Journal of Hydrology, 40 (1979) 283—297 283

[1]

ESTIMATING SEDIMENT TRANSPORT IN A BRAIDED GRAVEL CHANNEL — THE KAWERONG RIVER, BOUGAINVILLE, PAPUA NEW GUINEA

G. PICKUP and R.J. HIGGINS

Department of Geography, University of Papua New Guinea, Port Moresby (Papua New Guinea)
Hydrology Section, Bougainville Copper Ltd., Panguna (Papua New Guinea)

(Received November 21, 1977; revised and accepted July 1, 1978)

ABSTRACT

Pickup, G. and Higgins, R.J., 1979. Estimating sediment transport in a braided gravel channel — the Kawerong River, Bougainville, Papua New Guinea. J. Hydrol., 40: 283—297.

It is difficult to estimate sediment transport in braided rivers because of the complex hydraulics of rapidly changing multi-channel systems. This paper describes an algorithm for generating sets of braided-river hydraulic parameters for use with sediment transport equations. The algorithm uses random number-based simulation techniques and empirically determined probability distributions of individual hydraulic variables from the White River (U.S.A.) and the Kawerong River. A test of the suitability of the algorithm for the estimation of sediment transport was carried out over a period of two years using the Meyer-Peter and Muller equation on eight reaches of the Kawerong River in which sediment transport is known. The test produced a mean absolute error of 16.3% suggesting that the algorithm may have some potential in braided-river modelling.

INTRODUCTION

One of the problems of river modelling is the estimation of sediment load using transport equations. This requires information on the hydraulic geometry and flow conditions in the watercourse as well as discharge and sediment characteristics.

Obtaining representative hydraulic data for a braided stream is difficult for a number of reasons. Firstly, the number, direction, shape and size of channels vary over short distances as flow paths join and divide. At the same time, channels may rapidly change position, shape, size, slope, flow resistance, velocity and discharge as waves of erosion and deposition move along the channel and as bars and islands are built and destroyed. Other problems are the high velocities and coarse sediment load encountered in braided gravel rivers which make stream gauging and sediment sampling a difficult and hazardous business.

Under these circumstances, braided rivers cannot always be treated in the same way as single-channel rivers when applying sediment transport equations. At any one discharge, many different sets of channel conditions are possible and the hydraulic parameter values used in the equation must fully represent the range of conditions which occur in the river.

There are two possible ways of determining representative hydraulic parameters for a braided river. The first method is to obtain measurements of the characteristics of the individual channels in a braided cross-section which are then lumped together and where appropriate, averaged. When averaging is carried out, raw values may be used or they may be weighted by the proportion of discharge carried by each channel. The problem with this approach is that averaged hydraulic parameters may not produce the same sediment transport rate as that obtained when each channel is treated separately.

The second approach to deriving a set of representative hydraulic parameters for a braided river is to accept that variations in channel conditions occur but to assume that these variations conform with some kind of frequency distribution. If the parameters of the frequency distribution can be obtained, it becomes possible to generate sets of hydraulic conditions similar to those occurring in the river, using simulation techniques based on random numbers. This data may then be used in association with an appropriate sediment transport equation to estimate sediment transport.

This paper describes an application of the second approach to the Kawerong River on Bougainville Island, Papua New Guinea. This river is being used for tailings disposal by a mining venture and is regularly monitored to the extent that the input of sediment and average rate of sediment transport through each reach of the river are known. This makes it possible to test the accuracy of the braided-river algorithm which is developed in subsequent sections.

PREVIOUS WORK ON BRAIDED-STREAM HYDRAULICS

At present little is known about the hydraulics of braided streams probably because they are difficult to work in. Some information is available from geomorphic studies presented by Hjulstrom (1952), Leopold and Wolman (1957), Ning Chien (1961), and Kingstrom (1962) while sedimentary studies have been carried out by Doeglas (1962), Williams and Rust (1969), and MacDonald and Bannerjee (1971) among others. Only two major quantitative studies of braided-stream hydraulics seem to be available, these being Fahnestock's (1963) work on the White River and a report by Church (1970) on the sandur of Baffin Island.

This paper draws extensively on the work of Fahnestock (1963) both for basic and for comparative data. The White River and the Kawerong River have very similar characteristics, making it possible to substitute data from one to the other where field observation was not possible. This was particularly important with parameters such as roughness which could not be determined on many channels in the Kawerong River because channel geometry and slope changed too rapidly for measurement. Where this type of problem was encountered, the extensive hydraulic geometry data collected by Fahnestock was used.

CHARACTERISTICS OF THE KAWERONG RIVER

The Kawerong River lies on the west side of Bougainville in the Solomon Islands and drains the area surrounding the Bougainville Copper Mine at Panguna. The river occupies a narrow steep-sided valley and has gradients of up to 7% below the mine site, decreasing to about 2% at its junction with the Jaba River, 9 km downstream (Fig. 1).

A data collection and monitoring programme is conducted on the Kawerong and Jaba Rivers. This programme includes regular surveys of the amount and extent of deposition of tailings and waste rock from the mine, stream gauging, bed-material sampling, suspended load sampling and the collection of water-quality data. A predictive capacity for the river is being developed (Higgins, 1977) to assist waste-disposal planning for the anticipated life of the mining operation.

As a result of the monitoring programme, it is known how much sediment has entered the system over the last nine years and where it has been deposited, making it possible to determine sediment transport rates for each section of the river. Being derived from reliable input and deposition measurements, sediment transport rates are not dependent upon bed-load sampling techniques. Wash-load has been excluded from total sediment load by the criterion of Einstein (1950).

