JOURNAL OF HYDROLOGY

NEW ZEALAND

Published twice annually by the New Zealand Hydrological Society

Volume 20 | 1981 | Number 2

SURFACE, SUSPENDED AND BEDLOAD SEDIMENT — CLUTHA RIVER SYSTEM

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ABSTRACT

Surface-water samples, taken daily at five sites on the Clutha River and its tributaries for a period of 21 months, were used to compute an average trap efficiency of 80% for Roxburgh reservoir, and to compute suspended-sediment discharge. These were compared with volumes of sediment deposited in the reservoir, and with suspended-sediment discharges from the tributaries estimated using sediment rating-curves.

The grain size of sediment deposited in Roxburgh reservoir was compared to that of suspended sediment in the Clutha and Shotover Rivers. Material coarser than 0.14 mm was transported as bedload in the Clutha River at Clyde and formed 23% of the total sediment load. In the Shotover River, material coarser than 0.3 mm was transported as bedload, forming 14% of the total load. Using these estimates of bedload, reasonable agreement was obtained between the estimates of sediment discharge made from the surface water sampling programme, from suspended-sediment rating curves, and from siltation surveys.

INTRODUCTION

Plans for developing the hydro-electric resources of the Clutha River above the Roxburgh Power Station stimulated a review of available sediment data by S. M. Thompson (1978). His estimates of sediment quantities were based on successive surveys of siltation in Lake Roxburgh. From his report it was evident that the total quantity of sediment transported by the river could not be accurately estimated without measuring the trap efficiency (defined here as the percentage of suspended sediment deposited in the lake) of Lake Roxburgh. From 1977, surface suspended-sediment samples were taken daily from the Clutha River at Alexandra and from the Manuherikia River at Shaky Bridge to determine the amount of suspended sediment flowing into Lake Roxburgh. Twice daily samples were taken from the Roxburgh power station tailrace by station staff to determine the amount of suspended sediment flowing from the lake.

Shortly after this programme began it was realised that the method could be extended to give information about relative magnitudes of sediment sources within the catchment, and the programme was extended to include daily sampling of the Kawarau River at Bannockburn Bridge and of the Clutha River at Lowburn Bridge (Fig. 1).

