 m, and Three Johns, 1417 m, and a storage raingauge at South Head, 1580 m, (Fig. 3). Because the major sediment sources in North Branch (Fig. 3) extend from about 1000 m to 1430 m, storm rainfalls at these higher altitudes should more closely represent the storm impact on eroded surfaces. Accordingly, the available reliable records from all raingauges were compared to estimate cyclone Alison rainfalls at higher altitudes. In brief, storm rainfalls may be 20-50% greater and long-term rainfall totals 15-40% greater at higher altitudes than that at Waipawa Fork. Maximum rainfalls recorded at Glenwood and Waipawa

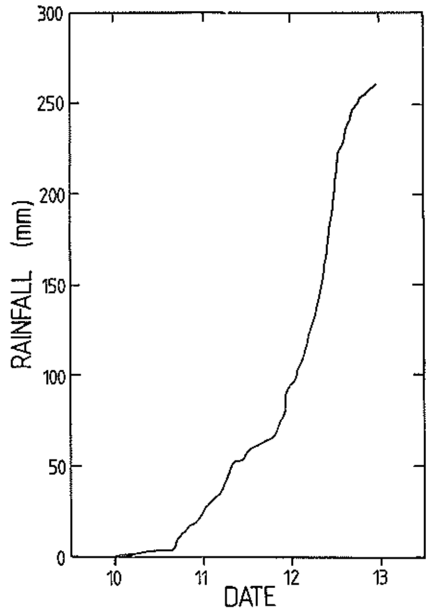

FIG. 4—Cumulative rainfall pattern at Glenwood during cyclone Alison of 10-12 March 1975.

Fork are given in Table 2 and the storm cumulative pattern at Glenwood is shown on Fig. 4. The total storm rainfall catch at Waipawa Fork was 44% higher than that at Glenwood. If at higher altitudes cyclone Alison rainfalls averaged 40% greater than those at Waipawa Fork then higher-altitude maximum rainfalls (Table 2) approximated 170 mm in 6 hours, 260 mm in 12 hours, 380 mm in 24 hours and 540 mm for the entire storm.

About 40 hours after rain began in the basin, when 148 mm had fallen at Glenwood, the heaviest sustained rainfall occurred producing 72 mm

TABLE 2—Maximum rainfall amount duration (mm) for durations between 12 minutes and 72 hours during cyclone Alison at Glenwood and Waipawa Fork.

	(min)			(hr)						
Station	12	18	30	1	2	6	12	24	148	72
Glenwood	6.1	8.1	12.6	21.2	34.3	85.9	130.3	187.9	238	265
Waipawa Fork*	—	—	—	31	49	124	188	271	343	382

* Recorded values have been adjusted owing to erratic gauge functioning.

in 4½ hours—an intensity of 16 mm/h. At Waipawa Fork, with 44% higher storm rainfall, about 105 mm fell in the 4½ hours; and at higher altitudes, again adopting a 40% increase above Waipawa Fork, about 150 mm probably fell in the same 4½ hours—an intensity of about 30 mm/h.

Comparison of aerial photographs taken before and after cyclone Alison (Survey No. 2800, 9 Feb 1975 and SN 2846, 8 May 1975) shows that the larger actively-eroding surfaces in North Branch (Table 1) had enlarged locally by a total of about 1 ha. For the entire North Branch the total actively-eroding surface increased from 25.2 to 26.2 ha, an increase of 4%. In the Armstrong tributary (Fig. 3) where all the eroding surface is very active it increased from 15.7 to 16.3 ha, an increase of 3.8%. It is certain that the heavy rainfalls of cyclone Alison during 11-12 March produced the recorded enlargement of eroded surfaces. Areas designated "slightly active" remained essentially the same in extent after Alison.

In North Branch the rock waste which contributes to the downstream coarse sediment load of Waipawa River originates from erosion of the regolith and the bedrock slopes, gullies and channels. Much of the regolith consists of up to 1 m of fine-grained matrix, apparently volcanic ash (Grant, 1977), containing weathered rock fragments. This material is vegetated. Elsewhere the regolith comprises old scree accumulations on slopes, to several metres thick, only parts of which are vegetated.