Between 1968, when mining operations began, and mid-1976, 226 Mt (megatonnes) of sediment have entered the Kawerong River from the mine area. Of this, 46 Mt were hydraulicked fine overburden, 2 Mt resulted from mine catchment erosion, 108 Mt were concentrator tailings and 70 Mt were eroded from the waste rock dump. As a result of this vast increase in sediment load, 79 Mt of material have been deposited in the Kawerong valley and on the flood-plain of the Jaba within the area leased by the company for tailings disposal (Fig. 1).

Since the hydraulicking of fine overburden ceased prior to 1971, most of the sediment input to the river has been tailings and waste rock. In comparison with these, catchment erosion and the normal load of the river are negligible. The tailings, which come from the mine concentrator, consist of sand and silt-sized particles. The waste rock varies in size from boulders to silt but, on average, more than 80% of it is gravel. Particle size distributions for tailings and waste rock are presented in Fig. 2.

Most of the gravel has been deposited in the Kawerong valley. Deposition has not occurred uniformly along the river however (Fig. 3), but has concentrated in the lower section where the gradient declines rapidly. Virtually all the tailings pass through the Kawerong as wash load even though wash-load concentrations may be as high as 250,000 ppm. Once the tailings have reached the Jaba, deposition begins and continues to the delta in response to the much

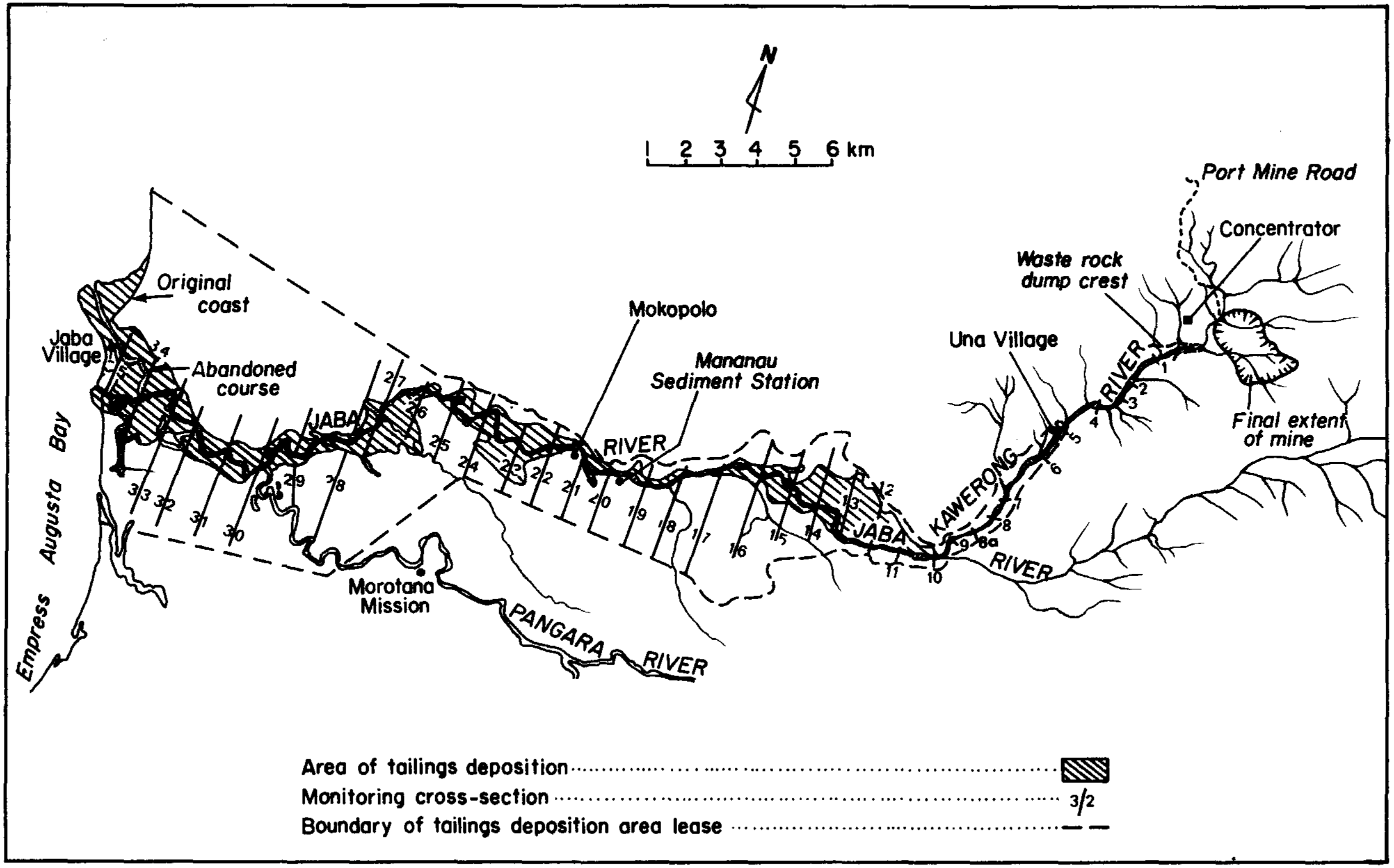

Fig. 1. Location map showing river monitoring cross-sections and the extent of deposition, Kawerong and Jaba Rivers, Bougainville. The deposition is mapped for December 1974 at the end of the period used to test the braided river algorithm.