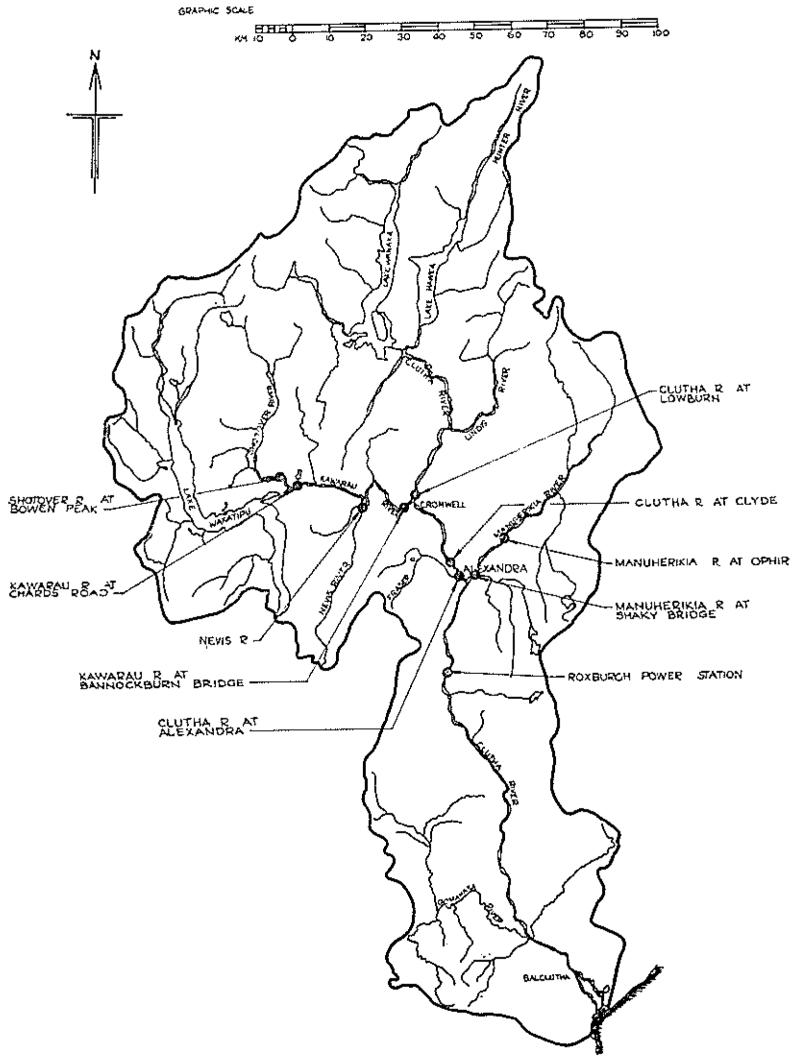

FIG. 1—Clutha River catchments.

Three lakes contribute 83% of the Clutha River flow at Roxburgh and the sediment contribution from these lakes is almost nil. The remaining 17% of the water is from tributaries which contribute almost all the sediment. During floods the proportion of tributary water varies considerably depending upon the areal distribution of rainfall, antecedent moisture conditions, and the level and outflow from the lakes. Consequently, for the Clutha River, there is no unique relationship between discharge and sediment concentration as is commonly assumed for rivers and an alternative method of computing suspended-sediment load must be adopted.

METHOD

Surface samples were taken with a bucket at three points across the width of the river. Each sample was tested on a Spectronic 20 photo-absorption meter and the average light transmissivity determined.

When the sediment concentrations were low and transmissivity high, surface samples for periods up to one week were mixed together giving an average suspended-sediment concentration for that week. An operating rule was set whereby samples with transmissivities exceeding 95%, collected on consecutive days, could be mixed. This represented a sediment concentration of approximately 10 g/m^3. This reduced the amount of laboratory analysis to daily samples with a high sediment content, and to samples representing average concentrations for periods of up to a week when the sediment concentration was low. The laboratory analysis followed procedures set out by the Interagency Committee (1941). Periodically, depth-integrated samples also were collected in order to relate surface sediment concentration to the average concentration.

COMPARISON OF CONCENTRATIONS DERIVED BY DEPTH-INTEGRATED AND SURFACE SAMPLING

Surface sediment concentrations were compared with depth-integrated concentrations (Fig. 2) and logarithmic or polynomial curves were fitted by least squares to the data. Generally each curve was extrapolated downwards to pass through the origin and upwards so that it was parallel to the line of equality (where the depth-integrated concentration was the same as the surface concentration).

Each site has an individual relationship between surface and depth-integrated concentration. A possible explanation of this can be sought in terms of the settling velocities of individual particles and turbulence of the flow (Rouse, 1937). In rivers where either the settling velocity is low or the turbulence is high, sediment concentration at the surface should approach the average concentration. Below Roxburgh Power Station the sediment size is small (all coarse sediment is deposited in the lake) giving a linear relationship between surface and average concentration. In the Manukerikia River the channel slope is steeper giving high turbulence and a linear relationship between surface and average concentration.