Erosion of the fine-grained regolith and exposed bedrock produces screes on slopes and accumulations of rock materials in rock gullies and channels. This erosion is active in the intervals between storms, in both summer and winter. Erosion of old scree material occurs by gullying only during heavy rainfalls, when erosion both of the fine-grained regolith and of the bedrock may also occur. During cyclone Alison scree erosion on erosion surface 5 enlarged the very active area by 0.4 ha. On surface 1 (Fig. 3) 0.6 ha of vegetated fine-grained regolith was destroyed, and some bedrock deeply gullied. The resulting materials, plus rock wastes which had accumulated since the last major storm on slopes and in gullies and channels, comprised the bulk of the sediment transported by cyclone Alison floodwaters. The largest proportion of the total coarse sediment supply came directly from bedrock.

SEDIMENT DEPOSITS

On two channel reaches of North Branch much of the transported bed load was deposited owing to reduction in hydraulic energy gradient: on the main North Branch channel immediately upstream of its confluence with Centre Branch (Fig. 3) and on the Armstrong tributary immediately upstream of a major right-angled confluence.

Main North Branch Channel

The remnant alluvial deposits of cyclone Alison in the main North Branch channel are shown in Fig. 5. The depositional reach, 300 m long, was surveyed and five cross-profiles were measured to calculate both total sediment volume and the volume of the deposit tranported further downstream. Coarser channel armouring material defines the base of the cyclone Alison deposits (Fig. 5). The average longitudinal slope of the alluvial surface (S=0.14) was markedly less than that of the channel bottom (S=0.16). The large volume of coarser bed material from the steeper (S=0.35) Centre Branch channel must have choked the channel and greatly enhanced the deposition of travelling bed load in North Branch. It is unlikely that all of the coarse sediment load from North Branch was deposited in this reach but the deposit is assumed to constitute a very high proportion of the total.

A large flood on 15 June 1975 transported down stream much material from the cyclone Alison deposits. Subsequently the reach changed little, as shown by photographs taken in March 1976 and January 1977 (Fig. 5), and by measurements and observations in February 1977 (Table 3) and April 1978, until 21 March 1979 when a medium-sized flood transported more of the deposits from the North Branch reach.

Armstrong tributary, North Branch

A depositional reach, 230 m long. (Fig. 3) was surveyed using six cross-

FIG. 5—Cyclone Alison deposits along the main channel of North Branch, looking upstream. The depositional surface remnant shown is 7 to 8 m above the coarser channel armouring material which defines the earlier stream bed level. This reach remained essentially the same until the flood of 21 March 1979. Photo taken January 1977.

TABLE 3—Area details, estimated volumes of Alison's channel deposits and derived sediment yield and denudation values for the North Branch of the Upper Waipawa Basin.

		Main North Branch	Armstrong tributary
1. Drainage area	(km^2)	1.60	0.297
2. Eroded surface area	(km^2)	0.409	0.163
3. Sediment supply area	(km^2)	0.354	0.163
4. Total alluvial deposit	(m^3)	44,400	5,700
5. Alluvium subsequently transported downstream	(m^3)	37,100	3,200
Percentage of total		84	56
6. Sediment yield from drainage area	(m^3/km^2)	27,750	19,190
7. Sediment yield from supply area	(m^3/km^2)	125,400	35,000
8. Denudation of drainage area	(mm)	28	19
9. Denudation of supply area	(mm)	125	35

profiles for the estimation of volumes. The upstream 75 m had an average channel slope of S=0.31 while the lower 155 m had a slope of S=0.22; the surface profile of the alluvial deposit essentially paralleled the channel slope. Consequently, backfilling must have been inefficient and depositional volumes do not represent the total storm yield because large quantities must have passed out of the reach during the flood. Nevertheless comparison of results with those from the main channel is of interest (Table 3).

