HIGH COUNTRY RIVER PROCESSES

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HIGH COUNTRY RIVER PROCESSES:

A technical discussion of results from research on the Kowai River system, Springfield, Canterbury.

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PREFACE

The wise management of land and water resources requires as a basis a sound understanding of the landscape processes which act to modify these resources. Of particular significance are processes affecting the movement of solid material into, along and out of the steep streams and rivers common in this country. At present our understanding of these processes is meagre, a state of affairs which is reflected in the lack of success of some attempts at river management, particularly when considered in the long term.

In the apparently complex environment of steep streams, it is extremely difficult to make measurements of the relevant variables, or even to decide which variables are relevant, let alone to interpret these measurements in terms of processes. It is, therefore, a major achievement of the authors of this report to be able to present a substantial body of data describing the sediment characteristics of present and past streams. They have further used this data as a basis for inferring the processes acting in steep streams; inferences which reflect their own very intimate involvement with the Torlesse/Kowai system, consisting of innumerable long and hard days (and nights) living with the river. Their willingness to put forward these propositions is wholly admirable, since sustained discussion seems likely to result, and it is through discussions such as this that further ideas are generated and tested and scientific progress is made.

This report thus constitutes a most valuable and timely discussion document which will serve to focus the attention of scientists, engineers and land managers on the problems of high country river processes.

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18 November 1981

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Mr J. Kennard, Professor K.F. O'Connor and Dr M.P. Mosley read and made comments on drafts of the work at various stages but special thanks must go to Dr T. Davies for his detailed criticism of the final manuscripts. The authors, however, remain responsible for the material contained herein.

Thanks go also to Miss P. Prendergast who drafted many of the figures, and to Mrs N. Thompson and Mrs O. Cattanach who typed numerous draft versions of the work as well as the final manuscript.

Gratitude is expressed to Mr and Mrs M. Milliken of Brooksdale Station and Mr and Mrs R.F. James of Benmore Station for their continuing patience and tolerance in allowing access to their properties and for the interesting and valuable discussions we have had with these people. Mr L. Milliken of Brooksdale Station was able to give particularly useful advice on the history of pastoralism in the Kowai catchment earlier in the century.

Finally, further thanks must go to Professor K.F. O'Connor former Director of the Tussock Grasslands and Mountain Lands Institute for his support during the course of this study, and who was able to approve the publication of this material shortly before his retirement from the post of Director of the Institute.

INTRODUCTION

AN OUTLINE

A sub-catchment (Torlesse Stream) of the Kowai River, Canterbury, has been the site of an interdisciplinary study of the relationships between erosion and stream sedimentation (Hayward 1975). It was logical to extend the stream sediment investigation of that study (Hayward 1978) into the Kowai system proper in order to establish changes in the nature and distribution of the stream sediments with distance downstream.

The sediment sampling study, comprising Part I of Paper A in this volume, analyses the changes in size, distribution, form and rock type of the river gravels from a headwater mountain stream to the wide braided river beds of the middle reaches of the Kowai River. Part 2 of Paper A discusses the possible implications for the management that these sediment studies have for this and other similar river systems. It is believed that, if thought necessary, it is possible to design a river training programme to guide the river towards a more manageable pattern.

Paper B of this volume compares the results of the present river gravel survey with those from a sedimentological analysis of fluvio-glacial outwash gravels deposited several thousand years ago within the lower reaches of the Kowai system. This comparative study is used to indicate differences in the hydrologic environment prevailing at their respective times of deposition, and aids in our understanding of the processes at work in hill and high country rivers today.

Both Papers A and B relate to the Kowai River system, but the authors wish to emphasise that the findings from these studies are believed to have application to other similar gravel bed river systems.

ENVIRONMENTAL BACKGROUND

LOCATION AND LANDFORM:

The study area lies on the eastern flank of the Torlesse Range, in the vicinity of Mt Torlesse (1963 m), Castle Peak (1998 m) and Foggy Peak (1734 m), approximately 80 kilometres to the west of Christchurch city. It covers the upper to middle reaches of the Kowai River (Figure 1). Figure 2 shows the geographical setting of the river systems and gives an indication of the large volumes of gravel transported by the Kowai River into the Waimakariri River.

The drainage pattern is essentially dendritic,with some sections of the major drainage channel being structurally controlled by major SW-NE trending faults. The principal drainage channel, the Kowai River, drains eastward to the Waimakariri River, decreasing in altitude from 1068 m above sea level in its headwater region to 366 m at its junction with the Waimakariri River, a distance of approximately 30 kilometres (Figure 3).

The wide variation in altitude,and hence climate, provides,a range of plant habitats, resulting in a rich and varied flora. The two most important physiognomic vegetation types are beech forest and scrubby fescue tussock grassland. The remainder of the area is occupied by high altitude grassland, scrub, bog, eroding subsoil, rock scree,and bedrock. Hayward (1967),for the greater Waimakariri catchments, lists as a percentage of the total land area: grasslands 40%; scrublands 5%; forest 30%; bare rock, scree and fell-field 20%; and river bed and lakes 5%.

BASEMENT GEOLOGY:

The basement rocks characteristically consist of a structurally complex suite of "greywacke" sandstone, siltstone and argillite with minor conglomerate, chert and spilite, belonging to the "Torlesse Supergroup" (Carboniferous - Lower Cretaceous). Andrews (1974) describes in detail the geology of Torlesse Supergroup sediments from a nearby area. The rocks are of low metamorphic rank. Complex folding, faulting and resultant jointing have produced an intensely fractured and veined bedrock that is particularly susceptible to weathering and erosion (Blair 1972). The "Torlesse" sediments have had a complex history and were last uplifted to form the great bulk of the Southern Alps and adjacent ranges during the "Kaikoura Orogeny", a mountain building episode which may still be continuing,but which was at its peak about two million years ago.

GLACIAL GEOLOGY:

Gage (1977) lists the five distinct episodes of Late Pleistocene glacial advances which took place in the Waimakariri valley, the first occurring soon after the climax of the Kaikoura Orogeny,with the last event ending some 13,500 years ago. The separate glaciations were distinguished by differences in the elevation, surface gradients, distribution, weathering,and extent of defacement of landscape elements (terraces, moraines). Definitive dating of these glacial events is not yet possible.

The same five episodes can be recognised in the Kowai valley, specifically by means of sequences of outwash surfaces and river terraces along the Kowai River. Numerous examples of glacial landforms including moraines, kame terraces, and outwash surfaces are found within the upper Kowai River catchment. Marden (1976) describes these landforms in more detail.

LAND USE;

For much of the history of European settlement in the area, extensive pastoralism has been the dominant land use over much of the catchment, with semi-extensive pastoralism on the lower altitude river flats. More intensive farming has characterised the lower reaches of the catchment(in the vicinity of Springfield township), especially in the last three decades. Under a soil and water conservation plan administered by the North Canterbury Catchment Board, a large portion of the higher altitude areas of the catchment (above approximately 1000 m) was retired from sheep grazing between 1971 and 1975. Even before this time more intensive development was taking place on the lower altitude hills and river flats, and semi-intensive pastoral farming now dominates those areas. Of particular relevance to the riparian zone of this watershed has been the three-fold increase in cattle numbers within the major part of the catchment, between the years 1965 and 1978. (TGMLI unpublished data).

CLIMATE:

Hayward (1967) presents climatic data recorded in, and adjacent to, the Kowai River catchment. The climate of the greater Waimakariri catchment is dominated by prevailing winds from the west and north-west, which create a rainshadow effect for those areas lying to the east of the Southern Alps. Typically for Fohn winds, the westerlies become increasingly warm and dry with distance to the east, and the Kowai catchment receives less thantenth of the north-west precipitation falling on the most westerly regions of the Waimakariri catchment.

The Kowai catchment's average annual preciptation, about 1,000 mm, is derived mainly from easterly or southerly storms,and moderate to high rainfall intensities of long duration are fairly common for such events. Snowfall becomes significant as a component of annual precipitation above 1500 m, where it constitutes about 30% of overall precipitation. Above 1500 m, snow cover persists from May through to November, but because of the effect of the westerly winds only short term cover occurs at mid to low altitudes

The proximity of mountain ranges means that diurnal variations in temperature may be quite large, and frosts may occur in any month, climatic conditions becoming more rigorous with altitude. For a site to the west of the catchment, at an altitude of 900 m, average temperatures are indicated (Hayward 1967) as being 12.5 - 13.0°C for December/February, and 0.5 - 2.0°C for June/August.

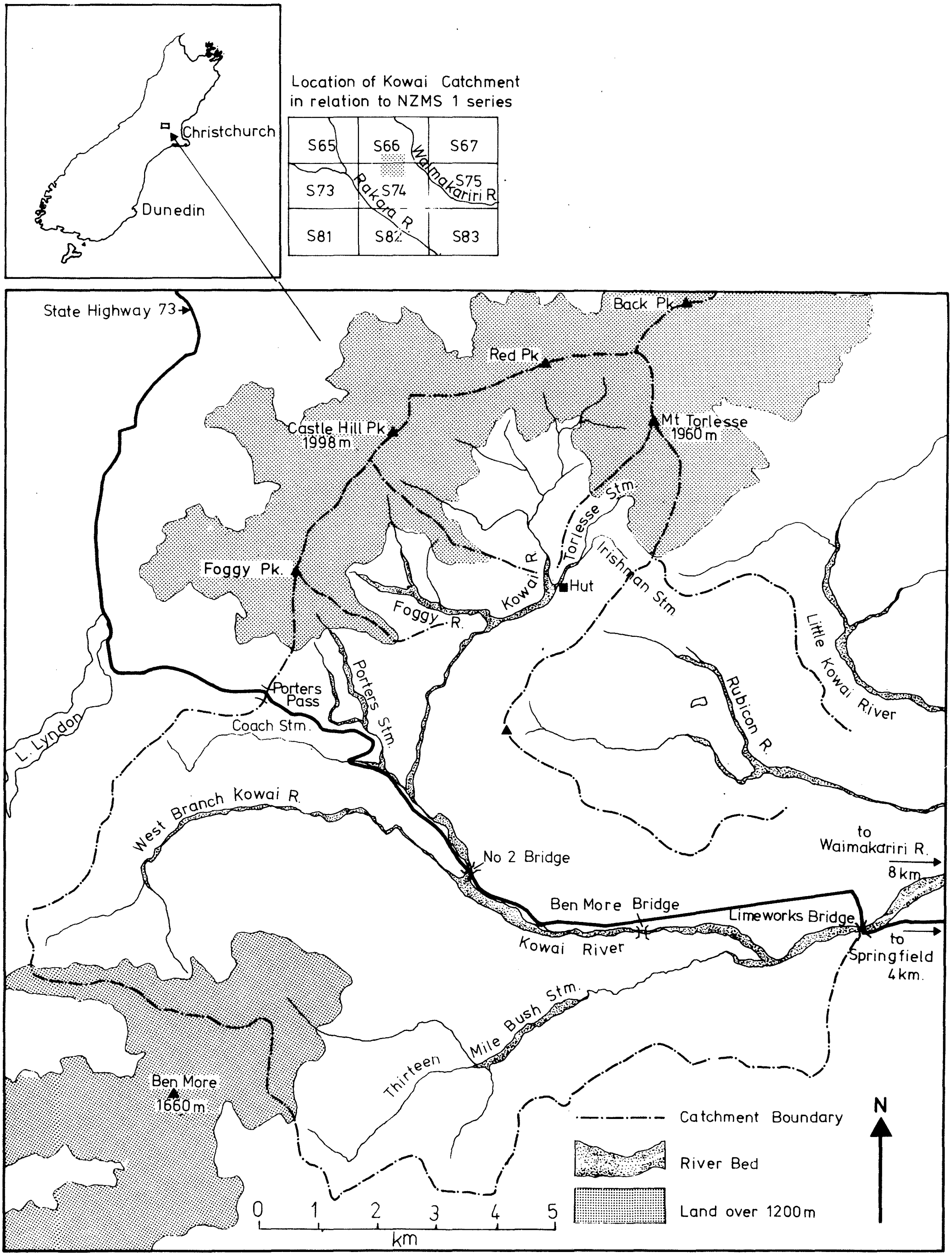

Figure 1: Location map of Kowai River catchment.

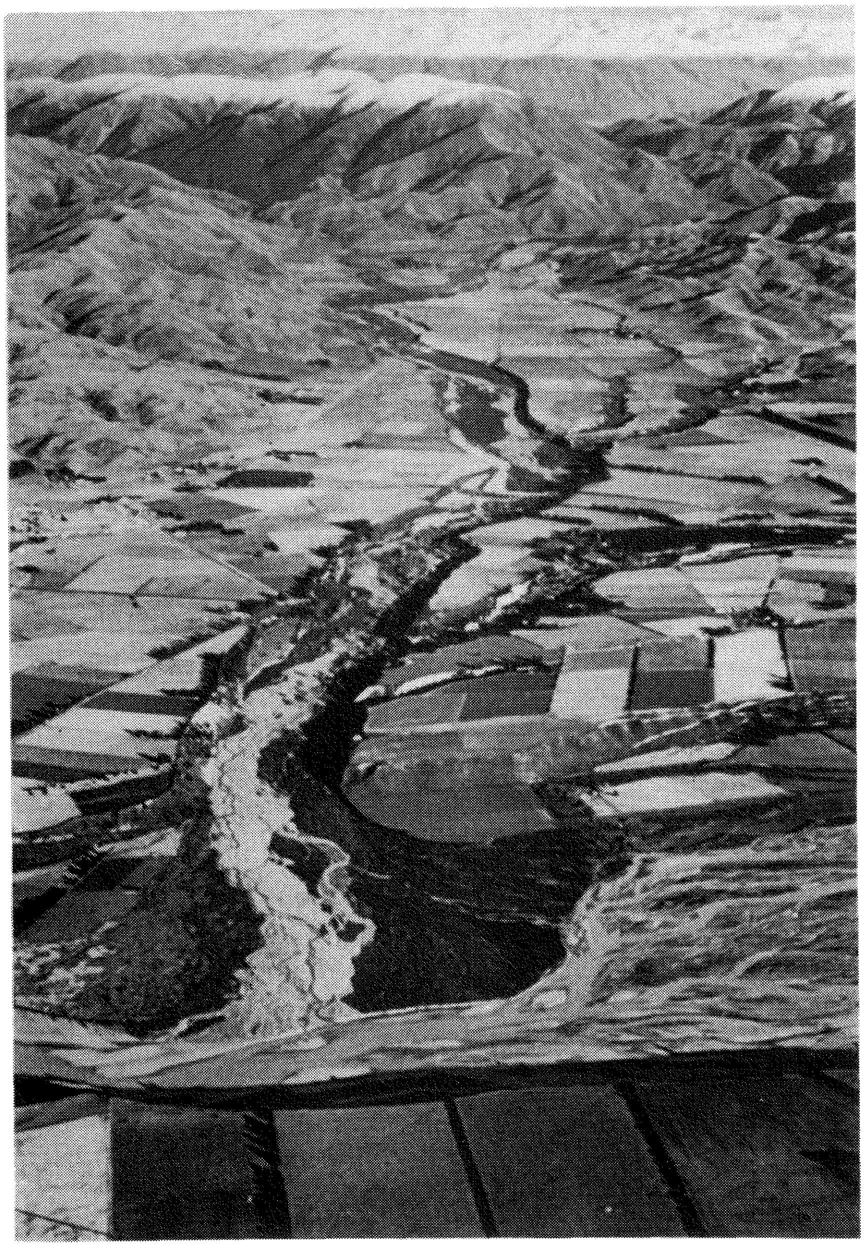

Figure 2: Geographic setting of Kowai River catchment, with confluence with Waimakariri River in immediate foreground indicating the quantity of debris being transported by the Kowai system.

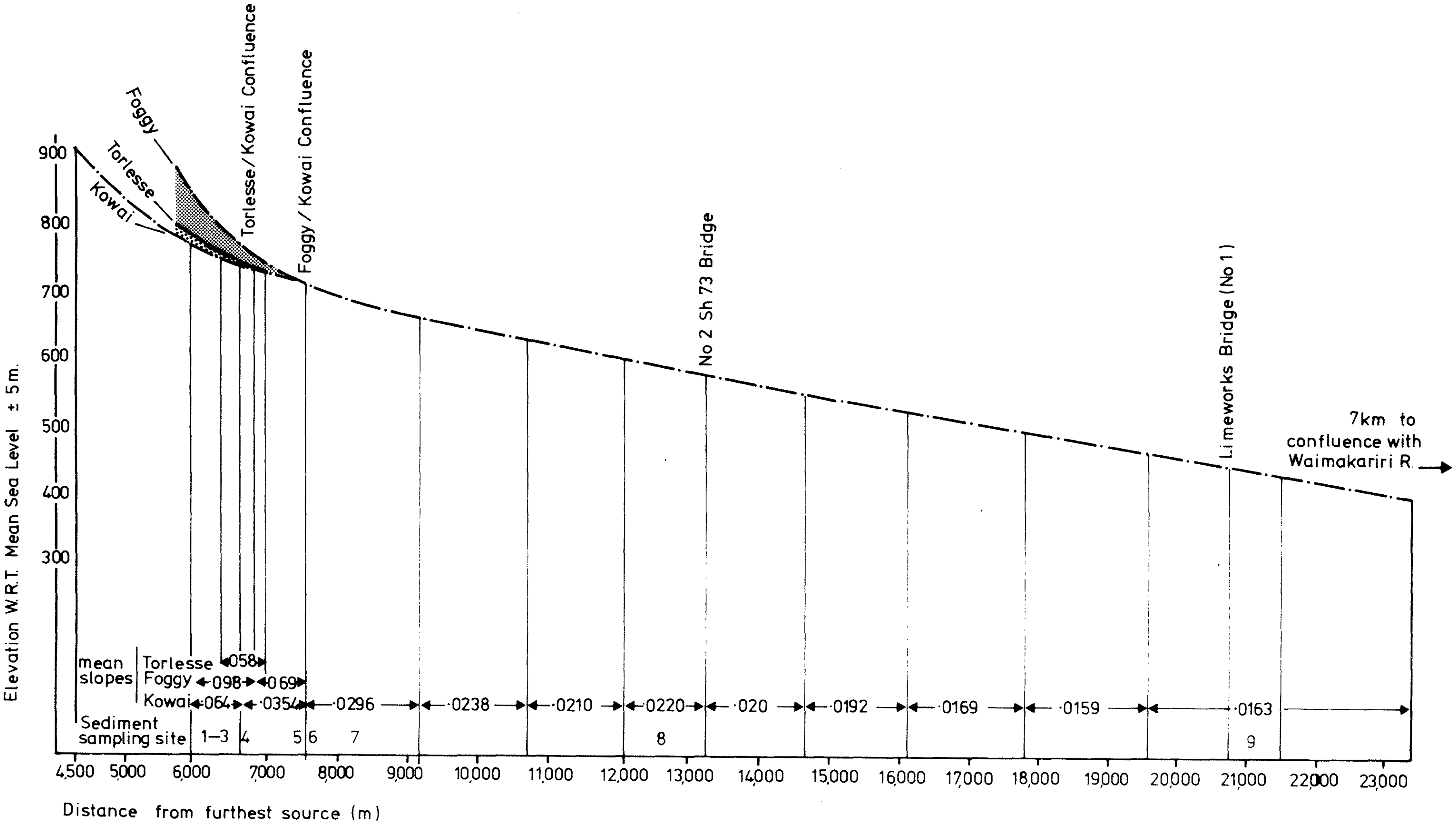

Figure 3: Profile plan of the Kowai River and upper catchment tributaries showing average stream slopes for defined reaches of riverbed.

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PAPER A

R.J. BLAKELY/P. ACKROYD

THE BEHAVIOUR OF THE KOWAI RIVER SYSTEM

Part 1: Characteristics of the present
Kowai River gravels

Part 2: Some implications for river management

PART 1: CHARACTERISTICS OF THE PRESENT KOWAI RIVER GRAVELS

1. INTRODUCTION

As stated in the summary to this volume, Part 1 is an investigation of sediment size distribution and textural changes over much of the length of the Kowai River. The nine separate sites sampled for Part 1 cover the complete range of channel forms found in the Kowai catchment, from headwater mountain streams to the wide, mobile, braided riverbeds of lower elevations.

It is visually evident that in this river system there are marked changes in bed morphology and sediment properties over the length of the system. A comprehensive sediment sampling programme was expected to establish the nature of these evident changes.

In order to clarify the relationship between bed morphology and sediment properties, it was thought necessary to carry out a two-fold sampling programme aimed at establishing the most reasonable measure of sediment properties within definable reaches of riverbed. The two methods of sediment sampling are compared and contrasted in the course of this investigation and the potential and limitations of each discussed.

2. AIMS OF THE STUDY

The first objective of this paper is to compare the sediment size parameters obtained by the two different methods at each site: firstly, sampling the gravels on the surface layer only, using a line transect method (Wolman 1954), and secondly, sampling the gravels by taking a bulk sample of the top 0.5 m of river bed at several sites at the same location. Section 4 describes these methods more fully. From these results it is proposed to show the suitability of each method for its end use: process studies for research purposes, gravel resource surveys for civil engineering works, or river engineering data requirements for catchment board works.

The second objective is to study the overall changes in sediment size distribution, sediment shape and rock type, as the gravels move downstream from a relatively confined, stable headwater channel to the wider, more unstable river beds of the lower reaches.

It is not suggested that these are the only methods, or the best ones available, nor is it suggested that the results obtained are typical of all river systems elsewhere. However, some of the basic principles of fluvial transport are well illustrated in this relatively undisturbed high country river.

3. CHANNEL SEDIMENTS AND BED MORPHOLOGY

SOURCE OF BED MATERIAL:

The bulk of the gravels sampled were derived from within the Kowai and tributary valleys. Possibly minor amounts of material may have been transported into the Kowai catchment from the Rakaia during glacial episodes. They comprise a mixture of reworked gravels, deposited during past glaciations, and recent debris from the present cycle of headwater gullying and undercutting of valley sides and screes. Within the study area a combination of factors, including high intensity rainfall periods and steepness of valley slopes, as well as the erodible nature of the bedrock, has produced numerous source areas from which gravel is being derived.

PRESENT CHANNEL MORPHOLOGY

A photographic depiction of the sampling sites is given as Figures 4.1 to 4.6. As these figures show, present riverbed morphology varies considerably from sites 1 to 9. Sites 1 to 4 are located in the headwater reaches, with sites 5 to 9 covering the middle and lower reaches of the system. (The location of the sampling sites within the system is shown in Figures 3, 6 and 7). In the upper reaches (Figures 4.1 and 4.2), the channel width is confined and generally consists of a single thread channel, 1-2 metres in width, between well vegetated banks. Areas of active bank and hill slope erosion may occur, and during flood flows large quantities of gravel may be transported with a minimum of alteration to bed morphology. Large rounded boulders, up to 3 m in diameter, often form small waterfalls and cataracts as part of a well ordered pool and riffle system of the sort described by Leopold et al (1964). Flood terraces composed mainly of finer gravels occur approximately 1-2 m above the channel in areas where the river has taken wider sweeps to form bays. This confined and stable channel is typical of sites 1-4, with the exception of site 2 which has more changeable bed morphology. Site 2 is located on a tributary of the Torlesse stream having greater inputs of sediment than other parts of the Torlesse system due to the occurrence of several active source areas of erosion.

Below site 4 (Figure 4.2) the Torlesse stream flows into the Kowai River proper. At this point a discontinuity in sediment characteristics occurs, since a small

Figure 4.1: Part of Torlesse Stream catchment with Torlesse/Kowai confluence in distant foreground, Irishman Stream in foreground with Torlesse Stream (partly obscured) to right. Locations of sediment sampling sites are indicated.

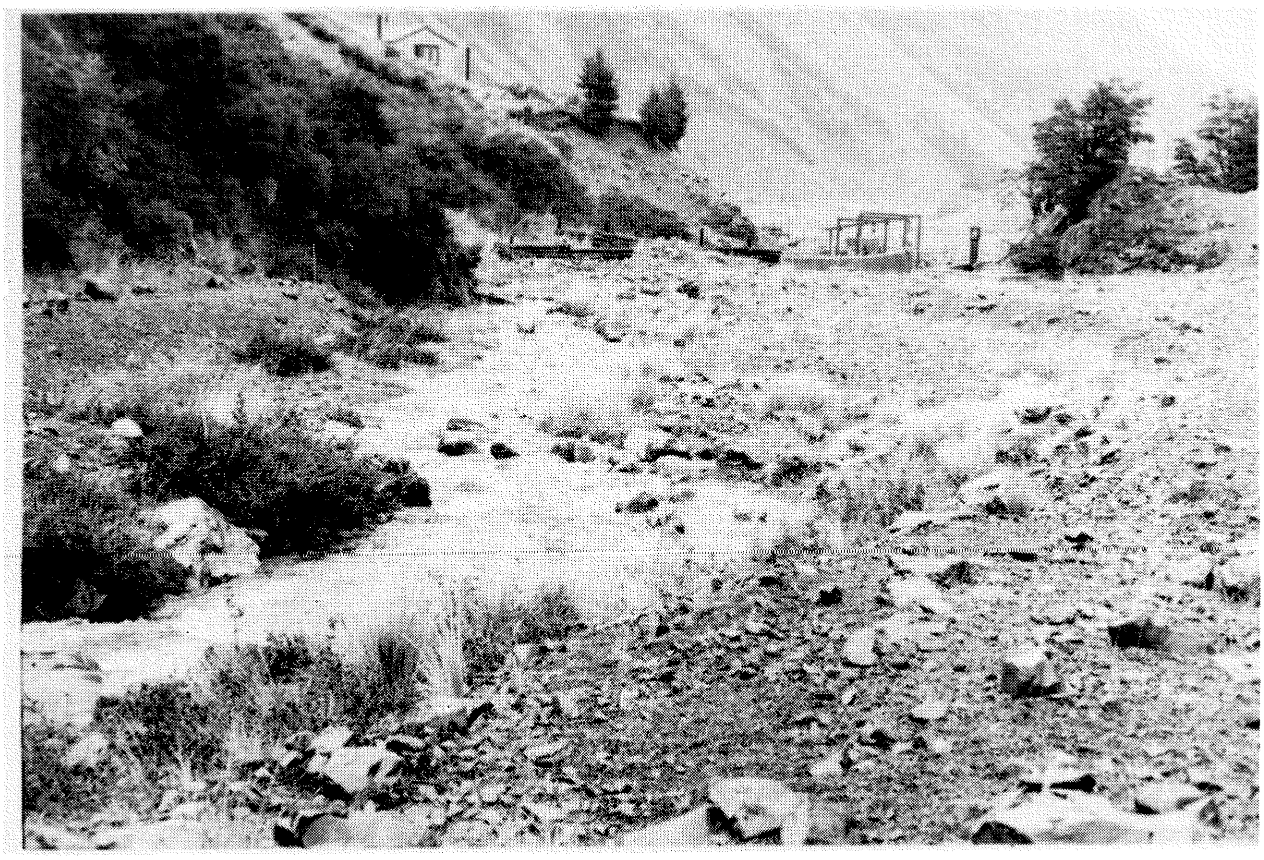


Figure 4.2: Torlesse Stream at bed-load sampling site, immediately upstream of confluence with Kowai River – sediment sampling site 4.

Figure 4.3: Kowai River below confluence with Torlesse Stream and looking downstream to confluence with Foggy River – sediment sampling site 5.

Figure 4.4: Foggy River showing the extensive fan development at the Foggy/Kowai confluence. Kowai (out of view) flows right to left across bottom of photograph – sediment sampling site 6.

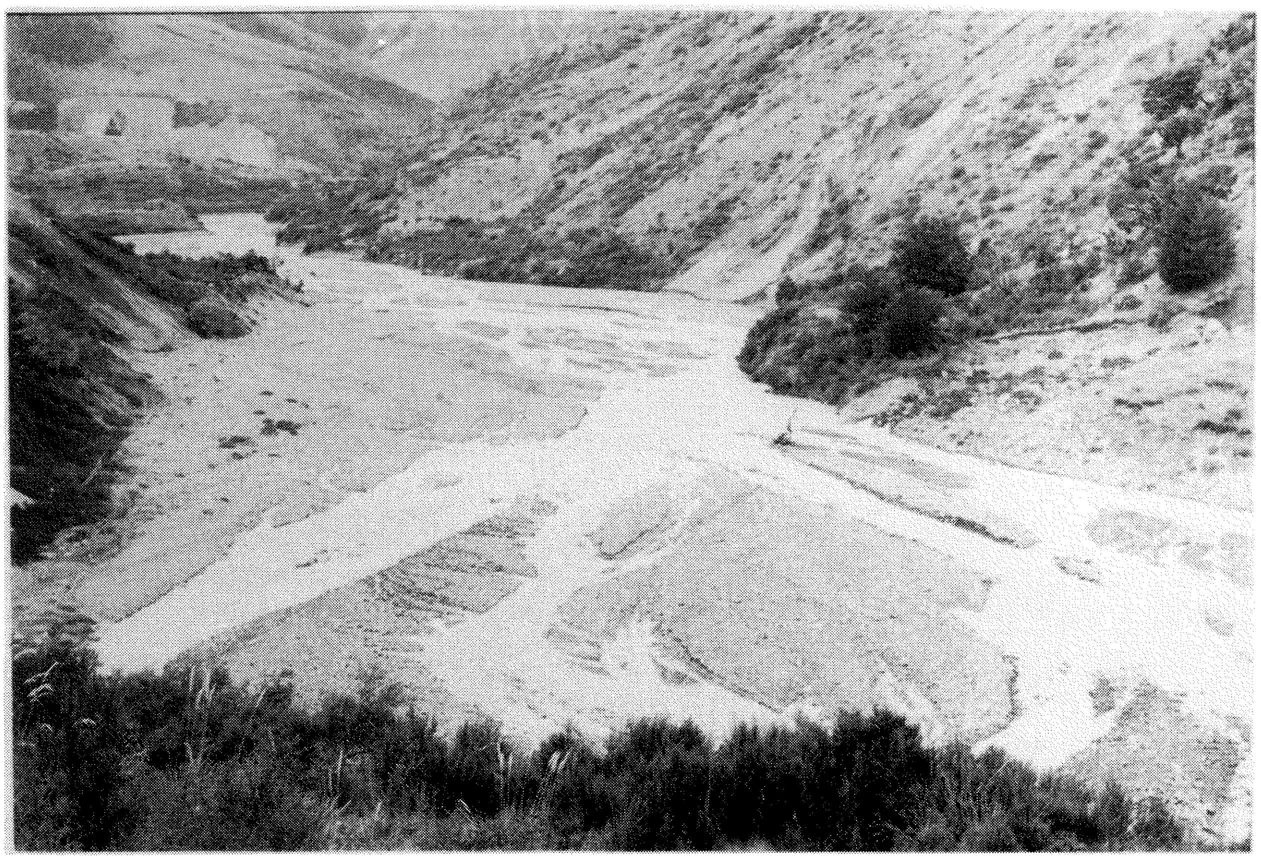


Figure 4.5: Kowai River, looking upstream to Foggy/Kowai confluence, exhibiting typical braided river characteristics – sediment sampling site 7.

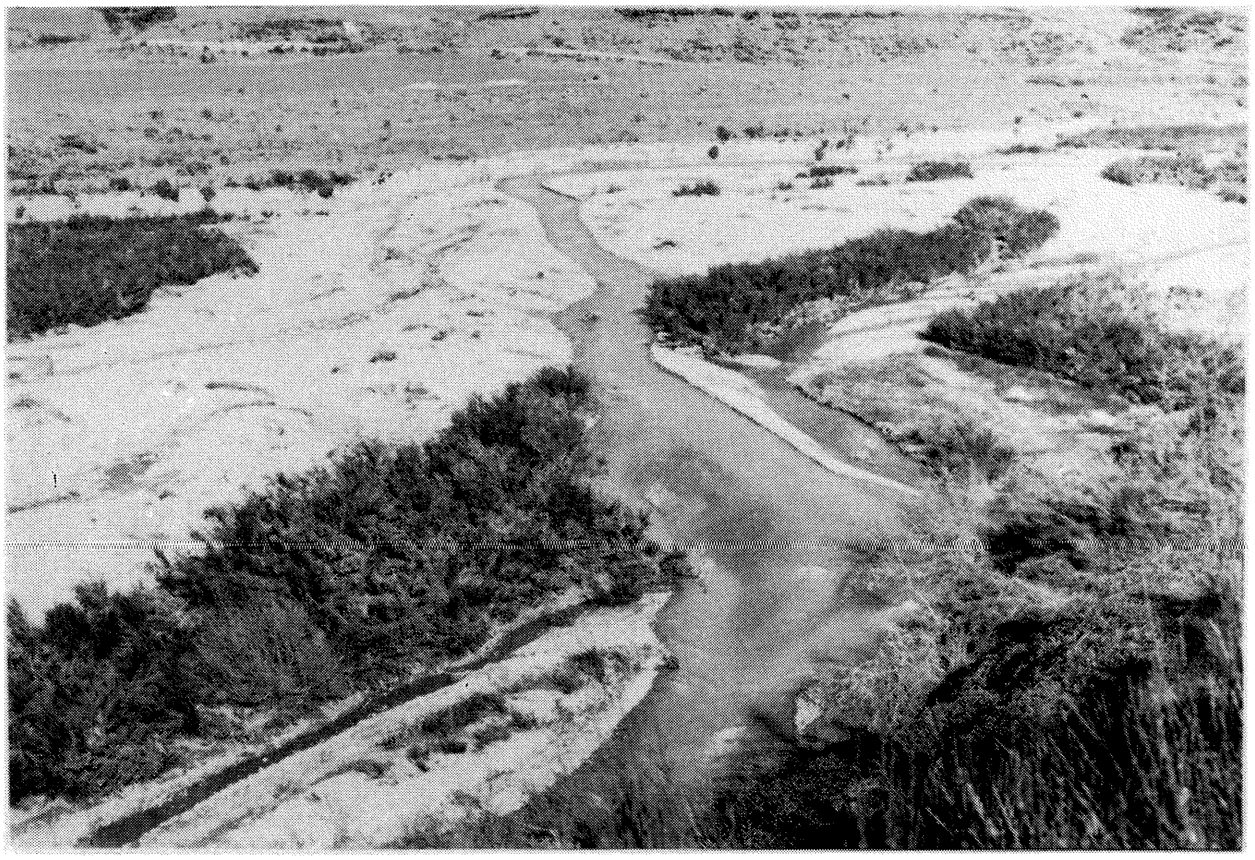


Figure 4.6: Kowai River near Ben More bridge with bed forms typical of sediment sampling sites 8 and 9. Note the actively eroding riparian terrace on far bank and the presence of semi-permanent islands within the riverbed.

tributary flows into the much larger Kowai River. The nature of this discontinuity will become apparent in section 5. At site 5 the active bed of the river is already much wider (up to 60 m) with the river capable of working most of this width during major floods. In this reach, the bed consists of more rounded boulders, up to 1 m in diameter, interspersed with finer angular gravels. The river channel itself consists of a series of pools and riffles, but this pattern is less ordered and less distinct than that observed in the upper reaches.

Although sites 5, 6, 7, 8 and 9 are located on the middle and lower reaches of the system, site 5 (Figure 4.3) can be considered a transitional channel pattern between the 'mountain stream' of the upper reaches and the 'braided riverbed' of the lower reaches. Essentially it is a pool-riffle channel system which, when overloaded with gravel, becomes temporarily braided. An important factor in this braiding process is the sediment supply rate from upstream sources.

Further downstream (sites 6, 7, 8 and 9), the riverbed becomes even wider (up to 150 m) and is a typical braided river. Here the channel pattern can change frequently (monthly), with flood flows spreading into many channels and covering most of the riverbed. A pool-riffle pattern of sorts is still discernible in the stream channel, but it is of a more transient nature than was the case for the Torlesse stream. The larger boulders tend to be buried by the finer gravel sizes. The river in the lower reaches is still actively eroding its banks, these mainly being composed of old river terrace gravels, while 'gorge' reaches of river appear related to bedrock controls.