At the other sites channel slopes are low and the sediment is coarser,

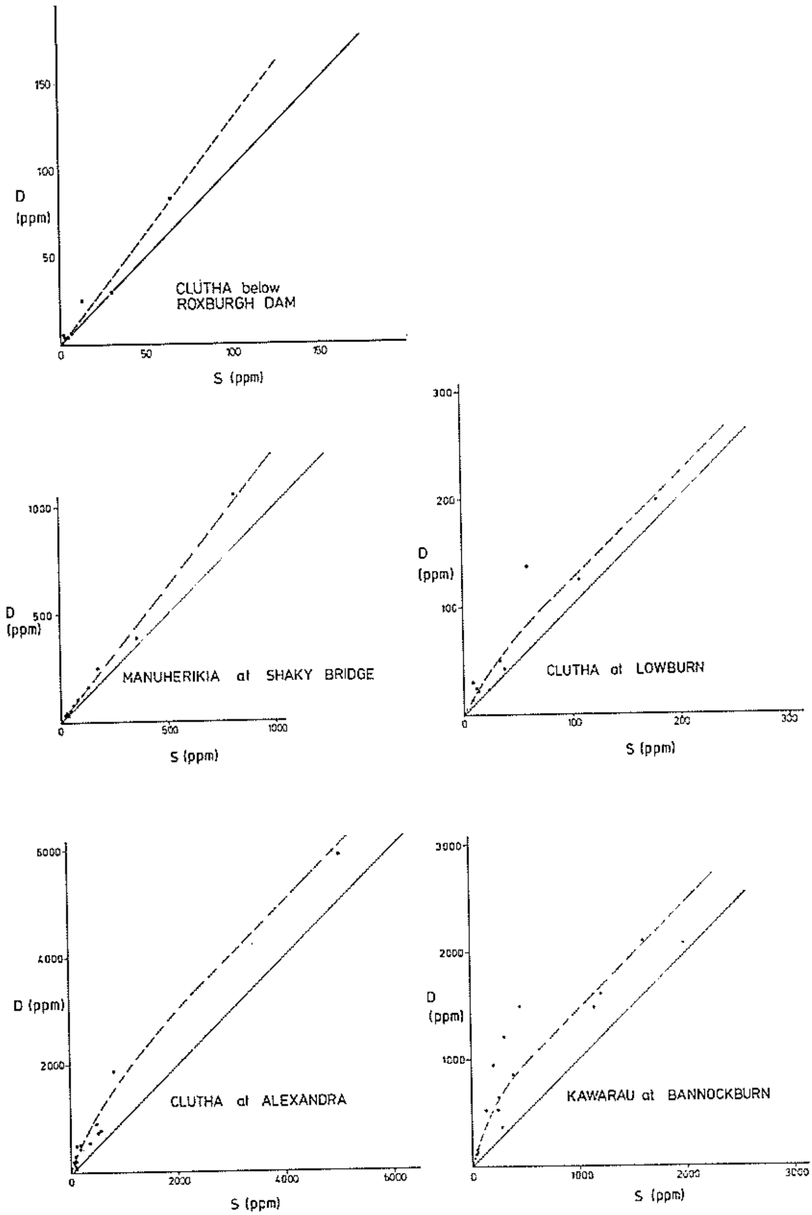

FIG. 2—Depth-integrated concentration (D) versus surface concentration (S).

and the highest sediment concentrations are found near the bed at low flows. As flow increases, turbulence increases, particle size remains relatively constant, and the concentration becomes more uniform over the depth. Under conditions of high turbulence, the surface concentration should approach the average concentration. This indicates that during large floods field parties could take surface suspended-sediment samples rather than depth-integrating samples, saving time, and improving safety in debris-laden rivers. Relationships such as those described above could be used to determine average sediment concentrations.

Hydrological records

Flow of the Manuherikia River at Shaky Bridge was estimated by multiplying flow recorded at Ophir by 1.189, the ratio of runoff estimated from the catchment areas and areal distribution of mean annual precipitation. Flow of the Clutha River at Alexandra was then estimated by subtracting Manuherikia flow from Lake Roxburgh inflow (calculated from power station records).

The hydrological recording site on the Clutha River at Lowburn gave the flow at Lowburn and also was used to estimate flows in the Kawarau River at Bannockburn bridge by subtracting Clutha River flows at Lowburn from those at Clyde (Fig. 1).

Suspended-Sediment Transport

Depth-integrated concentrations were estimated from the surface sediment concentrations by applying the equations derived by least squares for each site. These values represent the average concentration for the 12-hour period on either side of the sample. Where two or more samples have been mixed, it represents the average from twelve hours before the first sample to twelve hours after the last. These concentrations are multiplied by the total water discharge over the same period to obtain the suspended-sediment transport (Table 1).

TABLE 1—Suspended sediment quantities (Mt) from surface samples.

Site	16.9.77 to 28.6.79	15.4.78 to 22.6.79	15.7.78 to 15.2.79	13-16 October 1978
Clutha at Alexandra	4.10	3.48	2.49	0.95
Manuherikia at Alex.	0.13	0.13	0.12	0.05
Kawarau at Bannockburn	—	3.13	2.22	0.73
Clutha at Lowburn	—	0.31	0.21	0.03
Clutha at Roxburgh PS	0.85	0.78	0.68	0.47

During the tweny-one months of sampling, the Clutha River at Alexandra contributed 97% of the suspended sediment flowing into Lake Roxburgh and the Manuherikia River 3%, that is, 4.10 and 0.13 Mt respectively. In this period 0.85 Mt were discharged from the power station leaving 3.38 Mt or 80% deposited in Lake Roxburgh. The sampling period included a large flood in October 1978 in which suspended-sediment transport almost equalled the annual average.