Particle Sizes of Deposits

The Alison deposits along the main channel reach of North Branch were sampled using a grid-by-number surface sampling method in which only particles having a rolling (intermediate) diameter (d) greater than 8 mm were measured. Using the subscript of d (10, 25 etc) to show the percentage of particles smaller than d in the sediment population the deposit is characterised as follows: d_{10}=14 mm, d_{25}=19 mm, d_{50}=38 mm, d_{75}=283 mm and d_{90}=891 mm.

Particle size distribution is bimodal; a mode in the 8-20 mm range dominates the Alison alluvium and another in the 0.7 - 1 m range characterises the exposed channel armouring material (Fig. 5). The largest boulder observed in the channel bed had a rolling diameter of 2.7 m but the boulder's well-defined weathering rind indicated that it had not been transported far from its last lengthy resting place.

Particle sizes in Armstrong tributary were not measured but the overall pattern was similar—fine-grained Alison deposits, overlying a much coarser material in the channel bottom.

These deposits exclude much of the finer suspended sediment load which constitutes a considerable proportion of bed material in lowland river channels. The following discussion deals only with the coarse, or gravel, sediment yield.

SEDIMENT YIELDS, NORTH BRANCH

Areas supplying sediment directly to the North Branch drainage system (Table 1) are contiguous with channels or zones of concentrated drainage. Classification of eroded surfaces is based on aerial photo interpretation and field inspection.

Land areas given in Table 3 are map projection areas. They were determined by planimeter from 1:2000 scale maps with 5-m contours, showing the drainage network and boundaries of eroded surfaces. (Maps produced by Photogrammetric Branch, Lands and Survey Dept from aerial survey No. 2800 of Feb. 1975).

Areas supplying sediment represent 22% of the North Branch drainage area but 55% of the Armstrong tributary drainage area. Consequently larger specific sediment yields were expected from Armstrong tributary. However comparison of specific sediment yields for both drainage area and supply area (Table 3), suggests that much of the Alison alluvium in the Armstrong tributary passed out of the measured channel reach during the Alison flood. Therefore the Armstrong tributary sediment yield and denudation values are gross underestimates and are not used here.

In Armstrong tributary the 0.6 ha area of vegetated regolith which was eroded during cyclone Alison (assuming a thickness of 0.7 m) represents c. 4200 m^3 of sediment, the bulk of which would have been transported as suspended load.

In the main North Branch channel reach, the 44,400 m^3 (Table 3) estimated for the total deposit is assumed to represent the greater part of its coarse sediment yield during cyclone Alison, although it is a conservative estimate. The specific yield value of 27,750 m^3/km^2 also must be conservative. Over the North Branch drainage area average denudation depth both for a time preceding and during cyclone Alison was c. 28 mm.

From the conservative estimate of sediment yield from North Branch of c. 28,000 m^3/km^2 during cyclone Alison, if that flood can be allocated a return period, we can estimate the minimum average annual specific sediment yield from North Branch. It is a minimal value because it neglects the yields during floods of both greater and lesser magnitude, and the effects of storms prior to Alison in either preparing sediment for transport or flushing it out of the basin. Most of the coarse sediment yield of North Branch is supplied by bedrock erosion in Armstrong tributary, while much results from gullying of old scree material on eroded surface 5 (Fig. 3).

A series of annual maximum floods for the upper Waipawa River at Fletcher's Crossing bridge (Fig. 2) was compiled for the 24-year period January 1958 to April 1981 (Appendix 1). Between 1975 and 1982 three major sediment transporting floods occurred in the upper Waipawa, these were in March 1975 (12.56 m), March 1979 (12.45 m) and December 1980 (12.54 m). Each flood flushed most, or all, of the available coarse rock debris from North Branch. After Alison, March 1975, notwithstanding two floods >11.8 m (Fig. 6) of 12.00 m and 12.25 m, a large supply of loose rock debris was again available in North Branch in February 1976. Following another 12.00-m flood in September 1976 a large sediment supply persisted in February 1977, in April 1978 and until the March 1979 flood transported the bulk of it downstream. No observation of sediment supply was made prior to the December 1980 flood but afterwards little loose material remained (D. J. Hamilton, Hawkes Bay Catchment Board, pers comm). Aerial photos of March 1981 (SN 5943) show a small accumulation of loose debris in Armstrong tributary, and in April 1981 a 12.05-m flood occurred. By February 1982 a large supply of loose rock debris was available for fluid transport.

