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A brief review of hydraulic modelling of braided gravel-bed rivers in New Zealand

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Abstract

Hydraulic modelling of braided gravel-bed rivers in New Zealand is a development confined to the last two decades. Interest in hydraulic model studies came about due to calls for information on braided river processes, the high costs of river control works and the lack of reliable analytical tools. Models of braided gravel-bed rivers are distinctive amongst hydraulic models in that the bed material is geometrically scaled and the channel is free to migrate both vertically and laterally. Most studies have used linear undistorted scale models in the 1:30 to 1:50 scale range. The D_{50} of the model bed material is usually close to 0.5 mm and channel slopes are generally ~ 0.01. Sediment supply is usually steady and water flows are both steady and unsteady, with some experiments using simulated hydrographs. Bed load sampling intervals vary from 5 hours to 1 minute. In recent studies flume dimensions and the frequency of bed load sampling have increased. Most studies attempt to verify the model using prototype data and generally hydraulic similarity and process similarity are reasonably good. From the review of hydraulic modelling seven key research themes have been identified: the relationship between bed load transport rate and channel morphology, the accuracy of bed load transport equation predictions, variability in bed load transport rates, quantification of braided river channel morphology, equilibrium between channel flow and sediment transport, model verification and dynamic similarity, and recognition of the inadequacies of the field (prototype) data base.

Introduction

Hydraulic modelling of braided gravel-bed rivers is a relatively recent development. The first serious attempts in New Zealand began in the late 1970s in what was then the Agricultural Engineering Department at Lincoln College. Activity at Lincoln University and the University of Canterbury steadily continued over the next two decades but the modelling of braided rivers never developed into a major area of research. At first sight this may appear surprising, given the abundance of braided rivers in New Zealand. However considering the small size of the academic community in New Zealand actively concerned with braided gravel-bed rivers, the lack of enthusiasm of the majority of engineers to adopt hydraulic modelling approaches (Smart and Thompson, 1986) and the small number of international institutes involved in scale modelling of braided gravel-bed rivers, the progress made in New Zealand is significant.

Hydraulic modelling of braided gravel-bed rivers in New Zealand has wide potential scope for application, and practical and economic benefits as an engineering and management tool. Firstly, the scope for modelling braided gravel-bed rivers is enormous. The bed material of most New Zealand rivers is gravel (Carson and Griffiths, 1987) and where the bed and banks are composed of gravelly alluvium, braiding is commonplace. This is particularly true of the rivers which rise in the Southern Alps and flow east over the Canterbury Plains, South Island, of which the Rakaia and Waimakariri are the best known. These rivers are very important natural resources (Blakely and Mosley, 1987; Davies, 1987). They are used for agriculture, hydropower, fisheries, gravel extraction and recreation; however, they also pose a considerable erosion and flood hazard. For example the Waimakariri (near Christchurch) threatens a greater concentration of lives and property than any other river in New Zealand (Griffiths, 1979, 1991). Since the advent of European settlement, training of such braided gravel-bed rivers has posed major problems for engineers. The enormous costs of setting up and maintaining river control works, the lack of detailed understanding of braided river processes and the lack of theoretical approaches has considerably restricted the effectiveness of river engineering practices (Henderson, 1986). One area of potential progress is in the use of hydraulic models (Davies, 1987; Griffiths, 1989).

Calls for hydraulic model studies of braided gravel bed rivers in New Zealand have arisen due to the need to better understand braided river processes and to test engineering design equations. Hydraulic models are needed because of the deficiencies in currently available analytical methods and the practical difficulties of extensive fieldwork (Young and Davies, 1990). For example, Davies (1987) argues for the use of hydraulic models to assist in solving problems of bed load transport in braided gravel-bed rivers. Although Davies acknowledges the limitations of this approach, he emphasises the great value of hydraulic models in reproducing the characteristic forms of braided rivers under controlled conditions and in estimating total bed load transport (which is virtually impossible to measure in a large braided river). Griffiths (1989) emphasises the need for laboratory models to test design equations for determining the characteristics of a single-thread channel having a water and bed load transport capacity equivalent to a given braided gravel-bed river. These are but two examples; the scope for using hydraulic models in the study of braided gravel-bed rivers is large and represents an economically viable investment. For example, the annual costs of maintenance works on a large braided river engineering scheme may be in the order of NZ$150,000; for the same money a 1:50 hydraulic model of a braided gravel-bed river could be set up. Whilst the annual maintenance costs of the river engineering scheme will certainly get no cheaper, the model may provide new information to improve the design of engineering works.