Jowett (1979) emphasises the large quantity of sediment ransported by this twenty-year return period event. Also of interest is the variation of Lake Roxburgh trap efficiency with through-flow. Over the four days of the flood, the trap efficiency averaged only 53%, which is very much lower than the long-term trap efficiency of about 80%. Similar decreases in trap efficiency are evident in other floods.

Further upstream, sampling of the Kawarau and Clutha Rivers was carried out between 15 April 1978 and 22 June 1979. In this period the Kawarau River contributed 3.13 Mt (91%) of the suspended sediment and the Clutha River 0.31 Mt (9%). As a check, the total for the Clutha at Lowburn plus the Kawarau, 3.44 Mt, can be compared with the 3.48 Mt of suspended sediment measured at Alexandra over the same period. The slightly higher figure at Alexandra is accounted for by the sediment contribution from the intermediate catchment but has been reduced by the backwater effect of Lake Roxburgh, which reduces the water velocity at Alexandra and results in the transfer of some sediment from suspended to bed load. In times of exceptional flood, considerably more suspended sediment was measured at Alexandra than at the Kawarau confluence, and the intermediate tributaries can be considered to have supplied at least this amount of suspended sediment.

A clear picture of the distribution of sediment sources has emerged from the sampling programme. At the Manuherikia-Clutha confluence, 97% of the suspended sediment entering Lake Roxburgh comes from the Clutha River and only 3% from the Manuherikia River. At the Kawarau-Clutha confluence, 91% of the suspended sediment comes from the Kawarau River and 9% from the Clutha River. Of the suspended sediment entering Lake Roxburgh, about 3% is from the Manuherikia River, 1% is from the catchment between Alexandra and the Kawarau-Clutha confluence, 88% is from the Kawarau River, and 8% is from the Clutha River above the Kawarau-Clutha confluence.

Comparison with volume of sediment deposited in Lake Roxburgh

This method was used by Thompson (1978), but without an accurate estimate of trap efficiency. This calculation has been repeated using some more accurately determined lake volumes calculated directly from 1978 to 1979 survey, rather than by planimetry of plotted cross-sections, and incorporating a trap efficiency derived from the suspended-sediment sampling programme. These results are shown in Table 2.

TABLE 2—Lake Roxburgh volumes from siltation surveys.

Date	Lake volume (10^6 m^3)	Change in volume (10^6 m^3)	Average annual rate of deposition (10^6 m^3/a)
February 1979	75.64		
July 1978	78.41	2.77	4.71
July 1974	82.43	4.02	1.00
July 1970	87.26	4.83	1.21
July 1961	101.24	13.98	1.55

Between 1961 and 1979 the average annual rate of deposition has been 1.46×10^6 m^3. The density of deposited sediment was calculated by Thompson (1978) to be 1.27 t/m^3.

Over the period between the 1978 and 1979 surveys, 2.77×10^6 m^3 (=3.52 Mt) were deposited and the daily sampling programme showed 2.61 Mt of suspended sediment flowing into Lake Roxburgh and 0.68 Mt out (see Table 1). The difference is in part due to the amount of sediment contributed by the catchment between Alexandra and Roxburgh and the amount of sediment transported as bedload at Alexandra.

Normally the catchment around Lake Roxburgh contributes little in the way of water and sediment; however, during the October 1978 flood, rainfall intensities in this region were exceptionally high, and large quantities of sediment were transported. The area between Cromwell and Alexandra contributed at least 0.19 Mt of sediment over the four days of the flood (Table 1), a specific yield of 380 t/km^2. This is slightly less than the specific yield of the Nevis River, as we would expect from an inspection of storm isohyets of Jowett (1979).

The yield from the Nevis River over the longer period 15 July 1978 to 15 February 1979 was 15.8% higher than the yield over the flood (Jowett, 1979; Table 5). This suggests an estimated $380 \times .158$ t/km^2 specific yield from the catchment between Cromwell and Alexandra. From the storm isohyetal map presented by Jowett (1979) the precipitation around Lake Roxburgh during the October 1978 flood was approximately 25% higher than in the Cromwell to Alexandra catchment. Hence the suspended sediment yield from the 320 km^2 catchment around the lake can be estimated to be about 0.18 Mt.