These observations suggest that floods up to c. 12.0 m transport little, if any, sediment, from North Branch, while floods greater than c. 12.4 m transport large quantities of sediment. Replacement of a loose sediment supply, mainly by bedrock erosion, takes place very quickly, e.g. in 11 months after Alison, and in a maximum of 14 months after the December 1980 flood with some replenishment occurring after three months. The available quantity of loose rock waste may be approximately proportional to the length of time of accumulation.

Prior to cyclone Alison the flood of March 1970 (12.41 m) was the most recent one likely to have flushed large quantities of sediment from North Branch, although a 12.26-m flood in April 1972 may have transported small quantities. However, even from 1972, the interval prior to Alison when no sediment-flushing floods occurred was nearly three years. This interval was more than adequate for the accumulation of a large supply of rock waste for transport by Alison floodwaters in March 1975. This situation is confirmed by aerial photos taken in February 1975 (SN 2800). Photos taken in May 1975 (SN 2846) show that not only was the loose rock accumulation flushed out of North Branch but that bedrock on eroded surface 1 and old scree on surface 5 were deeply gullied.

It cannot be said that the period prior to March 1975 tended to either over-supply or starve Alison of sediment. Beyond transporting loose rock waste, Alison generated sufficient power both to increase its sediment supply by erosion and to transport these large extra quantities from the basin. Similarly, prior to the largest recorded flood in March 1965 (12.85 m) which transported from North Branch greater quantities of sediment than Alison (see later), the interval back to the last major transporting flood, in June 1963 (12.51 m), was only 21 months. This suggests that a large proportion of its sediment load resulted, as in Alison, from erosion during the storm itself. Erosion during major storms may produce a total coarse sediment load which is a function of the storm intensity-duration characteristics. If so, the sediment load of Alison floodwaters was not biased by preceding events.

The flood magnitude of cyclone Alison has a recurrence interval of approximately 7.5 years (Fig. 6). The storm maximum rainfalls of 380 mm in 24 hours and 170 mm in 6 hours have respective return periods of c. 11 years and c. 7 years (Tomlinson, 1980). Because the expected time of travel of the flood peak to Fletcher's Crossing bridge would be nearer 6 hours than 24 hours the return period of c. 7 years is more applicable. Hence the flood-derived value of 7.5 years is adopted. When the sediment

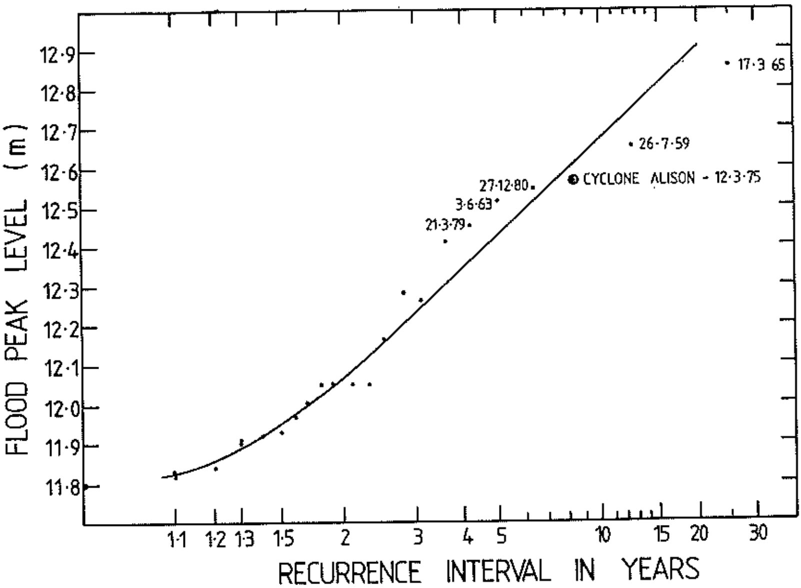

FIG. 6—Recurrence intervals of annual maximum floods of the Upper Waipawa River at Fletcher's Crossing bridge for the 24-year period 1958-1981 (on Gumbel probability paper).

yield value of c. 28,000 m^3/km^2 is divided by 7.5 we obtain c. 3700 $m^3\ km^{-2}\ a^{-1}$ which is the minimal estimate of the average annual coarse sediment yield from North Branch.