Site 6 (Figure 4.4) is an active gravel fan. The erosion of large volumes of gravel stored in terraces upstream from this site leads to the frequent passage of gravel waves through this reach, so maintaining the gravel fan. Sites 7, 8 and 9 (Figures 4.5 and 4.6) show the progressive development of the braided riverbed with distance downstream, details of which have been discussed above.

Changes in the channel morphology from sites 1-9 are associated with the changes in sediment regime downstream, as will be described in following sections.

4. SAMPLING METHODS

Both studies utilize the phi (Ø) scale devised by Krumbein (1934), a logarithmic scale to the base 2. Figure 5, adapted from Folk (1968) shows the relationship between the phi size classes, the size in millimetres, and Wentworth's (1922) size classes. The broad division into the lithotypes of gravel, sand, and mud is also indicated. As stated by Folk, the phi scale "... is a much more convenient way of presenting data than if the values are expressed in millimetres ...", though for these studies the millimetre equivalents of the phi units are usually indicated.

THE LINE TRANSECT METHOD

Five line transects were measured across the present active river bed at each of the nine sites along the Kowai River system. The lines were spaced to span at least five pool-riffle cycles covering a reach of river at least 200 m in length. Each line traversed the present active surface and a gravel terrace surface approximately 0.5 m to 1.0 m high, related to a major storm event in April 1951 (probably having a return period of at least 50 years). Point sampling of riverbed gravel was carried out at set intervals along each line, with the parameters of each particle 'struck' being recorded. It is impracticable to record the parameters of particles smaller than 8 mm, and any such material was recorded as a 'fine gravel' count and included as such in the total sample count. At all sites sampled in this study the fine gravel count was about 30% of the total sample count. The method used is essentially the same as outlined by Wolman (1954).

After experimenting with different distances between sample points along any one line transect, it was decided to sample particles at 0.5 m intervals along four of the transects whilst the fifth line was sampled at 0.2 m intervals. Only in this way could consistently repeatable results be obtained. The 0.2 m spacing appeared to sample more accurately over a small area of river bed, thus giving detailed variations, but the 0.5 m spacing made it possible to sample the larger areas of river bed necessary to cover the full range of bed forms present at each site.

A minimum of 200 particles greater than -3.0ϕ (8 mm) were sampled at each site. These were taken from the surface layer only (top 20 cm or depth of largest particle). This number was found by experiment to give repeatable results with less than a 5% error in the size distribution. The number of particles necessary for this level of sampling accuracy will obviously vary with each river, but in general a minimum of 200 particles will be sufficient for rivers such as the Kowai, where particles range in size from silt to boulders over 2 metres in diameter.

THE BULK SAMPLING METHOD

At sites 5, 6, 7, 8 and 9 bulk samples were taken. At each site, three 5-gallon drums were partly filled with gravel by collapsing an exposed face into the drums.

Millimeters	Phi (Ø)	Wentworth Size Class	
4096	-12		GRAVEL
1024	-10	Boulder (-8 to -12Ø)	
256	- 8		
64	- 6	Cobble (-6 to -8Ø)	
16	- 4	Pebble (-2 to -6Ø)	
4	- 2		
3.36	-1.75		
2.83	-1.5	Granule	
2.38	-1.25		
2.00	-1.0		
1.68	-0.75		SAND
1.41	-0.5	Very coarse sand	
1.19	-0.25		
1.00	0.0		
0.84	0.25		
0.71	0.5	Coarse sand	
0.59	0.75		
0.50	1.0		
0.42	1.25		
0.35	1.5	Medium sand	
0.30	1.75		
0.25	2.0		
0.210	2.25		
0.177	2.5	Fine sand	
0.149	2.75		
0.125	3.0		
0.105	3.25		
0.088	3.5	Very find sand	
0.074	3.75		
0.0625	4.0		
0.053	4.25		MUD
0.044	4.5	Coarse silt	
0.037	4.75		
0.031	5.0		
0.0156	6.0	Medium silt	
0.0078	7.0	Fine silt	
0.0039	8.0	Very fine silt	
0.0020	9.0		
0.00098	10.0		
0.00049	11.0	Clay	
0.00024	12.0		
0.00012	13.0		
0.00006	14.0		

Figure 5: Phi scale of grain size and Wentworth's size classes (adapted from Folk 1968).

Most of the parameters determined are shown in Figures 6 and 7. Table 1 lists the measures of average size as determined by each sampling method, whilst statistical parameters relating to the size distribution are detailed below:

Mode: The most frequently occurring particle diameter, determined from percentage frequency histograms. A sediment size distribution can be uni- or multi-modal, in the latter case at least one secondary mode will occur.

Median: The size at which 50% of the particles are larger and 50% of the particles are smaller: the 50th percentile.

$$Md = \emptyset 50$$

Mean: Folk's term is Graphic Mean (Mz), and corresponds to the overall size of the sediment.

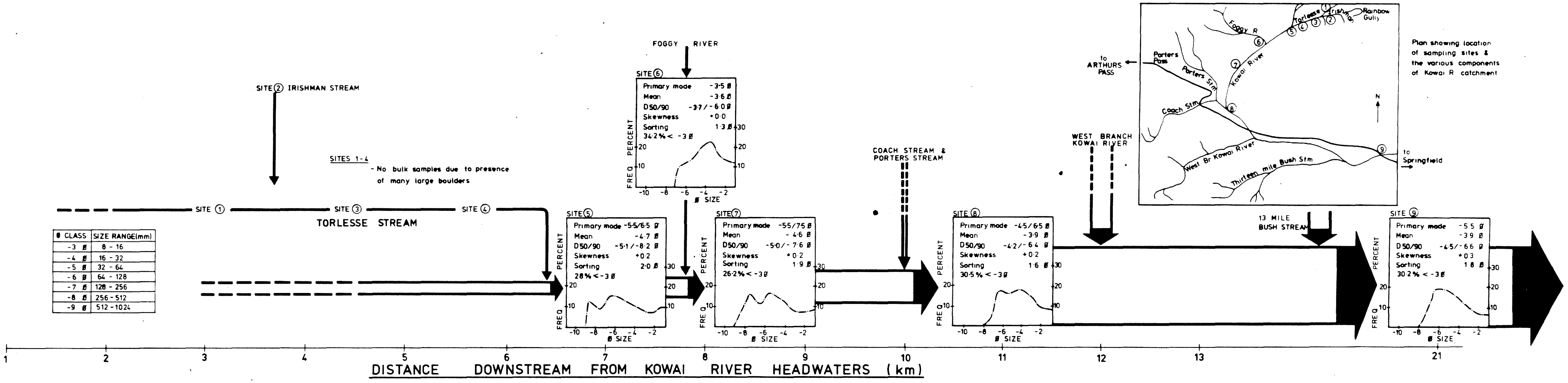
$$Mz = \frac{\emptyset 16 + \emptyset 50 + \emptyset 84}{3}$$

D_{90}: A measure of sediment size frequently used in engineering surveys, measuring that size of sediment of which 90% of the sample is finer. Engineers reverse the cumulative frequency curve usually used by geologists, measuring 'per cent finer than' as opposed to 'per cent coarser than'. To avoid confusion, the term D_{90} has been retained, but on the cumulative curves used in this study, D_{90} determines the sediment size of which 10% of the sample is coarser. This size becomes thereby the equivalent of engineers' D_{90}.

Skewness: Size distribution curves may be similar in average size and in sorting, but one may be symmetrical (mean and median coincide) and the other asymmetrical (mean and median differ). Skewness measures the degree of asymmetry as well as the sign. Curves with excess fine material (a tail to the right) have positive skewness and those with excess coarse material (a tail to the left) have negative skewness (refer to size distribution curves, Figures 6 and 7). Inman's formula is a measure known as Graphic Skewness (SK_G).

$$SK_G = \frac{\emptyset 16 + \emptyset 84 - 2\emptyset 50}{\emptyset 84 - \emptyset 16}$$

Folk (1968) suggests the following verbal limits for his measure of skewness and these are considered applicable to Inman's (1952) formula:



ø CLASS	SIZE RANGE(mm)
-3 ø	8 - 16
-4 ø	16 - 32
-5 ø	32 - 64
-6 ø	64 - 128
-7 ø	128 - 256
-8 ø	256 - 512
-9 ø	512 - 1024

SITE ⑤
Primary mode -5·5/6·5 ø
Mean -4·7 ø
D50/90 -5·1/-8·2 ø
Skewness +0·2
Sorting 2·0 ø
28% < -3 ø

SITE ⑥
Primary mode -3·5 ø
Mean -3·6 ø
D50/90 -3·7/-6·0 ø
Skewness +0·0
Sorting 1·3 ø
34·2% < -3 ø

SITE ⑦
Primary mode -5·5/7·5 ø
Mean -4·6 ø
D50/90 -5·0/-7·6 ø
Skewness +0·2
Sorting 1·9 ø
26·2% < -3 ø

SITE ⑧
Primary mode -4·5/6·5 ø
Mean -3·9 ø
D50/90 -4·2/-6·4 ø
Skewness +0·2
Sorting 1·6 ø
30·5% < -3 ø

SITE ⑨
Primary mode -5 5 ø
Mean -3 9 ø
D50/90 -4·5/-6 6 ø
Skewness +0 3
Sorting 1 8 ø
30·2% < -3 ø

Figure 7: Systems diagram of bulk sample sediment size frequency distribution and associated parameters.

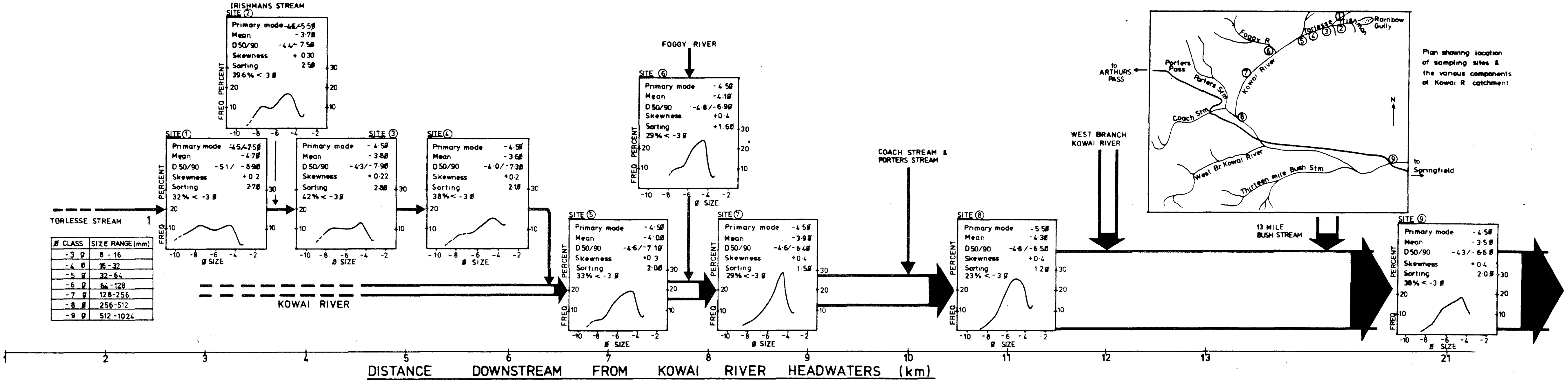


Figure 6: Systems diagram of surface sample sediment size frequency distribution and associated parameters.

TABLE 1: Measures of average size in phi units

Site No.		1	2	3	4	5	6	7	8	9
Mode *	Bulk	--------- No Data ----------				-6	-3	-5	-4	-5
	Surface	-4	-4/-5	-4	-4	-4	-4	-4	-5	-4
Median	Bulk	--------- No Data ----------				-5.1	-3.7	-5.0	-4.2	-4.5
	Surface	-5.1	-4.4	-4.3	-4.0	-4.6	-4.8	-4.6	-4.8	-4.3
Mean	Bulk	---------- No Data -----------				-4.7	-3.6	-4.6	-3.9	-3.9
	Surface	-4.7	-3.7	-3.8	-3.6	-4.0	-4.1	-3.9	-4.3	-3.5

* Whole phi unit in which mode occurs

+ 1.00 to + 0.30 - strongly fine-skewed
+ 0.30 to + 0.10 - fine-skewed
+ 0.10 to - 0.10 - near-symmetrical
- 0.10 to - 0.30 - coarse-skewed
- 0.30 to - 1.00 - strongly coarse-skewed

Sorting: measures the spread of the distribution, that is, the range of particle sizes over which the sample is spread. Poorly sorted gravels have a large range in sediment sizes while well sorted gravels have a small size range. Note that this classification has the opposite meaning to that used in the soil grading classification.

$$So = \frac{\phi 75 - \phi 25}{2}$$

As with the skewness values the following verbal classification for sorting is that suggested by Folk (1968):

under 0.35φ	very well sorted	1.00 to 2.00 φ	poorly sorted
0.35 to 0.50 φ	well sorted	2.00 to 4.00 φ	v. poorly sorted
0.50 to 0.71 φ	mod. well sorted	over 4.00 φ	extremely poorly sorted
0.71 to 1.00 φ	mod. sorted		

RESULTS FROM LINE TRANSECTS, SITES 1 - 9

The following points become apparent from a study of the results, as presented in Figures 6 and 8.

(i) With the exception of site 4, the size distribution curves for samples collected in the upper part of the catchment are multi-modal whilst those from sites along the braided lower reaches, especially below site 6, show a dominant single mode. Site 4 appears to be borderline between uni-and multi-modal form. Thus with distance downstream the sediment size distribution changes towards a single mode distribution.

(ii) In all cases the dominant particle size is the -4φ fraction (16-32 mm).

(iii) There is an initial rapid decrease in mean, median and D_{90} parameters from sites 1 - 5. Downstream of site 5 no consistent trends were noted in changes of median, mean or D_{90}. However, there does appear to be a significant decrease in all these values between the two sites at either end of the catchment, that is, between site 1 and site 9.

(iv) Sites in the upper reaches have a sediment distribution that is 'very poorly sorted' (So = 2.0 - 4.0 Ø) whilst those in the lower reaches are 'poorly sorted' (So = 1.0 - 2.0 Ø). Numerically site 9 is the most poorly sorted of the middle to lower reaches of the river.

(v) The skewness curves show that samples collected between sites 1 and 9 were all positively skewed (i.e. showed an excess of fine material $SK_G > 0.0$).

INTERPRETATION:

The bimodal distribution clearly shown at site 1 and still apparent at sites 2 and 3 has the following components:

(a) Sediments of the -7Ø primary mode are derived from reworking of ancient fluvio-glacial deposits (refer to Paper B in this volume). These consist of rounded sandstone 'greywacke' boulders which are often key elements in this stable pool-riffle channel system (Hayward, 1978).

(b) Sediments of the -4Ø mode (16-32 mm) are derived from a combination of sources, the main ones being: under-cutting of scree slopes, weathered bedrock exposures in headwater gullies, and reworked river terraces. At higher elevations, snow and debris avalanches have been observed to transport significant volumes of rock debris directly into the channel system. All of these sediments collect in channel pools in smaller floods and are scoured out, forming riparian terraces during major floods.

The change to a single mode sediment size distribution for surface sediments begins at site 4 but becomes more marked below site 6 and corresponds to a change in river pattern which occurs at the confluence of the Kowai and Foggy Rivers (Figure 4.5). The river bed becomes braided downstream from this site. It appears as though the inflow of large quantities of gravel is a key factor influencing the change from a multi-mode distribution to a predominant single mode centered on the -4Ø particle size fraction (16-32 mm). Within the Torlesse Stream catchment the gravel input may not have accumulated in quantities sufficient to affect the distribution, until the lower reaches (site 4). Site 5, just below the confluence of the Torlesse Stream and the Kowai River, can be expected to show the effect of the much greater quantities of gravel brought down by the Kowai River.

Indeed examination of Figure 8.5 shows the multi-modal bulk sample to be overlain by a uni-modal surface sample. This characteristic of the riverbed at site 5, and also sites 7 and 8, indicates the effect of a surface layer of gravel. As will be shown it is difficult to separate the effects of the two sampling methods but the surface of the river does appear to consist of a mobile layer (primary mode 16-32 mm) which overlies a coarser bed (primary mode > 64mm). More detailed sampling would be necessary to confirm or disprove this observation.

The large inflow of angular gravels of the -40 size fraction carried by the Foggy River (site 6) is believed responsible for the maintenance of the single mode distribution through the lower reaches of the river. The effect of the inflow of finer angular gravels in the middle and lower reaches is that they tend to bury the larger, more rounded boulders except when these are exposed by floods during scour cycles. The larger boulders (-70 size fraction), like those comprising the primary mode at site 1, are probably 'relics' derived from the reworking of ancient fluvio-glacial deposits. Certainly ample quantities of similar sized, and larger, rounded boulders can be observed in fluvio-glacial outwash exposures along the length of the Kowai River.

In effect, the Kowai becomes a typical braided river below about site 6 and, according to Folk's (1968) criteria, such rivers would be characterised by the poorly sorted nature of their sediments. Although all sites sampled were either 'poorly sorted' or 'very poorly sorted' (i.e. have a large range of sediment sizes), the degree of sorting numerically improved between the upper reaches of the river (range So = 2.1 → 2.8) and the middle and lower reaches (range So = 1.2 → 2.0). This sorting characteristic occurs in part because the larger boulders tend to be left in the upper channel reaches, while the finer sizes are washed downstream. Abrasion and the breakdown of coarse sediments occurs within the stream channel to form finer grade products. Larger unstable rock fragments tend to break down into primary 'cubic' shapes (see section 6), thus increasing the proportion of similar sized particles. At site 9, vegetation in the riverbed traps the finer sediment sizes, and erosion of outwash terraces upstream supplies larger boulders to the bed, thus creating a wider range of sediment sizes in the riverbed, and hence the decrease in the sorting value for that site.

The positive skewness of the samples is mainly due to the burying of the coarser-sized gravels by the finer, recently eroded material. As a result the larger boulders become more numerous with depth and they may not be adequately represented

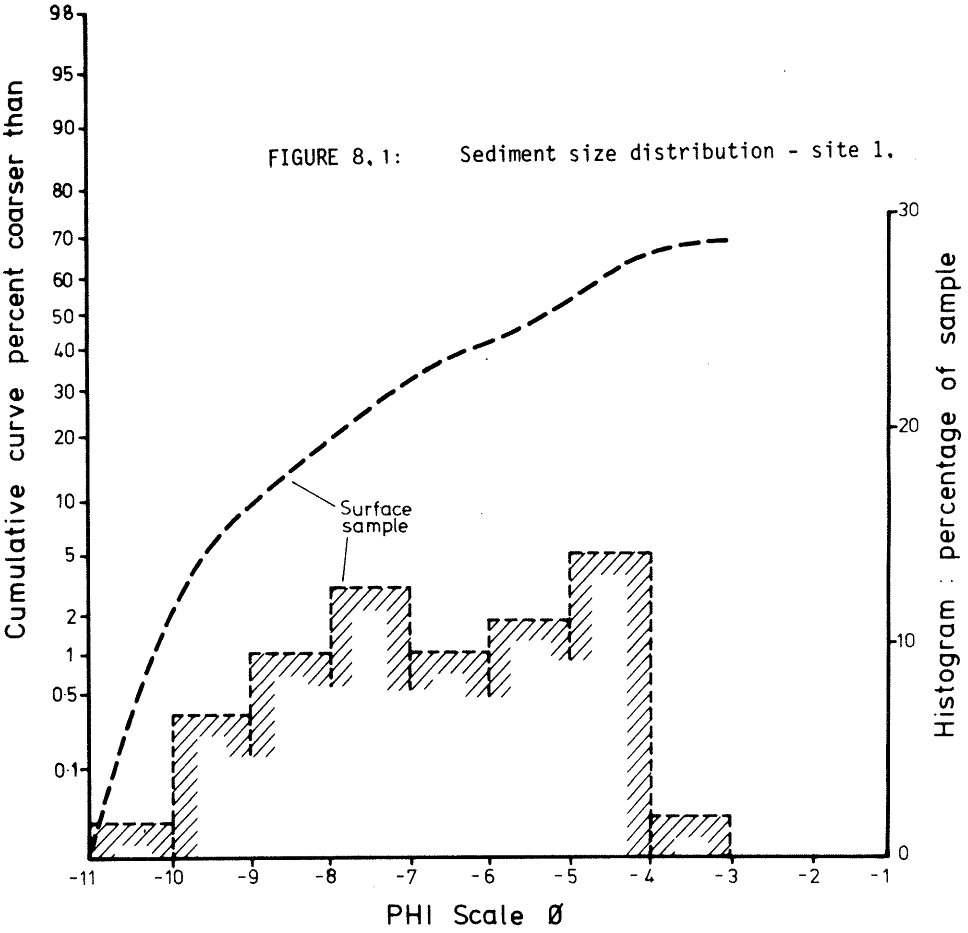


FIGURE 8.1: Sediment size distribution - site 1.

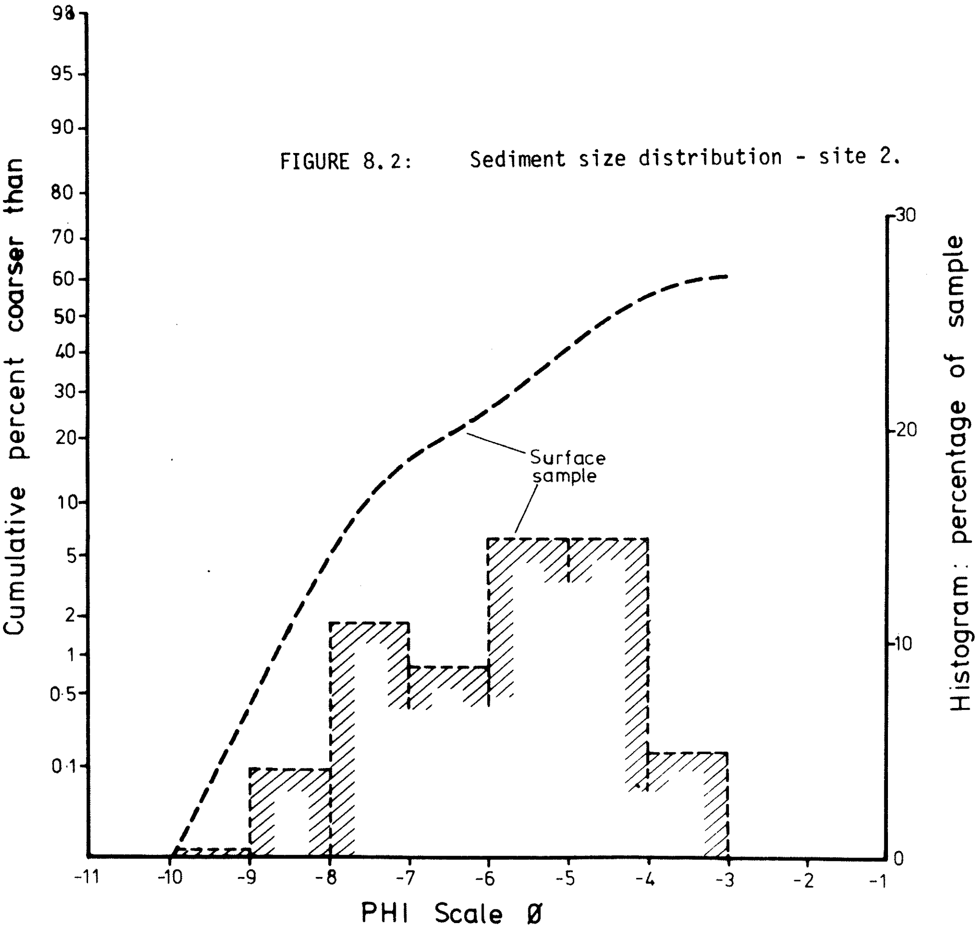


FIGURE 8.2: Sediment size distribution - site 2.

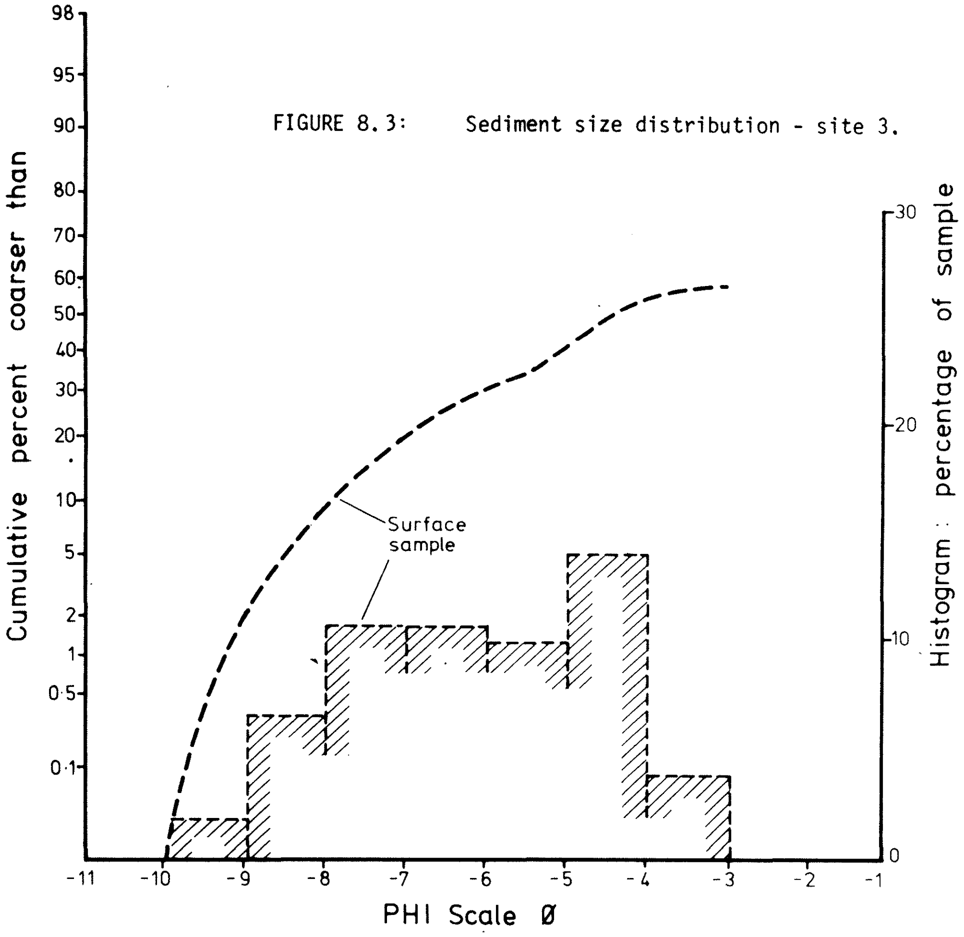


FIGURE 8.3: Sediment size distribution - site 3.

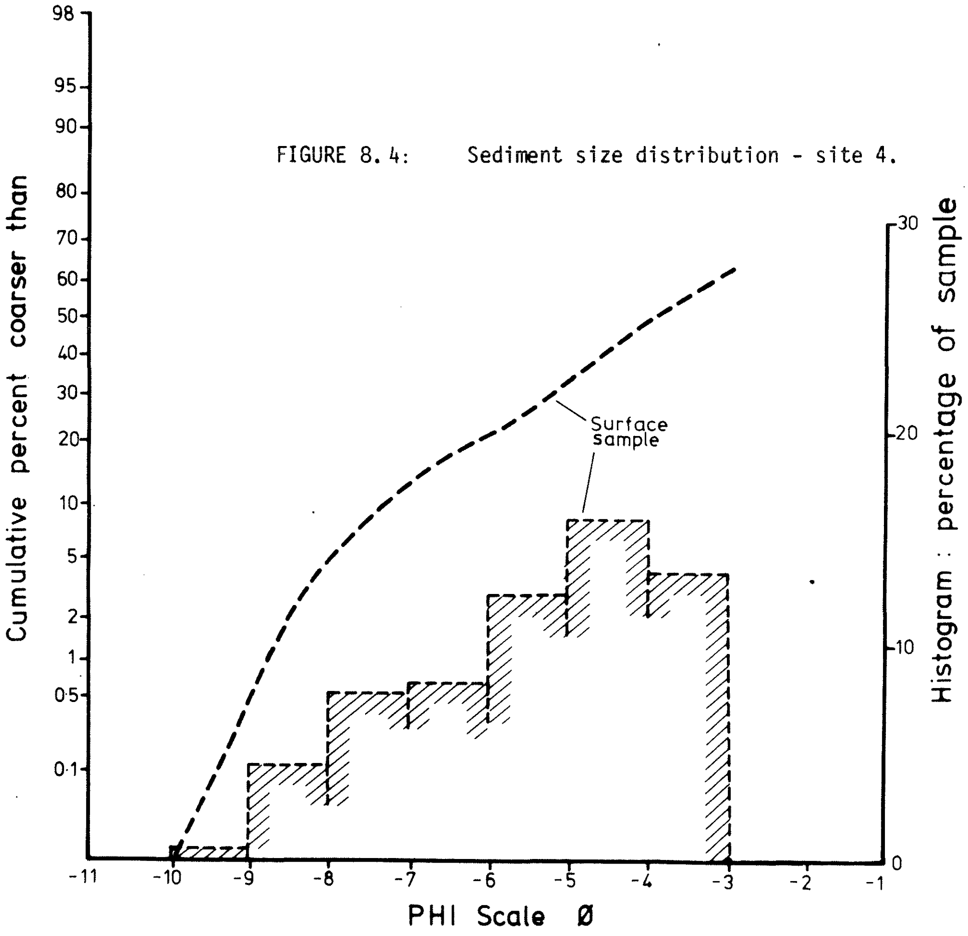


FIGURE 8.4: Sediment size distribution - site 4.

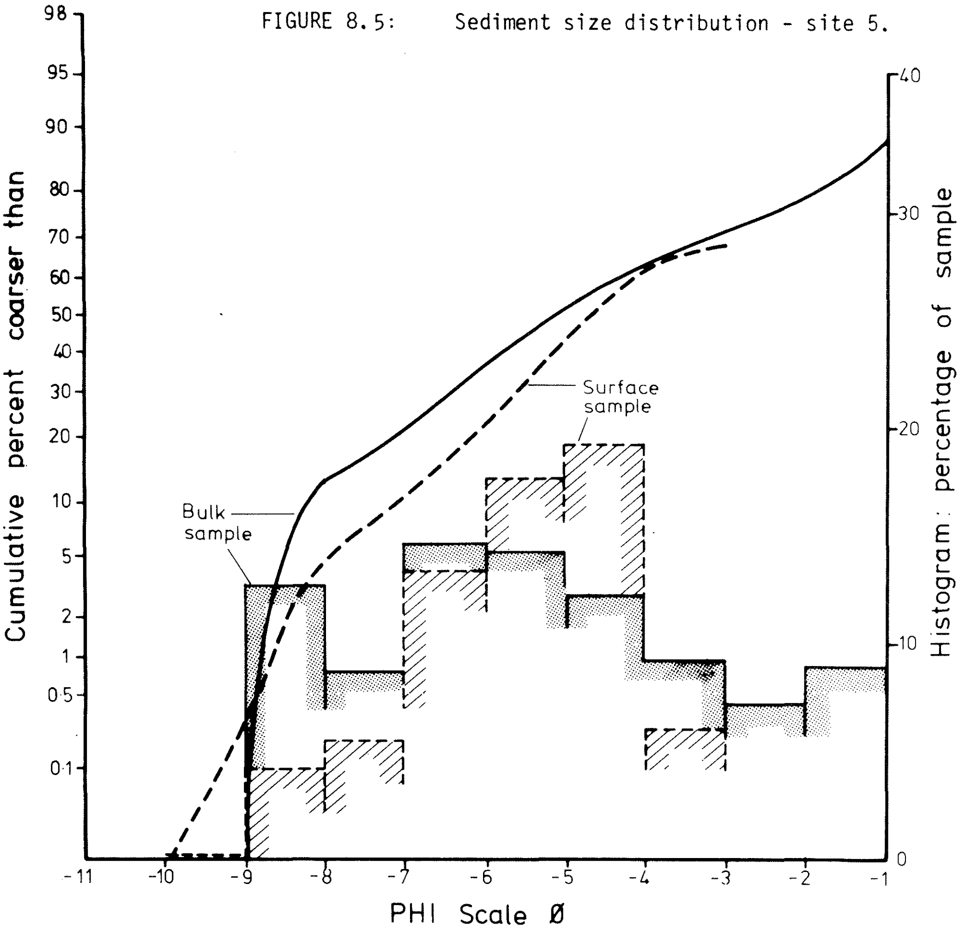


FIGURE 8.5: Sediment size distribution - site 5.

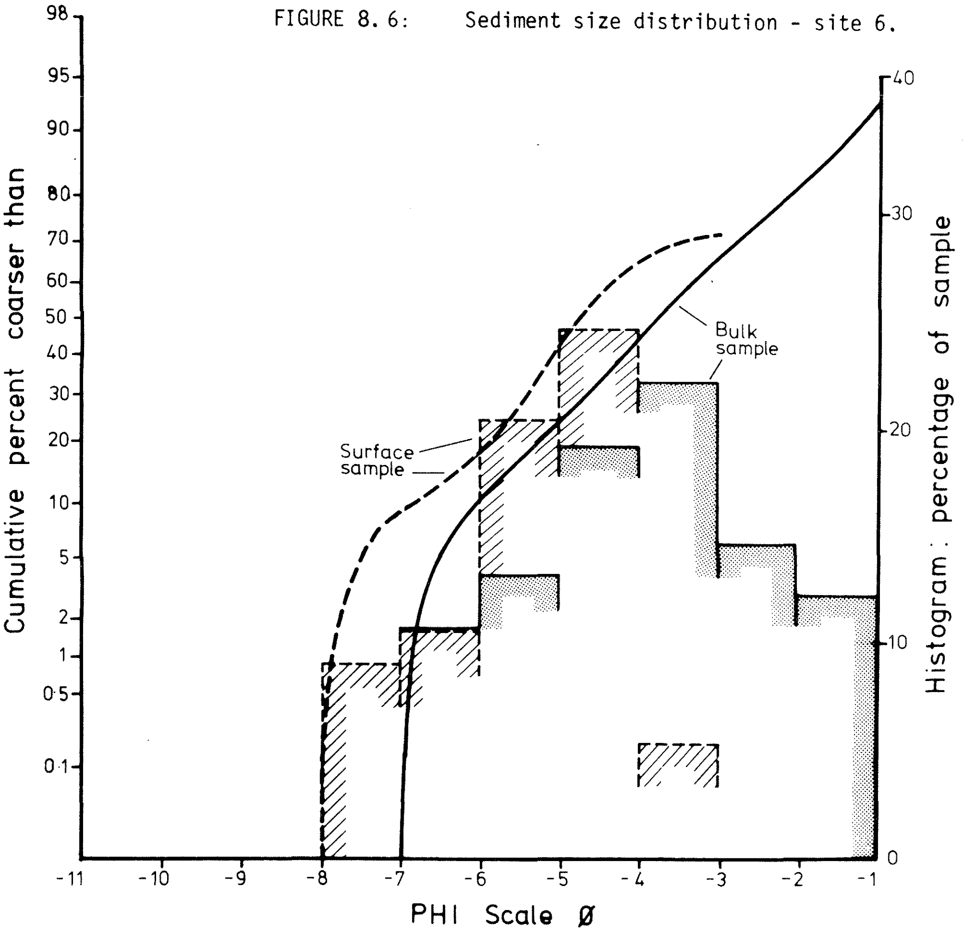


FIGURE 8. 6: Sediment size distribution - site 6.