Outside New Zealand small laboratory models of rivers have been widely used. However not all models have been developed using formal Froude scaling criteria e.g. Schumm and Khan (1972) produced a crudely scaled generic model to look at the transition between meandering and braiding. Significant progress in the development of Froude-scale models has been made by Ashmore (1985, 1988, 1991) in studies of braiding processes and bed load variability, by Southard *et al.* (1984) investigating braiding processes, by Fujita (1989) examining bar formation, and by Ashworth et al. (1994) in describing sedimentary architecture. This review is concerned with Froude models.

The aim of this short review is to define the characteristics of braided gravel-bed river hydraulic models and discuss work undertaken in New Zealand over the last two decades. The review concludes with a short summary of the main research themes investigated thus far.

Definition of Hydraulic Modelling of Braided Gravel-bed Rivers

Hydraulic modelling of braided gravel-bed rivers involves the direct physical simulation of fluvial forms and processes at reduced scale (Fig. 1). Under laboratory conditions small stream systems are created which mimic the behaviour of large rivers. In designing such models, limitations imposed by scale and resource constraints result in models which usually only approximate the prototype. The general characteristics of these models are:

(1) approximate dynamic similarity between the model and the prototype in as much as length dimensions are scaled linearly and there is Froude number similarity between the two systems,
(2) the bed and banks of the model are deformable,
(3) the fluid and bed materials are usually the same in the model and prototype,
(4) bed and bank materials are granular and non-cohesive,
(5) bed slopes are generally steep, and
(6) vegetation and other ecological factors are not usually modelled.

Braided gravel-bed river hydraulic models are distinct amongst hydraulic models in that the bed material is a geometrically scaled version of a gravel bed and the channel is free to migrate both vertically and horizontally. The channel produced is a three dimensional self-formed version of a prototype river with clearly developed braid bars and sedimentary features. This is in contrast to many other flume studies of gravel-bed channels which have used narrow rectangular or trapezoidal flumes (e.g. Kuhnle and Southard, 1988). These studies have largely been designed to study bed load transport and usually present only a two-dimensional picture of the river system. The obvious problem in modelling braided gravel-bed rivers is to produce a flume model of sufficient size to reproduce both the mechanics of gravel transport and the overall form of the braided channel. The flume model must be small enough to reap the benefits of modelling at reduced scale but large enough that sediment transport mechanics are the

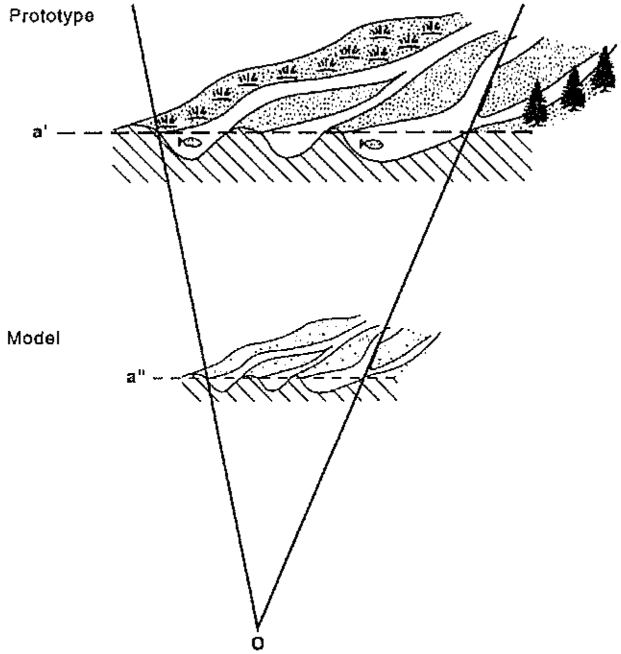


Figure 1 Two geometrically similar braided river systems. The two straight lines passing through the planes of the prototype (a') and the model (a") converge to a common point 0 (the homology centre). Proportionalities in the two systems are equal, however reduction in scale often results in loss of information. For example, the riparian vegetation and in-stream biota are absent in the model.

Table 1 Summary of the main characteristics of hydraulic model studies undertaken in New Zealand.