We may derive a more realistic value for average annual coarse sediment yield from North Branch by considering the three largest floods during the period 1958 to 1981 (Fig. 6). The flood of 17 March 1965 transported very large quantities of sediment, depositing them throughout the channel for at least 3 km down stream of the North Branch—Centre Branch confluence. This flood had the greatest single impact on channel morphology since the 1930s, and perhaps earlier. Some of its channel geometry changes have been noted by Grant (1977). In April 1965 the writer inspected the sediment supply areas of North Branch and climbed up the steep rock slopes of Armstrong tributary to its eastern divide; the rock slopes had been "washed clean" of nearly all loose rock. Recently the lateral remnant surface of the 1965 alluvial deposition on the surveyed reach of this tributary was identified by growth-ring counts of beech seedlings. The surface was consistently higher than that of the Alison deposits. The cross-sectional area of the 1965 deposits represents a volume 1.7 times that of the latter. This factor applied to the volume of Alison deposits (44,400 m^3) measured in the main North Branch produces a conservative yield of c. 47,000 m^3/km^2 (see later) for the flood of March 1965. When the two values of c. 28,000 m^3/km^2 and c. 47,000

m^3/km^2 for the 1975 and 1965 floods are plotted against their respective flood levels (Appendix 1) on semi-logarithmic paper a yield value of c. 33,000 m^3/km^2 can be interpolated for the flood of 26 July 1959. The sum of these three yields is c. 108,000 m^3/km^2 which when divided by 24 (period length in years) gives c. 4500 $m^3 km^{-2} a^{-1}$.

The minimum average annual specific sediment yield from North Branch calculated by dividing the derived 1965 flood yield of c. 47,000 m^3/km^2 by its flood recurrence interval of 17.5 years (Fig. 6) is c. 2,700 $m^3 km^{-2} a^{-1}$. This is considerably lower than the c. 3700 $m^3 km^{-2} a^{-1}$ determined from estimates of cyclone Alison deposits. Before the 1965 flood the Centre Branch channel near its confluence with North Branch (Fig. 3) was about 7 m lower than it was prior to cyclone Alison in 1975 (Grant, 1977). Consequently, 1965 sediments from North Branch did not accumulate appreciably immediately upstream of Centre Branch but instead were deposited, with those from Centre and South branches, to depths of 5-7 m down stream producing the greatest single impact on channel morphology for several decades. It is not possible to estimate the 1965 sediment yield from North Branch. From the cross-sectional area of aggradation (Grant, 1977: Fig. 14) of c. 370 m^2 downstream of the confluence of North and Centre branches a comparable aggraded reach c. 360 m long would store the estimated sediment yield from both branches of c. 47,000 m^3/km^2. Photo records show that this requirement was more than fulfilled. Therefore because the 1965 derived yield value of c. 47,000 m^3/km^2 is an underestimate, the average annual specific yield value of c. 4500 $m^3 km^{-2} a^{-1}$ is almost certainly very conservative.

To place the value of c. 4500 $m^3 km^{-2} a^{-1}$ in clearer perspective let us briefly consider the three floods which rank immediately below cyclone Alison (Fig. 6). The floods of December 1980 and March 1979 transported much sediment from Armstrong tributary and the June 1963 flood also transported much coarse sediment from supply areas. However all these quantities have been neglected in the estimate of a yield of c. 4500 $m^3 km^{-2} a^{-1}$ which must be a very conservative value.