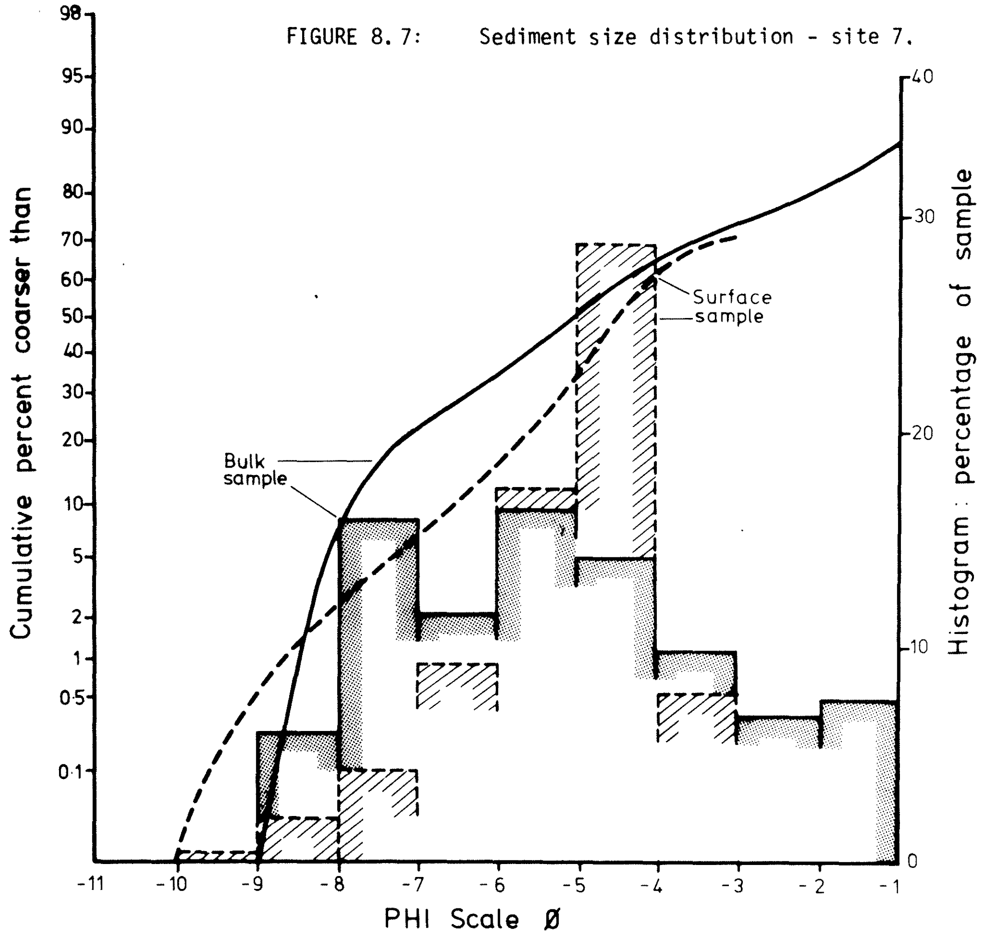


FIGURE 8. 7: Sediment size distribution - site 7.

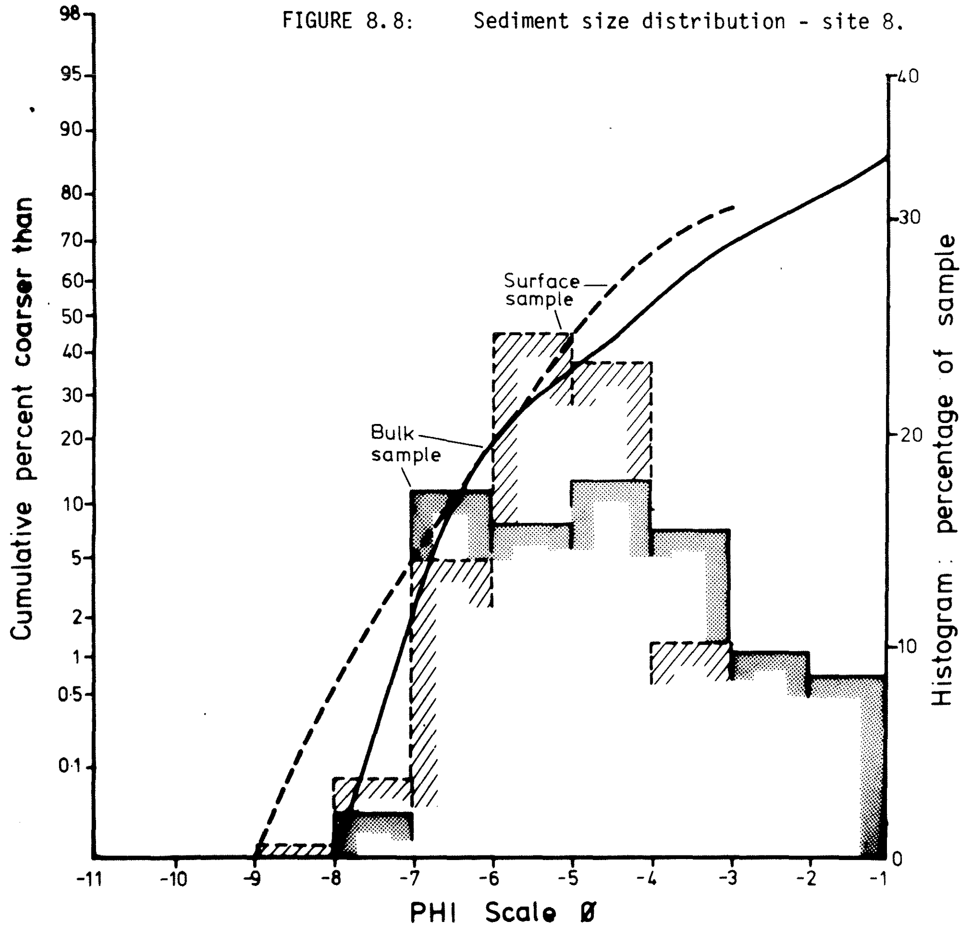


FIGURE 8. 8: Sediment size distribution - site 8.

FIGURE 8.9: Sediment size distribution - site 9.

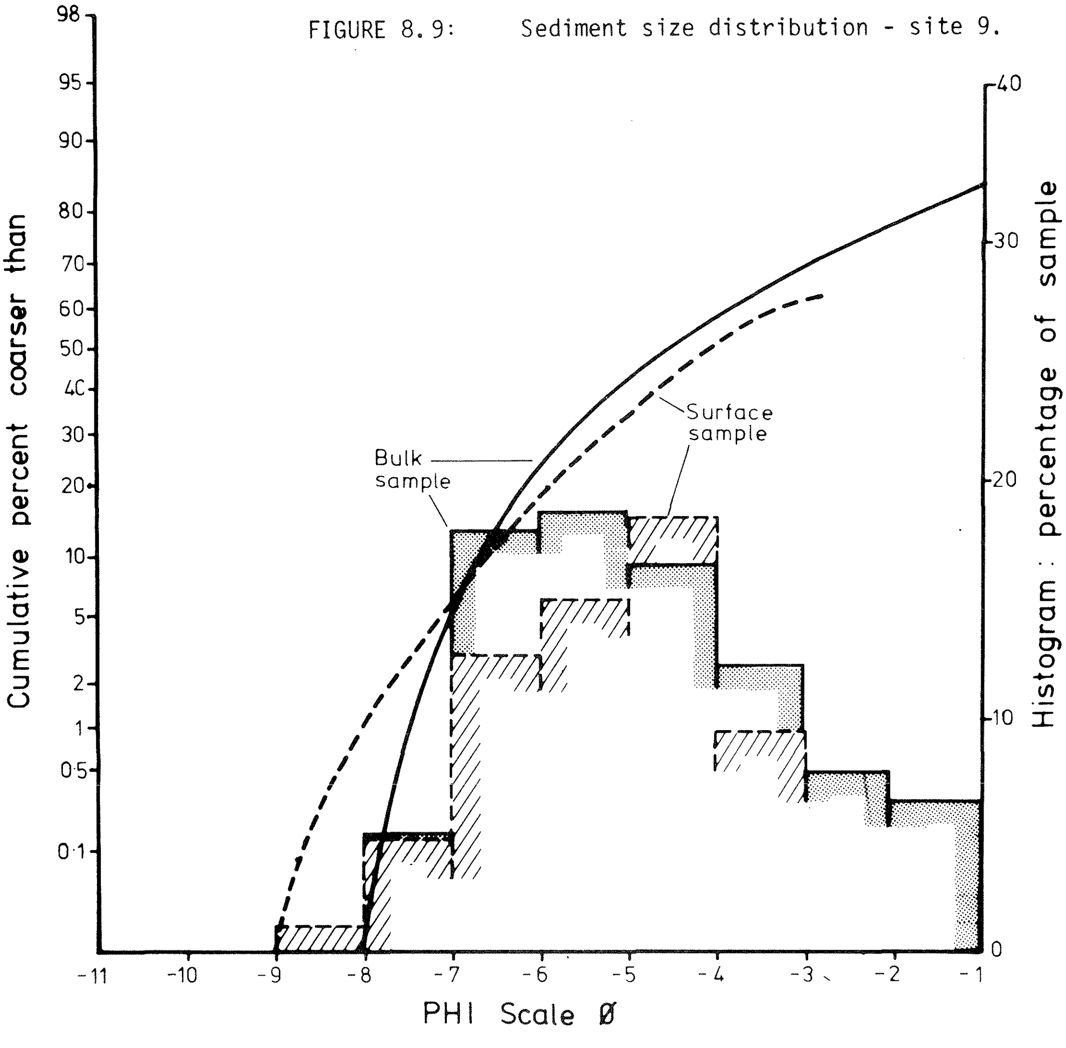


Figure 8.1 – 8.9: Cumulative percentage frequency (curve) and percentage size distribution (histogram) for sediment sampling sites. No bulk samples were obtained for sites 1–4 due to the presence of many large boulders.

in a line transect survey, especially in areas where there are appreciable inflows of fine gravel. The Foggy River, responsible for a large input of fine angular debris into the Kowai River, is probably responsible for an increase in skewness values at, and downstream of, site 6. With further distance downstream the breakup of larger particles within the streambed itself helps to maintain the excess of fine sediments in the surface layer (positive skewness).

Upstream of the Foggy River, sites 2 and 5 have the most positive (fine-skewed) values. Site 2 is located on a tributary of the Torlesse Stream where there are numerous erosion source areas supplying fresh debris to the riverbed. Site 5 is located below the confluence of the Torlesse and Kowai Rivers, with the Kowai carrying sufficient quantities of fine gravel to periodically'drown' the pool-riffle system through that reach of river.

The evidence from this study is that skewness values are closely related to the input of the more angular, finer-sized particles into the stream system. In the confined upper channel, with its well-developed pool-riffle system, the tendency in skewness values is towards symmetry, whereas the more unstable, braided riverbeds of the lower reaches show a tendency towards increasing positive skewness values.

Processes involved in the maintenance of a braided channel with distance downstream, and variations to size distribution parameters, include:
(1) The high erosion rates in headwater catchments, due mainly to large areas of intensely jointed and fractured thin-bedded sequences of sandstone and argillite .

(2) The processes of abrasion and particle breakdown, (see section 6).

(3) In-channel deposition of material derived from (1) and (2) above, leading to channel diversion into unconsolidated riparian deposits.

Hong and Davies (1979) have stated that braiding cannot be ascribed to any one set of parameters such as: "range of flows, the sediment grading curve, excessive sediment load, erosion of bank material ......". However, while braiding in the Kowai River may not depend solely on the three factors listed above, we have observed that in the field situation these processes correlate with the development of this braided channel system.

With respect to this study area, the gravel assemblage has a primary mode between 16 and 32 mm in intermediate diameter, mixed with the products of abrasion (fine gravels, sand, and silt sizes) and reworking of riparian deposits. It has been observed by the authors that during relatively small floods (return period 3-12 months) the gravel beds behave like a slurry, able to move the larger boulders (120-250 mm intermediate diameter) short distances downstream (10-100 m) in a manner described by Pierson (1980) for debris flows. Finer sizes (silts and clays) eroded from slopes and headwater gullies, or generated within the streambed, are flushed in waves downstream into the Waimakariri River.

COMPARISON OF RESULTS FOR LINE TRANSECT AND BULK SAMPLE ANALYSES

This comparison was only carried out for sites 5 to 9. For sites 1 - 4 in the Torlesse Stream, no bulk sampling was carried out because of the presence of large boulders up to 3 m in diameter. These sites could practically be sampled only by means of the Line Transect method.

In general, the parameters measured from samples collected at each of the sites by two different sampling methods, show a remarkable similarity. In most cases the results at any one site do not differ by more than one phi (Ø) fraction. This degree of similarity is such to ensure that samples from the same site, collected by different methods, furnish particle size data that in each site (5 - 9) the mean, median and primary mode values fall within the pebble category, whilst the D_{90} value falls within the cobble category.

Bulk samples for sites 5, 7 and 8 have two primary modes within one per cent of each other, and a bimodal distribution, whilst the line transects show a single mode. Sampling by both methods gives positively skewed distributions and poor to very poor sorting.

INTERPRETATION:

From the results presented in Figures 6 and 7 it is apparent that over the reach sampled in the Kowai River System, the results obtained by the method of sampling particles "by number" (Wolman, 1954) in the surface layer (approximately 20 cm deep) give a size frequency distribution generally within one phi unit of the results obtained using a bulk sampling "by weight" method (0.5 m deep).

One apparent difference is that the bulk sampling method used does not represent the proportion and distribution of the fine sediments in the active layer of the riverbed (<50 cm) , as shown by the skewness parameter differences. Conversely the line transect method does not adequately represent the distribution of larger boulders (>250 mm diameter) which tend to occur below the surface layer and of which the bulk sample is a more sensitive measure. Another difference is the bimodal size distribution shown in the bulk samples at sites 5, 7 and 8, but which is not apparent at these sites using the line transect method. Once again this may be the result of the larger boulders (-60 and 70 size fraction) being found just below the surface layer in which the -40 size fraction dominates.

Taking into account the differences between the results of the two sampling methods, it appears as if the bulk sample could be more truly representative of the actual stream bed composition at the sampling site,and give an indication of the potential for bed armouring. The surface sampling method appears to show more clearly the characteristics of the gravels actually transported by the river,and the nature of the channel morphology and its roughness characteristics.

6. GRAVEL MORPHOLOGY STUDIES

A survey of sediment shape was made by estimating each particle's sphericity and its angularity. Sphericity was measured quantitatively while angularity was estimated qualitatively. The results are presented in Table 2.

SPHERICITY:

This was calculated by measurement of the three major axes of each particle as outlined by Krumbein (1941). The ratios of the intermediate to the long diameter (b/a) and the ratio of the short to intermediate diameter (c/b) are laid off on the axes of the chart shown as Figure 9. Where the values intersect on the diagram, the sphericity may be read off to the nearest two hundreths. Values given cover only the size range -5.00 to -7.50 (32 mm -192 mm). These were the limits chosen for the computer analysis of the raw data since it was impractical to measure the three major axes of particles smaller than the 32 mm lower size limit and there were few boulders larger than -7.50 of which three axes could be measured.

As shown in Table 2, all sphericity values fall between 0.64 and 0.66 except for site 9 (0.61). They are all close to the boundary between disc and bladed particles, each axis tending to be two-thirds the dimension of the next largest axis.

No obvious reason can be found for the slight drop to 0.61 for site 9. The introduction of a large volume of sediment eroded from old outwash terraces approximately four kilometres upstream from site 9 could explain part of this change. (see Paper B).

TABLE 2: Sphericity and angularity values

	Site No.	Sphericity	Angularity	
		(Mean value for each site)		
Torlesse Stream	1	0.66	2.9	Irishman Stream
	2	0.64	2.7	
	3	0.65	3.0	
	4	Insuff. axes measured	3.1	
Kowai River	5	0.64	2.8	Foggy River
	6	0.64	2.7	
	7	0.64	3.0	
	8	0.64	3.2	
	9	0.61	3.3	

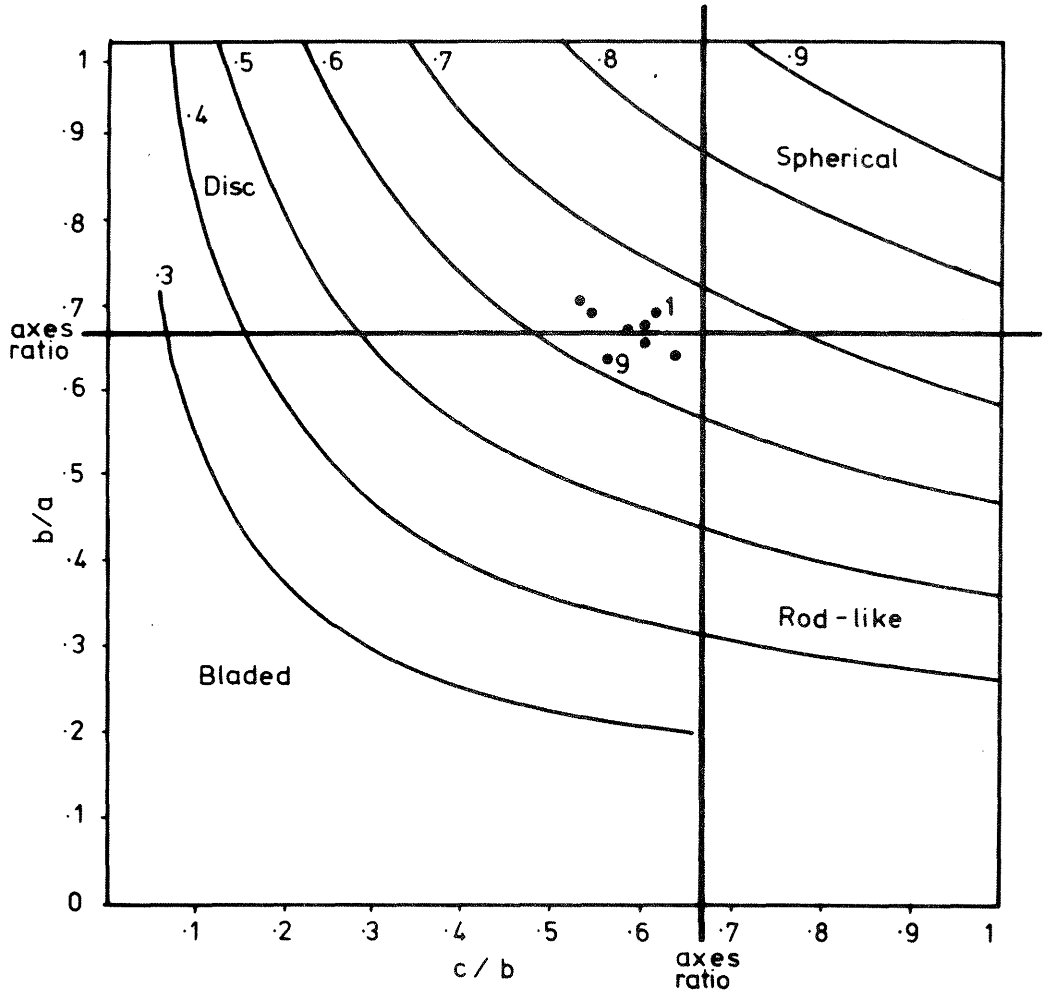


Figure 9: Krumbein's 1941 chart for determining particle sphericity values. The curves represent lines of equal sphericity. Sphericity plots for the nine sampling sites are shown, most being intermediate between sites 1 and 9 which are at opposite extremities of the system. Super-imposed on the diagram are the axes for Zingg's (1935) particle shape categories (see section 4 Part B).

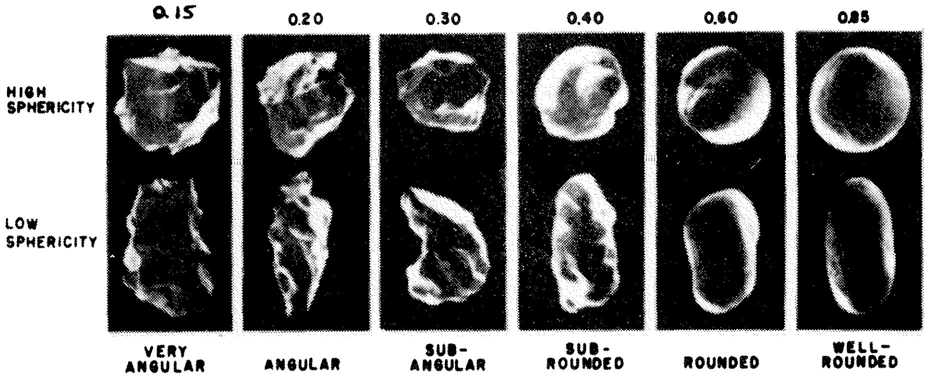


Figure 10: Powers (1953) visual scale of roundness (from Journal of Sedimentary Petrology 23).

TABLE 3: Rock axes analysis (for rocks with large axis >30 cm).

Site	$\Sigma^{b}/_{a}$	Number of Samples	Mean Value (Standard Deviation)	$\Sigma^{c}/_{a}$	Number of Samples	Mean Value (Standard Deviation)
1	23.15	33	0.70 (0.16)	8.59	21	0.41 (0.20)
2	11.45	17	0.67 (0.18)	3.96	9	0.44 (0.19)
3	21.66	33	0.66 (0.19)	5.13	11	0.47 (0.19)
4	16.31	23	0.71 (0.20)	8.12	18	0.45 (0.20)

ANGULARITY: ('EDGE ROUNDNESS')

An estimate of angularity (or 'edge roundness') was made for sites 1 - 9 using the "visual comparison" method (Powers, 1953). Each particle was compared by eye with a set of standard photographs showing typical particles for each angularity group. A scale of 1 to 6 was used (Figure 10), though in this study no well rounded particles were found.

Although not an exact measure, different people carrying out the estimates on the same sample arrived at mean roundness values with an accuracy of ± 10%.

As can be seen from Table 2, mean angularity does not change significantly (within the 10% error range) for sites 1, 3 and 4 in the Torlesse Stream, but site 2 has a significantly lower value (i.e. particles are more angular than those in the main Torlesse Stream). This characteristic was apparent in field observations in the research area.

The Kowai River bed angularity values tend to gradually increase from site 5 to site 9 (i.e. the edges of particles become more rounded with distance downstream). The Foggy River bed, as with the Irishman's Stream bed, consists of more angular particles.

INTERPRETATION AND DISCUSSION:

Sphericity remains relatively unchanged as the particles are moved downstream. This constancy in particle shape was noticed during the field work where there seemed to be a definite relationship between the axes of at least the larger boulders. Axes analyses for those rocks encountered during line transect sampling between -5.00 and -7.50 are presented in Table 3 for eight sites. In general the b axis is approximately two thirds the a axis, with the c axis approximately two thirds of the b axis.

Many of the rock fragments sampled in this study also appeared to have a characteristic rhombic or psuedo-rhombic shape which persisted at least through the boulder, cobble and pebble sizes. This characteristic has also been observed on actively eroding bedrock source areas and hence is probably a reflection of some structural control in the bedrock. Folk (1968) suggested that a pebble population results from massive rocks that undergo blocky breakage along joint or bedding planes, while Main (1975) suggested a geometrical relationship between joint planes in part of this catchment and thought that the joint pattern he investigated was "... imposed by stresses that created the numerous faults in the area..." From model studies of deformation under compressive stress (Badgley, 1965) it is apparent that if deformation is continued long enough, conjugate-shear angles can increase to around 90°, forming typically cubic shapes. It is hypothesied that it is the bedrock joint pattern and bedding planes which control the breakdown of the coarse gravels into ever smaller, but similar, shapes regardless of their location in the stream system.

From the results presented,and from observations in the study area,it is evident that during sediment transport particles are broken down into smaller particle sizes along with rounding of sharp edges. The fine size fraction so produced, is a factor in the maintenance of a mobile braided riverbed downstream from the Foggy River confluence as discussed in the previous section. An indication of the amount of 'fines' produced in the river bed is shown by Figure 11, which shows the results of a number of individual suspended sediment sampling runs (where the greatest number of observations were in flood recession). The results presented in Figure 11 show an increase in discharge of suspended sediment with distance downstream up to some maximum concentration. It is deduced from these results and observations that the bulk of the suspended sediment load of a river is actually generated within the river bed itself,as a result of the processes of abrasion and particle breakdown mentioned above, along with the reactivation of older deposits of material via bank erosion. Sediment yield levels off with distance downstream, and may indicate a balance between the rate of suspended sediment transport and deposition of fine sediments below about site 8. This process could be further examined by making sediment observations on both rising and falling limbs of the flood hydrograph.

The initial rounding of edges after particle breakdown is rapid, until a relatively stable particle shape is reached. This appears to be typically a particle of intermediate axis 16 to 32 mm, sphericity 0.64 and angularity approximately 3.0 (sub-angular). Clearly these values represent a primary modal value and there tends to be a normal distribution of values about this mode for each parameter.

An implication from this discussion is that,although braided river beds visually appear to be disordered, there are in fact organised processes working through the river system, this being evident from the systems diagrams (Figures 6 and 7). Essentially the gravels making up their river beds consist of three main components:

(i) Relic subrounded boulders eroded from riparian terrace banks.
(ii) Freshly broken rock fragments derived from recent headwater erosion gullies.
(iii) Fines produced by abrasion and particle breakdown of (i) and (ii) above.

It is difficult to estimate confidently the proportion of sediment supplied by riparian sources or from headwater erosion, as this would vary with each river system. Further study is also needed in this area.

7. PARTICLE COMPOSITION STUDY

Table 4 presents the results of the rock type analysis for sites 1 - 9. Many irregularities in the distribution of rock types were found between sampling sites. This is due mainly to the influx of new material from tributaries such as the Irishman Stream and Foggy River. The Irishman Stream shows a noticeable increase in the percentage of argillite in the bed-load as compared with the Torlesse Stream. Source areas of this material in the upper catchment are actively eroding headwater gullies, especially Rainbow Gully, within the Irishman Stream catchment. Similarly, below the Kowai/Foggy River confluence there is a noticeable increase in the percentage of argillite, this increase being attributable to numerous argillite outcrops in the Foggy River catchment.

Other rock types which vary between components of the catchment are coloured spilites and volcanic material. Both of these are absent in the Foggy River and upper Torlesse Stream catchments; source areas being the Kowai River, upstream of its confluence with Torlesse Stream, and the Irishman Stream catchment.

It is apparent that the lithology of a catchment headwater affects the degree of erosion in that catchment, and in particular,it is believed a strong correlation exists between the presence of argillite bands and the severity of active erosion within a catchment. The Foggy River and Irishman Stream,the most unstable and mobile of the riverbeds surveyed, have numerous active erosion source areas within their catchments, and also have larger volumes of argillite in their bedload than the other portions of the river system surveyed.
The reason for the erodibility of argillite or thinly bedded argillite/sandstone sequences is related to the intensity with which fracturing is developed in such incompetent, thinly bedded sequences, whereas more massive sequences of sandstone break up into larger blocks (Blair, 1972). The argillite and volcanic rocks break down rapidly into 'fines' and are flushed downstream, their percentage of the total bedload decreasing with distance downstream from a source area (Table 4).

Thus the main factors which affect rock type distribution at a given sampling site include not only the effect of a relative increase or decrease of other rock types due to the in-channel processes, but also their relative abundance and availability in the source areas of the catchment upstream.

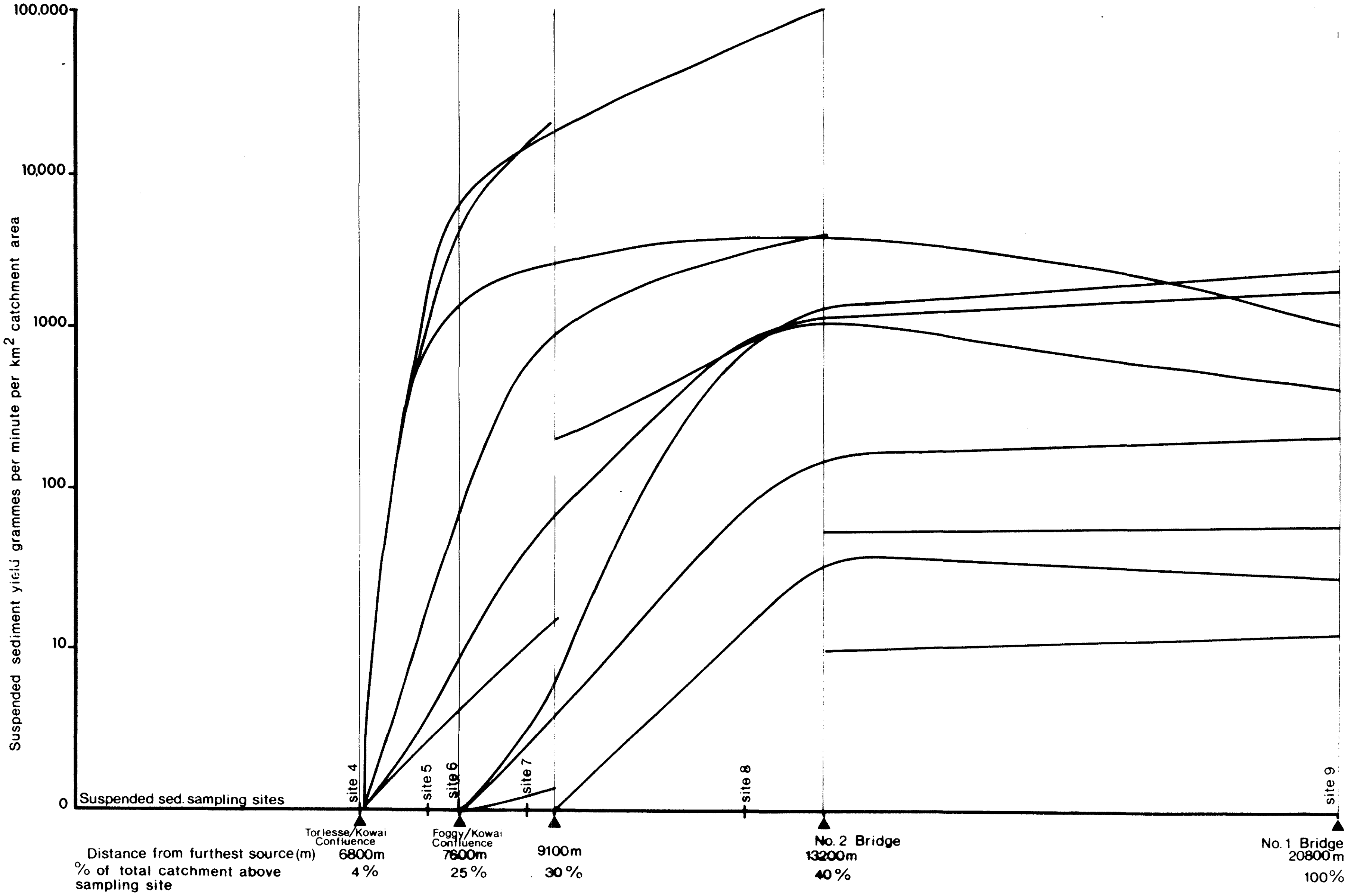


Figure 11: Suspended sediment sample runs at selected sites on the Kowai system.

TABLE 4: Rock type analysis (sediment larger than 32 mm as a percentage of total sample).

Site No.	1	2	3	4	5	6	7	8	9
Sandstone	99.5	79	93	95	83	82.5	80	86	95
Volcanics Chert Spilite	-	5	1.5	1	11	-	6.5	6	2
Argillite	0.5	16	4.5	3	5	12.5	11.5	5	2
Chipwacke Conglomerate	-	-	1	1	1	5	2	3	1

8. CONCLUSIONS

COMPARISON BETWEEN BULK SAMPLING AND LINE TRANSECT SURFACE SAMPLING METHODS

The similarity in results obtained by the line transects and the bulk sieve analyses should not be assumed to hold true for future studies in other similar river systems without some initial trial sampling. Even though the results from each method show a good correlation, we recommend that only one method be adopted and utilized throughout the study. The choice of sampling method will be influenced predominantly by the bedload characteristics of the river to be sampled (i.e. the proportion of sediments smaller than 8 mm and larger than 250 mm).

Where stream beds are armoured with boulders too large to sample practically using the bulk sieve method (250 mm), the line transect sampling method is the obvious one to adopt. Similarly, bulk sampling is impractical when the depth of river gravels is less than approximately 0.5 m or where there are access problems. The line transect method gives useful and easily obtained information for river process studies, while bulk sampling methods have the advantages of providing information on the suitability of gravels for use in civil engineering works. These advantages have to be weighed against problems of ease,and costs of access and subsequent sample analysis. A sample of approximately 100 kg appears to be sufficient to give results to the degree of accuracy obtained in Table 2. Nevertheless, spacing of sample points and quantities collected will vary depending on variations in channel morphology (size of largest particles). For the purposes of most process studies, where cost and access are important factors, it is believed that the degree of accuracy obtained from several small bulk samples at one site is greater than one large sample at that site, due to the natural variation in gravel deposits over the river bed. Obviously where several boulders larger than 250 mm are encountered, small bulk samples become less representative and line transect surface sampling should be considered.

A limitation of the line transect method is that it becomes difficult to measure diameters of particles less than about -4.00 (16 mm) and hence is not applicable to streams with a larger proportion of their bed load (approximately greater than 50%) finer than this size. It is recommended that no fewer than 200 particles larger than 16 mm for each site be measured.

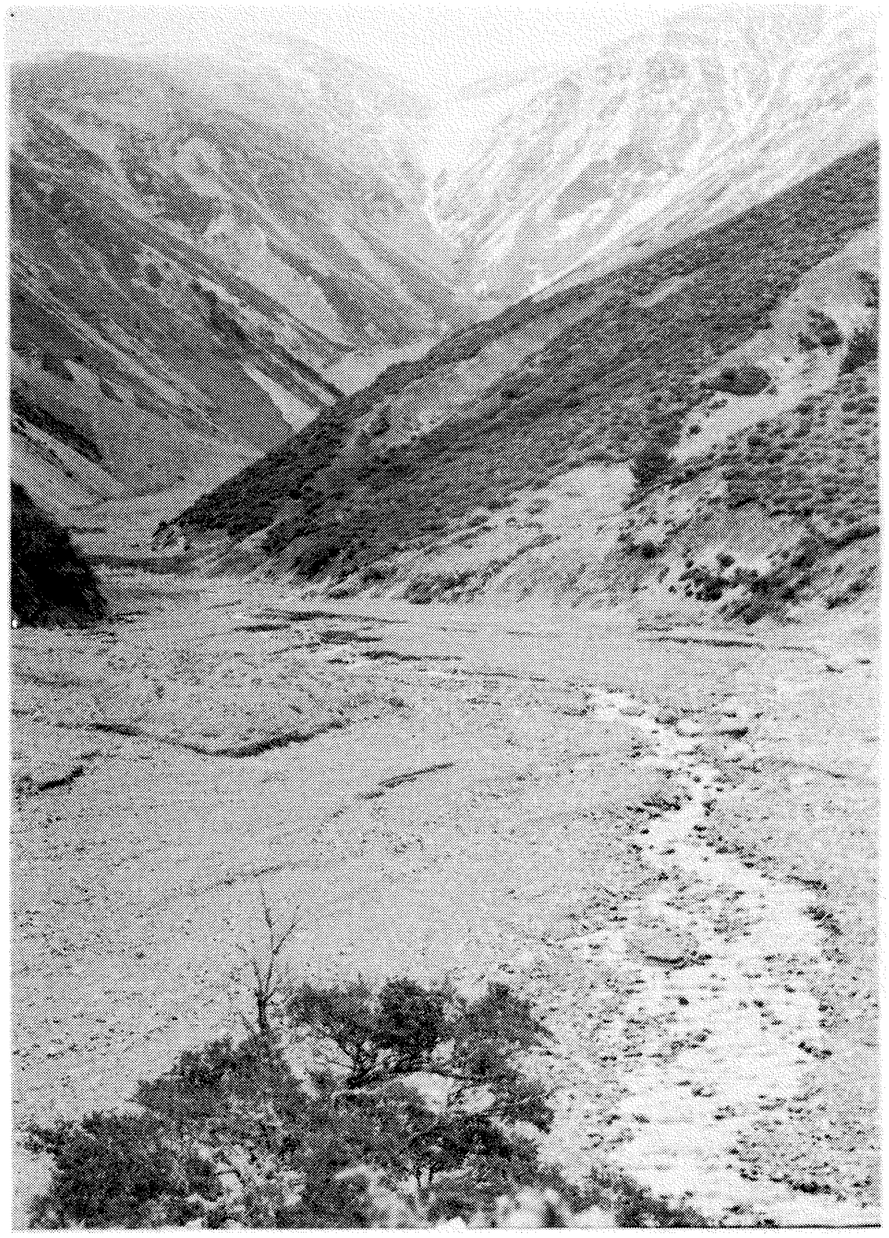


Figure 12: Foggy River catchment with its large number of erosion source areas and gravel choked stream bed.