Information gained from particle-size analyses of suspended sediment and the particle-size distribution of sediment trapped in the lake can be used to determine the proportion of sediment carried as bedload. Particle-size analyses of depth-integrated suspended-sediment samples taken from the Clutha River at Clyde and the Kawarau River at Chards Road (Figure 3a) indicate that the coarsest material in suspension at both sites lies between 0.2 mm and 0.25 mm in diameter. A large set of samples taken over one flood from the surface of the Kawarau River at Bannockburn (Figure 3b) show that the largest material in the surface water is between 0.09 mm and 0.125 mm in diameter.

Sediment gradings of suspended and bedload samples from the Shotover River at Bowens Peak (Figure 3c) show that there is a sharp distinction between the size of material transported in suspension and as bedload. Only about 10% of the material is of a size that can be transported in either manner. For this reason we selected the particle size of which 90% of the suspended sample is finer, ($d_{90\%}$), as the cut-off between suspended and bedload sediment. The $d_{90\%}$ size of depth-integrated suspended sediment from the Clutha River at Clyde and the Kawarau River was 0.14 mm, and from the surface samples taken from the Kawarau River at Bannockburn, 0.08 mm. At Alexandra, where the river is more tranquil because of backwater effects from Lake Roxburgh, even finer material will have dropped from suspension. The size of suspended sediment at Alexandra was determined for only one event and in that event the $d_{90\%}$ size at Alexandra was 0.04 mm finer

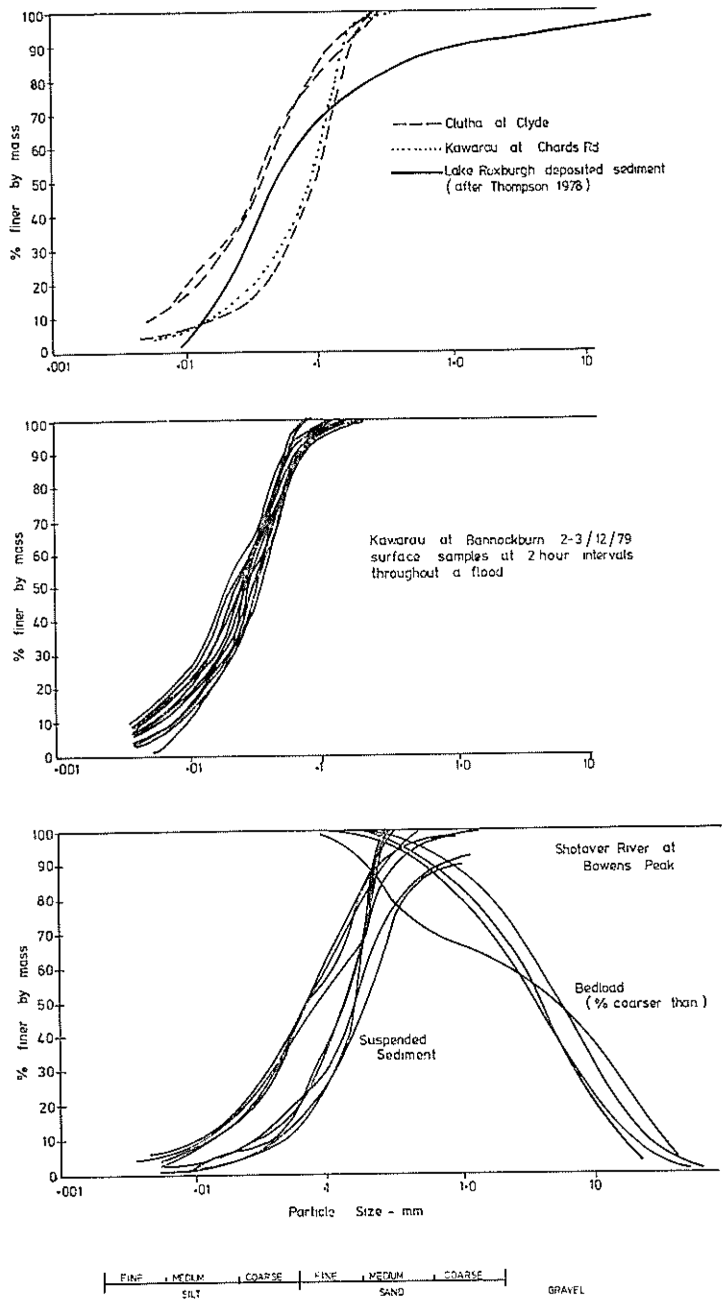

FIG. 3—Sediment grading curves.

than at Clyde. Thus it is estimated that material coarser than about 0.10 mm will be transported as bedload below Alexandra (Figure 3).