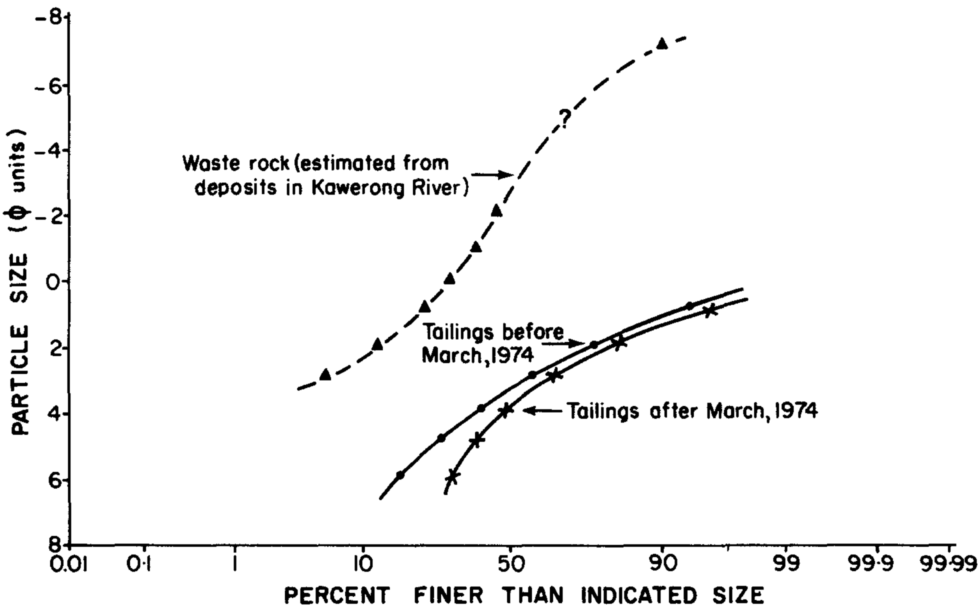

Fig. 2. Size distributions of tailings and waste rock input to the Kawerong River.

lower gradients downstream of the Kawerong.

For most of its length the Kawerong River has a braided channel. Short sections in which the flow is confined to a single channel do occur particularly at low flow but these are not common. Flow is supercritical in most channels and velocities can reach 3—4 m/s making measurement very difficult. Channel changes occur frequently and rapidly, often faster than it is possible to measure using normal survey techniques.

ESTIMATION OF BRAIDED-RIVER HYDRAULIC PARAMETERS

Sediment transport equations require values for most or all of the following hydraulic parameters; width and mean flow depth, velocity, hydraulic resistance and energy slope. Because of the difficulty of lumping individual channels together to derive composite parameter values, this data must be available for each channel. It is therefore necessary to know or to be able to generate values of each parameter for each channel and to have two additional sets of data. These are: the frequency distribution of channel numbers and the frequency distribution of the proportion of total flow carried by each channel. With this information available, it is possible to use simulation techniques to generate representative sets of hydraulic data using the algorithms described in subsequent sections.

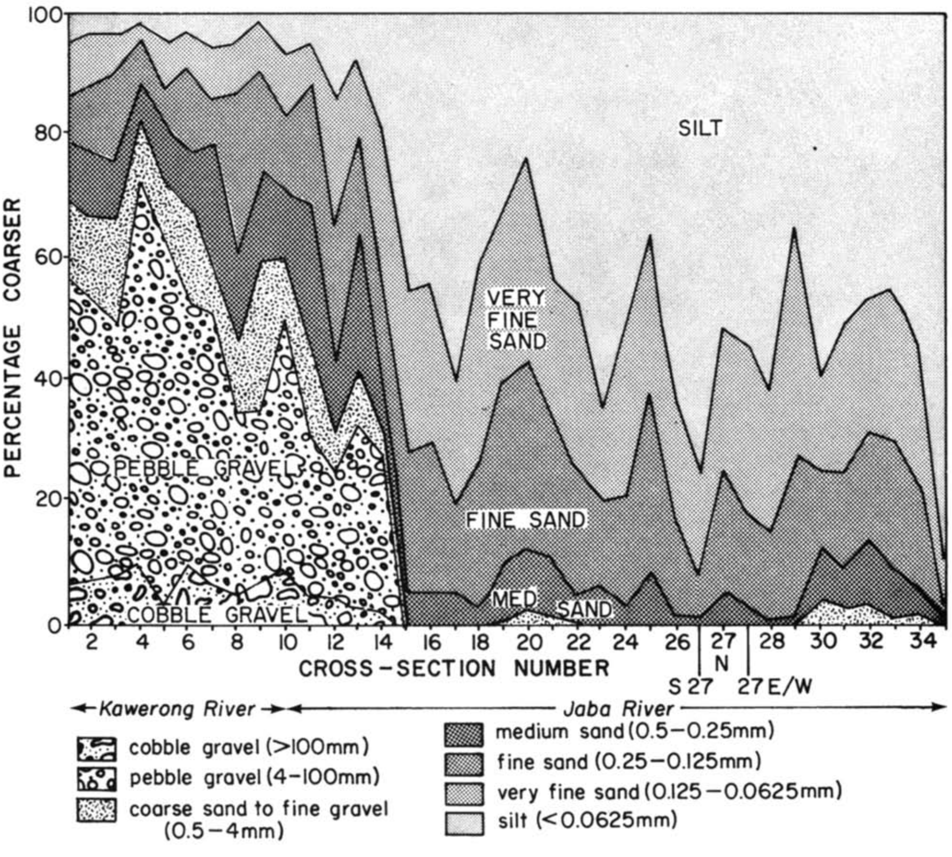

Fig. 3. Size distribution of deposited material, Kawerong and Jaba Rivers.