SEDIMENT YIELDS, UPPER WAIPAWA

Field observations suggest that the coarse sediment yields from Centre Branch and South Branch (Fig. 3) are comparable with, if not greater than, that of North Branch. For this study a yield of c. 4500 $m^3 km^{-2} a^{-1}$ is assumed for all three branches of the upper Waipawa River.

To estimate coarse sediment yields from Middle Stream and Smith Stream basins (Fig. 2), their respective erosion surface areas were measured from maps produced by NZ Forest Service staff using aerial photos of 1966 (SN 1698), and each drainage area containing the major erosion surfaces was determined. These, along with the lumped data for North, Centre and South branches, are given in Table 4. For the latter the proportion of erosion surface area to drainage area is 0.34. This coefficient was calculated for Middle and Smith basins for each of which a sediment yield value was then derived from the product of 4500 $m^3 km^{-2} a^{-1}$ and the respective basin coefficient divided by 0.34. Similarly a sediment yield was derived for the headwaters of Mangataura Stream

TABLE 4—Preliminary estimates of average annual specific coarse sediment yields, and volumes, from basins of the Upper Waipawa River.

Basin	A Eroded Surface Area (km²)	B Coefficient A/D	C Estimated Sediment Yield ($m^3\ km^{-2}\ a^{-1}$)	D Drainage Area (km²)	C x D Sediment Volume (m^3/a)
North Branch)					
Centre Branch)	1.81	0.34	4,500	5.36	24,000
South Branch)					
Middle Stm	0.76	0.16	2,100	4.66	10,000
Smith Stm	1.23	0.24	3,200	5.23	17,000
Mangataura Stm	0.27	0.11	1,400	2.41	3,500
					54,500

(Fig. 2). Estimates of annual sediment yield for Middle, Smith and Mangataura basins (Table 4) are based on the ratio of eroded surface area to drainage area and extrapolation of the estimated sediment yield of North, Centre and South branches. Improvement of these estimates will depend not only on the availability of higher-standard mapping and more refined identification and classification of sediment sources, but also on consideration of differences of basin precipitation, channel slope and channel form.

The estimated average annual coarse sediment volumes supplied from the upper Waipawa sub-catchments total c. 55,000 m^3/a (Table 4). To estimate the total average annual yield of coarse sediment to the Waipawa River affecting the Ruataniwha Plains (Fig. 1) it is necessary to add to this value estimates for:

1. Those headwater areas, of the basins of Table 4, outside the severely eroded areas already considered.
2. The entire Makaroro River basin to the north of the upper Waipawa River (Fig. 2).
3. All basins to cover their downstream sediment source areas on greywacke—especially riparian sites.
4. Sediment supplied from channel deposits.

DISCUSSION

The bulk of the sediment supply of North Branch comes from exposed highly-shattered bedrock, by erosion both between storms and during major rainstorms such as Alison. Floods with a peak level below c. 12.0 m at Fletcher's Crossing bridge probably transport little, if any, sediment from North Branch; but floods >c. 12.4 m transport large quantities. The load transported during major storms may be a function of their rainfall intensity-duration patterns. During Alison the most intense sustained rainfall, c. 150 mm in 4½ hours, started about 40 hours after rain began.

Similarly, about 21 hours after the storm of 17 March 1965 commenced on the Kaweka Range, 60 km north, the most intense rainfall, 56 mm in 1½ hours, started and this was probably responsible for the transport of the large debris loads later observed in channels (Grant, 1969). A 3-year period, at least, prior to Alison was suitable for the accumulation of a large supply of loose rock waste and, as well as transporting this, Alison floodwater eroded much bedrock and some old scree material. Therefore there is no basis for believing that Alison transported significantly less than its potential. However, for other reasons outlined, the annual sediment yield estimate of c. 4500 $m^3 km^{-2} a^{-1}$ from North Branch, which represents its average annual erosion rate, is a very conservative value. Nevertheless it is valuable to compare it with other New Zealand data from geologically and physiographically similar regions (Table 5).