Figure 13: Kowai River immediately downstream of confluence with Foggy River. Note the paucity of large boulders compared with Figure 4.3.

CHANGES TO THE KOWAI RIVER GRAVELS IN RELATION TO PRESENT RIVER PROCESSES

For reaches of the river channel studied the bulk sediment size distributions of the river gravels are predominantly bi-modal (except for site 6). However, one characteristic to emerge from this study is that the actively braided lower reaches of the river have a more normal surface sediment size distribution, while the more stable pool-riffle sections of channel (Sites 1-3) tend to have bi-modal distributions. The major influence on the size distribution in the lower reaches is the influx of large quantities of sub-angular recently eroded sediment from the Foggy River Catchment (Figure 12) overlying the bi-modal sediments as shown in figures 8.6 to 8.9 . These surface gravels are normally distributed about a single mode centred on the size range 8-16 mm (-30 from the bulk analysis). The influence of these gravels on the river bed morphology and processes of sediment transport and deposition downstream from the Foggy/Kowai River confluence is significant. Channel patterns change to mobile braided river beds (Figure 13), altering their form in every small flood, while the upstream channel form changes less frequently.

The constancy of channel form in the upstream reaches corresponds to a reduced availability of finer sized gravels (less than 32 mm). As remnant lateral fine gravel deposits stored in the riverbed, upstream of the Foggy River confluence, are flushed out, large relic boulders are exposed. These serve to maintain the channel profile. Exceptions occur in a few headwater gullies where active erosion is occurring, allowing downcutting and headwater erosion by the river. Until the next major flood redeposits these fine gravel terraces (return period greater than 20 years), the river channel can be expected to alter only slowly as the more stable multi-modal sediment distribution becomes dominant, and fresh erosion debris is 'flushed' through the system.

Another characteristic to emerge is that sediments eroded from the actively eroding bedrock source areas in the upper catchments rapidly disintegrate into their inherent, structurally controlled shapes and sizes. A small decrease in mean size and an increase in edge roundness occurs from site 1 and site 9. The resultant 'fines', along with those supplied by bedrock disintegration and undercutting of alluvial fans, screes and terrace banks, are key elements in the development and maintenance of the mobile gravel beds downstream. Some of these fine gravels, sands, silts,and clays are flushed into the Waimakariri River, while the rest are deposited in the river bed or trapped in flood terraces by broom, gorse and other scrub species (Figure 4.6). It is hypothesised that the continual supply of inherently weak rock fragments and finer sizes (smaller than 8 mm) is of primary importance to the maintenance of mobile braided river beds.

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THE BEHAVIOUR OF THE KOWAI RIVER SYSTEM

PART 2: SOME IMPLICATIONS FOR MANAGEMENT

1. INTRODUCTION

The implications that the Kowai River studies have for management practices are believed to be applicable to a number of similar river systems to the east of the major axial ranges in both the North and South Islands. Throughout these areas the retirement of higher altitude lands from pastoralism has been followed by more intensive pastoral development at lower elevations, with river berms and flood plains becoming potential 'new lands' for development. In addition, small gravel bed river systems are increasingly recognised as vital natural resources by both wildlife and water resource development interests. It is on such small river systems that human impacts are most evident, and where the potential for restoration of ecological and physical damage is highest. Kerr _et al_ (1980) present some Canadian experiences on this topic.

There is a need to be aware of the consequences of development on such potentially fragile areas but this need not preclude the possibility of development taking place. Indeed, the authors believe that parts of these undeveloped riverbed lands, usually growing a variety of noxious weeds and carrying very low stock numbers, may offer a most profitable area of investment for our now scarce energy and capital resources.

It is essential, however, that any development of marginally productive river flats, including the sensitive 'riparian' zone alongside the river channels, be integrated into a soundly based river and floodplain management programme. In turn, this programme must be based on a sound knowledge and understanding of past and present river processes. It must also be realised that the benefits which accrue from such a development programme will only be reaped over a period of at least 30 years.

Where applicable, the following discussion uses the example of the Kowai River to demonstrate the specific application of more general concepts. However, the Kowai River does not exhibit all the characteristics of many larger New Zealand gravel bed rivers, as it lacks complete floodplain development of the lower reaches.

Figure 14 illustrates the application of river floodplain terminology as used in this discussion.

2. RIVER MORPHOLOGY

A river system can be considered as being analogous in plan form to a tree. Figure 15a, modified from Schumm (1977), illustrates this analogy wherein branches are equivalent to the various catchment tributary channels; roots are equivalent fo floodplain channels (including depositional fans or marine deltas); and the connecting 'trunk' can be considered as the transfer channels. Transition channels occur in that reach of river where transfer channels change to floodplain channels. Figure 15b illustrates the development of an alluvial fan, showing the different channel systems discussed above. In some cases (e.g. the Waimakariri and Manawatu Rivers), braided floodplain channels which flow across broad alluvial fan surfaces, change to single thread "silt phase" channels a few kilometers upstream of the tidal reach of the river.

Figure 15c illustrates such an idealised river system in its unmodified state. In several Canterbury and North Otago gravel bed rivers (e.g. Rakaia, Rangitata, Waitaki Rivers), the braided alluvial fan channel system extends to the sea. From studies in several gravel riverbed systems in New Zealand it is apparent that the critical area from a management point of view is in the transition channels, where river processes often exhibit a very sensitive response to changes, both in the supply of sediment from the transfer channels, and to changes in channel pattern downstream in the "floodplain zone". Artificial changes affecting sediment supply include gravel extraction and channel realignment activities. A balance between the rate of gravel supply and rate of removal is necessary if serious deposition or scour is to be avoided in lower reaches.

Transition channels are usually located at the heads of alluvial fans; geomorphic features which range in size from the large-scale outwash fans of the Canterbury Plains (Suggate 1963), to the smaller steeper fans of the hill and high country (Carryer 1966). In the lower reaches of many of these fans there is a marked change in channel slope from the steeper surface of active gravel deposition to the gentler, 'silt-phase' floodplain. These two components of a fan are separated by a geologic 'hinge-point'. With large scale outwash fans, the change in shape is

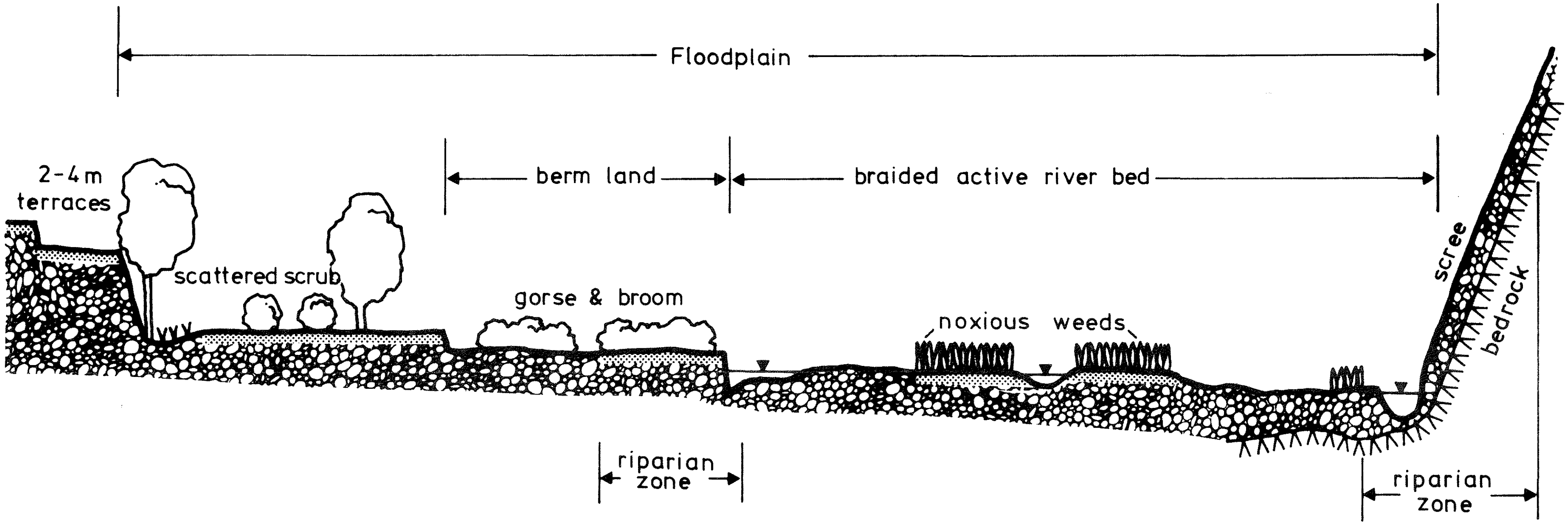
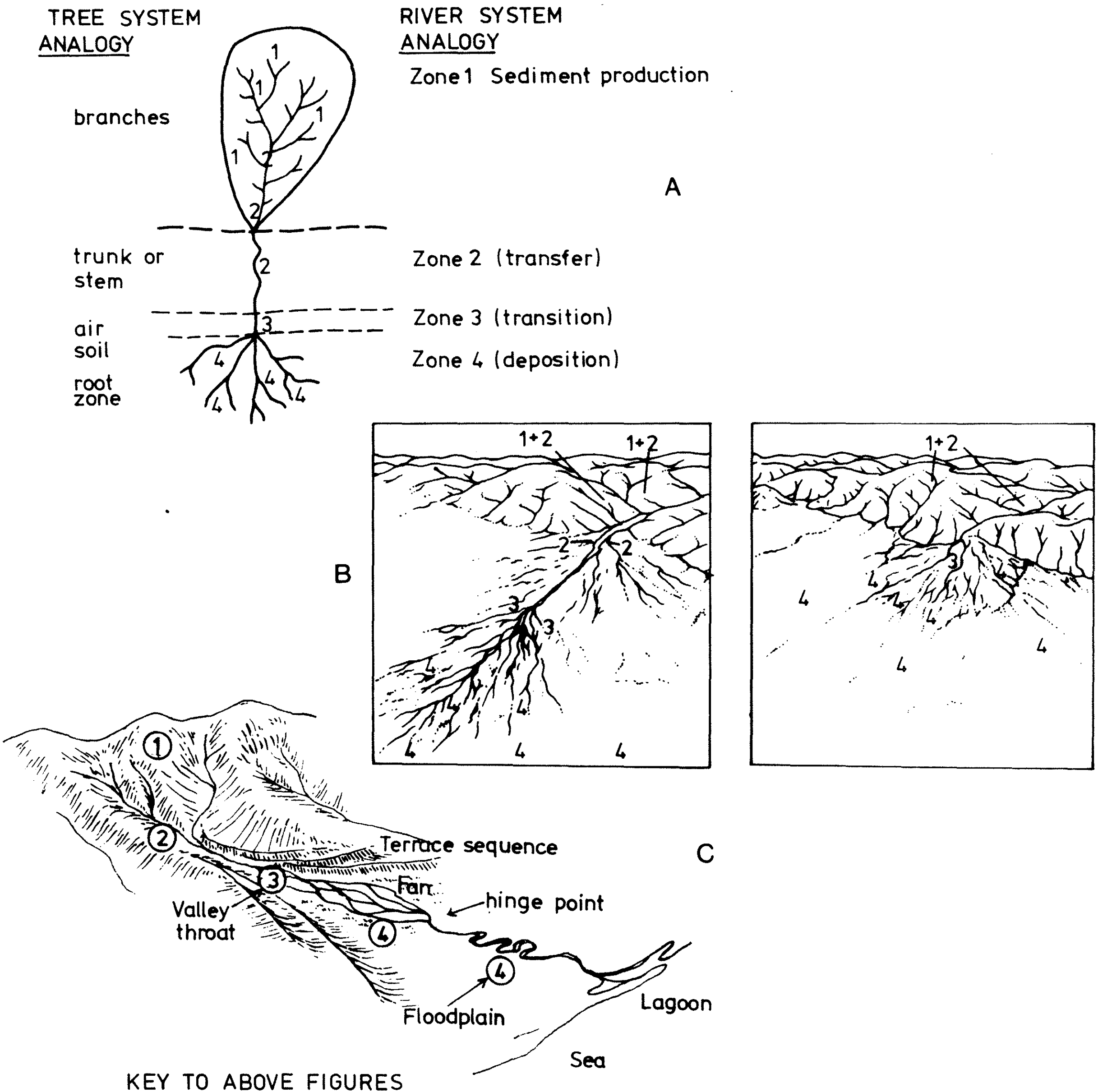


Figure 14: Explanation of river floodplain terminology used in the text.



KEY TO ABOVE FIGURES

Zone 1	Catchment channels : sediment production with temporary storage of coarse sediments in channel deposits.
Zone 2	Transfer channels : transfer of sediment with limited temporary stage.
Zone 3	Transition channels : cyclic scour & fill of sediment through often unstable channels.
Zone 4	Floodplain fan & delta channels : deposition of generally finer sized sediments.

Figure 15: The development of an idealised river system.
A. Model of a river system: an analogy with a plant form (modified from Schumm 1977a).
B. Model of alluvial fan development.
C. General model of an alluvial gravel bed river system draining "Torlesse group" rocks.

usually related to the intersection of two ancient outwash surfaces and it appears that the lower, flatter gradient surface(s) have been, in part, derived from reworking of the older, steeper, surface(s). The Waimakariri is a good example of this process where Darfield and Halkett surfaces have been downcut during formation of the Yaldhurst surface (Suggate 1958).

The understanding of the derivation of the present floodplain sediments, and sediment size parameters, from reworking of older deposits, (see Paper B of this publication), is believed to be important in establishing a soundly based management programme for gravel bed rivers. With this understanding, schemes can be devised and implemented to work with the natural river processes, these being modified only where necessary and feasible. In the long term (>30 years) scheme maintenance costs should be minimized and benefits to both human and wildlife interests, maximized. Such management programmes will be discussed further in sections 5 and 6.

3. A PERSPECTIVE ON PRESENT PROCESSES OF SEDIMENT SUPPLY IN N.Z. GRAVEL BED RIVERS

The Riparian zone is a vital buffer zone between man's agricultural developments and his most vital life support resource - water (Odum 1978). Conway (1979) and McColl et al (1981) stress the importance of the riparian zone in the maintenance of good water quality. In many areas, older local residents often recall what are now radically altered rivers as having several narrow winding streams, deep pools, and abundant fish and plant life, a situation depicted in Figure 16. It was in the riparian zone that the naturally eroded sediments from highly-fractured bedrock in the mid-slope zone of the steep upper catchments were filtered out. This material which in 'greywacke' country tends to have a naturally high nutrient status, (D.S.I.R. 1968), supports prolific vegetative growth and it was here that the ancient podocarp trees obtained their greatest size.

The rapid and continuing trend in many of our present gravel bed rivers, especially since forest clearance, is one of channel widening and straightening with frequent fluctuations of bed level as waves of gravel move downstream to be redistributed along the channel system (Grant 1977; O'Loughlin 1969; Griffiths 1969; Nevins 1971). In many cases this lateral erosion is limited only by geologic and man-made controls such as rock outcrops, bridges and river control structures.

Such trends have presented problems to many agencies, particularly to catchment boards who have been taking observations and recording data with a view to a better understanding of the nature of river processes and sedimentation problems in areas of concern to them. However "... the urgency of the many practical problems facing water and soil managers dictates that such research as can be undertaken must often be of an immediate and ad hoc nature." (Dils et al 1977). Although there is still an urgent need to obtain more reliable data on river processes and management problems for New Zealand's gravel-bed rivers (Evans et al 1964), such recent studies of river processes that have been carried out (e.g. O'Loughlin 1969; Thomson et al 1969; Brougham 1978; Hayward 1978; Mosley 1978) make necessary a reappraisal of more traditional views on relations between land management, hydrology, erosion, and stream sediments.

Retirement and revegetation of depleted high country land has traditionally been justified by the assumed benefits that would arise from reduced downstream river control problems and improved water quality (Leenards et al undated). However, such an approach to river control problems is too simplistic as a means in itself, because the significance of gravel supply from active headwater erosion in relation to gravel derived from within wide river beds and riparian land erosion is not at all clear. It is true to say that the riverbeds and riparian lands in the upper catchments of our gravel bed rivers are a major source of debris to the lower channels, (Stringer et al 1978), but a significant proportion of sediments eroded from headwater rock faces does not have direct access to a stream channel. Even in cases where rock faces have collapsed into headwater gullies a major storm is required to mobilise even part of the deposited coarse gravels (Mosley et al 1976).

The Waimakariri River system poses a greater threat to the largest area of property than any other river in New Zealand. From 1929 to 1973 mean bed levels at a change in slope of the river profile, approximately 3 - 18 km from the mouth, have risen up to one metre at some cross-sections even though large volumes of gravel have been extracted for roading (Figure 17). Degradation has occurred upstream of this critical aggrading reach. Griffiths (1979) and (Nelson 1928), showed that a large proportion of sediment (approx. 65%) is being derived from the re-working of in-channel

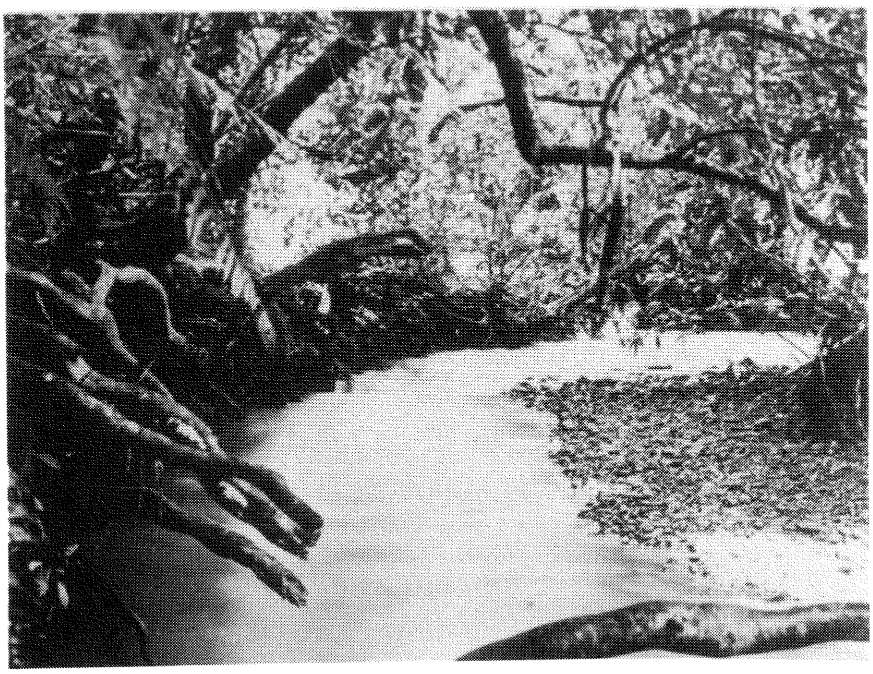


Figure 16: Probable riparian vegetation before forest clearance; a stable environment for fish and plant life. Stream flowing through Hays Reserve, Banks Peninsula.

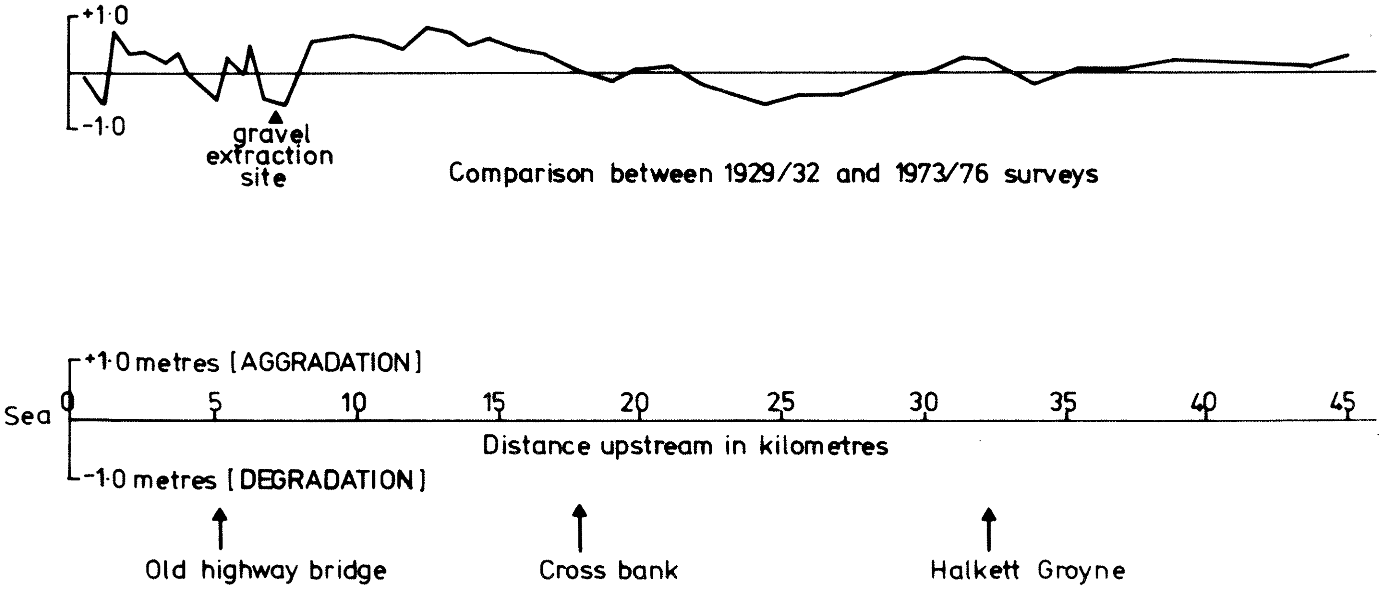


Figure 17: Mean bed level changes: Waimakariri River 1929/32 to 1973/76. (From Griffiths 1979).

sediment and bank erosion. The understanding of the rates of these same processes, relative to headwater gully and slope erosion, was central to the preparation of a management plan for the South-east Ruahine Scheme (Brougham 1978).

From the sort of research that has been carried out on the Waimakariri River, it is clear that there is a two-fold source for much of the gravels in braided river systems. Schumm (1977b, uses the terminology Type 1 and Type 2 sediment sources for the Ruahine Range. Type 1 includes that material derived from the continual weathering of exposed headwater rock faces producing fresh angular rock particles (Figure 18). This material is then combined with that resulting from the reworking of ancient slope, terrace and alluvial fan deposits in the upper catchments. Type 2 sediment includes that resulting from the erosion of floodplains and the reworking of riverbeds in the middle reaches of river systems (Figure 19). Thus, in downstream reaches a proportion of upper catchment material is combined with the Type 2 material, but for many catchments the latter sediment sources appear to be the more important (Griffiths 1979).

4. RIVER RESPONSE TO RIPARIAN SEDIMENT INFLUXES

Table 5 describes how the different channel forms found over the length of the system can reflect variations in sediment supply rate and size distribution as discussed in Part 1 of this paper. Clearly each reach of a river system will respond differently to sediment inputs from either in-channel processes (e.g. abrasion) or from erosion of riparian sources (including headwater gullying). This response will be considered in the context of two time scales.

i) Flood flows:- During a flood event, influxes of sediment into a reach of river lead to complex responses in channel form and hence fluctuating flood levels. In general, as flows increase entrainment of sediment begins on a limited scale, until a 'threshold' is reached, at which time general bed-load movement begins. This threshold can be lowered by bank erosion supplying sufficient fine sediments to 'mobilise' or 'lubricate' the larger sizes so that the bed-load is moved <u>en masse</u>. This phenomenon is sometimes referred to as a "gravel wave", and can be considered as an extension of the sort of process responsible for debris flows (Pierson 1980a and b, Oaks <u>et al</u> in prep.).
"Whenever well-graded soil and rock debris (i.e. material having an even distribution of particle sizes) is mixed with a critical amount of water,

TABLE 5: SEDIMENT SUPPLY AND CHANNEL FORM

(Refer to Figure 33)

Sediment Sampling Site No. (Sediment 'types')	Channel Zone	Influence of sediment sources on river behaviour
Sites 1,2,3,4 Torlesse Stream	Zone 1 Upper catchment channels Stable form	Minimum influence: sediment inflows pass through a series of energy dissipation steps formed over large relic boulders. Channel pattern and form rarely changes except in high return period floods. (10 years +)
Site 5 Kowai River upstream of the Foggy River confluence	Zone 2→3 Transfer and transition channels Stable/unstable forms	Dependent on sediment supply from upstream.Bed forms fluctuate between multiple single thread channels and braided unstable beds for return period flows of 2 to 10 years. 'Transition' channels develop temporarily during the passage of 'gravel waves'.
Site 6 Foggy River fan	Zone 4 Gravel fan channels Cyclic store and release of gravels downstream	The major source of mobile gravels to the Kowai River, the influx of which corresponds to a change to unstable braided forms downstream. Channel patterns change in flows with return periods 2 to 6 months. Temporary storage zone for gravels.
Sites 7,8,9 Main Kowai River channel downstream of Foggy River	Zones 2→3 Transfer and transition channels Mobile gravel bed forms	Sediments derived upstream are combined with that from erosion of riparian terraces and banks. These riparian sources help maintain the braided river beds. Transition channels may develop during the passage of 'gravel waves', with localised gravel deposition. Channel form becomes unstable during flows of return period 1 month and greater.

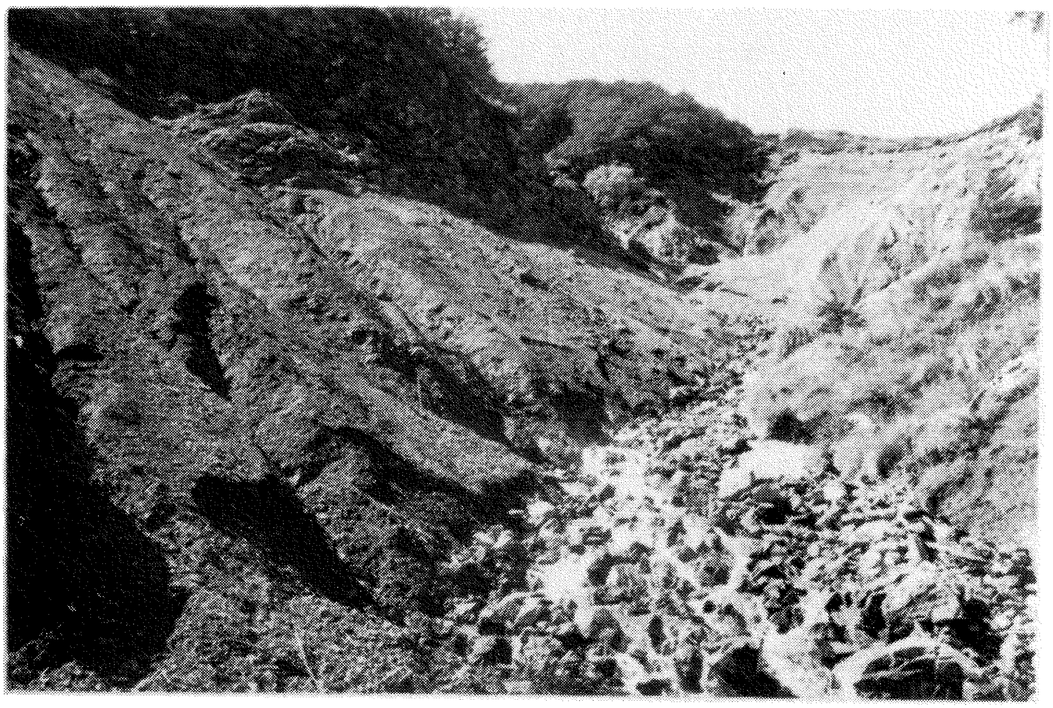


Figure 18: Headwater erosion of freshly weathered rock faces: "Type 1" sediment Rainbow Gully, Torlesse Catchment.

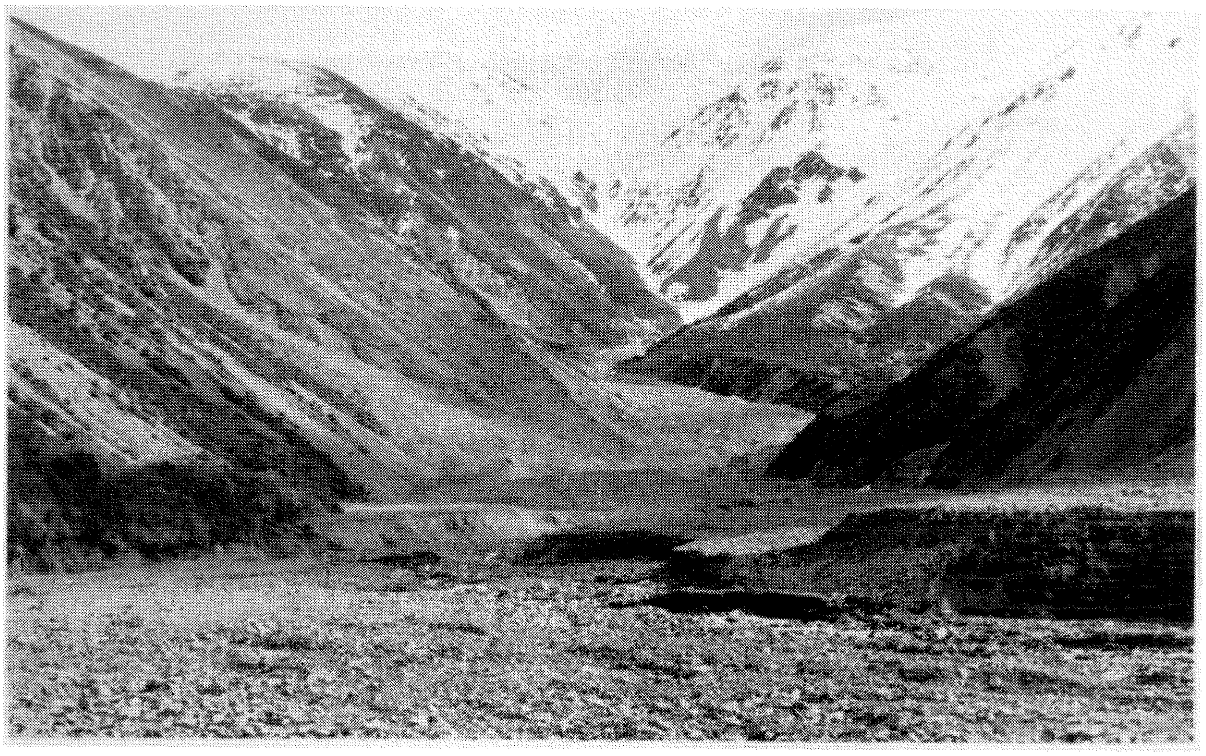


Figure 19: Riparian terrace deposits ("Type 2" sediments). Gravel held in temporary storage between major floods: Foggy River Catchment. (Note large volume of "gravel wave" deposits in background).

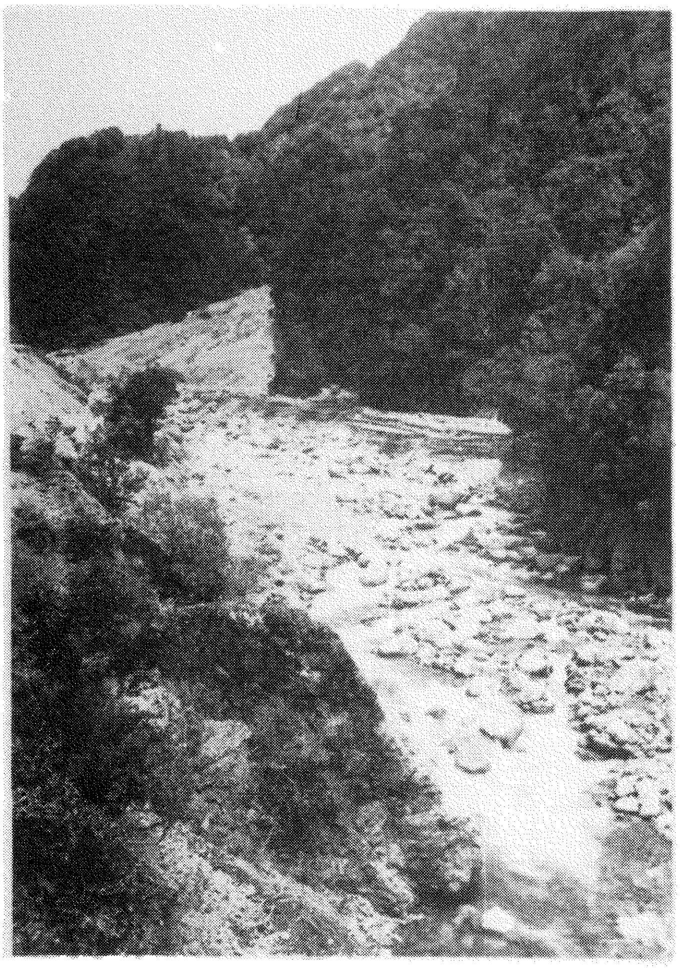


Figure 20: Otira River looking upstream towards a debris flow. Remnant gravel terrace (height 6–8m) deposited during December 1979 flood located on true left bank. (M.W.D. photo).

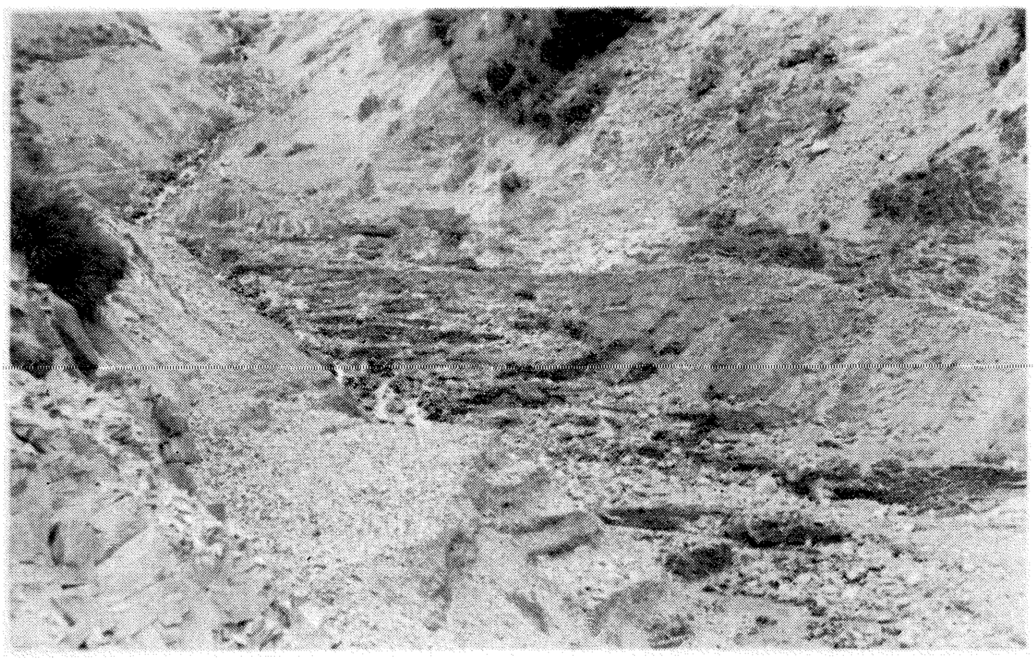


Figure 21: Remnant terraces following the passage of a "gravel wave" (or "slug" of gravel), Torlesse Catchment.