NUMBER OF CHANNELS

Little is known about the factors controlling the number of channels in a braided river. Fahnestock (1963) has shown that, in general, the number of channels increases with discharge but this response is not always instantaneous and may have a time lag. He also notes that channel number increases with valley width but the effect of valley constrictions or rapid increases in width may not be felt for some distance downstream.

The only attempt to predict channel numbers in braided reaches so far seems to be that of Howard et al. (1970) who developed a simulation technique based on a random-walk process. This model cannot be used to predict how the number of channels varies without maps or air photographs of the system which show its characteristics in sufficient detail to allow the determination of branching parameters. Data of this type cannot be obtained for the Kawerong River because the river changes too quickly for mapping and the water is so heavily laden with sediment that channels cannot be photographically distinguished from surrounding valley deposits.

At present, it seems that the only way to determine the number of channels in a reach at different flows is to count them in the field. This is currently being done on the Kawerong River but as yet, insufficient data are available to establish the frequency distribution of channel numbers for the whole range of discharges experienced by the river.

In the absence of adequate data for the Kawerong River, channel numbers have been generated using data for the White River collected by Fahnestock (1963). These data are plotted in Fig. 4 together with existing information on the channel numbers in the Kawerong River. It appears that no real difference between the two rivers exists. However, at low flows, there does seem to be a tendency for the Kawerong to have more channels than the White River. This possibly reflects differences in the method of data collection rather than differences in channel numbers. Fahnestock's data were collected from photographs taken from above the river whereas in the Kawerong channel numbers were determined by field counting. Many of the Kawerong channels are very

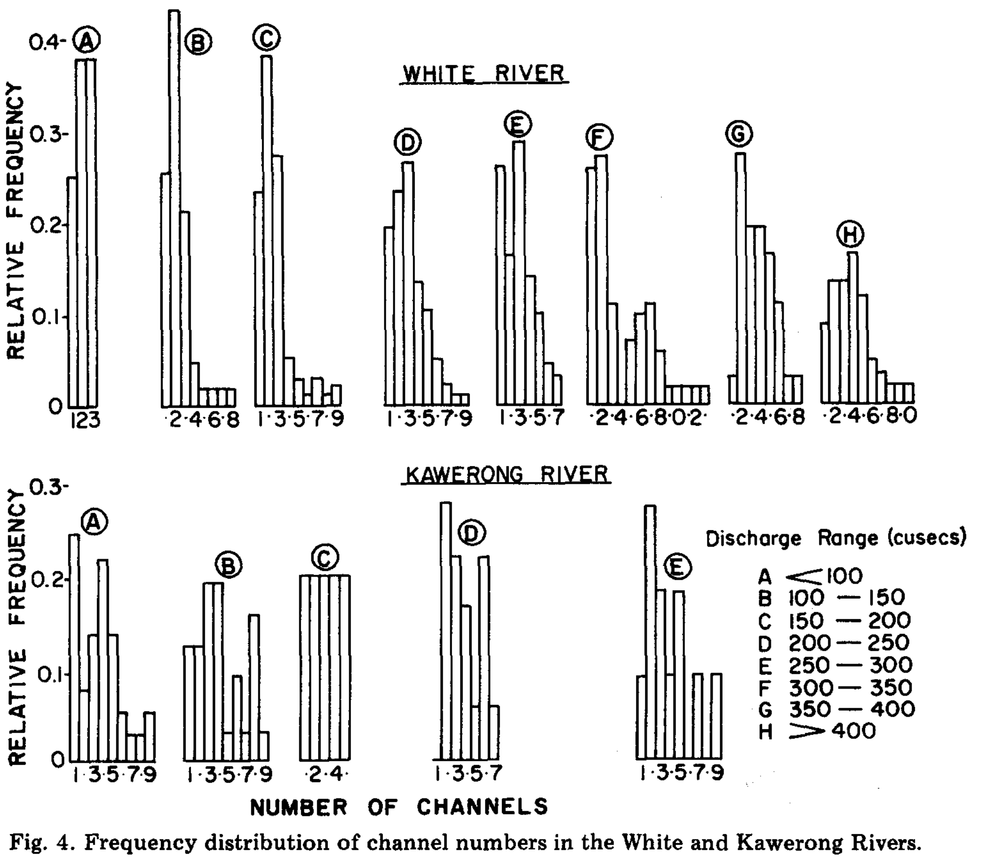

Fig. 4. Frequency distribution of channel numbers in the White and Kawerong Rivers. Source of White River data: Fahnestock (1963).

small (for example, 15% are less than 1 m wide) and it is possible that channels of this size were not discernible on Fahnestock's photographs. Even if there are differences between the White River and the Kawerong River, sediment transport rates are insensitive to quite large variations in channel number once there are more than three or four channels because the extra watercourses carry a very small proportion of total flow.

The method used to generate channel numbers was to incorporate the White River channel number frequency distributions into a computer programme as a look-up table. Random numbers are then generated and the number of channels is selected according to the random number and the data in the table. This procedure treats channel branching as a stochastic process but ensures that the generated data correspond with the known characteristics of a braided river.