The upper Tukituki basin adjoins the upper Waipawa to the south (Fig. 1). Above Folgers Lake, where most of the sediment was estimated, the drainage area is 77 km^2, but if only the mountainland area of 45 km^2 is used it gives a yield of 4,800 $m^3 km^{-2}$-a^{-1}. However, comparison of the Waipawa and Tukituki yields will be valid only when a more accurate value is obtained for the upper Waipawa and when this is adjusted to the total mountainland drainage.

Comparison of the upper Waipawa sediment yield with available values from other regions (Table 5) is tentative because of the different estimation techniques used. However the data indicate that coarse sediment yields from the central Ruahine Range may be some of the highest, if

TABLE 5—Coarse sediment yields for some New Zealand basins in sandstone —argillite mountainland.

Region and Stream	Drainage Area (km^2)	Sediment Yield ($m^3 km^{-2} a^{-1}$)	Reference
Central Ruahines			
Upper Waipawa	1.6	>4,500	This study
Upper Tukituki	77	2,800	Report to Hawkes Bay Catchment Board; D. J. Hamilton, 16 June 1981
Southern Ruahines			
West Tamaki	11	2,500	)
No. 1	3.8	2,800	) Stephens, 1977
Raparapawai	8.4	2,300	)
8 basins	1.6-12 (West Tamaki and Raparapawai excluded)	av 2,000	Mosley, 1978
Tararuas, North Island			
Mangahao	81	1,600	Thompson, 1976
Otaki	—	1,100	Manawatu Catchment Board report, cited in Mosley, 1978
Seaward Kaikouras, South Island			
Floodgate	—	1,800	Thomson and Macarthur, cited in Pearce and O'Loughlin, 1978
Torlesse, South Island			
Torlesse	3.9	15	Hayward, 1979

not the highest, in New Zealand. They also far exceed available values for California, Japan, the Alps, Himalayas and Papua-New Guinea; but they are similar to Taiwan, 5500 m^2 km^{-2} a^{-1} (cited in Mosley, 1978).

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APPENDIX 1

Annual maximum floods for the Upper Waipawa River at Fletcher's Crossing Bridge, January 1958 - April 1981, with notes on their compilation and frequency analysis.

Year	Date	Flood Level (m)
1958	11 May	12.16
1959	26 Jul	12.65
1960	11 Dec	11.84
1961	28 Jun	11.93
1962	2 Dec	11.92
1963	3 Jun	12.51
1964	22 Jun	11.91
1965	17 Mar	12.85
1966	19 Jul	11.90
1967	4 Jun	11.83
1968	20 Jun	12.05
1969	25 Nov	12.05
1970	18 Mar	12.41
1971	4 May	12.05
1972	16 Apr	12.26
1973	14 Jun	12.18
1974	16 Jun	11.97
1975	12 Mar	12.56
1976	9 Sep	12.00
1977	16 Apr	11.82
1978	23 Jun	11.80
1979	21 Mar	12.45
1980	27 Dec	12.54
1981	14 Apr	12.05

Flood Compilation: Flood levels were recorded from 1 Aug 1974 to 13 Dec 1979 by Foxboro pressure bulb recorder and subsequent flood records were obtained manually. For the period 1958* to July 1974 flood levels were derived from Glenwood rainfalls using a regression relation, based on 1974-79 records, which links flood peak level to the corresponding wettest rainday at Glenwood. Where Y is peak flood level (m) at Fletcher's Crossing** and X is the Glenwood wettest day (mm) the relation determined is:

$$Y = 0.007\,X + 11.38$$
$$Se = 0.24\text{ m}$$

$r = 0.69$ ($p < 0.01$)

For 1958-81 the 50 largest flood peaks were compiled and from these the accompanying 24-yr annual flood series was extracted.

*1958 was the first complete record year at Glenwood.
**No major mean bed level change has occurred at the bridge from 1958 to 1981 (Grant, 1977).

Flood Frequency: The annual flood series was analysed using the formula of the US Geological Survey (Dalrymple, 1960):

$$T = \frac{n + 1}{m}$$

where

T=recurrence interval in years
n=number of years of rcord
m=magnitude of flood, the highest being 1

Results are presented in Fig 6.