Using the particle-size distribution derived by Thompson (1978) and shown on Figure 3, 73% of the deposited sediment in Lake Roxburgh is finer than 0.14 mm, and 67% finer than 0.10 mm. This suggests that about 67% of the sediment deposited in the lake arrives in suspension, and the other 33% arrives as bedload. Surface sediment samples taken between the 1978 and 1979 surveys indicate that 1.93 Mt of suspended sediment was deposited (Table 1). This, plus the estimate of 0.18 Mt from the catchment area around the lake, represents 67% of the total sediment deposit. The total sediment deposit of 3.15 Mt computed in this manner compares favourably with the 2.77 x 10^6 m^3 (3.52 Mt) of deposited sediment which was surveyed.

Surveys upstream of Alexandra indicate that there is no significant aggradation or degradation and hence all sediment passing Cromwell can be expected to pass Alexandra. A comparison thus can be made between the sediment passing Cromwell and sediment surveyed in the lake. The Kawarau and Clutha Rivers together yielded 2.43 Mt of suspended sediment and the Manuherikia River 0.12 Mt (Table 1). The remaining 320 km^2 catchment around the lake is estimated to yield 0.18 Mt and the larger catchment between Alexandra and Cromwell, 0.22 Mt. This gives a total suspended sediment deposit of 2.31 Mt which, being finer than 0.14 mm, would be about 73% of the total deposit according to the particle-size distribution of deposited sediment. The total deposit of 3.16 Mt calculated in this manner is close to that surveyed (3.52 Mt) and to that estimated from the Alexandra samples (3.15 Mt). The comparison of the grain-size analysis of Lake Roxburgh sediment with the grading curves of suspended sediment gives a proportion of bedload sediment at Alexandra which, at about 30% is high, but this appears justified by the agreement between the estimates made on this basis and the volume of deposited sediment measured in Lake Roxburgh.

Suspended-sediment yield from the tributary streams can also be estimated by the more conventional technique of applying sediment-rating curves to flow data. This was done by Jowett (1979) for the tributary streams of the Clutha River above Lake Roxburgh and a yield of 3.65 Mt of suspended sediment was estimated for the period 15 July 1978 to 15 February 1979. This exceeds the amount sampled as input to Lake Roxburgh by almost 1 Mt. Assuming that 80% (that is, the trap efficiency determined from the surface sampling programme) of the suspended sediment is deposited, then only 0.6 Mt of the surveyed deposit in the lake is required to be transported as bedload at the tributary sampling sites. This would be about 16% of the suspended load and, from the particle-size distribution of sediment within the lake, represents material coarser than about 0.3 mm. This estimate agrees with the suspended-sediment gradings from the Shotover River at Bowens Peak (Figure 3) where the average $d_{90\%}$ is 0.3 mm.

CONCLUSION

This study illustrates some of the uncertainties within sediment estimates. Bedload can, by various estimates, form 10 to 30% of the total sediment load of a river.

The maximum suspended-sediment size in the Clutha and Kawarau Rivers from depth-integrated samples is less than 0.25 mm and a series of sediment measurements in the Kawarau River showed that the maximum grain-size in surface samples had no appreciable variation throughout one flood.

Particle-size distributions of sediment deposited in Lake Roxburgh show that a large proportion of the river's sediment load is coarser than 0.25 mm and it is inferred that most of this is transported as bedload. The proportion of bedload at sampling sites on the steeper, more turbulent tributaries is lower than at Clutha River sampling sites.

There is considerable variance in the relationships between depth-integrated and surface-sediment concentrations. More comparative samples might refine the precision of these relationships.

Agreement between suspended-sediment volumes computed at two sites on the same river was very good. The immediate aims of measuring the trap efficiency of Lake Roxburgh and determining the relative importance of tributaries as sediment sources were achieved within a shorter time than the period usually taken for data collection by more conventional sediment-rating methods. Surface sampling can be carried out simply by residents near the site. Reasonably accurate estimates of suspended-sediment discharge can be obtained quickly, providing that suitable relationships between depth-integrated and surface concentration are available.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the work of field staff at Alexandra and Cromwell who collected the samples and, in particular, the laboratory staff for their analyses of sediment concentration and particle size. The Commissioner of Works has given permission for this publication.

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