Flow in each channel

Although a braided stream may have a large number of channels, most of them carry only a very small proportion of total flow. In the Kawerong River, reaches with up to 15 channels have been gauged, but in every case, the largest three carried 80—90% of the flow.

The frequency distribution of flows in individual channels is shown in Fig. 5. This has an exponential form, but there is considerable variation from reach to reach. Several attempts were made to generate distributions of the type shown in Fig. 5. In the most successful algorithm, the discharge in the first channel, q_1 was determined as:

$$q_1 = r_1 Q \tag{1}$$

while the discharge in all subsequent channels but the last one is given by:

$$q_n = r_n \left(Q - \sum_{j=1}^{n-1} q_j \right) \qquad (n < m) \tag{2}$$

The discharge in the last channel is then given by:

$$q_m = Q - \sum_{n=1}^{m-1} q_n \tag{3}$$

where Q is total discharge; r is a random number; q_n is the discharge in channel n, and; m is the total number of channels in the cross-section.

Samples of frequency distributions of flow in individual channels generated using this algorithm are illustrated in Fig. 5 below similar observed distributions.

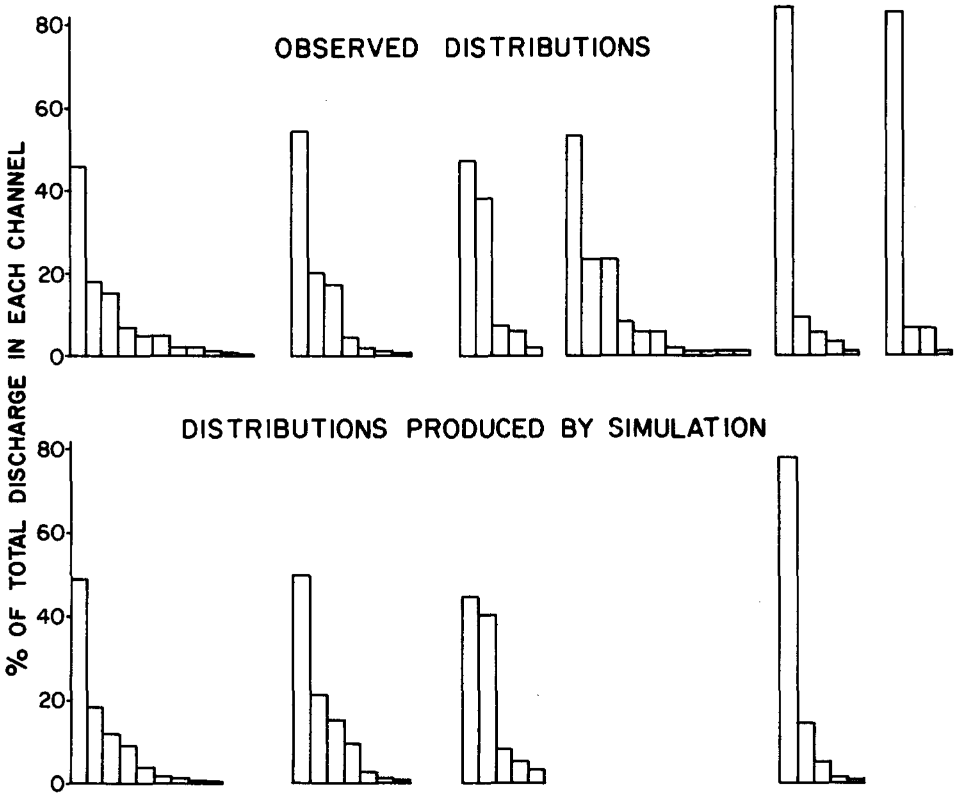

Fig. 5. Observed and simulated distributions of the proportion of total flow in individual channels in the Kawerong River.

Channel shape

Channel shape varies widely from channel to channel and from reach to reach in a braided river. Where the channel is stable, its shape might be expected to vary with discharge, slope, perimeter sediment and resistance to flow. However, exploratory plots of Fahnestock's (1963) data and data collected from the Kawerong River suggest that these relationships are either not present or they are submerged by other-variable noise. Several factors add to the apparently random nature of channel shapes. Firstly, some channels may be eroding while others in the same reach are silting or stable. Secondly, because channel and flow conditions change so quickly, large measurement errors should be expected in variables such as slope, velocity and hydraulic resistance. Channel depths may also be subject to measurement error because many channels are very shallow and have supercritical flow to the extent that waves may be several times greater than mean flow depth.

Under these circumstances, channel shape is effectively a random variable. In both the White River and the Kawerong River the frequencies of width/mean