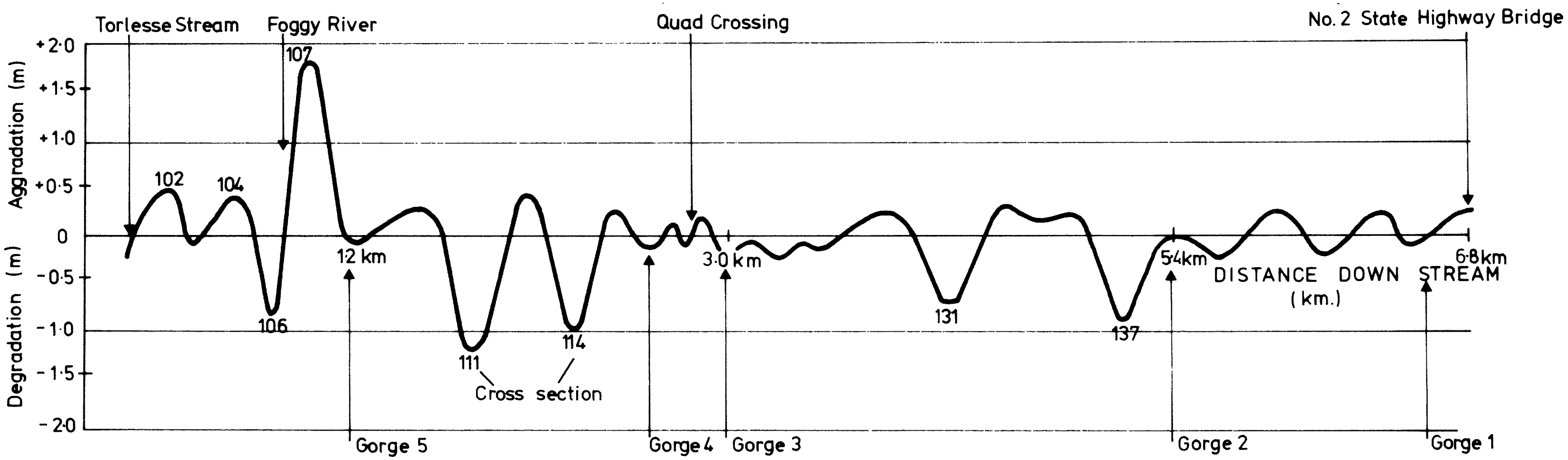


Figure 22: Mean bed level changes: Kowai River 1975–1980.
(total of 49 cross sections) (not to scale)

a structurally coherent slurry forms (very much resembling fresh wet concrete), which is capable of flowing rapidly downhill and transporting even large boulders in suspension." (Pierson 1980b). Without excessive sediment inputs sediment transport is initiated by the tractive force on the bed increasing to some threshold value as bed shear stress increases with flow. Thus the net result of the passage of a 'gravel wave' through a reach of river is a local rise in bed levels and an alteration in the nature of the flow regime, with turbulent clear flow changing to strongly discoloured 'planar' flow. This transition corresponds to the infilling of pools and a resultant increase in the effective energy gradient of the channel system (Hayward 1980 Appendix X1).

It is misleading to assume that a given cross-section has a given flow capacity as bed forms often change radically during the passage of a flood wave. This is particularly so in the upper reaches of steep confined gravel bed rivers. Experience in the Kowai River shows that water levels can rise rapidly, over 5 m in the upper reaches of such relatively small river systems, during the passage of flood waves through a confined reach. This often rapid rise is caused by the interaction of mobilised sediments with water, rather than by water alone. There is evidence for such high flood levels in such spatially separated rivers as the Foggy River (1951 flood), the headwaters of the Tamaki and Mangatewaiiti River (March 1975 cyclone, Mosely 1977), Otira Gorge (December 1979 floods, Figure 20) and several rivers in the Kaikoura area (March 1975 cyclone, Bell 1976).

As flow volumes decrease, bed levels tend to go through a rapid series of scour and fill cycles leaving behind remnant terracettes (Figure 21) as evidence of the flood wave passage.

The sorts of process described above typically occur in the upper catchment channels and transfer channels where flow spreading is limited by older terraces and side slopes. Indeed the very presence of lateral erodible terraces leads to the initiation of further influxes of sediment as these deposits are undercut with rising bed levels. Further downstream in the transition reaches, available channel width increases leading to a corresponding decrease in flood terrace height. Edge rounding, particle breakdown and increased access to new sources of fine sediments from bank erosion ensures a sufficient supply of fine sediments (<8mm diam.) to balance the loss arising from selective transport of fine sediments downstream. This supply of fine sediment sizes, may act as the catalyst which ensures that braided channels are maintained.

(ii) Long term (>5 years): Evidence for changes to riverbeds on this time scale comes from changes in cross-sectional areas, longitudinal profiles and aerial photographs as recorded by surveys at five yearly or greater intervals. Such surveys often indicate the presence of the 'gravel waves' referred to earlier. In many channels these 'waves' can be clearly observed, but cross-section surveys may lack the detail and intensity required to measure the scale of such processes.

Mean bed level changes of up to 4 metres have been measured in the upper catchment and transfer channels of the Waipawa River (Grant 1977), and similar changes are not uncommon for many alpine rivers and streams in both the North and South Islands. In the middle and lower reaches of rivers (transition and floodplain channels), mean bed levels have been observed to rise up to 1.0 m in critical reaches (see Figure 17). Figure 22 illustrates mean bed level changes which have occurred in the Kowai River between 1975 and 1980. As can be seen, the level of bed fluctuation tends to decrease with distance downstream. It has been primarily influenced over this relatively short time period, by the large volumes of sediment being eroded from riparian terrace deposits in the Foggy River (Figure 19), and also the decrease in channel slope and increase in channel width with distance downstream.

5. RECENT HISTORY AND SEDIMENT SOURCES OF THE KOWAI RIVER

RECENT HISTORY

To give a perspective on the present state of the Kowai River system, it is necessary to look at its past behaviour, particularly in response to man's influence over the last 600 - 700 years. In comparison with Paper B which will look at changes in the order of thousands of years, this section will study changes occurring over hundreds of years and, in particular, those occurring during the last 80 years. Data on the regime of the Kowai River at Limeworks Bridge is summarised for reference purposes in Table 6.

TABLE 6 : KOWAI RIVER REGIME : HYDROLOGIC PARAMETERS

A. Catchment Areas and local Channel Slopes

CATCHMENT	Area (km^2)	Channel Slope
Torlesse Stream Catchment at confluence with the Kowai R.	3.7	0.058
Kowai River Catchment at confluence with Foggy R.	16.0	0.035
Foggy River Catchment " " " Kowai R.	6.4	0.069
Kowai River Catchment at the Limeworks Bridge	84.2	0.016

B. Flow Regime at the Limeworks Bridge

* Two year dominant flow	Q2	120 m^3/sec
* Fifty year flow	Q50	373 m^3/sec
** Low flow (approx. 1 year in 10)		0.3 m^3/sec

C. Sediment Regime (Refer Table I, Part B)

Location in the Catchment	Sediment Size Parameters ('Wolman' Surface Sample Method)			
	D50 (Median)		D90 (ninety percent finer than this size)	
	Phi size	mm	Phi size	mm
Foggy River fan (confl. with Kowai R. Site 6)	-4.8φ	27.8	-6.9φ	119.4
Kowai River bed (u/s of Foggy R. confl. Site 5)	-4.6φ	24.2	-7.1φ	137.2
Kowai River bed (d/s of Foggy R. confl. Site 7)	-4.6φ	24.2	-6.4φ	84.4
Kowai River bed (Limeworks bridge Site 9)	-4.3φ	19.6	-6.6φ	97.0

* based on M.W.D. T.M.61 Calculation

** based on Malven County Water Race records, river actually dry at the bridge due to flow all abstracted by water supply intake upstream.

On the basis of evidence available (Molloy 1964, 1967, 1969), it appears as though some 1000 years ago the Kowai River Catchment was forested, the timber line being about 1500 m elevation with alpine shrubs grading into gravel scree slopes above this altitude. The forest was predominantly beech (*Nothofagus* spp.), but podocarps such as rimu (*Dacrydium cupressinum*), miro (*Podocarpus ferrugineus*) and totara (*Podocarpus totara*) did occur at several sites along the foothills in the high-rainfall, medium-altitude zones (1000 - 2000 mm rainfall; 300 - 700 m altitude).

There is now no clear evidence as to the extent to which riverbeds would have been forested. They are sites which, because of their erosional history have meant that relict soil and vegetation remains have not been preserved. However, it seems reasonable to assume that about 1000 years ago they would have at least supported a scrub vegetation with scattered forest pockets. It is postulated that the riverbeds had two or three narrow channels from 5 to 10 metres in width, winding through a dense mat of tree and shrub roots. Occasional areas of fresh gravel would have spread through the forest floor with the passage of flood waves. The floodplain and riparian zone itself probably supported dense stands of Kowhai (*Sophora* spp.), hence the use of "Kowhai" as a name for New Zealand rivers. It could also have supported a mixture of podocarps, and other hardy trees and shrubs such as cabbage trees (*Cordyline banksii*), ribbonwoods (*Hoheria lyalli*), broadleafs (*Griselinia littoralis*), *Coprosmas* spp., *Cassinia* spp., and *Olearia* spp. Many of these species can still be seen growing in isolated pockets, in both the Kowai and adjacent river valleys even under the now adverse conditions of wind exposure, stock grazing, and damage by noxious animals (Douglass et al 1979).

Molloy (1977) summarises available knowledge of the fire history of part of inland Canterbury. This evidence points to widespread forest destruction between 500 and 1000 years ago. This destruction is generally attributed to Polynesian fires, though whether by accident or design is uncertain. It is probable that there were changes in some channel patterns following these fires, the rotting of tree roots, and the reworking of the now deforested floodplains by floods under the new hydrologic regime. It is postulated that channel form altered from several narrow meandering channels to a 'braided' channel form with many inter-connected channels. These channels continually reworked a wide floodplain composed of gravels interspersed with deposits of fine sediments and islands of tussock grassland.

Additional evidence for this deduction comes from studies of similar changes in channel behaviour following forest clearance on steep alluvial floodplains and fans in other areas of New Zealand. (Brougham 1978). The timing of this change in channel form varies within New Zealand according to the timing of forest clearance. In many areas of the South Island high country, it is probable that this change was well established before the advent of European pastoralism in the 1850s and 1860s. Molloy (1962) describes a picture of rapid accelerated erosion well before European occupancy: "Soils were removed wholly or in part, screes were extended to lower altitudes and fans and floodplains were rejuvenated by a fresh supply of rock waste...." It should be noted, however, that such recent changes (< 1000 years) in erosion features river and morphology are postulated to be true only for specific sites within high country catchments. Tonkin et al (1981) have demonstrated that most screes in the alpine areas of the South Island predate these more recent changes.

What remained of the vegetation by 1860 was systematically, and at times accidentally, cleared by European settlers, once again by fire and later with the axe. The valuable podocarp hardwoods went first for timber, as did the kowhai tree, prized for use as ground durable fence posts. The river floodplains in headwater valleys, largely devoid of forest by about the 1850s, were soon heavily stocked with sheep. Milliken (pers. comm.) describes the flood plains of about 1920, as being expanses of tussock and matagouri encompassing a riverbed which by then was between 50 and 200 metres wide. At this time several thousand sheep were grazed for short periods in the riverbed until noxious weeds (broom, blackberry, and gorse) began to reduce the available grazing area. This latest vegetation change has occurred over the past 50 years, becoming particularly pronounced in the last 20 years. Figure 23 illustrates this vegetation type, while Figure 24 illustrates the spread of broom and gorse into bermlands since 1943.

The Kowai River channels, since about 1970, appear to have become confined, partly because of the stabilising effect of broom and gorse on the riverbed. The presence of these noxious weeds has reduced grazing pressure in the sensitive riparian zone and allowed some floodplains to revegetate. Evans (1977) discusses the role of noxious weeds on berm lands. Table 7 gives a summary of changes in the active Kowai river bed since 1943 in

TABLE 7: SUMMARY OF CHANGES IN AREA OF ACTIVE RIVERBED, KOWAI RIVER 1943-1980.

(from No.2 to No.1 bridges, approx. 8.0 km - see Figure 25).

Date of Aerial Photo	Floodplain Area (incl. active bed) (ha)	Area of Active River Bed (ha)	Mean Channel Width (M)	Percentage Active Bed : Floodplain (%)
1943	166.8	54.9	68	32.9
1960	171.3	69.2	87	40.3
1965-66*	183.4	81.9	102	44.6
1975	172.7	35.9	45	20.8
1980	167.4	59.8	75	35.7
Mean Values	172.3	60.3	75	34.9

* Due to a corner of the river bed missing from the 1965 photographs, this area was derived from interpretation of channel patterns still visible on the 1975 photographs.

Figure 23: Broom and gorse vegetation growing on Kowai River berm land looking upstream towards Malvern County water intake site (1980).

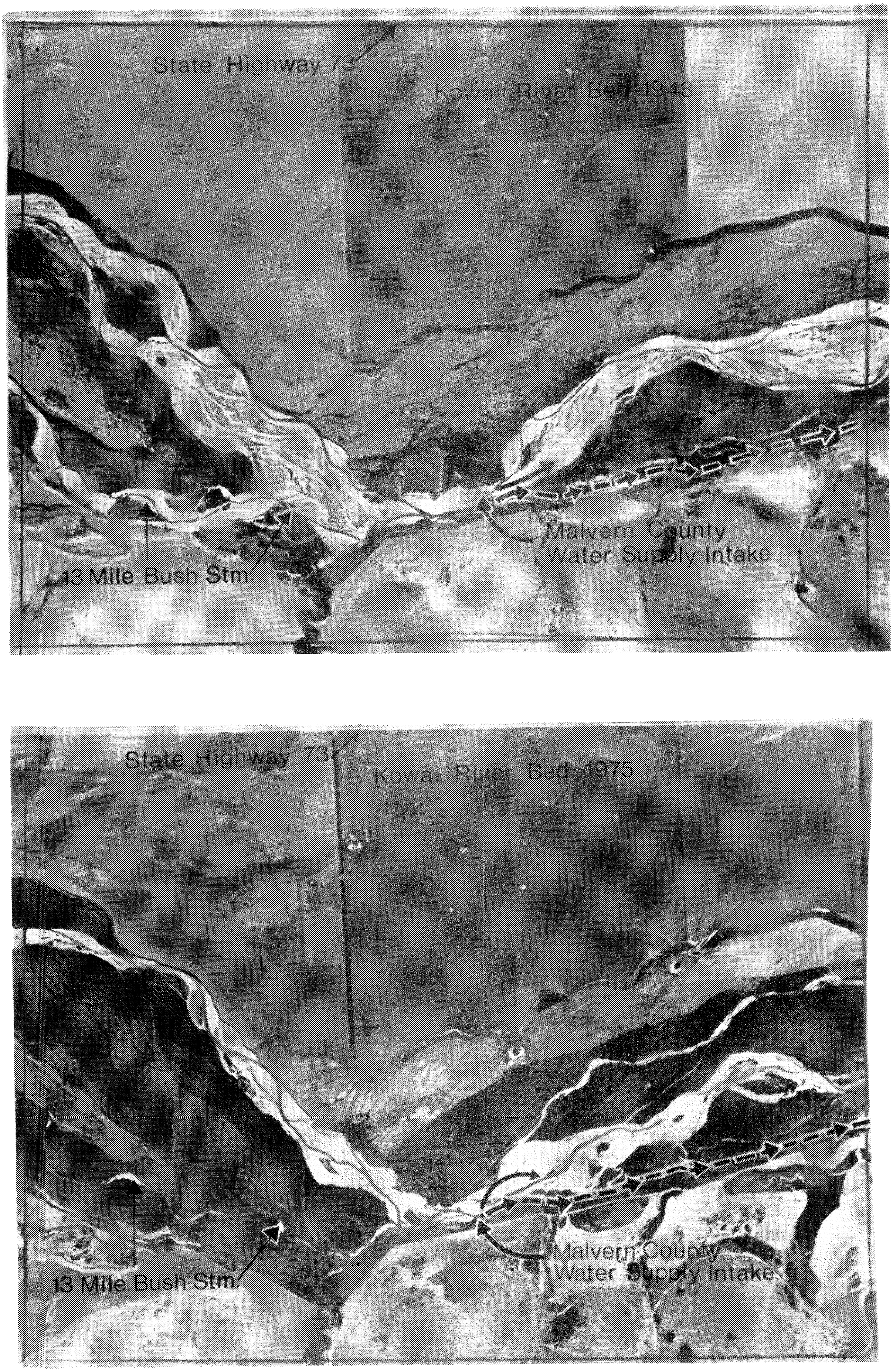


Figure 24: Kowai riverbed vegetation changes 1943–1975 – the dark tones are primarily broom with scattered gorse.

the reach from State Highway 73, No.2 bridge to No.1 bridge (Limeworks bridge). Figure 25 illustrates active channel instability for a reach of river downstream of the Ben More Bridge.

Recently a policy of spraying the riverbeds to kill off noxious weeds, combined with bulldozing dead scrub and oversowing, has led to heavier grazing of the middle reaches of the Kowai River (Figures 26, 27). This development has led directly to several areas of former scrub and noxious weeds being replaced by gravel and silt during floods. Several hectares of such riverbed berm land have been lost to the riverbed in the last two to three years during floods which had 'return periods' of about three to six months. With ground cover on the developed berms comprising grasses, regenerating broom,and dead scrub there is only limited root material holding the floodplain together. The flushing out of the finer-sized sediments (< 8 mm diameter) during 'freshes' leaves only the coarser gravels to deposit in the central areas of the riverbed. Gravel deposition may extend onto remnants of the floodplain during the peaks of flood waves. This process ensures the continuation, and in some reaches the extension, of the braiding of river channels, which in turn attack banks and inundate the recently developed rough pasture.

Table 8 gives a summary of changes to active bed widths and gravel storage volumes from 1975 to 1980. This data is taken from a more detailed study by Adamson (1980).

From Table 8 the more important trends occurring in the Kowai system can be summarised as follows:

(i) Upstream of the Foggy/Kowai confluence the riverbed tends to exhibit cycles of scour and fill. Localised bed widening may occur through undermining of side slopes, leading to development of a 'gravel wave' immediately downstream.

(ii) Immediately upstream and downstream of the Foggy/Kowai confluence local fluctuations of up to 1.8 m in bed level have occurred, while further downstream there has been a trend towards increasing active bed width through erosion of riparian deposits including the scouring of temporarily stored gravels in wider sweeps of the river.

TABLE 8: CHANGES IN ACTIVE BED WIDTHS AND GRAVEL STORAGE KOWAI RIVER 1975-80
(Data from cross-section surveys, Adamson 1980)

Reach location (see Fig.3, Paper A)	Length of reach (M) (No. of sections)	Mean change in active bed width (M)	Approx. changes in gravel storage (M^3)
KOWAI RIVER			
Torlesse Stream Confl. to Foggy River Confl.	900 (8)	+ 0.9*	- **
Foggy River Confl. to Quod Crossing	1500 (17)	+ 0.6	- 26.067
Quod Crossing to No. 2 Gorge	2000 (17)	+ 8.8	- 20.221
No. 2 Gorge to No. 2 Bridge	1200 (7)	+ 10.4	- 13.161
No. 2 Bridge to No. 1 Bridge	8000 (10)	+ 33.9***	No data
FOGGY RIVER			
Castle Stream Confl. to Foggy Fan	2000 (17)	+ 46.6	+ 55.704

* Using total available bed width in flood ('effective channel width').

** No meaningful volumetric changes could be calculated for this reach due to wide variations in bed widths between surveys.

*** Determined from aerial photographs.

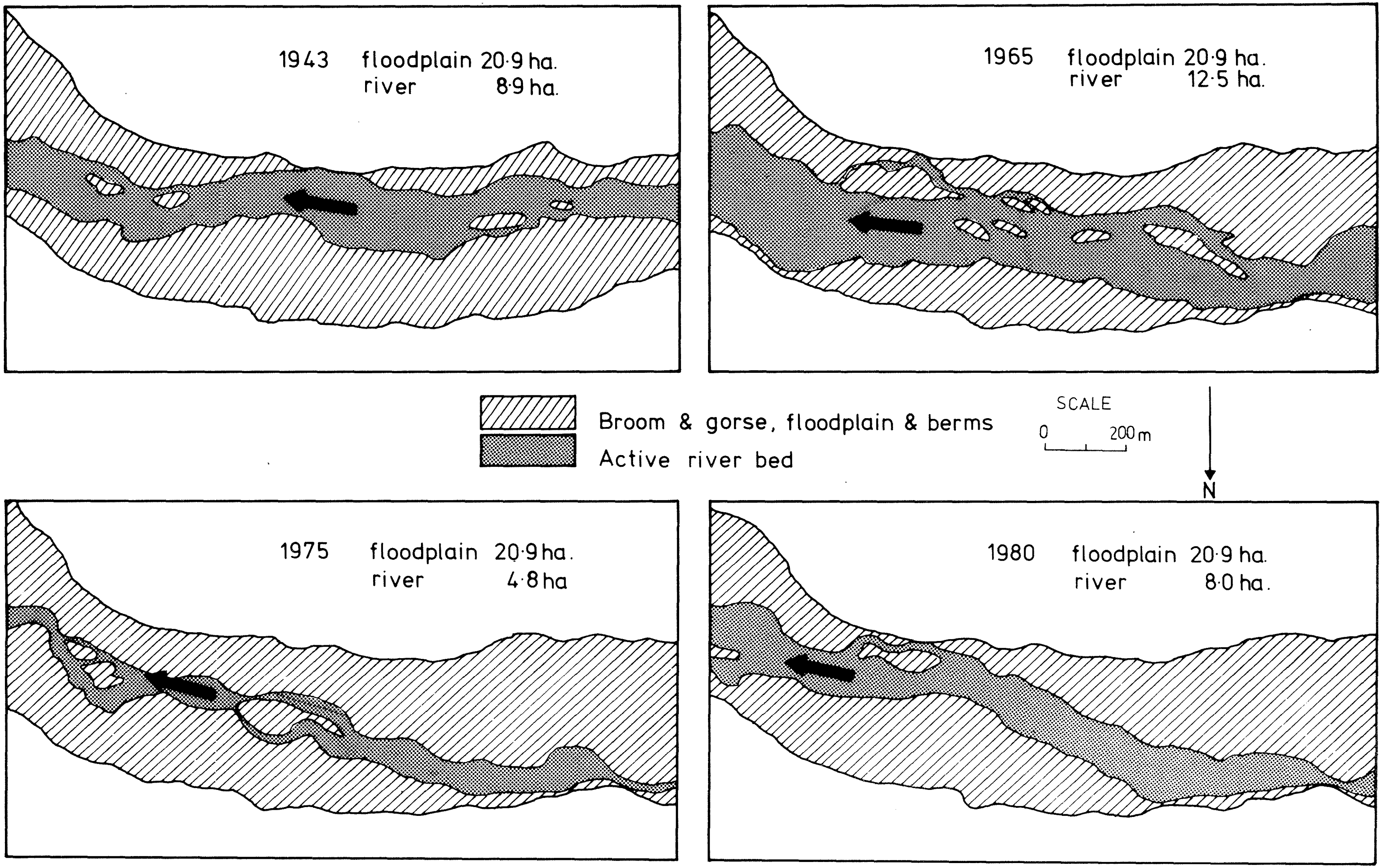


Figure 25: Changes in Kowai riverbed downstream of the Ben More bridge: 1943 to 1980.

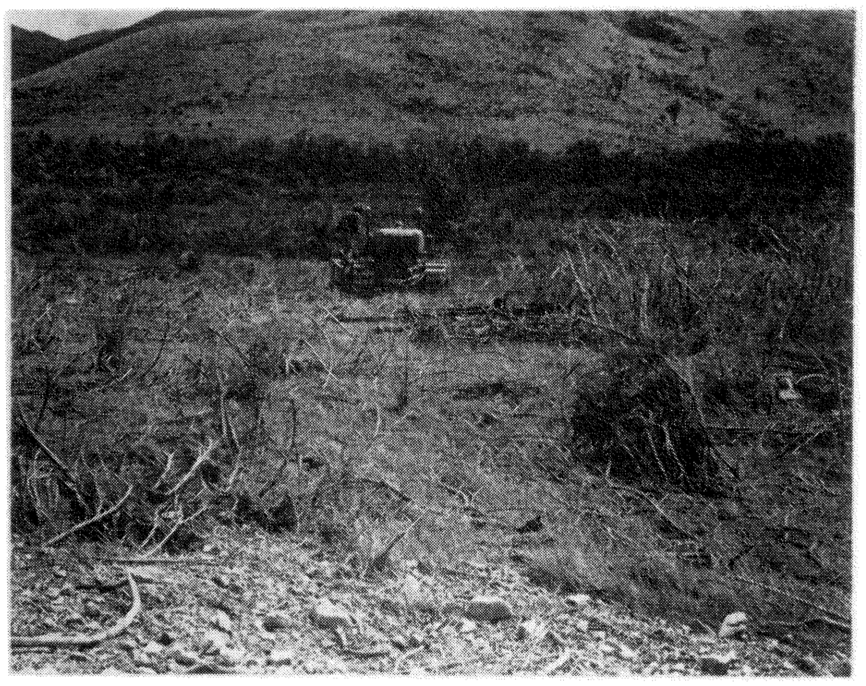


Figure 26: Kowai riverbed development: crushing broom and gorse: December 1979.

Figure 27: Kowai riverbed development: grazing after noxious weed spraying December 1979.

(iii) The Foggy River bed tends to aggrade and widen its active bed, mainly through erosion and reworking of riparian terrace deposits related to earlier large floods such as those discussed in section 4. However, if total channel storage is considered, (active channel plus older riparian terrace deposits), there is a net loss of stored sediments from this tributary.

Because of the large changes in active bed width occurring over relatively short periods of time, it is not possible to define an 'effective bed width' as has been done for the Waimakariri River system (Griffiths 1979). Changes in gravel storage volume are calculated by averaging the active bed widths for each survey and multiplying by the average change in mean bed levels for each reach. This figure is then multiplied by the distance between the end sections. The final figure obtained therefore includes sediment eroded or deposited in the river bed itself and also that from riparian bank erosion including that of partly vegetated gravel bars and islands. While the data presented is approximate, it nevertheless gives a valid picture of the general trend of sediment movement over the survey period. Future surveys should establish 'effective widths' covering the whole floodplain, (e.g. the area accessible to the river in major flood with a return period of 50 years or more).

The net result of floodplain development for grazing, without river management works has been a wide variation over time in the percentage of the river floodplain occupied by the active river bed (20.8 - 44.6%). In addition there has probably been net loss of the finer sediments, carried mainly on suspension, during 'freshes' and floods.

RIPARIAN SEDIMENT SUPPLY AND CHANNEL FORM

For the purposes of this paper, riparian sediment sources will be considered as being those able to be mobilised by the river during flows up to those of a fifty year return period. This includes berm land and accessible portions of the unprotected floodplain.

Sources of riparian sediment can be grouped into four major zones as summarised in Table 9 and illustrated by Figures 28 - 32. These zones, in turn, can be related to the components of a drainage system as identified in Figure 15, although gradations occur between zones. In order

TABLE 9: SOURCES OF RIPARIAN SEDIMENT

Classification of Land Unit and Description Unit and Description of Stream Morphology	Source of Riparian Sediment (excl. in-channel particle breakdown)	Reference to Illustration
Zone 1: High Country Catchment Channels - often ephemeral streams with very steep slopes (>.06) - often originate as mid-slope springs at rock outcrops - general narrow bouldery beds less than about 20m wide	- head water gulleys - riparian slips - rock outcrops - steep, weathered slopes of scree and exposed subsoil	Figure 28
Zone 2: Hill and High Country Transfer Channels - often confined by valley sides and rock outcrops - perennial flows with steep slopes (>0.015) - bed width variable 5-500m. Occasional large bays where gravels are temporarily stored. Steep narrow gorges between braided reaches	- low altitude scree slopes - old and recent fans - erosion of terraces both old and vegetated - reworking of recent flood wave deposits	Figure 29
Zone 3: Foothills: Upper Floodplain ('valley throat') Transition Channels - often characterised by a break in channel slope and a widening of the floodplain width - braided very unstable riverbed often significantly higher in the middle than the sides - channel patterns fluctuate between meandering and braided depending on flood frequency and sediment inputs upstream - active riverbed usually very wide (200m+) - slopes typically 0.005 - 0.025, but can vary widely	- terrace and bank erosion - erosion of partly vegetated islands in the riverbed	Figure 30, 31

TABLE 9 Contd:

Classification of Land Unit and Description Unit and Description of Stream Morphology	Source of Riparian Sediment (excl. in-channel particle breakdown)	Reference to Illustration
Zone 4: <u>Floodplain Channels</u> - often at the confluence with the parent river or upstream of the tidal zone at the coast - can occur at the intersection of 2 alluvial outwash surfaces - wide braided river beds on moderate channel slopes typically 0.005 to 0.025 but vary widely - channels often perched above surrounding flood plain particularly if flows have been restricted for many years by stopbanks - floods are often unconfined and can spread into other neighbouring channels draining the alluvial floodplain	- reworking older islands in the riverbed - bank erosion	Figure 32

to establish the channel patterns and forms of a river system and to allow classification in terms of sediment source zones, a thorough study of historic aerial photographs, vegetation changes, and sediment movement patterns over as many years as possible is necessary.

The location of these components or zones with respect to the Kowai system is shown on Figure 33. Zone 1 corresponds to the high country catchment channels. Zone 2 (transfer channels) corresponds to all the riverbeds, including floodplains or berms, from headwater streams to the Waimakariri River confluence,but excluding reaches defined as zones 3 and 4. Zones 3 and 4 are not fully developed in the Kowai system as the main riverbed acts primarily as a transfer channel with temporary storage of sediments within its entrenched floodplain. Reaches indicated as zone 3 type (transition channels) in Figure 33, are those that fluctuate between transfer and floodplain channels. This fluctuation is dependent on the rate of sediment supply from upstream reaches during floods. Reaches conforming to the zone 4 type (floodplains and fans) include the confluence of the Kowai with Foggy River, 13 Mile Bush Stream and the Waimakariri River.

In the upper catchment of the Kowai River, the bulk of the gravels are derived from the Foggy River catchment. This catchment is an eroded,steep, confined, high-country valley with sparse riparian vegetation. Large volumes of gravel are held in 'temporary' storage in the valley floor (Figure 19), with the finer fractions being preferentially flushed downstream. The stored gravels are derived, in the main, from the undercutting of old slope or fan deposits together with the erosion of sediments that were partially bound by vegetation on the valley floors. The combination of very steep slopes and the confined nature of the riverbeds in these upper catchment areas allows the full range of gravel sizes to be transported during intense rainstorms. Such rainstorms have had, and will continue to have, a significant effect on channel morphology in the upper catchments and also on the downstream channel patterns.

In April 1951 a prolonged rainstorm affected the eastern foothills of the Southern Alps, the following quote being from a local observer: "The heaviest flood I can remember. All roads,bridges and railway(...) washed away. Extensive slips on hills..." (N.Z. Met. Service 1951). Rainfall data from Mt Torlesse Station (6 km west of Springfield) gave a total precipitation of 282 mm over 48 hours with a maximum 24 hour fall of 166 mm. Evidence obtained from local

Figure 28: Upper catchment sediment sources: weathering of fresh rock fragments supplying screes: Kowai river headwaters.

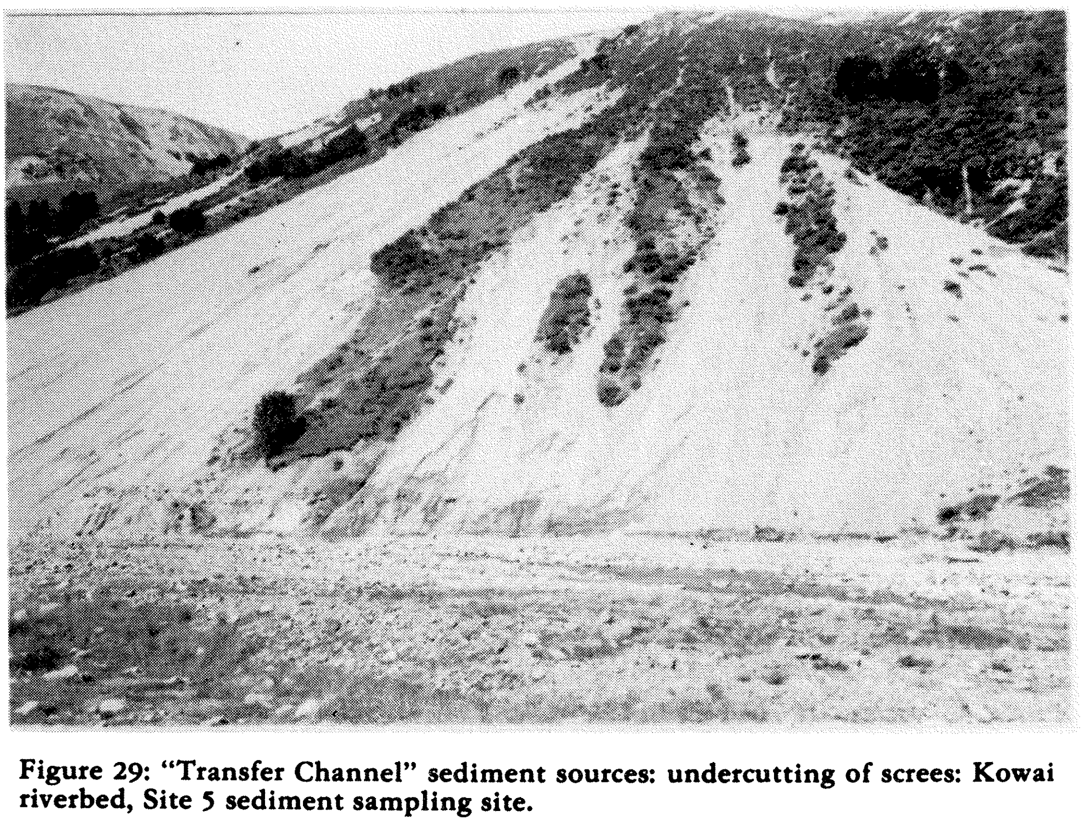


Figure 29: "Transfer Channel" sediment sources: undercutting of screes: Kowai riverbed, Site 5 sediment sampling site.