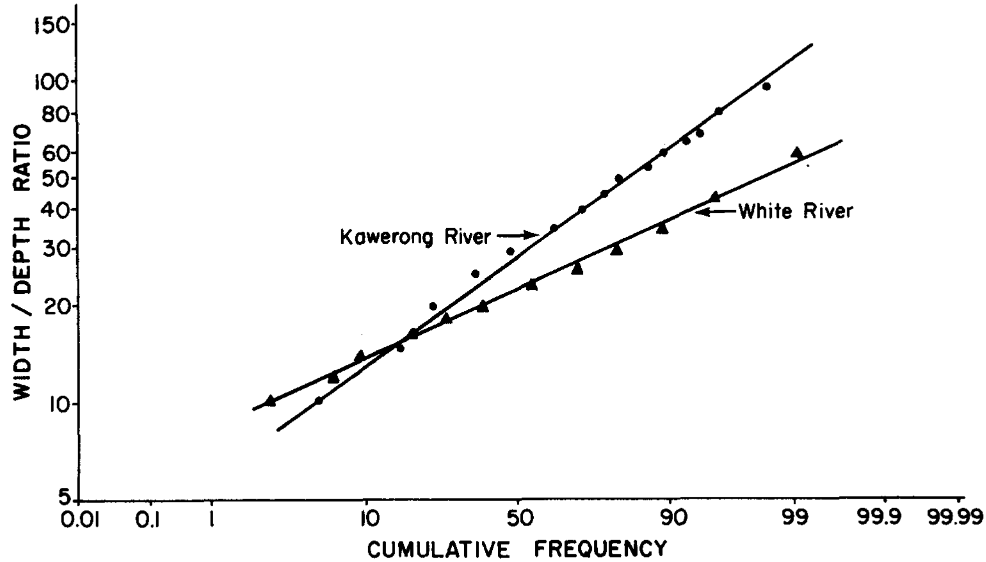

Fig. 6. Frequency distribution of channel width/mean depth ratios for the White and Kawerong Rivers. Source of White River data: Fahnestock (1963).

depth ratios are log-normally distributed (Fig. 6) and may be generated by random numbers using the algorithm of Naylor et al. (1966):

$$X = \exp\left[\mu_x + \sigma_x \left\{\left(\sum_{i=1}^{12} r_i\right) - 6\right\}\right] \tag{4}$$

where X is the variable; x is its natural log; μ_x is the mean of the x values; σ_x is their standard deviation; and r_i is a random number.

The values of μ_x and σ_x are respectively, 3.137 and 0.3701 for the White River and 3.337 and 0.625 for the Kawerong River.

Channel slope

Although the slope of a braided river may decrease consistently in the downstream direction, within any one reach the slope of individual channels may vary quite extensively. At present, there is no evidence to show that this variation in slope is other than a random process making it possible to generate individual channel slopes from a probability distribution.

The frequency distribution of individual channel slopes expressed in terms of the ratio of channel slope to reach slope from three reaches of the Kawerong is shown in Fig. 7. Like width/depth ratio, this variable seems to be log-normally distributed and can be generated using the same method. The values of μ_x and σ_x in this case are −0.183 and 0.777, respectively.

Resistance to flow

Resistance to flow in a stream varies with discharge both at-a-station and downstream but usually the variation is fairly small in streams with coarse bed material. Besides these, additional variations in flow resistance in braided streams can be expected because the size of bed material varies extensively over short reaches (see, e.g., MacDonald and Bannerjee, 1971). Similarly bed forms and the hydraulic characteristics of the flow change rapidly from reach to reach and eddy losses will be highly variable.

Like width/depth ratio and channel slope, resistance to flow may be effectively treated as a random variable. Plots of Fahnestock's (1963) data for the White River show that flow resistance seems unrelated to discharge, channel slope or shape although this may be partly due to measurement error which is unavoidably high in fast-flowing rapidly-changing braided rivers.

In the Kawerong River, values of the Strickler roughness coefficient, k, vary between about 35 and 55 but this is from a very limited sample. The more extensive data from the White River (Fahnestock, 1963) indicate that k values are log-normally distributed (Fig. 8) and the normal relationship between flow resistance and discharge is submerged by other factors.

Since there is little information available and data collection is very difficult, it has been assumed that the distribution of k values for the Kawerong River has similar characteristics to that of the White River. The frequency distribution for the Kawerong River has therefore been established by shifting the

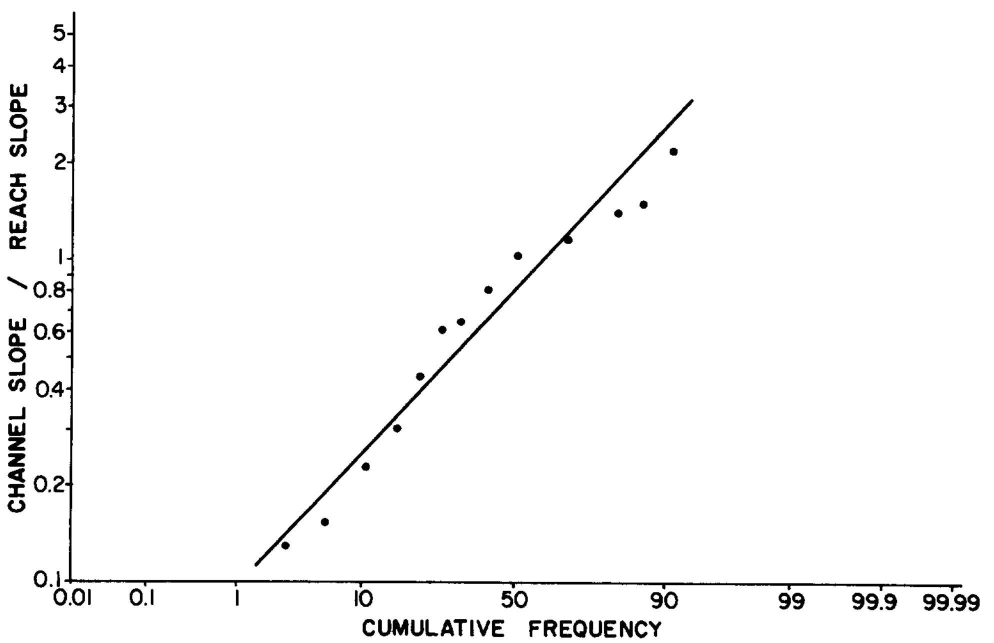

Fig. 7. Frequency distribution of channel slope/reach slope ratios, Kawerong River.