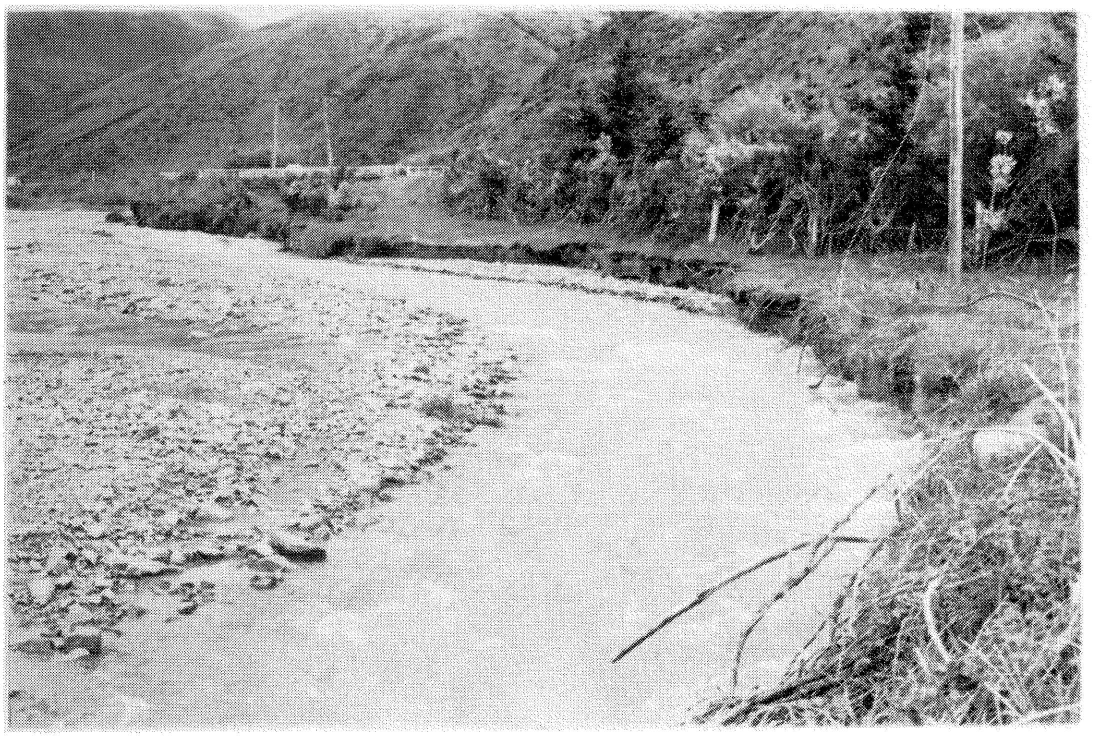


Figure 30: "Transition Channel" sediment source: erosion of fertile floodplain: Kowai riverbed downstream of No. 2 bridge: (note: telephone pole washed out).

Figure 31: "Transition Channel" sediment source: erosion of old outwash terrace approximately 10m high: (note: provides a continual supply of sediment to the County Water Supply intake 1km downstream).

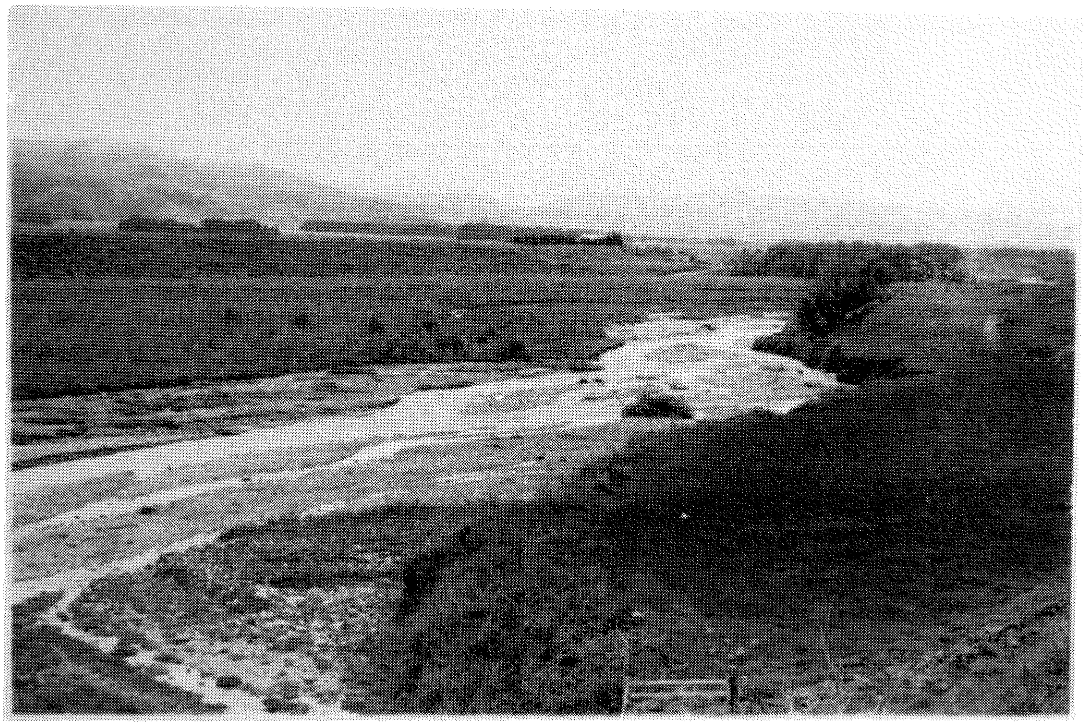


Figure 32: Partly developed "floodplain channel": Kowai river looking downstream towards the Limeworks Bridge (note: broom covered berm entrenched in old outwash surface).

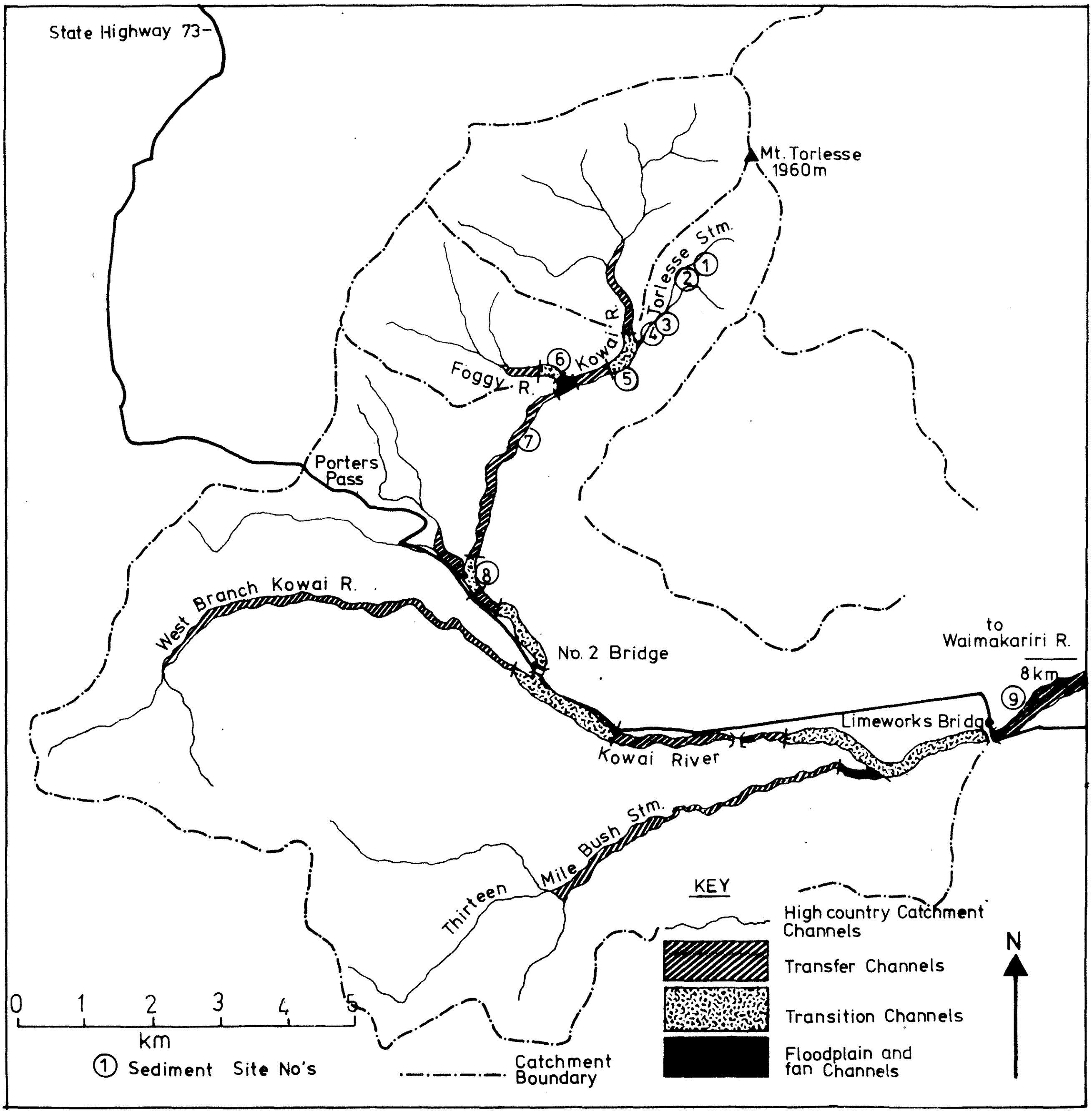


Figure 33: Location of channel zones within the Kowai river system: (note: location of sediment sampling sites).

Figure 34: An apparently "stable channel" reach in the Kowai river downstream of the Ben More bridge: (note: coarser gravels along the banks and even channel meander pattern).

farmers, field observations, and meteorological data suggests that the April 1951 event was responsible for major reworking and redeposition of riparian flood terraces, fans, and screes throughout the upper catchment channels. Transfer channels were widened and large volumes of gravel flushed downstream. Within the Foggy River channel some of the terraces, apparently deposited at this time, are up to 5 metres in height. The impact of the 1951 storm on the sediment regime of the river system is still apparent in the supply of sediment to the transfer and transition channels from present day erosion and reworking of the riparian terrace deposits dating from this event.

In the reach upstream and downstream of the Kowai No.2 bridge, the valley floor widens, slopes decrease slightly and floodplains (river flats) develop as the coarser sediments are deposited (Figure 27). Such riverbed features characterise the 'middle reach' of the river, shown as transfer and transition channels in Figure 33.

There is no alluvial fan development in the main Kowai River channel system, other than small scale development of gravel wave deposits similar to a fan deposit within the wider transitional channel reaches.

To summarise, the continual addition of gravel, particularly fine gravels, sands and silts, may act as a catalyst to maintain the unstable braided riverbed downstream of the Foggy River/Kowai River confluence. Where the river has a form and width suited to the passage of the water and sediment supplied to it from upstream reaches, then bed forms appear to remain stable for several years (Figure 34). The presence of local variations in bank stability, (rock outcrops, vigorous vegetation, compacted clay banks, artificial structures) can often induce local downstream stability, within what may be a generally unstable reach of river. In the case of the reach of river shown in Figure 34, the active riverbed is confined by the Ben More bridge, 100 m upstream. Upstream of the bridge the active channel width is up to 100 m narrowing to approximately 20 m width at the bridge itself.

From the study of the Kowai River system and other similar rivers in N.Z. it appears that the nature of the channel zones discussed is almost certainly influenced by the geologic and climatic settings of the catchment, a relationship in need of more investigation.

6. RIVER AND RIPARIAN LAND MANAGEMENT OBJECTIVES

VALUES

The use of natural resources often creates a conflict of interests. In the case of the use of water and fertile lands associated with it, this conflict can result in the resources of water and soil being utilised at well below their potential productivity, accompanied by a deterioration in water and environmental quality.

There is no single measure of environmental or water 'quality' but there are several parameters which indicate a degree of quality for water and its associated environment. The level of disolved oxygen, biological oxygen demands, frequency and sediment concentration of flows, water temperature and toxic nutrient levels all contribute towards 'water quality'. The presence and health of fish species, the presence of deep swimming holes with good quality water, the diversity and condition of indigenous and exotic vegetation along a stream, and the fertility of the floodplain soils also contribute towards the quality of the river environment. In order to manage such a rich and varied resource, a careful study of the interaction between natural and man-induced processes is necessary. There will never be the perfect, balanced solution, but it is important that all aspects of potential use, and the effect of this use on other natural processes are evaluated.

A soundly based management programme for berm and riparian land use is a common need in the development of all river systems. This is particularly true in relation to the maintenance or improvement of water quality (McColl et al 1981). Conway (1979) emphasises the value of riparian strips to the maintenance of water quality in production forest environments. Where man has failed in the past to manage wisely the resources of water and soil, the consequence has always been a decrease in water and soil quality, and a decline in productivity. The latter results both directly from an increase in the natural rate of erosion and sedimentation processes within catchments, and indirectly through impaired drainage outfalls and the decreased availability of river flows for water and power supply schemes, wildlife and recreation. Some of our ground water resources may be more sensitive to changing river regimes than is yet realised. During low flow periods, the management of river channels in known groundwater recharge zones could be of vital importance (Takahashi et al 1974; North Canterbury Catchment Board, 1980). Mandel (1974) suggested that rivers crossing the Canterbury Plains are a primary source of groundwater recharge. This subject needs further investigation.

Many of New Zealand's gravel bed rivers, and with their associated berm and riparian lands, could at present be classified as 'marginal lands', for it is marginally economic to restore them to their potential productivity and quality using the present criterion for generating a 10% internal rate of return on invested money It then becomes an important task to define objectives for river management in terms of more than river control works. alone.

Knowledge of the components of a river system, and the processes operating within it, will allow the most effective methods of riverbed and riparian land management to be devised, enabling the most efficient use of government funds for soil and water conservation works. If protective works in river floodplains (i.e. channels and berm land) were to be integrated into farm/forestry plans, the land which is now costing money to protect could, in some cases, generate more than sufficient income to cover its long term development (Green 1967; Pricket 1973; Nelson 1981).

While short term productivity on riverbed leases may increase through land development without river management works (i.e. increased stocking rates), longer term (5 years plus) potential productivity and quality of the riverbed and water resource will be impaired. The problem faced by farmers with river flats is how to increase productivity and control noxious weeds without increasing the risk of bank erosion and flooding. Local Catchment Authorities, County Councils and the Lands and Survey Department have an important role to play here in providing direction and incentitives for farmers to develop such land in a balanced way, combining sound principles of soil and water conservation, with farm and forestry operations. Where this approach is adopted it is likely that wildlife and recreational interests could benefit in addition to the farmer and landowner.

DESIGNING A RIVER MANAGEMENT SCHEME

Proposals which may change existing land use along a river should be designed by a team representing the interests of the people affected by a scheme and those who may be involved in its implementation. Such a team could include: a design engineer, a soil conservator, an earth scientist, a forester, a landscape architect, an agricultural economist and a representative from the local people living in the area affected. The investigation and design of the South-east Ruahine Scheme was based on such an inter-disciplinary approach. While the reasons for including most members of the team are self-evident some comment is warranted concerning the others.

To make the best decision with the available data, a method of comparing alternative management proposals for a floodplain is necessary hence the need for a trained economist. An economic evaluation of proposed schemes is often carried out *after* a scheme has been designed. In many cases, an objective for river and floodplain management should be to *include* such economic evaluation as part of the investigation and design process. Possible objections to a scheme on aesthetic grounds can be met by including the services of a suitably trained landscape architect. Although initially more expensive, this should result in fewer objections to the final proposals.

A major problem with a scheme based on multiple riparian land use principles is in selling its benefits to the local farmers, hence the importance of including local representatives. Further, no effort should be spared in the education of all affected people as to the need for, and the short and long term benefits from, the proposed river management scheme.

GENERAL OBJECTIVES FOR BERM AND RIPARIAN DEVELOPMENT AND CONSERVATION

The following principles and objectives should form the basis of river management schemes where schemes are considered desirable. Clearly they are not the final statement on this subject, but are presented to provide a framework to build on. They are primarily addressed to the problem of braided gravel riverbed management for those reaches where rivers and streams emerge from the hill and high country on to their outwash floodplains.

1. To design and develop a channel capable of passing flows of water and sediment without frequent overflows onto the river's floodplain, while minimising excessive inflows of sediment to the river from riparian erosion processes (i.e. those inflows which contribute to aggradation problems).
2. To manage the gravel resources of the riverbed to the benefit of the overall river management scheme limiting, where practical and desirable, the downstream movement of gravel into the meandering silt-phase channel system.

3. To design and develop land use practices on the berm and riparian land which can withstand overflows of water and sediment with a minimum of damage, and to control the spread of those overflows to the level of protection required for that reach of river.
4. To zone the floodplain land tenure according to a system of 'levels of risk' from erosion, deposition and flooding, and make the necessary changes to the legal title and conditions of use of such land, in accordance with these risks.
5. To protect any structures and services on the floodplain which are essential for the productive use of the floodplain in accordance with the objectives listed above.
6. To maintain or improve the quality of the water passing through the floodplain and to maintain or improve the quality of the soil and vegetation on the floodplain.
7. To safeguard and conserve wildlife habitats where practical including necessary wetlands and indigenous forest remnants; to maintain such minimum flows of water as are found to be necessary for fish, wildlife,and recreational uses,and to provide access and protection for sites suited to the recreation needs of the area.

Objectives 1, 2,and 3 form the primary objectives of river and floodplain management. If these are carried out with due consideration for the unique environment of the floodplain, the remaining 4 objectives should be fulfilled.

7. TECHNIQUES OF RIPARIAN LAND MANAGEMENT

REVIEW OF PROBLEMS AND PRESENT PRACTICES

The present practices of riparian land management must be seen in the context of the particular problems that occur within the three major components of a river system.

i) Upper Catchment Channels

In general, the first priority for work in these areas of hill and high country has been to maintain or improve existing vegetation and to control noxious weeds and animals. More recently, retirement of large areas of high country from grazing by domestic stock has been implemented with the object of conserving high altitude vegetation. Control of grazing, whether by domestic stock or noxious animals, will be a continuing problem for future management. The question of noxious weeds is a difficult one as gorse and broom are virtually the only vigorous woody colonisers in many riverbeds and help stabilize loose gravel banks. A case could be made for the retention of such plants along a riparian strip until such time as more suitable planting can be established. The South Canterbury Catchment Board has made recommendations to plant berm lands with productive tree species as time and funds permit, but noxious weeds are considered at least marginally effective in berm stabilisation in the meantime (Evans 1977).

Limited work on scree and gully stabilisation is carried out typically using revegetation techniques integrated with small structures such as debris dams and terracing (Ministry of Works 1973, see also Figure 35). Stream control works are carried out to protect roads, bridges, buildings and fertile river flats. Afforestation for soil conservation and production mainly using *Pinus radiata* is becoming common policy on unstable and marginally productive catchments. A problem which needs specific study in this regard is the effect of afforestation or deforestation on slope stability and downstream channel behaviour. Similarly slope stabilization measures often do not allow for undercutting of the base of the slope by stream erosion. Policies set for upper catchment land uses may have an important long term effect on downstream channel stability and water yield (Pearce 1979), but each catchment requires separate study because of its unique characteristics of rock type, soils, vegetation, and climatic setting.

(ii) Transfer Channels

In the transfer channels, the main problem which may require treatment is to limit, where practical, the river's access to riparian sediment deposits. Most work on such steep, gravel-bed rivers has been confined to isolated bank protection works and planting of old riverbed and terrace areas in willows, poplars, and in a few cases, other productive tree species.

'Gravel traps' have been built in the upper reaches of a few rivers in an attempt to limit the rate of downstream sediment movement and riparian erosion. These consist of debris fences across the bed with mass plantings of willow and poplars, alders and other suitable species (Figure 36). With consistent maintenance of plantings and debris fences, some success

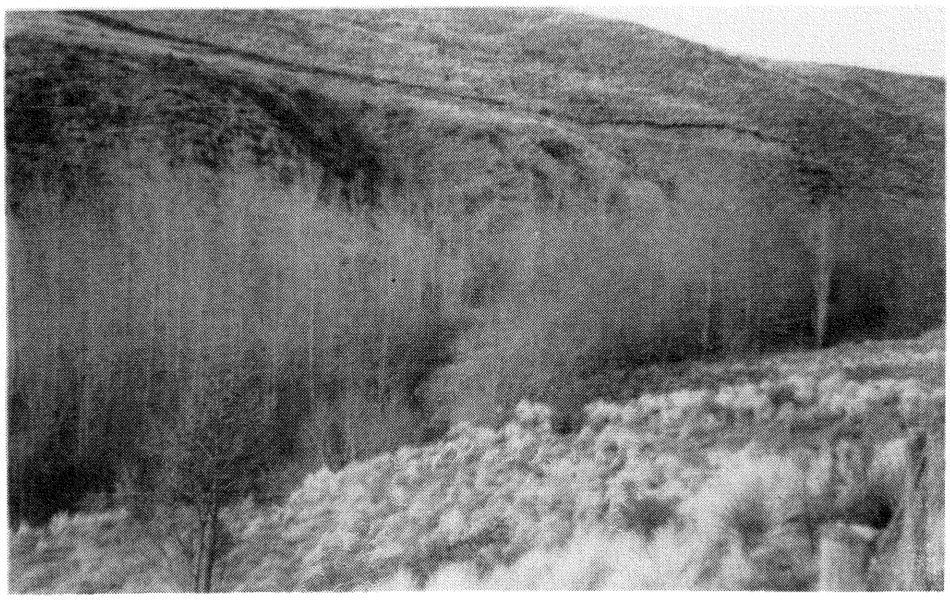


Figure 35: Gully control measures in Firewood Stream, Mt Dobson, eight years after remedial measures. Treatment includes waratah and netting fences with plantings of poplar and willow. Some native regeneration.

Figure 36: Gravel 'trap', Cowan Street, Opihi Catchment. Plantings include poplars, alders and willows in conjunction with fencing.

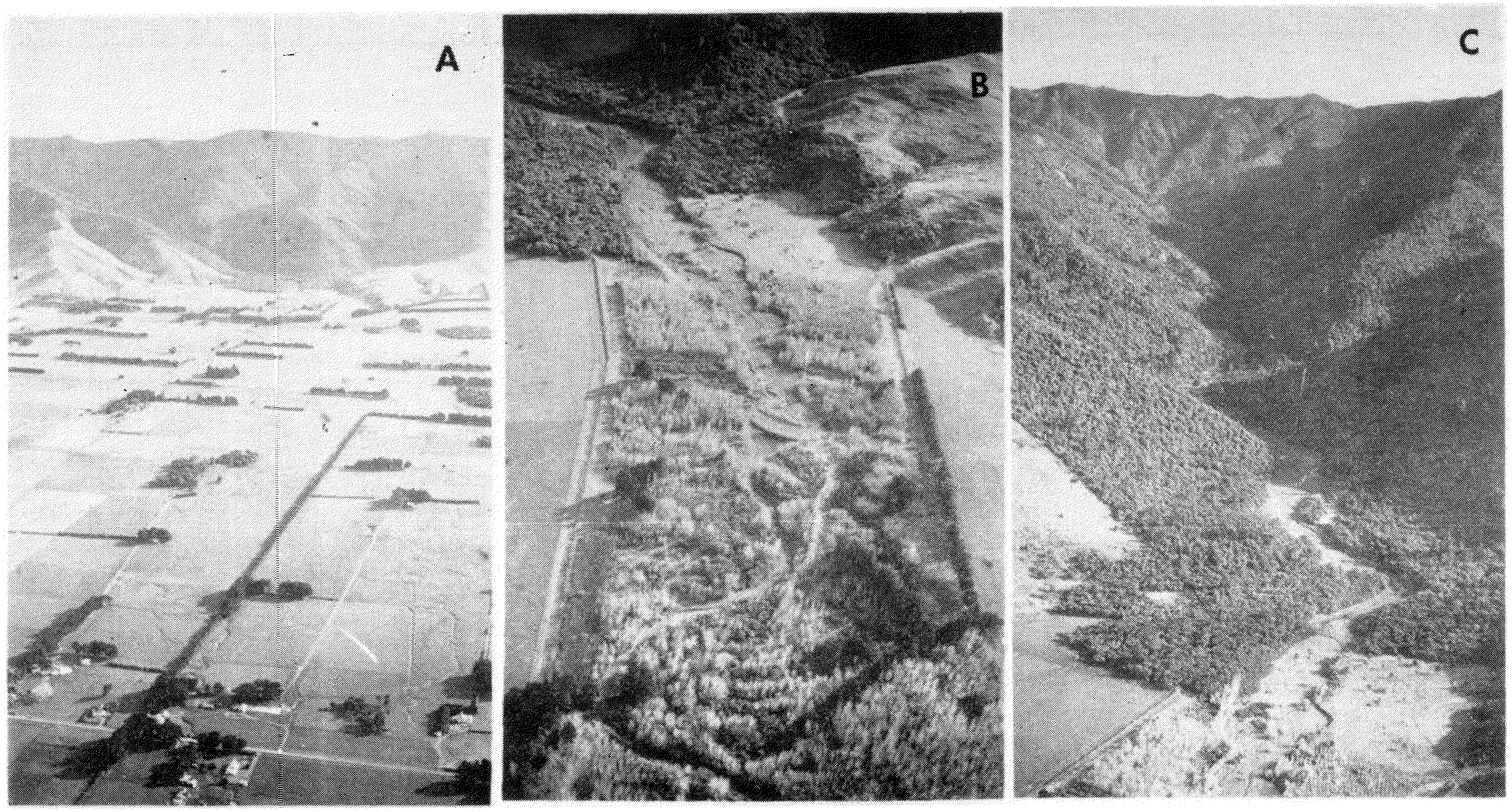


Figure 37: Kumeti Gravel Reserve, a) Kumeti floodplain, with reserve located in distant foreground. b) Reserve, excluding downstream end with grade control weirs. Note the gravel diversion dam in centre and stop-banking at sides. Plantings include poplars, willows and pinus radiata with native revegetation in foreground. c) Contributing catchment for reserve with Ruahine Range in background. (M.P. Mosley photo).

has been achieved in filtering out coarse sediments (> 8-16 mm gravels) at sites with channel slopes less than approximately 0.02 and catchment areas less than approximately 50 km^2.

Water supply intakes tend to be sited either along rock banks or incorporating some form of weir to stabilise bed levels. Infiltration pipes buried below the riverbed have been used on some rural water supply scheme intakes where the channel is unstable and surface flows unreliable. These have proved successful, requiring minimal maintenance (Wise pers. comm.). It is probable that additional stable sites will be required for water supply intakes (Blakely et al 1981).

(iii) Transition and Floodplain Channels

In the transition reach ('valley throat'; Mosely, 1978) it is possible to carry out limited river management works, primarily because energy gradients (i.e. slopes) tend to decrease as valley floors widen allowing floods to spread, depositing sediment in waves of coarser gravels. From these channels, often the entrenched upper reaches of alluvial fans (Figure 23c), rivers flow out across unconfined alluvial fans and floodplains.

In these sections of a river, design and development of control reaches and the management of riparian land uses appear to be key problems at present. The major works that have been carried out on nearly all the major rivers in New Zealand are within these reaches as it is here that damage has been great enough to justify such expense. Problems are caused both by aggradation and degradation. Debate continues as to whether the excessive loads of river sediments which contribute to flooding, originate in the floodplain zone or the upper reaches of the river. In other reaches a deficit of sediment can result in scour of the riverbed, undermining of works and lowering the water table.

Gravel reserves: Excessive gravel movement can be reduced in some catchments through the construction of gravel traps and mass planting of riverbeds; the whole forming a 'gravel reserve'. Figures 37a,b,c, depict the gravel reserve on the Kumeti Catchment, South East Ruahines. In essence, a 'gravel reserve' is developed by selecting a suitable area of unstable river bed and berm land, usually covering an aggrading fan and the degrading area upstream. This is mass planted with a variety of species, predominantly shrub willows but also productive and amenity species such as poplars, eucalyptus, and pines. A few hardy native species adapted to that site can also be used. Low weirs, fences, retards and groynes are incorporated into the design to provide initial stability to the plantings until they become vigorous enough to filter out sediments with the increase in floodplain roughness. It is stressed that such 'reserves' do not trap gravel permanently, but rather reduce the rate of transport through that reach. This is done by inducing natural deposition, often in areas where deposition would naturally occur under a forested environment. With the adjustment of the channel system to the changed regime through this reach (anywhere from 1 to 20 years) sediment will continue to filter through the reserve, but at more manageable rates than prior to the planting. Other benefits from such reserves include improved wildlife habitats, improved water quality (by reducing suspended sediments), the provision of recreation areas and revenue from timber sales. It appears as if these reserves are only effective on small river systems where catchment areas are less than about 100 km^2. In time, the maximum size of catchment that can be managed may be more precisely defined.

Gravel reserves have been designed, built, and planted in parts of New Zealand by several local Catchment Authorities (Marlborough Catchment Board 1969; Stringer et al 1978; Brougham 1978). Although they have had a generally beneficial effect on river management problems, maintenance costs have often been high until vegetation is well established (Hubbard 1976). The technique can only be successfully applied where conditions of available channel width, slope and flow regime are suitable. These criteria have not been well established.

Gravel extraction: Gravel extraction has been of major benefit in critical aggrading reaches. In the Waimakariri River up to 150,000m^3 per year were extracted for roading purposes in the early 1960s. Dalmer (1965) states: "If this [extraction rate] could be trebled without altering the conditions of supply of sediment, artificial maturity of the river might be achieved". The results of tests carried out by the Materials Testing Laboratory of the Ministry of Works, Christchurch, show that the best bed-load materials for construction purposes are found in the lower reaches of rivers, and as beach deposits (Johnson pers. comm.). Only those rivers with significant source areas of Torlesse Group rocks produce high quality gravels in their lower reaches. Weathering, abrasion, and particle breakdown result in the destruction of less competent lithologies. In the future, this resource will become increasingly valuable as a source of building and construction material, because the number of rivers in New Zealand having excess of such gravels in reaches suited to their economic extraction, is limited. The management of sites and the quantities extracted need to be carefully monitored so that river control schemes and the river environment are protected. Wing (1979) has shown how management of gravel extraction could be modified to safeguard fisheries' resources.

River control: Most recent river control schemes are based on the assumption that confining the channel to a single thread control channel will limit the river's access to new sediment sources and induce degradation to some new stable bed (Nevins 1969; Henderson 1966; Acheson 1968). In practice there has been varying success. Some rivers are on such steep slopes, and carry such high sediment loads directly from their upper catchment sources, that few training works can withstand their onslaught unless expensive bank protection structures are continually maintained (Henderson 1966).

There are many rivers, however, particularly in their lower reaches, where carefully designed training works have modified a formerly wide braiding riverbed into a single thread channel (Brougham 1978). The aims of such works is to induce channel scour down to an 'armoured' bed of larger boulders; with banks protected either alternatively or continuously with combinations of willow planting, retards, and rock. The design width selected for such work is of critical importance. As the single channel is created, the old braided river bed areas can be developed into either farmland or forestry, depending on the type of river and the local catchment authorities' policy on river management. Only through continual maintenance and improvement can modified channel forms be held. If unrestricted, such reaches of river would return to their former spreading habit threatening the productivity of fertile farmland adjoining the river. The lower Waimakariri is a case in point (Dalmar 1965). Detailed references to such river works can be found in Acheson (1968). The Wairau Valley Scheme and the Kaikoura Scheme (Marlborough Catchment Board 1959 and 1969 respectively) also describe such works. The Otaki River Control Scheme (Manawatu Catchment Board 1975) gives an account of typical problems encountered in the floodplain reaches of such unstable gravel bed rivers.

The development of criteria for stable channel design based on a fundamental understanding of braided river processes remains an important, though as yet incomplete, task. Griffiths (1980) has recently made progress in this field. The authors believe that where gravel bed river management is warranted, the integration of soundly based riparian land use practices, with channel design and control work, is essential.

AN APPROACH TO MANAGEMENT FOR THE KOWAI RIVER SYSTEM

The Kowai River provides a suitable case study for the possible format of management schemes for similar rivers. A three-fold approach is suggested in the development of the potential productivity of the river's floodplain and in the improvement of water quality for supply schemes:

1) Assessment of sediment sources in the upper catchment and treatment of those where on-site and downstream benefits justify the expense of the control works.

2) The construction and planting of gravel reserves at appropriate sites in the transfer and transitional channel systems.

3) River training work and riparian reserve planting in the lower reaches downstream of Kowai No.2 bridge

The relative importance of each of the above phases of work will vary between catchments, but the possible application of this approach to the Kowai River itself is detailed below.

Whether erosion features are natural or man induced is unimportant in the control of fresh erosion debris, but certainly all possible steps should be taken to ensure that no new sites are allowed to develop. As Hayward (1980) points out for the Torlesse subcatchment of the Kowai River system, only a few localised point sources of eroding bedrock at present contribute sediment directly to the stream system. If it was thought necessary to prevent sediment entering the Torlesse Stream system less than one percent of the catchment would need to be treated. For the greater Kowai catchment it is observed, although not quantified, that overall a similar proportion of point sources of sediment input occur. However, it may not be feasible to rehabilitate eroding bedrock, and management through controls on land use, either on a local or catchment-wide scale, may be the most effective long-term approach.

The construction of gravel reserves could be implemented with a view to slowing down the rate of gravel movement through the middle and lower reaches of the Kowai. However, where large inputs of fresh gravel do occur, as at the Foggy River confluence, even to slow down the transport rate may not be a practical proposition. Indeed, as Hayward (1980) again points out, if too many sediments were to be prevented from entering a stream channel, the channel may tend to degrade, giving rise to new problems of slope and riparian land instability.

The control of riparian erosion, as occurs in the lower reaches, is another matter, and requires the restriction of the active streambed to some 'designed' width and form by means of protective structures and plantings. It should be emphasised that the objective is not to create a single stream channel through the lower reaches but rather the design of a stream bed with the width necessary for the passage of flood flows of water and sediment (Griffiths 1980). In practice, this channel width will vary with the local conditions, within a range necessary for that reach of river and the economics of protecting the floodplain. For the Kowai River below the confluence with 13 Mile Bush Stream, the channel design width based on a regime equation where channel width is a function of the two year flood (M.W.D. 1980), is 50 metres. It should be possible to reduce this width to 30 m as upstream berm land is revegetated. Using the approach to stable channel design developed by Griffiths (1980), it may be possible to improve the accuracy of this design channel width. A specific study of the reach of channel would be required, comprising both an analysis of apparently stable channel reaches (Figure 34) and field experiment.

The stability of the Kowai River and its sensitivity to training works depends to a large extent on the presence of large subrounded relic boulders as discussed in Paper B. These boulders are important, in part as channel 'armour' (Henderson 1966), and as the key structural elements of the pool and riffle system (Leopold et al 1964), which acts to dissipate the stream energy (Hayward 1980). The development of these channel forms would be vital to the limiting of excess scour and to dissapate excess stream energy.

The transfer and floodplain reaches of the river (where development has begun) are, at present, characterised by wide unstable riverbeds which have a surfeit of fine gravels drowning out the pool-riffle system. The larger, underlying boulders are only periodically exposed as the fine gravels are flushed downstream in major storm events (Figure 38). Thus the obvious first step in a management plan for the lower river is to reduce the quantity of fine gravel moving through the system.

The sources of fine gravels in the streambed, as discussed in Part 1 of this paper, are:

i) freshly eroding headwater source areas,
ii) reworking of riparian deposits,
iii) particle breakdown within the stream bed (including abrasion).

Control of riparian erosion, in conjunction with gravel reserves in the mid-reaches of the river, would diminish the amount of fine material supplied to the streambed and hence reduce abrasion within the streambed. It is postulated that, by reducing the supply of the finer-sized (smaller than 8 m diam.) particles in this way, the sediment size distribution in the river-bed would alter and the bed forms change to a more orderly and stable pool-riffle system. The relic boulders would become key elements in the structure of the rapids (riffles) since they would no longer be swamped by large quantities of fine gravels. As the channels were narrowed into hydraulically more efficient channels much of the finer gravels, sands, and silts would be flushed downstream, a proportion being redeposited on the planted berms. As vegetation became established in the wider sweeps of the 'transfer' and 'transition' reaches, trapping efficiency for the primary mode gravels (16-32 mm diam.) would increase and berm lands would tend to aggrade. In this way the flood-plain surface would be restored to a higher level in relation to the low flow channel (Wolman and Leopold 1957). Thus channel capacities should increase, while sedimentation on berms should provide a more fertile environment for vegetation such as willow and poplar species. After several years with soil development on the more stable sites, the possibility of diversification into a multiple use conservation/farm/forestry system may be possible. In the longer term (100 years plus) the stream's access to riparian and in-channel sediment sources would be significantly reduced, leading to a stabilization of channel form and floodplains.

With the present level of development along braided rivers like the Kowai, it is not economically feasible, at present, to carry out the relatively intensive approach suggested above.

Demand for high quality water, stable water intake sites, and land requirements for multi-purpose farm/forestry schemes may change this situation in the future (Nelson 1981). The careful management of landuse in the riparian zone and on berm lands therefore becomes a priority if our soil and water resources are to be developed, or in some cases conserved, to the benefit of all users.

8. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

It is essential, in designing any programme of work to manage a river, that there is a reasonable understanding of the whole river system and the controlling factors in its behaviour, particularly those processes relevant to long term riverbed stability and maintenance of water quality.

In studying a river as a whole system of interdependent processes, the management of certain reaches will become critical to the success of a catchment and river control scheme. Concentrating resources of capital and labour initially in these critical reaches and working from these sites should lead to long term savings from decreased maintenance of channel works upstream and downstream.

Two important sites have been identified as important in gravel river system management:

(a) the geologically unstable headwater gullies, and
(b) the transition channels ('valley throats').

Considering the former sites, the maintenance of a vigorous vegetative cover separating the erosive elements of water and wind from the often highly erodible soil and rock formations should always be a vital part of the management of hill and high country catchments. Once exposed to weathering and fluvial processes, erosion of intensely fractured bedrock will be difficult, if not impossible, to stop. Careful evaluation of eroding sites is required as it is misleading to assume that control of sediment sources in steep 'greywacke' upper catchments is always of benefit to downstream river control problems (Mosely 1980).

Only some channels will be amenable to management. Many of the steep gravel rivers draining geologically unstable mountain lands may be too difficult to control economically. But there are many other relatively 'tamer' rivers where river channel works and floodplain development are possible and often very necessary. The integration of these channel works with berm land management has been largely neglected. More work needs to be carried out in identifying which rivers can be managed economically, which cannot, and those that are best left as 'wild'rivers.

Implementation of a river training scheme will be followed by an initial period of adjustment during which greater quantities of gravel will move downstream than before. Once a degree of stability has been attained, and the pool-riffle system well developed, the extent of these initial problems should reduce. It may become necessary to modify the scheme if excessive scour occurs or,conversely, if too much fine gravel continues to be entrained. River training is a strategic exercise and there is going to be a delicate balance between input of gravel to the stream system and the output. If this balance is not achieved then problems of scour or aggradation will occur. The development of the floodplain zone of a river system can only be justified when the objectives and benefits of such work are clearly understood by the people and agencies responsible for its wise use. If the long term productivity of our river valleys and floodplains is to be maintained or even restored to its potential, then the co-operation and understanding of all interested parties is essential.

RECOMMENDATIONS

The above discussion has identified the following areas where further research is needed for, the design of river management schemes:

1) Study of rates of supply of fresh sediment from weathering and slope undercutting in upper catchment areas.

2) Study (if feasible) of the relative proportions of sediment by volume derived from fresh erosion, abrasion,and riparian erosion processes.

3) Study of processes of abrasion and particle breakdown within the channel system.

4) Study of river channel formation in response to steady and unsteady inputs of water and sediment.

5) Study of the relationships among bed sediment size, bed armouring,and local scour depth.

Figure 38: A reach of riverbed upstream of the Ben More bridge: (note: the presence of large subrounded boulders up to 400mm in diameter: with "fines" flushed out).

6) Study of the extent to which a braided channel can be confined laterally before either excessive local scour or local aggradation occurs.

7) Use of photogrammetric techniques for monitoring rates of gravel movement in rivers.

8) Development of productive and environmentally stable multiple uses of riparian and berm lands.

In any proposal for gravel river and floodplain development, the following aspects should be undertaken as part of the design approach:

1) Aerial photography, supplemented by closely-spaced cross-section surveys, to monitor channel changes. Cross-sections should include the full floodplain width. Photography and surveys should take place at times suited for revealing the channel's response to both high and medium flows.

2) Surface sediment size analysis, or bulk sampling where necessary, should be carried out at the same time as cross-section surveys.

3) Monitoring of hydraulic geometry, water flow, bedload movement and suspended sediment at stable and unstable reaches.

4) Detailed mapping of berm land, soils, and vegetation.

5) Where applicable riparian revegetation trials may be necessary to establish the suitability of species for protection, production, or aesthetic purposes.

6) Collation of a historic record of past channel behaviour over as long a period as there is either aerial photographic record or reliable local information.

7) Results obtained should be integrated with those of other similar gravel bed river systems, to assist in the more complete development of management criteria for channel design and riparian land development.

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PAPER B

P. ACKROYD/M. MARDEN

A COMPARISON OF FLUVIO-GLACIAL AND PRESENT RIVER BED DEPOSITS, KOWAI RIVER, CANTERBURY

A COMPARISON OF FLUVIO-GLACIAL AND PRESENT RIVER BED DEPOSITS, KOWAI RIVER, CANTERBURY

1. INTRODUCTION

The Kowai River valley is located on the eastern flanks of the Southern Alps between the two major glaciated valleys of the Rakaia and the Waimakariri rivers. Suggate (1965) describes the late-Pleistocene geology of these two major drainage basins. The Kowai river valley exhibits the same history of glacial advances and retreats as the Waimakariri system over that period of time. Table 10, adapted from Gage (1980), is the most recent glacial chronology applicable to the eastern side of the South Island.

Marden (1976), as part of a study of the late-Pleistocene geology of the Kowai river valley, carried out a detailed sedimentological analysis of two glacial outwash surfaces belonging to the Woodstock (>250,000 y.B.P.) and Otarama (>130,000 y.B.P.) glacial advances of the Waimakariri glacial sequence. These deposits were sampled from a location adjacent to one of the sites (site 9) sampled in the Kowai riverbed study (Paper A this publication). Site 9 is located approximately 5.5 km west of the township of Springfield on the Main West Coast highway (Figure 33, Paper A). The proximity of sampling sites for recent riverbed and fluvio-glacial sediment studies led to the possibility of a comparison between past fluvio-glacial and active riverbed deposits both in terms of their sedimentological parameters and the likely hydrologic regimes responsible for their deposition.

The propositions to be developed in this paper as a result of these investigations are:-

(i) That the older deposits were laid down by gravel bearing rivers comparable, in terms of the nature of the processes operating, to those of today. There is evidence that suggests, however, that while the nature of the processes may have been similar, the magnitude of flow and/or flood volumes certainly differed.

(ii) That the present riverbed gravels are, in part, derived from a reworking of fluvio-glacial deposits of the sort typified by the Otarama and Woodstock outwash deposits.

TABLE 10: Succession of glacial advances in the Waimakariri valley in relation to N.Z. glacial chronology (adapted from Gage 1980).

Glacial period	Interglacial period	Waimakariri advances	Estimated age (years)
	ARANUIAN		
		Poulter 1,2,3	—10,000
OTIRAN			
		Blackwater 1,2	—100,000
	OTURIAN		—130,000
WAIMEAN		Otarama	
	TERANGIAN		—250,000
WAIMAUNGAN		Woodstock	
	WAIWHERAN		
PORIKAN		Avoca	
ROSS			—1,800,000

It is necessary at this stage to point out that the Woodstock and Otarama deposits have been compared with the Kowai River deposit purely as examples which exhibit the sorts of material likely to be found in all glacial outwash deposits in this area. They have been used for this purpose because of Marden's (1976) prior sedimentological investigations, and their location adjacent to the active riverbed study (Part I Paper A). Both these factors allow for convenience of comparison between recent river gravels and fluvio-glacial deposits.

In the field situation it is apparent that upstream of site 9 there are only one or two very small exposures of either Woodstock or Otarama deposits, as these have been largely destroyed or obscured by succeeding glaciations. If glacial material is indeed a component of the Kowai River gravels,then that component is more than likely to have been derived from deposits belonging to either the Blackwater or Poulter advances (see Table 10). These deposits are more extensive than the older glacial deposits especially with respect to the middle and upper reaches of the catchment. An additional factor which confirms the importance of Blackwater and Poulter material in this regard is the "fresh", less-weathered appearance of their gravels.

To enable a valid comparison to be made between the two different studies it was necessary to take a larger bulk sample of the active riverbed deposit than was used in Part A and hence the data for site 9 of Paper A is not applicable to this paper. Figure 39 shows the relationship of the three sampled deposits to each other in the field situation.

2. COMPARISON OF OBJECTIVES

It should be noted that the scope of this study is much more limited than Marden's (1976) study and it was considered impractical to attempt the same level of accuracy. The objective of that earlier study was to find criteria that could be used to distinguish horizons of outwash gravel that were deposited during a succession of separate glacial episodes; the sedimentological investigations are necessarily quite detailed. This study is concerned with comparative sedimentology among the three samples and the implications that the results may have for our understanding of high country river processes. In order to facilitate the comparison all tables and diagrams are depicted with the oldest deposit (Woodstock) to the left and the youngest (Kowai River) to the right.

As did Marden (1976), the authors' of this paper have based their sedimentological work on Krumbein's (1934) phi scale, a logarithmic scale of particle size (see Figure 5 Paper A).

3. SIZE ANALYSIS STUDIES

Marden (1976) sampled the two distinct glacial outwash horizons by collapsing approximately 300 kg of gravel from exposed river bank into large drums. The samples were then wet sieved through a +3φ mesh (8mm) into a 44 gallon drum. Material larger than +3φ caught on the mesh was air dried and then dry sieved into phi fractions. The material less than +3φ was left in the drums for one month to allow the fines to settle and the material was later dried and sieved. The pan fraction of these samples (<4φ = <0.0625mm) was analysed by standard pipette techniques, as outlined by Folk (1968), though with some adjustment to withdrawal times.

The active riverbed sample was collected in six 5-gallon cans placed across the width of the Kowai River to ensure that the samples covered the complete range of bed material present. The method of collection (as for the bulk samples of Paper A) involved digging a hole deep enough to lay the can on its side and then collapsing an exposed face into the mouth of the can. The total weight of sediment collected was 238.982 kg compared with 300.835 kg and 326.391 kg for the two fluvio-glacial samples.

Constraints of time in this study did not allow for the use of the wet sieving method. Instead the larger boulders and cobbles were individually brushed to remove as much of the fines as possible before being dry sieved. Although this method will underestimate the percentage of fines when compared with the wet sieve method, it is believed the level of accuracy attained is sufficient to allow comparisons for the fraction coarser than +4φ. Sedimentological analysis of the pan fraction from the active riverbed sample was not carried out. The less accurate nature of the sample preparation method when the pan fraction itself constituted less than one percent of the total samples meant it was not possible to emulate the degree of accuracy attained in the earlier study.

Quantification of the size distribution was facilitated by the use of size distribution parameters similar to those used in Paper A but using Folk's (1968) formulae throughout, as defined below. These formulae are based on percentile measurements with the parameters being determined graphically

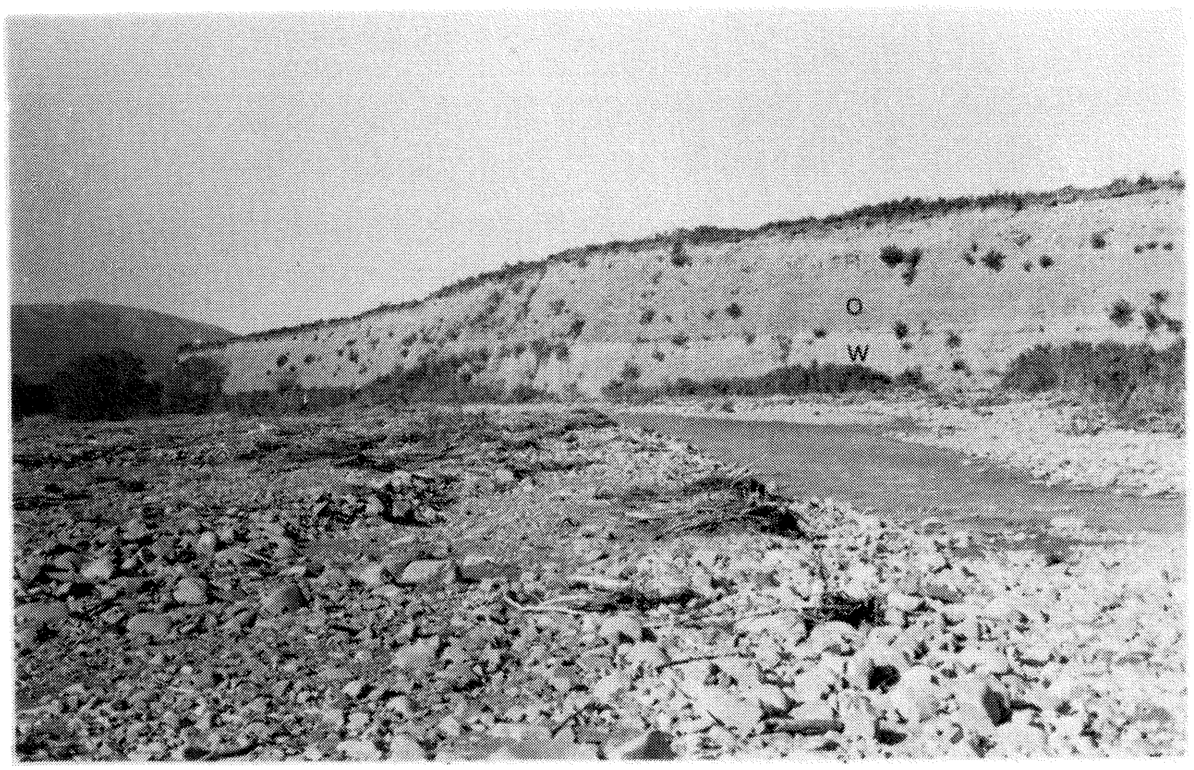


Figure 39: Exposure on true right bank of Kowai River immediately downstream of limeworks bridge. Light coloured Woodstock outwash gravels (W) underlie Otarama outwash gravels (0), which are in turn overlain by more recent channel deposits. Present day Kowai River gravels appear in the foreground.

from the cumulative frequency curve. Verbal and numerical classifications of sorting and skewness correspond to those defined for Part I of Paper A.

Median (Md): Half of the particles by weight are coarser than the median and half are finer with the diameter corresponding to the 50% mark on the cumulative curve.

$$Md = \phi 50$$

Graphic Mean (M_Z): The average size

$$M_Z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Sorting or Dispersion: Folk's term is Inclusive Graphic Standard Deviation (σ_I) as a measure of the spread of the distribution (i.e. the range of particle sizes over which the sample is spread).

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Skewness: Curves may be similar in average size and in sorting, but one may be symmetrical (mean and median coincide) and the other asymmetrical (mean and median differ). Skewness measures the degree of asymmetry as well as the sign (whether a curve has an asymmetrical tail on the left or right). Curves with excess fine material, a tail to the right, have positive skewness and those with excess coarse material, a tail to the left, have negative skewness. In a normal distribution the skewness value equals zero. Folk's term is Inclusive Graphic Skewness.

$$SK_1 = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Kurtosis: The measure of the peakedness of the curve. A normal probability curve plots as a straight line on probability paper. Kurtosis is the quantitative measure used to describe departure from normality, measuring the ratio between the sorting in the 'tails' of the curve and the sorting in the central portion. If the central portion is better sorted (i.e. has a small range of particle sizes) than the tails, the curve is excessively peaked (leptokurtic). If the tails are better sorted than the central portion, the curve is flat peaked (platykurtic).

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

Normal curves have $K_G = 1.00$ leptokurtic curves have $K_G > 1.00$.

RESULTS OF SIZE ANALYSIS

Size distribution

All material finer than +4Ø was grouped together in the pan fraction and similarly material with a diameter greater than -6Ø (128mm) was grouped in the -7Ø fraction, although no boulders larger than -7Ø (256mm) were recorded in the active riverbed.

Table 11 presents the weight distribution of the two fluvio-glacial samples and the active riverbed sample, hereafter referred to as the Kowai River sample. Figure 40 depicts this data as cumulative curves.

From Table 11 it is apparent that the Woodstock sample contains a greater percentage, by weight, of the very coarse cobble and boulder sized material, than either the Otarama or Kowai River samples, the latter two being within one percent of each other. The actual numbers of boulders are relatively small (Woodstock = 26, Otarama = 17, Kowai River = 6). Although the Woodstock sample contains the largest number of particles belonging to the very coarse fraction, Marden (1976) showed that the Otarama sample contains a greater percentage of most of the coarser grades of material, particularly that belonging to the pebble size range (-2Ø to -6Ø). The Woodstock sample, on the other hand, has a greater weight percentage in all phi grades finer than -2Ø . In comparison with Woodstock and Otarama samples the Kowai River sample has the same percentage as the Otarama for the sand sized range and the smallest weight percentage in the mud sized fraction.

Overall the Woodstock sample contains a higher percentage of the cobble and boulder sized material, a lesser percentage of pebble sized material and greater percentages of the granule, sand, and mud sizes than either the Otarama or Kowai River samples. Figure 41 shows each of the three samples subdivided into lithotypes; gravel, sand, and mud, expressed as weight percent of the total sample. Gravel is the most abundant lithotype in all samples; (Woodstock 75.07%, Otarama 82.57%, Kowai River 83.51%); whilst sand is the second most abundant lithotype in all samples (Woodstock 22.45%, Otarama 15.88%, Kowai River 16.11%). Similarly the Woodstock has a greater weight percentage of mud (2.49%) than the Otarama (1.55%) and the Kowai River (0.38%).

Percentage frequency histograms of the samples are shown as Figure 42. The dominant weight mode for the Woodstock sample lies within the -2Ø size fraction (4-8mm), the Otarama primary mode falls within the -4Ø size fraction

Table 11: Weight distribution of material in the three samples.

Ø	Lithotypes	Wentworth size classes	WOODSTOCK								OTARAMA								KOWAI RIVER							
			Weight kg	Cum.Wt.	%	Cum.%	Weight kg	%	Cum.Wt.	Cum.%	Weight kg	Cum.Wt.	%	Cum.%	Weight kg	%	Cum.Wt.	Cum.%	Weight kg	Cum.Wt.	%	Cum.%	Weight kg	%	Cum.Wt.	Cum.%
-7	GRAVEL	Cobbles & Boulders	42.077	42.077	13.99	13.99					34.292	34.292	10.51	10.51					26.924	26.924	11.27	11.27				
-6			22.943	65.020	7.63	21.61					41.697	75.989	12.78	23.28					42.675	69.599	17.86	29.13				
-5			20.768	85.788	6.90	28.52					28.334	104.323	8.68	31.96					35.899	105.498	15.02	44.15				
-4		Pebble	33.509	119.297	11.14	39.66	225.780	75.05	225.780	75.05	46.292	150.615	14.18	46.15	269.499	82.58	269.499	82.58	36.307	141.805	15.19	59.34	199.577	83.51	199.577	83.51
-3			32.015	151.312	10.64	50.30					44.842	195.457	13.74	59.88					25.266	167.071	10.57	69.91				
-2			43.063	194.375	14.31	64.61					43.138	238.595	13.22	73.10					18.288	185.359	7.65	77.56				
-1		Granule	31.405	225.780	10.44	75.05					30.904	269.499	9.47	82.57					14.218	199.577	5.95	83.51				
0	SAND	V.C.Sand	19.131	244.911	6.36	81.41					17.305	286.804	5.30	87.87					10.016	209.593	4.19	87.70				
+1		C.Sand	14.109	259.020	4.69	86.10					10.403	297.209	3.19	91.06					9.716	219.309	4.07	91.77				
+2		Med.Sand	10.443	269.463	3.47	89.57	67.565	22.45	293.345	97.51	6.620	303.829	2.03	93.09	51.843	15.88	321.342	98.45	11.037	230.346	4.62	96.39	38.508	16.11	238.085	99.63
+3		Fine Sand	13.339	282.802	4.43	94.00					8.265	312.094	2.53	95.62					5.848	236.194	2.45	98.84				
+4		V.F.Sand	10.543	293.345	3.50	97.51					9.248	321.342	2.83	98.45					1.891	238.085	0.79	99.63				
PAN	MUD	Silt & Clay	7.490	300.835	2.49	100.00	7.490	2.49	300.835	100.00	5.049	326.391	1.55	100.00	5.049	1.55	326.391	100.00	0.897	238.982	0.38	100.01	0.897	0.38	238.982	100.01
TOTAL			300.835		100.00						326.391		100.00						238.982		100.01					

(16-32mm) whilst that for the Kowai River sample occurs in the -60 size fraction (64-128mm). All three samples have secondary modes as shown by Figure 42 and, as Schlee (1957) points out, such polymodal distribution is characteristic of fluvial environments. In addition, the samples all have the -40 size fraction as either a primary or secondary mode; this is the size grade which occurs as a mode at virtually all the sites samples on the present, Kowai River.

Statistical analysis

Table 12 presents the results obtained from statistical analysis of the three samples with a discussion of the more significant characteristics below.

Mean, Median: Values for these parameters show an increase in the degree of coarseness of the samples from the Woodstock (oldest) with a mean and median both of -3.00 through to the Kowai River (youngest) with a mean of -4.10 and a median of -4.60. As stated previously the Otarama sample is half a phi unit coarser than the Woodstock, with the Kowai River about a whole phi unit coarser again, though all are in the 'pebble' category of Wentworth's (1922) classification (see Figure 5 Paper A).

Sorting: Sorting values are similar for the three samples, all fitting within Folks''very poorly sorted' (So = 2.0 to 4.00) category. Numerically there appears to be a slight improvement in the degree of sorting from the Woodstock through to the Kowai River sample. With the range of values being between 3.38 and 2.84, the significance of such a trend is debatable considering the variation in methodology.

Skewness: Again there appears to be a correlation in skewness values between the Woodstock (+0.096) and Kowai River (+ 0.33). Verbally this represents a transition from a near symmetrical distribution to a strongly positive skewed distribution (i.e. the proportion of fine sediment decreases), the latter to be expected in the Kowai River sample where the median is half a phi unit coarser than the mean.

Kurtosis: Kurtosis values for all three samples are very similar, approximately 1.00, with all values being within 0.1 of each other. Verbally the samples would be classed as platykurtic/mesokurtic.

TABLE 12: Statistical parameters

	Mean	Wentworth Size Class	Median	Sorting	Verbal Sorting	Skewness	Verbal Skewness	Kurtosis	Verbal Kurtosis	Modes*
WOODSTOCK	-3.0φ	Pebble	-3.0φ	3.38	Very poorly sorted	+0.096	Near symmetrical	0.928	Platykurtic/ Mesokurtic	-7 -4 -2 +3
OTARAMA	-3.6φ	Pebble	-3.6φ	3.03	Very poorly sorted	+0.163	Fine skewed	1.034	Platykurtic/ Mesokurtic	-6 -4 +4
KOWAI RIVER	-4.09φ	Pebble	-4.6φ	2.84	Very poorly sorted	+0.33	Strongly fine skewered	0.955	Platykurtic/ Mesokurtic	-6 -4 +2

* whole phi unit in which mode occurs

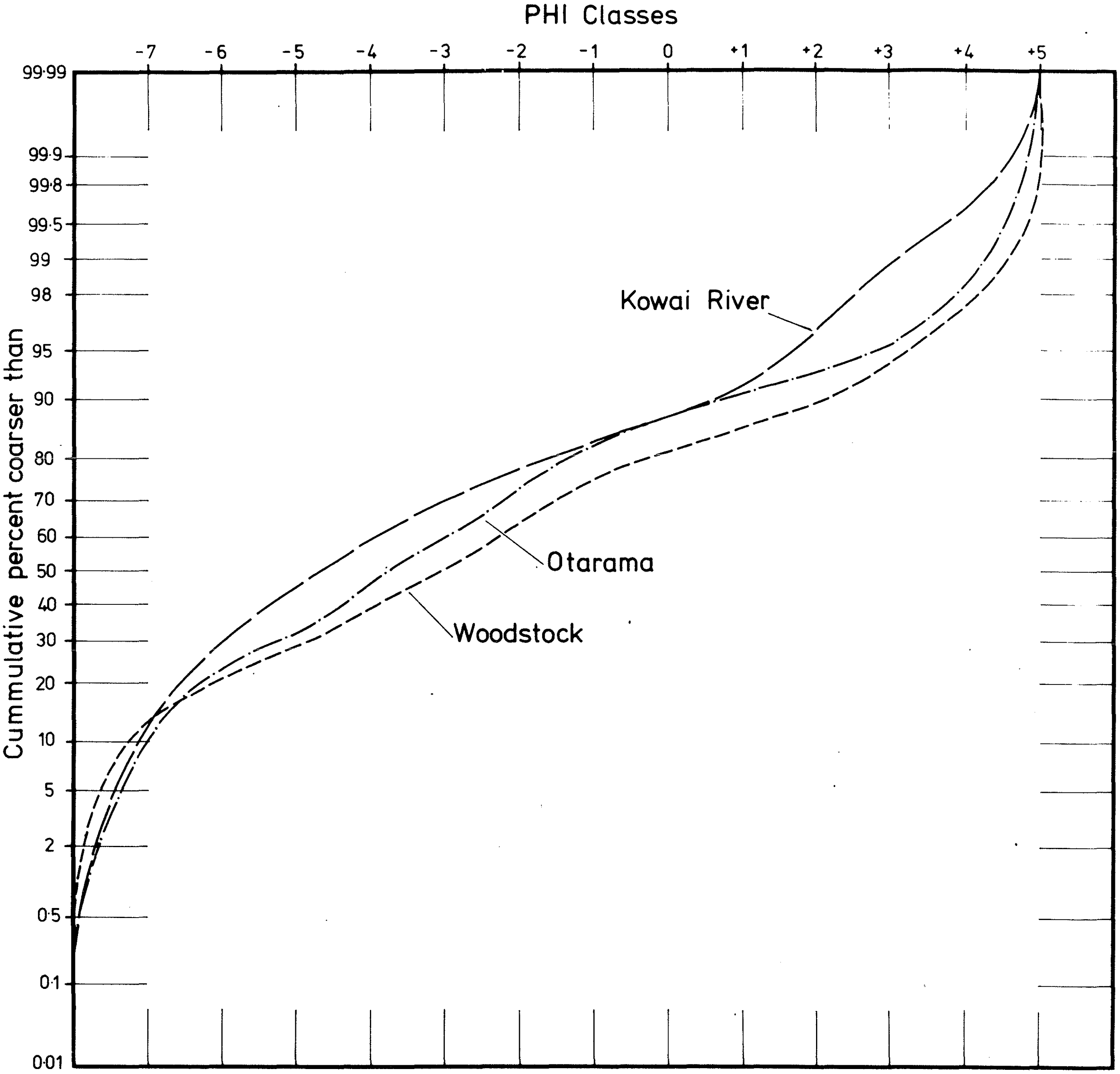


Figure 40: Weight distribution of material from each of the sample units expressed as cumulative curves of percentage of sample coarser than stated size.

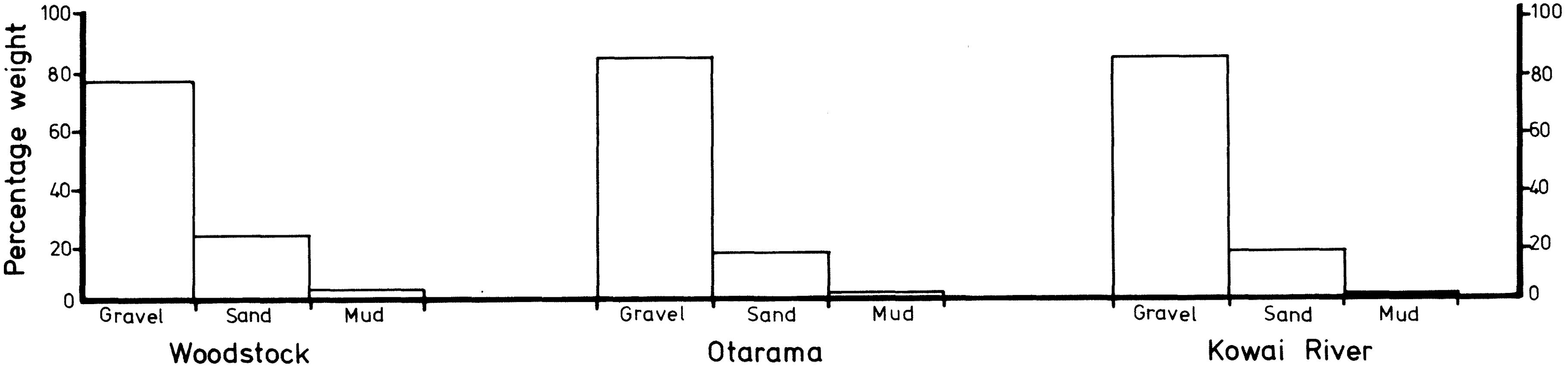


Figure 41: Weight distribution of the three lithotypes within each of the sample units.

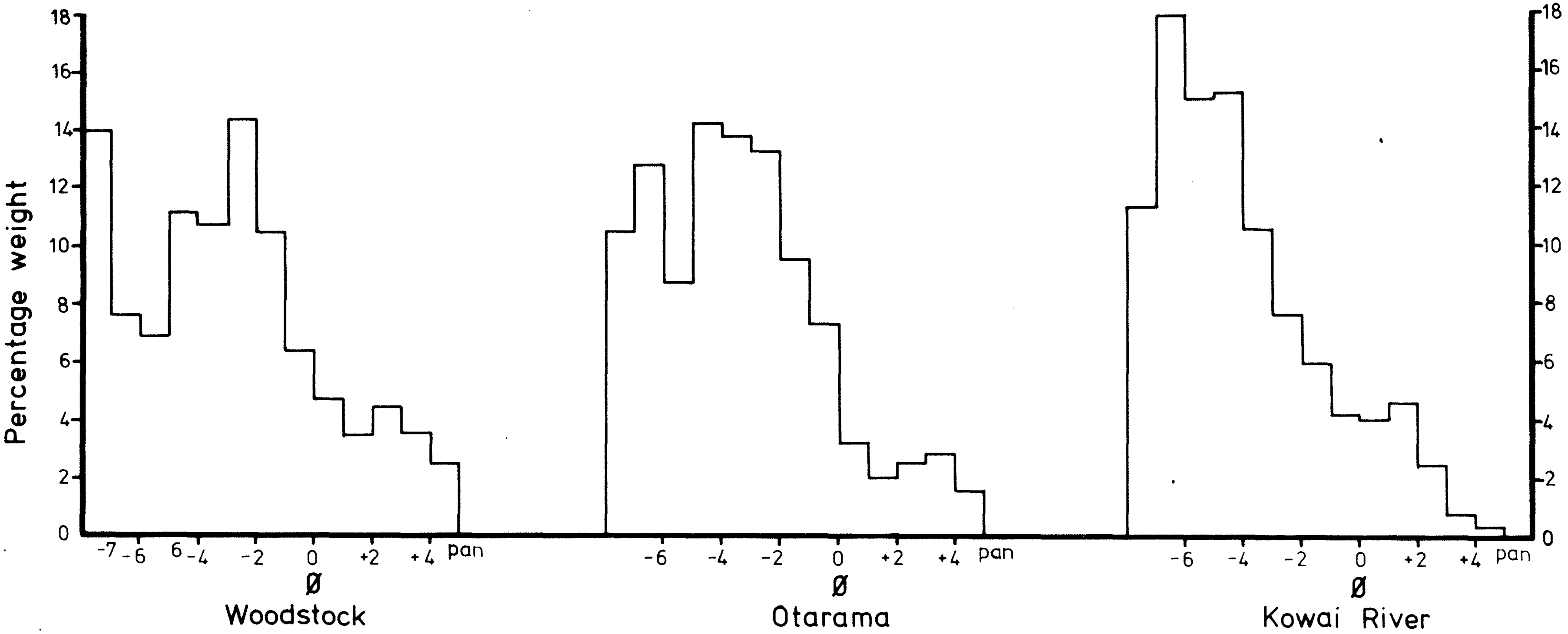


Figure 42: Weight distribution for each phi fraction within each of the three sample sites.

CONCLUSIONS FOR SIZE ANALYSIS STUDIES:

Marden (1976) was able to suggest a close similarity between the Woodstock and Otarama deposits,yet the results of this comparative size analysis suggest that the Otarama is as similar to the Kowai River sample, in its size distribution characteristics, as it is to the Woodstock sample.

A conclusion that arose from this apparent similarity is that the hydraulic conditions and transport mechanisms that operated during the sorting and deposition of the fluvial-glacial deposits must have been essentially similar to those occurring in the active riverbed today.

With reference to the two fluvio-glacial deposits Marden (1976) stated that: "differences in the relative abundances of the various grain size fractions can be explained in terms of:-

1) slight variations in the local hydraulic conditions that existed during the time of deposition of these two outwash gravel units;
2) sorting action by the two transport mechanisms that operated during the glacial advances, (i.e. ice and fluvial processes);
3) A deficiency of particular material in the source area."

Assuming a single source area for all the deposits, which seems likely despite the possibility of glacial ice having at some stage broken through from the Rakaia Catchment, differences in all three size distributions have then to be explained in terms of variations in hydraulic conditions or transport mechanism alone. Any attempt at explaining these differences is,however, more complex than might first appear,as the different size distributions (i.e. the increased coarseness of successively younger deposits) in conjunction with statistical tests and parameters,suggest an evolutionary relationship between fluvio-glacial and present river gravels.

The nature of the similarity between the samples was tested by means of Kolmogorov-Smirnov statistical tests using the chi-square approximation:

$$X^2 = 4D^2 \frac{W_1 \; W_2}{W_1 + W_2}$$

(D equals the largest difference between cumulative frequency distributions expressed as a proportion and W equals weight of the samples). All combinations of sample pairs were tested as shown below.

Woodstock - Kowai : $X^2 = 21.309$ *** significant at 0.1% level
Otarama - Kowai : $X^2 = 10.484$ ** significant at 1% level
Otarama - Woodstock : $X^2 = 6.261$ * significant at 5% level

The results show that, while at the 5% confidence level all the samples are significantly different, the greatest difference is between the oldest (Woodstock) and youngest (Kowai River) samples. The difference between the Otarama, which is intermediary in age, and the extremes is less significant. This statistical test indicates the gradational nature of the change in sediment size distribution between the three deposits. If this gradation is correlated with evolutionary development of successive deposits, we need to emphasize the time over which fluvial processes operated in the formation of each deposit. The nature of the processes themselves may be less important.

The increasing coarseness of the deposits over time is believed to be caused by erosion of riparian deposits, with the finer sized material being successively winnowed out and transported out of the system. The selection of modal groups is probably more a function of bedrock controls, both lithological and structural, on particle breakdown (as suggested in Paper A), than a function of hydraulic and stream transport parameters owing to the similarity in the modal sizes of the different samples. Modal size groups in the boulder and cobble size range can be expected for the Woodstock and Otarama deposits due to the presence of abundant morainic deposits in the area. The presence of a modal size group in the -6ϕ (64-128mm) size range for the Kowai River is less easily explained, in view of the limited transport of this size fraction by the present river. Consideration has to be given to the possibility that this modal group has been derived from older deposits following reworking by the present river.

Changes in statistical parameters also fit this postulated model. The two fluvio-glacial deposits are clearly very similar with the respective mean and median sizes being half a phi unit apart, skewness values approximating 0.0, kurtosis values approximating 1.00, and similar sorting values. The Kowai River sample has similar kurtosis and sorting values to those of the two fluvio-glacial deposits though, as mentioned previously, there is a tendency towards increased fine skewness for the Kowai River deposit.

If the original skewness and mean values at the source can be assumed to have been similar for both the Woodstock and Otarama samples, as suggested by Marden (1976), the apparent difference in these values at the sample locality could then be explained in terms of the combined effect of erosion and selective transport.