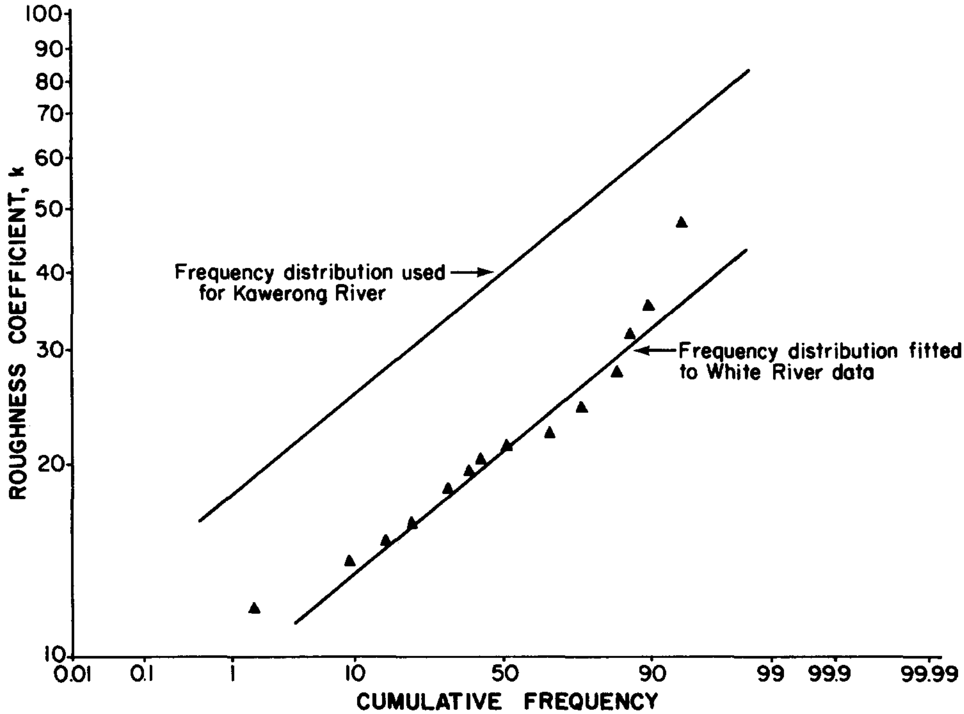

Fig. 8. Frequency distribution of the Strickler roughness coefficient, k, for the White River and the assumed frequency distribution for the Kawerong River. Source of White River data: Fahnestock (1963).

White River relationship along the scale until its mean corresponds with that of the Kawerong (Fig. 8). Individual k values may then be generated by the method used for width/depth ratio and slope generation.

Other parameters

Given discharge, slope, flow resistance and width/depth ratio from the relationships described in previous sections, the remaining hydraulic parameters required for the estimation of sediment transport can be determined as follows. Given that:

$$v = kD^{2/3}S^{1/2}; \qquad Q = Av \qquad \text{and} \qquad A = W \cdot D$$

where A is channel area; D is mean depth; W is width; v is mean velocity; and S is slope.

Then by substitution:

$$D = \left[\frac{Q}{k \cdot W/D \cdot S^{1/2}}\right]^{0.375} \qquad \text{and} \qquad v = \frac{Q}{D^2 \cdot W/D} \qquad (5), (6)$$

APPLICATION TO THE KAWERONG RIVER

Because sediment transport equations give such variable results, considerable care must be exercised in selecting an appropriate equation to suit a particular set of hydraulic and sediment characteristics. It was therefore decided to test a number of sediment transport equations on a single reach of the Kawerong River and to select the one giving the best results. This equation could then be used for sediment transport calculations for the whole of the Kawerong River, providing a good test of the accuracy of the braided-river hydraulic algorithms developed in previous sections.

Trial calculations of sediment transport were carried out for the reach between cross-sections *1* and *2* (Fig. 1) for the period 6 December, 1972 to 16 January, 1974. The equations used were those of Meyer-Peter and Muller (1948), Shields (as described by Brown, 1949), Maddock (1976) and the unit stream power equation for total bed-material load developed by Yang (1972). Only bed-material load was included in these calculations, and tailings, which pass through the system as wash load, were ignored. Mean daily discharges were used to represent the hydrograph and one set of hydraulic parameters was generated for each day. The results of the calculations were as follows:

Meyer-Peter—Muller equation	16.51 Mt
Shields equation	125.70 Mt
Maddock equation	6.48 Mt
Unit stream power equation	21.29 Mt
Actual bed-material discharges	16.71 Mt

The Meyer-Peter and Muller equation gave the best results and was selected for further testing with the hydraulics algorithms.

The main test was carried out for a period covering just over two years from 6 December, 1972 to 17 December, 1974. Eight reaches of the Kawerong were used and once again, mean daily flows represented the hydrograph, with one set of hydraulic parameters generated for each day. Median grain size, d_{50}, was used in the calculations with the Meyer-Peter and Muller equation instead of the effective size, d_m, recommended in the original paper and given by:

$$d_m = \Sigma\, p_i \cdot d_i$$

where p_i is the proportion of material in size group, i; and d_i is the mid-point of the size group.