By including the Kowai River deposit in the analyses as well (Table 12), it would appear as though adjustments to the skewness parameters could be best accounted for through reworking of gravel deposits by the stream system.

It is apparent that the change in mean particle size from the Woodstock (-3.00) through to the Kowai River sample (-4.10) is due not to an increase in the amount of coarse material, but rather to a reduction in the amount of 'fines'. This characteristic is substantiated by the skewness values as the sample with the largest mean particle size (Kowai River) also has the most positively skewed distribution (i.e. a smaller proportion of fine material). Conversely, the oldest sample (Woodstock) has the smallest mean particle size but is near symmetrical.

Evidence from the size frequency distributions of the samples, the statistical analysis of those distributions, and the comparative statistical test between the three samples suggests that these samples form part of an evolutionary sequence. All the material examined was taken from deposits with a glacial origin, with the Kowai river receiving material eroded directly from fluvio-glacial deposits and tills. We can therefore conceive of the Woodstock, or even an older glacially derived deposit, acting as a 'stock' of material which forms the basis of all younger outwash deposits. Such deposits would be expected to be poorly sorted, but the numerical difference in sorting (Table 12) could again be attributable to fluvial processes acting to improve the degree of sorting with the passage of time.

In saying that the time over which hydrologic processes have operated is more important than the nature of the processes themselves, we must not preclude the possibility that the scale of hydrologic processes operating in the Kowai system may have altered. The similarity in sediment size distribution does suggest, however, that the fluvial processes operating today are of a similar nature, though on a smaller scale, to those that operated at the time the fluvio-glacial deposits were laid down. That the scale of the processes has altered is evident from the apparent inability of the present river to readily transport the larger relic boulders.

4. SPHERICITY AND PARTICLE SHAPE ANALYSIS

Sphericity determines how close the three dimensions of an object are, and particle shape is a classification based on ratios between the three axes of a rock particle.

Detailed sphericity analysis of the Woodstock and Otarama outwash gravels had been carried out. Measurements of the long, intermediate and short particle axes were determined with metal callipers measuring, where possible, every pebble, cobble and boulder in the -3Ø to -7Ø size range (8mm - 256mm).

A similar sort of analysis was carried out on the Kowai River sediments though for the reasons mentioned in the introduction it was not possible to emulate the degree of accuracy of the earlier study. The pebbles for the Kowai River deposit were measured with a ruler to the nearest 2.5mm and hence, especially with regard to the -4Ø (16 - 32mm) and -3Ø (8 - 16 mm) size fractions, the data becomes more aggregated. It was also considered impracticable to measure every pebble in the sample. Although all the -7Ø (128 - 256mm) and -6Ø (64 - 128mm) were measured, only about 200 of each of the -5, -4 and -3Ø size fractions (8 - 64mm) were used.

Although the results obtained for the Kowai River sample will not be as accurate as those obtained for the two fluvio-glacial deposits, they are believed to be of sufficient accuracy for comparative purposes.

SPHERICITY ANALYSIS

In order to determine the sphericity (Ψ), the ratios of the intermediate to the long diameter (b/a) and the ratio of the short to intermediate diameter (c/b), are laid off on the axes of Krumbein's (1941) chart (see Figure 9 Part A).

RESULTS OF SPHERICITY ANALYSIS

The results of the analysis are presented in two forms. Figure 43 depicts the spread of all particles measured and plotted for the different phi groups of each sample with respect to the sphericity chart. Table 13 shows the mean sphericity and standard deviations for each phi fraction and the total samples. In addition the number of particles within each sphericity category between the range 0.2Ψ and 1.0Ψ were counted and plotted as histograms of percentage sphericity (Figure 44). Data for this figure is detailed in Table 14, this particular comparison being carried out for the total group samples.

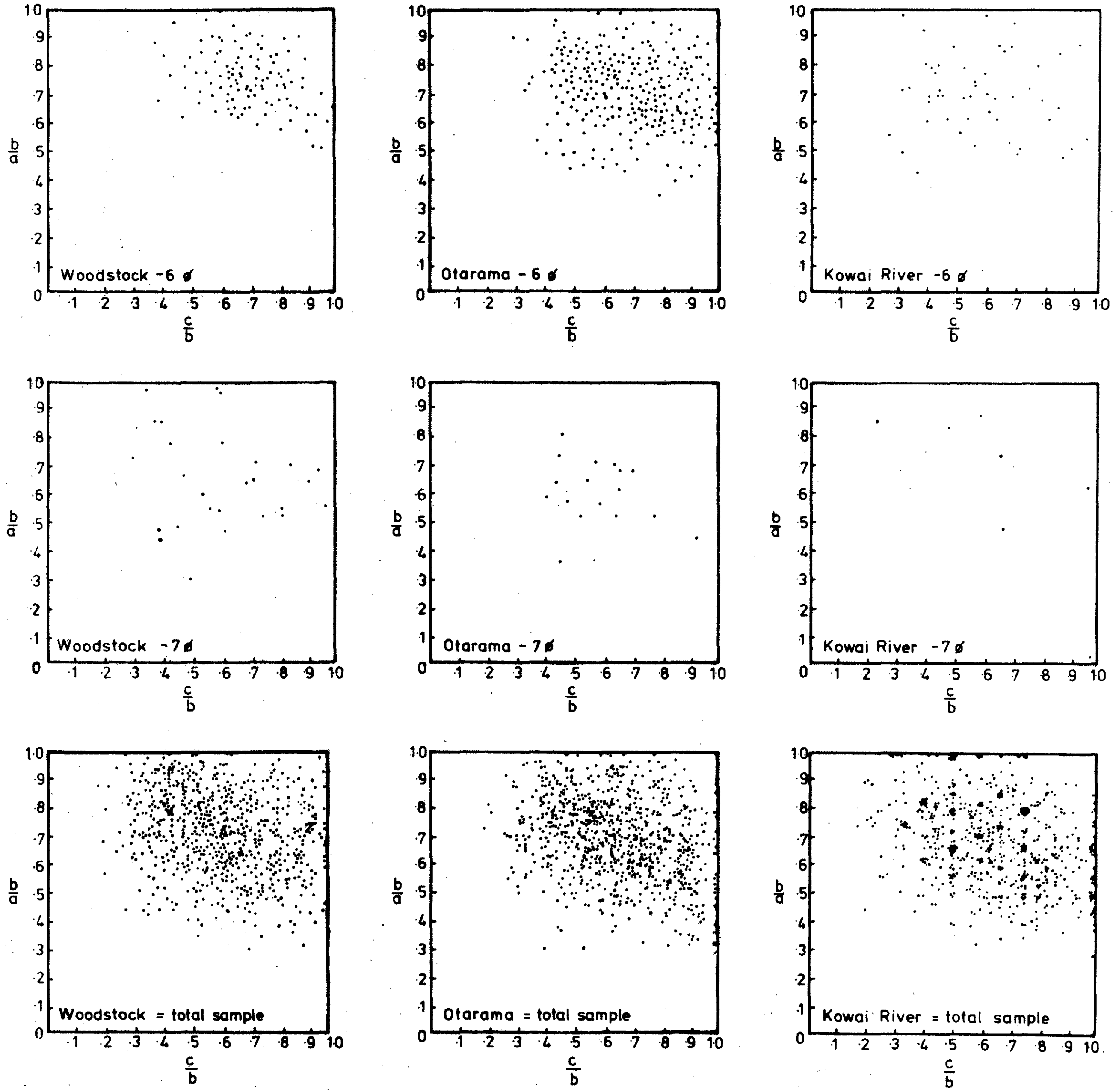
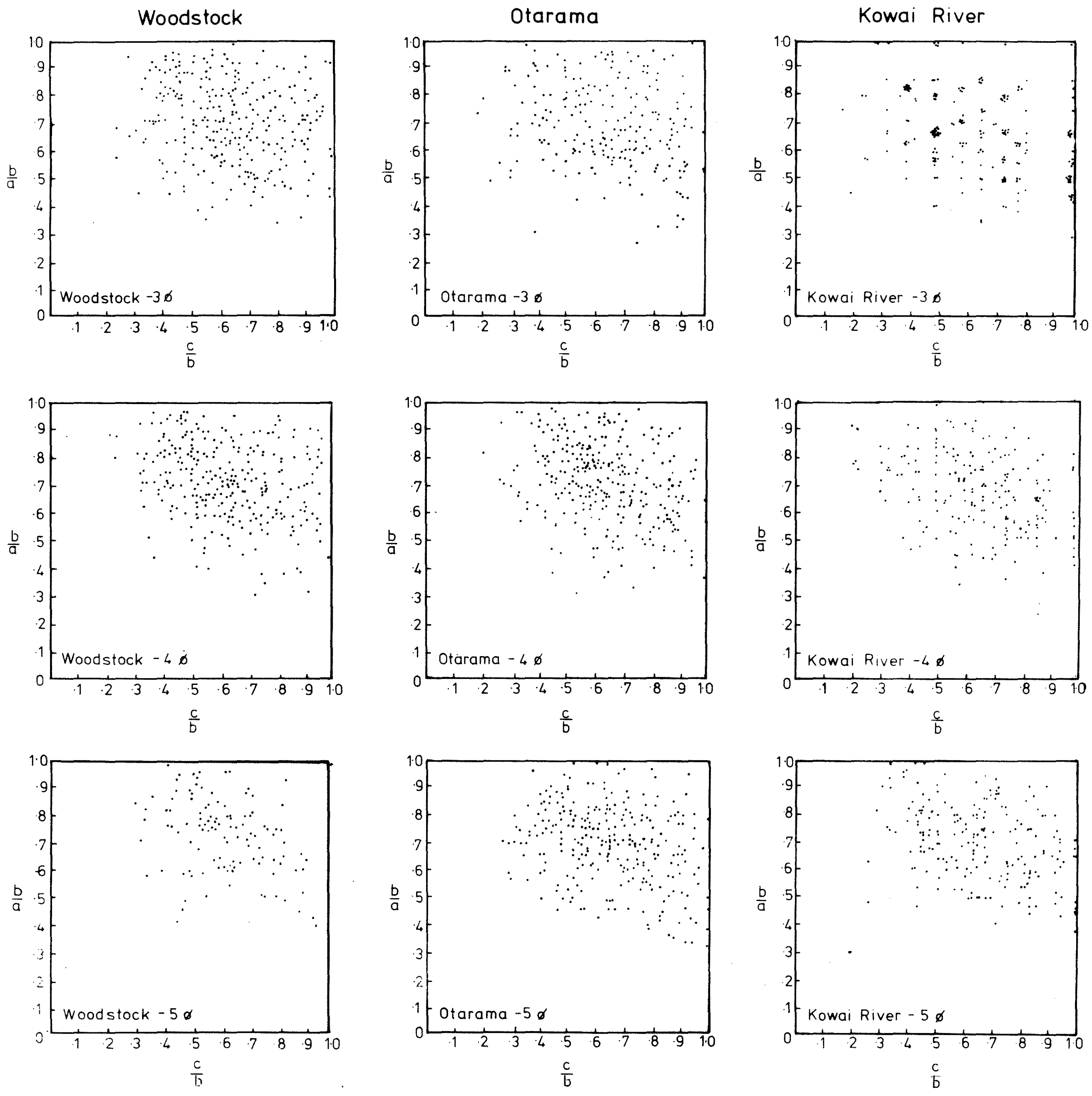


Figure 43: Sphericity plots showing the distribution of all the particles measured and plotted within each phi fraction and for the total samples. Aggredation of plots for Kowai River sample results from use of a different measuring technique to that used for the fluvio-glacial deposits.


Woodstock
Otarama
Kowai River
Woodstock -3 ø
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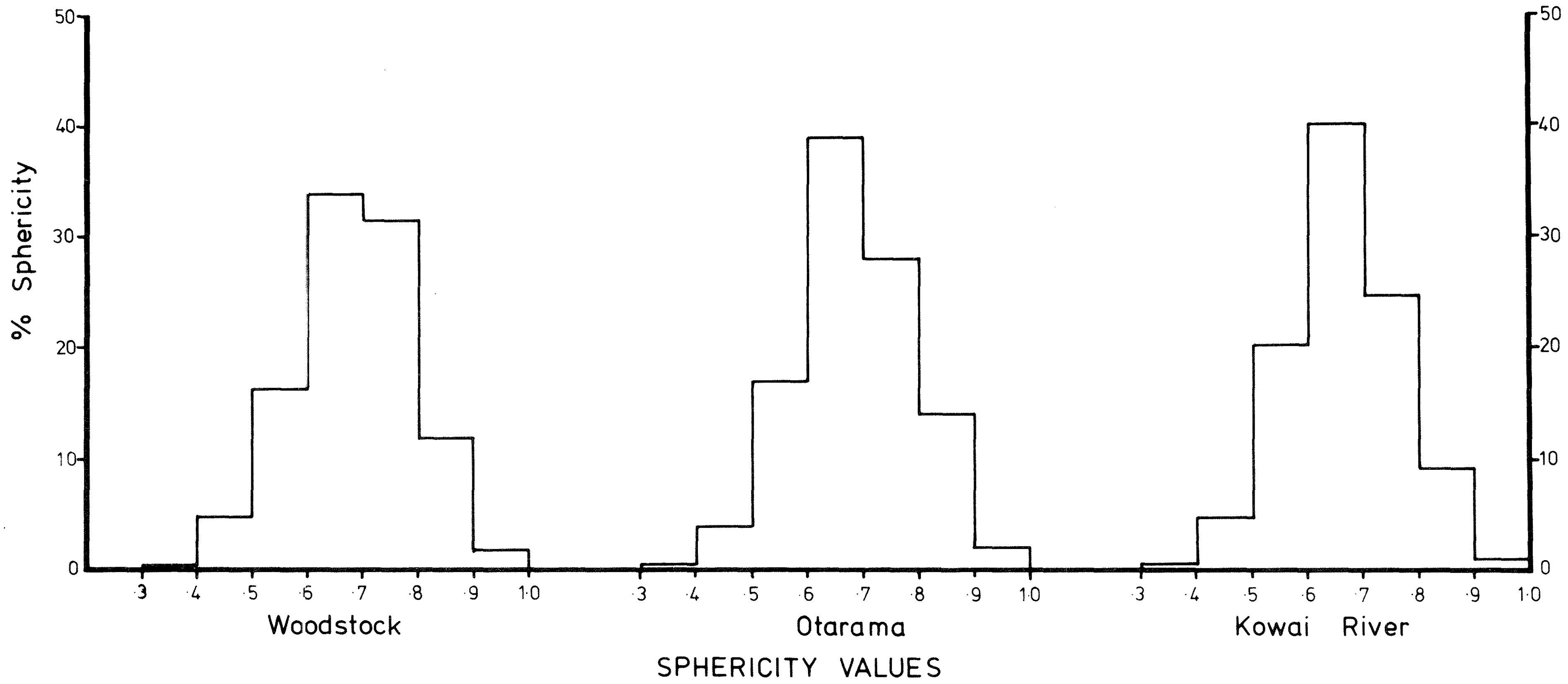

Figure 44: Percentage sphericity for the sphericity value range 0.3 – 1.0.

TABLE 13: Number of particles, mean sphericity and standard deviations.

Phi Size	No. of pebbles measured			Mean sphericity			Standard deviations*		
	Woodstock	Otarama	Kowai River	Woodstock	Otarama	Kowai River	Woodstock	Otarama	Kowai River
-7ø	26	17	6	.64	.65	.67	0.118	0.076	0.098
-6ø	112	181	50	.69	.68	.66	(0.042 ((0.109	(0.080 ((0.103	0.108
-5ø	178	289	199	.66	.67	.68	(0.017 ((0.099	(0.073 ((0.185	0.091
-4ø	312	327	200	.70	.67	.66	(0.012 ((0.127	(0.064 ((0.103	0.101
-3ø	350	250	200	.70	.67	.65	(0.016 ((0.113	(0.104 ((0.113	0.104
TOTAL SAMPLE	978	1064	655	.68	.67	.66			

* Marden's values are calculated for rock types within each phi group. Hence the range of values presented here.

TABLE 14: Percent and cumulative percent sphericity

Sphericity Values	WOODSTOCK		OTARAMA		KOWAI RIVER	
	Percent	Cum.%	Percent	Cum.%	Percent	Cum.%
0.2 - 0.3	0.0	0.0	0.0	0.0	0.0	0.0
0.3 - 0.4	0.1	0.1	0.4	0.4	0.2	0.2
0.4 - 0.5	4.7	4.8	3.8	4.2	4.7	4.9
0.5 - 0.6	16.2	21.0	16.8	21.0	20.1	25.0
0.6 - 0.7	33.8	54.8	38.8	59.8	40.1	65.1
0.7 - 0.8	31.6	86.4	27.8	87.6	24.6	89.7
0.8 - 0.9	11.9	98.3	10.4	98.0	9.2	98.9
0.9 - 1.0	1.7	100.0	2.0	100.0	1.1	100.0

In every case the sphericity values fall within the same quadrants of the Krumbein chart, though with some variation in the spread of the points. When the sphericity values are arranged into sphericity units (Figure 44 and Table 14), the similarity in the degree and distribution of sphericity attained by the particles within the three samples is readily apparent.

For all samples the mode and median fall in the 0.6Ψ to 0.7Ψ sphericity value range. One noticeable difference in the fluvio-glacial samples was that the Otarama sample had 5% more particles in the 'sphericity value' mode than the Woodstock. The Kowai River sample is quite similar to the Otarama sample though it has more of the 0.5Ψ - 0.6Ψ and 0.6Ψ - 0.7Ψ value ranges and less of the 0.7Ψ - 0.8Ψ and 0.9Ψ - 1.0Ψ value ranges than either the Woodstock or the Otarama. These differences, however, could be accounted for by the differences between the two sampling methods used.

To determine if any correlation existed between the degree of sphericity attained and grain size, the mean sphericity value for each phi fraction was determined. The mean of the total sample was then calculated from the sum of these mean values. Neither the mean for the phi fractions, nor the total means indicate any differences in sphericity between the three samples (Table 13). The numerical trend evident for the total sample means is not thought to be significant.

CONCLUSIONS FROM SPHERICITY ANALYSIS

All three samples have attained similar sphericity values consistent with the theory, developed earlier, that the recent river gravels are, at least in part, a derivation of fluvio-glacial deposits. One subtle distinction between the Kowai River and these two fluvio-glacial deposits may be in the level of sphericity attained. According to Holmes (1960), good evidence exists to show that glacial transport can, and does, enhance the development of a high degree of sphericity if the stone escapes crushing, and that the observed degrees of sphericity are chiefly the effects of glacial abrasion. Once a high degree of sphericity is attained the likelihood of crushing would presumably be greatly reduced. It is apparent from Table 14 that, in comparison with the two fluvio-glacial deposits, the Kowai River sample has lower percentages for those sphericity values greater than 0.7Ψ. Conversely, it usually equals or exceeds the percentages recorded by the fluvio-glacial deposits for those sphericity values less than 0.7Ψ. It then follows that the lack of enhanced sphericity in the Kowai River sample may indicate that at least part of the sample has been derived in a non-glacial environment.

Thus the sphericity data, although in part supporting the theory that successive reworking of earlier deposits has occurred, are consistent with the knowledge that at least some of the recent river gravels are being derived from freshly eroded material.

SHAPE FACTOR

The shape of a rock fragment in the stream bed is determined not only by the process of abrasion occurring in the stream bed but also by the 'original' shape of the rock fragment when it was removed from bedrock.

The Zingg (1935) shape classification is used in this study for determining pebble shape, the classification being based on the b/a and c/b ratios used in the sphericity analysis. Details of Zingg's classification and the terminology he employed are shown in Figure 45. Krumbein (1941) was able to combine the Zingg ratios on his sphericity diagram (see Figure 9 Part A) enabling not only the sphericity to be read but also the pebbles to be automatically classified according to Zingg. This method of analysis is only suitable for the larger sized particles where the three axes can be separately measured (-3Ø to -7Ø).

Drake (1972) outlines the dominant factors controlling the final shape of pebbles in a fluvial system. He suggests that spheres, because they are least susceptible to crushing, and are produced as a result of abrasion, are the most durable shape. Discs would be the next group to be favoured by combined crushing and abrasion as the more elongate pebbles are more easily destroyed. Of the latter, rods would be favoured over blades because although susceptible to crushing they are less affected by abrasion than blades.

RESULTS OF SHAPE ANALYSIS

Table 15 shows the number of particles measured, the percentage of particles within each phi unit and the total sample count for the four Zingg particle shape classes.

Disc shaped particles dominate almost every phi fraction between -3Ø and -5Ø for all three samples, (and through to -7Ø for the Kowai River sample). Blade shaped particles became more dominant for this very coarse size range for the Woodstock and Otarama samples. The low number of particles recorded in the coarser size groups preclude any definitive comparisons being made

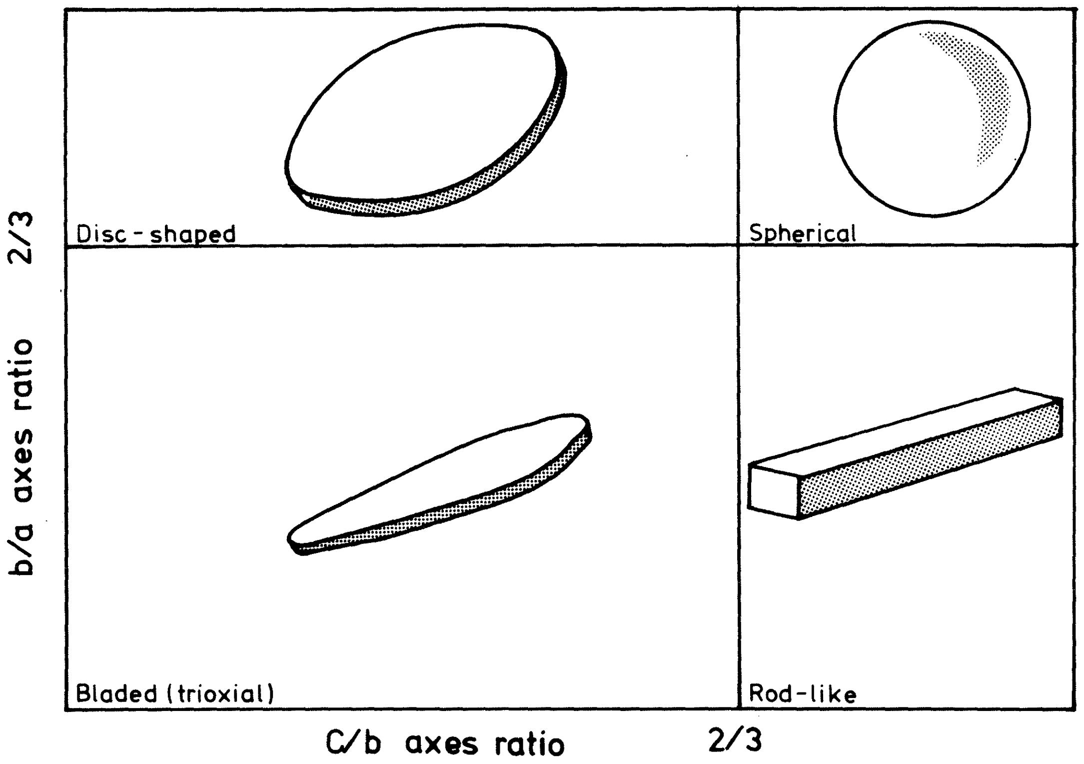

Figure 45: Zingg's classification of pebble shapes. Boundaries between the different classes are based on a b/a and c/b axes ratio value of two thirds.

Figure 46: Percentages of particles within each of the Zingg shape classes for the three total samples.

TABLE 15: Number of particles and percentage (in parentheses) of the four Zingg particle shape classes (W = Woodstock, O = Otarama, K = Kowai River)

Phi size	W	O	K	W	O	K	W	O	K	W	O	K	W	O	K
- 7	7 (26.92)	5 (29.41)	4 (66.67)	3 (11.54)	1 (5.88)	0 (0)	7 (26.92)	2 (11.76)	2 (33.33)	9 (34.62)	9 (52.94)	0 (0)	26	17	6
-6	42 (37.50)	64 (35.36)	23 (46.00)	49 (43.75)	62 (34.25)	10 (20.00)	15 (13.39)	44 (24.31)	7 (14.00)	6 (5.36)	11 (6.08)	10 (20.00)	112	181	50
-5	84 (47.19)	119 (41.18)	77 (38.50)	39 (21.91)	69 (23.88)	44 (22.11)	27 (15.17)	62 (21.45)	51 (25.63)	28 (15.73)	39 (13.49)	27 (13.57)	178	289	199
-4	137 (43.91)	141 (43.12)	71 (35.50)	67 (21.47)	66 (20.18)	39 (19.50)	53 (16.99)	74 (22.63)	58 (29.00)	55 (17.63)	46 (14.07)	32 (16.00)	312	327	200
-3	146 (41.71)	62 (24.80)	65 (32.50)	67 (19.14)	62 (24.80)	47 (23.50)	78 (22.29)	72 (28.80)	55 (27.50)	59 (16.86)	54 (21.60)	33 (16.50)	350	250	200
Sample total	416 (42.54)	391 (36.75)	240 (36.64)	225 (23.01)	260 (24.44)	140 (21.37)	180 (18.40)	254 (23.87)	173 (26.41)	157 (16.05)	159 (14.94)	102 (15.57)	978	1064	655

regarding intra phi unit shape properties for the three samples. In the three sample totals the order of dominance of particle shapes is disc, spherical, rod,and blade,except that the Kowai River sample has slightly more rods than spheres. The particle shape characteristics of the individual samples are depicted as Figure 46, this figure being derived from data in Table 15.

CONCLUSIONS FROM SHAPE ANALYSIS

As with the sphericity analysis,the results of the shape analysis suggest a close affinity between the three samples, at least at the total sample level. The ranking of particle shape within all three samples is consistent with Drake's (1972) criteria,except that these samples have a greater percentage of discs over spheres. As most of the rocks in the source areas of the Kowai River are texturally anisotropic (i.e. jointed and sheared), it is reasonable to assume that the rocks will fracture into less than spherical fragments than would be the case for isotropic rocks, and hence the dominance of disc shaped particles. Although the total samples are all quite similar, the supplanting of spheres by rods in the Kowai River ranking, like sphericity data, suggests transportation or development of that sample in regime where less crushing is involved, (crushing normally favours the creation of spheres). Crushing is likely to have been of greater significance to the fluvio-glacial deposits, considering the sheer mass of material involved. In the present stream system abrasion is of equal or greater significance.

The evidence from the shape analysis is consistent with the theory that progressively younger deposits are, at least in part, reworked samples of preceeding ones but, as with sphericity, apparently it also reflects properties of the component of freshly eroded material that is found within the present stream system. Like the sphericity data, the particle shape data also shows the limited effect that this fresh gravel component has on the overall sample composition.

5. PARTICLE COMPOSITION ANALYSIS

That there are limitations to the information that can be gained from an analysis of particle composition data is apparent from Marden's (1976) conclusions to his very exhaustive analysis of sediment properties. He was able to establish that:

> "There is no relationship between sorting and composition, skewness and composition,or between kurtosis and composition."

> "... no indication of the relationship between sphericity and grain size, and sphericity and composition is apparent over the phi size range considered here..."

> "No apparent relationship could be determined between particle shape and composition...."

The percentage particle composition data (Table 16) is presented here to allow a first order comparison between the three samples and it is not intended to substantiate any definitive conclusions. The data in Table 11 covers the size range - 70 to -30, and is derived from samples of the sort used in the sphericity analysis as described earlier. Thus, although the two fluvio-glacial samples represent every pebble, cobble,and boulder in the various phi groups, the Kowai River sample represents a smaller, though statistically valid, number of particles. A comparison of total sample composition is not possible as the fluvio-glacial samples included material finer than -30.

RESULTS OF PARTICLE COMPOSITION ANALYSIS:

There appears to be a general tendency for coarse sandstone particles to dominate the coarser size phi grades of all three samples, the dominance being most marked in the Kowai River sample.

Fine sandstone is the next most dominant particle type,especially so in the -40 and -30 size grades of the Kowai River sample.

With regard to the minor rock types,one characteristic is the lack of any volcanic material in the Kowai River sample and another is the greater percentage of argillite within the Otarama sample compared with the other two samples.

CONCLUSIONS FROM PARTICLE COMPOSITION ANALYSIS:

Sandstone is the most abundant lithotype for all of the phi fractions of Table 11, which is to be expected considering that sandstone is the most common lithotype in the source area. Coarse sandstone in particular dominates the coarser phi grades. This material is derived from the more massive sandstone blocks which are more competent than finer grained lithogies,having fewer planes of weakness developed within them (Blair 1972). As their coherent properties make them less prone to disintegration, over time these coarse sandstone boulders will become more concentrated in the

TABLE 16 : Percentage sediment sample composition -7ϕ to -3ϕ

(W = Woodstock, O = Otarama, K = Kowai River)

Phi size	Coarse Sandstone			Fine Sandstone			Volcanics			Chert			Argillite			Quartz			Miscellaneous		
	W	O	K	W	O	K	W	O	K	W	O	K	W	O	K	W	O	K	W	O	K
-7	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-6	68.75	82.67	98.46	17.86	7.18	1.54	0	0	0	4.46	0	0	1.79	7.73	0	7.14	2.22	0	0	0	0
-5	77.53	87.20	81.41	17.42	5.88	12.06	2.25	1.73	0	0	2.42	3.02	1.11	1.38	2.50	1.69	1.04	0.50	0	0.35	0.50
-4	85.88	82.64	78.00	6.07	4.91	20.00	6.28	2.89	0	0.48	2.20	1.50	0.48	6.62	0	0.64	0.28	0	0.16	0.46	0.50
-3	76.99	48.39	59.00	13.67	22.18	33.00	7.38	9.07	0	1.25	1.21	3.00	0.39	19.15	3.50	0.32	0	0.50	0	0	0.50

Number of particles for Woodstock and Otarama samples unknown but greater than for Kowai River.

Number of Kowai River particles same as for Table 15.

coarse phi fractions, especially if the gravels are being recycled. Finer than -60 other compositional types increase in importance, representing the more mobile and unstable portion of the stream bed sediments. Here the increasing anisotropy of the finer grained sediments facilitates rapid disintegration.

The -40 and -30 size grades of the Kowai River sample show a significant increase in the fine sandstone component compared with the two earlier deposits there is little of this material in the -60 size grade. Again this may be a function of the recycling of sediments wherein the more highly erodible lithologies such as volcanics and argillites are destroyed completely, thereby increasing the relative proportion of sandstones and, to a lesser extent, the cherts. Chert has only a limited occurrence and can be ignored for the purposes of this discussion, leaving fine sandstone the most resistant rock type after coarse sandstone.

Minor changes in composition between the three samples may be attributable to changes in source area over time, for instance the apparent increase in the amount of argillite during deposition of the Otarama unit. Argillite is unlikely to be concentrated as a result of reworking because of the extremely friable nature of the material, a characteristic that becomes more pronounced in weathered material.

The significant changes in rock composition between the three deposits (Table 16) can be accounted for as the result of recycling of some original gravel 'stock'. This recycling has resulted in the coarser sandstones dominating the larger particle sizes while the fine sandstones dominate the remainder of the gravel mix, at least to the -30 size grade, the finest size fraction studied here. The more erodible lithologies tend to be destroyed completely or restricted to very fine size grades and flushed downstream.

6. CONCLUSION

The textures of fluvio-glacial and recent riverbed deposits are all quite similar. What differences there are being more in the nature of trends occurring with time than sharp breaks. Hence they have not necessarily been derived from radically different fluvial regimes.

Earlier in this paper it was mentioned that although the processes of the hydraulic regimes responsible for the creation of the three deposits may not have altered significantly over time, it is probable from our evidence that the scale of these processes has changed.

Griffiths (1977) showed that only limited downstream movement of very large boulders (greater than one metre in diameter) can be expected in mountain stream beds in the absence of catastrophic events. These very large boulders he considers to be either glacial relicts or derived from landslide or snow avalanche deposits. The relict boulders of this study are not as large as those investigated by Griffiths, but they are of a magnitude greater than the median size of the sediment, up to -7φ and larger, versus -4φ. They probably have similar histories to those described by Griffiths. Considering the location of the Kowai River catchment on the eastern side of the Southern Alps, and the profusion of glacial features in the area, a derivation from the reworking of glacial deposits seems the likely origin of the larger boulders encountered in this study.

It was apparent from the sediment survey of the recent riverbed (Part A) that the present stream is not capable of moving the larger boulders (>6.0φ) more than short distances during flood flows. Such boulders, however, are widely distributed throughout the fluvio-glacial deposits, which themselves cover a much greater extent than the present river system. For this reason it is postulated that flood flows, at least of a magnitude greater than those that occur today must have taken place in the past, to account for the composition and extent of these outwash surfaces.

The results of the sediment analysis are not indicative of possible alterations in the processes of the hydraulic regimes over time, but if changes in flow patterns had occurred then these were likely to have been related to the occurrence of periglacial events aiding in the formation of the two fluvioglacial deposits. Flood flows larger than those occurring today are quite probable in the context of the Kowai River considering the possibility of catastrophic floods following the bursting of meltwater lakes, with kame terraces being one of the glacial features found within the catchment.

There is no clear evidence, however, that such regime changes were responsible for the differences between the three deposits. This and other more theoretical lines of evidence which may be postulated to account for these differences (e.g. geomorphic controls on drainage) appear to be less probable than a recycling of a gravel 'stock' by a stream system similar to that found today. As can be readily observed from a study of river processes, small streams show water and sediment transport similar in nature but different in scale to larger rivers that have the same slope and sediment sources.

We contend that the bulk of the material in the three deposits samples belongs to a common 'stock', with the more recent deposits being created largely from a recycling of earlier deposits. This original stock of gravel was probably created in the first great erosional episode following the uplift of the Torlesse and adjacent ranges of hills. The earliest episode in the Waimakariri glacial sequence was the "Avoca glaciation" (2,000,000 yr B.P.) which, being also the most extensive, would have created extensive outwash deposits of erosional material. There are now no deposits that can be attributed to the Avoca Glacial advance within the Kowai Catchment, these having been destroyed by succeeding glaciations. The Woodstock deposit, the earliest studied in this paper, was formed during the Woodstock advance which followed an interglacial episode after the Avoca glaciation and is therefore, in all probability, derived from Avoca material. No attempt has been made to sample a deposit of Avoca material.

Although there is undoubtedly a component of gravel derived from actively eroding bedrock source areas being carried through the system, we consider this material to comprise only part of the active streambed sediments, with its significance as a component diminishing with distance downstream. The exact proportions of fresh to reworked material remain indeterminate and there are a number of lines of evidence suggesting that the fresh material may be of only limited importance at this study site.

First, because of its isotropic properties, only the coarse sandstone can be expected to behave in a resistant manner during stream transport and, significantly, there are now few actively eroding areas of coarse sandstone. Most actively eroding areas are located in sequences of interbedded fine sandstones and argillites where the abrasiveness of the material is such that it can be expected to break down rapidly into very fine particles which are flushed through the system. In this respect the rare occurrence of argillite in the Kowai River sample is significant. Extreme abrasiveness occurs in the case of volcanic rocks which are actively decomposing in situ.

Second, there is the evidence from comparative studies of sediment textures and statistical parameters to show the present river gravel sample as exhibiting only subtle differences from the fluvio-glacial material. In turn, the postulated recycling of fluvio-glacial material can be used to account for most of these.

Finally, there is the evidence that the larger boulders,at least,are fluvio-glacial relicts related to a flow regime at least in order of magnitude greater than the present river flow regime. As a result of this study we wish to emphasise the importance of riparian sources of gravel to the overall composition of active streambed sediments. More research could be carried out to establishing the relative proportions of fresh to recycled material along a river course, but the importance of river gravels to river management programmes remains obvious.

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