With the strongly bimodal sediment size distribution found in the Kawerong River, this equation overemphasizes the coarse component of the load and gives an effective size which does not reflect the large proportion of fine material present. Under these circumstances, d_{50} is a more appropriate measure of effective sediment size.

The results of the main test are presented in Table I together with hydraulic data for each reach and the sediment parameter values used. Mean daily water temperature for the river was 27° C.

TABLE I

Observed and estimated sediment transport for the Kawerong River

Reach (cross-section No.)	Slope	Mean discharge (m^3/s)	Estimated sediment discharge (Mt)	Observed sediment discharge (Mt)	Per cent error
1–2	0.071	4.22	37.65	28.75	31
2–4	0.050	4.76	29.89	28.80	4
4–5	0.049	5.37	32.66	27.94	17
5–6	0.036	5.45	24.37	26.98	–10
6–7	0.031	6.04	23.95	25.54	–6
7–8	0.032	6.11	23.36	24.93	–6
8–8A	0.026	6.24	20.13	24.40	–18
8A–9	0.020	6.37	14.76	24.13	–39

Sediment parameters: specific weight = 2.65 g/cm^3; d_{90} = 95 mm; and d_{50} = 6 mm.

Results generally are satisfactory. The mean of the absolute per cent error values is only 16.3% which is considered acceptable for sediment transport calculations. The largest errors are at the upper and lower end of the river and it is likely that they could be reduced substantially if some allowance was made for downstream variations in bed-material size instead of using a single average value. Since the sediment size has a tendency to decrease downstream (Fig. 3) this would reduce the estimated sediment discharge in upstream reaches and increase it in the lower section of the river. Another factor is that the reach between cross-sections *1* and *2* experienced periods of scour during the test period. Although the reach had the capacity to transport 37.6 Mt of bed material, bed-armouring may have occurred, restricting the actual sediment supply.

CONCLUSIONS

A method for generating sets of braided river hydraulic parameters has been empirically developed. The method proceeds as follows:

(1) The number of channels is generated from a look-up table using random numbers;

(2) The discharge in each channel is calculated by random number techniques;

(3) Width/depth ratio, slope and resistance to flow are generated for each channel from known log-normal probability distributions.

The method can be used in association with a sediment transport equation to obtain estimates of bed-load discharge. Tests of the method using the Meyer-Peter and Muller equation on eight reaches of the Kawerong River give a mean error of 16.3%.

ACKNOWLEDGEMENTS

The authors wish to thank Bougainville Copper Ltd. for permission to publish and facilities for research. They are also grateful to the University of Papua New Guinea for financial assistance and computer time.

REFERENCES

Brown, C.B., 1949. Sediment transportation. In: H. Rouse (Editor), Engineering Hydraulics McGraw-Hill, New York, N.Y.
Church, M., 1972. Baffin Island sandurs: a study of Arctic fluvial processes. Geol. Surv. Can. Bull., No. 216.
Doeglas, D.J., 1962. The structure of sedimentary deposits of braided rivers. Sedimentology, 1: 167—193.
Einstein, H.A., 1950. The bed-load function for sediment transportation in open channel flows. U.S. Dep. Agric., Soil Conserv. Serv., Tech. Bull., No. 1026.
Fahnestock, R.K., 1963. Morphology and hydrology of a glacial stream — White River, Mount Rainier, Washington. U.S. Geol. Surv., Prof. Pap., No. 422-A.
Higgins, R.J., 1977. Monitoring and predicting the behaviour of a river carrying artificially high sediment load. Proc. 6th Australasian Conf. on Hydraulics and Fluid Mechanics, Adelaide, S.A.
Hjulstrom, F., 1952. The geomorphology of the alluvial outwash plains (sandurs) of Iceland and the mechanics of braided rivers. Proc. 8th Gen. Assem. — 17th Int. Congr. Int. Geogr. Union, Washington, D.C., pp. 337—342.
Howard, A.D., Keetch, M.E. and Vincent, C.L., 1970. Topological and geometrical properties of braided streams. Water Resour. Res., 6: 1674—1688.
Kingstrom, A., 1962. Geomorphological studies of sandur plains and their braided rivers in Iceland. Geogr. Ann., 44: 328—346.
Leopold, L.B. and Wolman, M.G., 1957. River channel patterns, braided meandering and straight. U.S. Geol. Surv., Prof. Pap., No. 282-B.
MacDonald, B.C. and Bannerjee, I., 1971. Sediments and bed forms on a braided outwash plain. Can. J. Earth Sci., 8: 1282—1301.
Maddock, T., 1976. Equations for resistance to flow and sediment transport in alluvial channels. Water Resour. Res., 12: 11—21.
Meyer-Peter, E. and Muller, R., 1948. Formulas for bedload transport. Int. Assoc. Hydraul. Struct. Res., 2nd Meet., Stockholm, pp. 39—64.
Naylor, T.H., Balintfy, J.L., Burdick, D.S. and Chu, K., 1966. Computer Simulation Techniques. Wiley, New York, N.Y., 352 pp.
Ning Chien, 1962. The braided stream of the lower Yellow River. Sci. Sin., 10: 735—754.
Williams, P.F. and Rust, B.R., 1969. The sedimentology of a braided river. J. Sediment. Petrol., 39: 649—679.
Yang, C.T., 1972. Unit stream power and sediment transport. J. Hydraul. Div., Am. Soc. Civ. Eng., 98: 1085—1826.