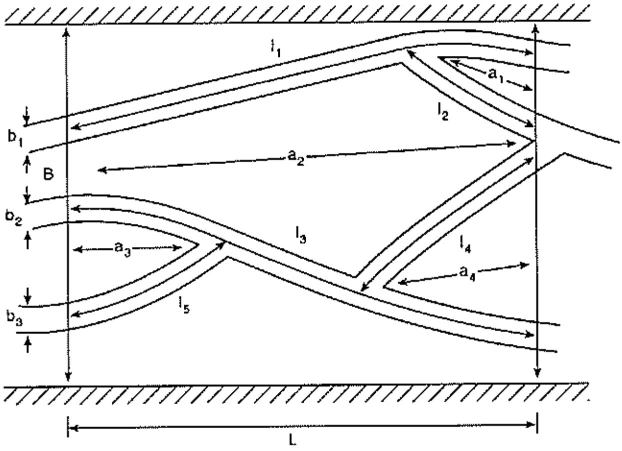
STUDY	SCALE	BED MATERIAL D_{50} (mm)	SLOPE	SEDIMENT SUPPLY (g s^{-1})	FLOW	BEDLOAD SAMPLING INTERVAL	FLUME DIMENSIONS (width/length) (m)	PROTOTYPE RIVER
Hong & Davies 1979	Distorted 1:2000	0.17	0.04 - 0.1	Variable 0.025 - 0.83	Variable	Not measured	2 : 5	Rakaia River
Davies & Lee 1988	1 : 50	0.5	0.01	Constant 1.53	Unsteady	5 hours	3 : 20	North Ashburton
Young & Davies 1990, 1991	1 : 50	0.5	0.0074 & 0.0115	Variable	Steady and Unsteady	1 min (steady flow) Variable (unsteady flow)	3 : 20	North Ashburton
Hoey & Sutherland 1989, 1991	1 : 30 to 1 : 50	0.57	0.01	Initially varied	Steady	15 mins	3 : 14	New Zealand gravel-bed braided rivers
Warburton & Davies 1994	1 : 50	0.5	0.0114	Constant 1.53	Steady	5 mins	3 : 20	Ashley River

same as in the prototype river. However, in reducing the size of the river system, inevitably some features, particularly the biological characteristics of the braided river environment, cannot be translated into the model (Fig. 1). This may not be a serious drawback as long as the model still exhibits the salient features of form and flow (Sabersky and Costa, 1964). Hydraulic models of this kind have been used in New Zealand to study general and specific problems associated with braided gravel-bed rivers.

Research in New Zealand

Table 1 summarises the main characteristics of models used in New Zealand to study braided gravel-bed rivers. Except for Hong and Davies (1979) all are linear undistorted scale models ranging from 1:30 to 1:50 in scale. With the exception of the Hong and Davies study where the model bed material was very fine-grained, the scale ratios used in these studies dictate that the D_{50} of the bed material used in the models is close to 0.5 mm. Slopes are generally steep (usually on the order of 0.01) however, some exaggerated slopes have been used e.g. Hong and Davies (1979) used 4 to 10%. Sediment supply to the model is highly variable. Some systems use constant steady feeds whereas other experimenters adjust the sediment supply to prevent aggradation at the head of the flume. This variability in a key model parameter is an area which has not been given due consideration. Both steady and unsteady flows have been used, with some experiments using simulated hydrographs e.g. Davies and Lee (1988). Bed load is usually sampled at the exit from the sand tray. Sampling intervals vary from 5 hours to 1 minute. Generally the frequency of bed load sampling has increased with growing recognition of the importance in variability and pulsing in bed load transport time series (Hoey and Sutherland, 1991). Flume dimensions have also increased in size to provide adequate space for modelling the full braided channel width and to satisfy the conditions for fully turbulent flow. Finally most studies, including the earliest work by Hong and Davies, have recognised the need to relate the model findings to a field prototype, either to test for hydraulic similarity (e.g. Warburton and Davies, 1994) or for process similarity (Young and Davies, 1991).

In a pioneering study of stream braiding, Hong (1978) and Hong and Davies (1979) set up a small sand tray 2 x 5 m (Table 1) to investigate the hypothesis that the geometric properties of braided streams are constant over a range of stream sizes. They also carried out observations on the dynamic similarity of braiding processes in the model and prototype and conditions necessary for braiding to occur. Two parameters (Fig. 2), the width ratio (W_r) and sinuosity (P) were used to describe the braided stream pattern. Using these parameters it was demonstrated that a degree of geometric similarity existed between the model channel patterns and the Rakaia River. It was also shown from measurements of flow depths and velocities that approximate Froude scaling dynamic similarity existed between the model and prototype. Time-lapse films, however, showed that braiding was associated with meander migration, cut-off formation and channel abandonment; at no time was any channel observed to divide in a classical braiding mechanism. Finally, using stability analysis based on stream slope, Froude number and width/depth ratio (Parker, 1976) Hong and Davies accurately predicted the number of braids in both the model and prototype. This was surprising since many factors thought to be crucial for braiding, such as flow variability, bed material size, sediment loads, bank erodibility, turbulence and decreasing bed shear stress, were not explicitly included in the analysis. However, many of these factors are implicitly included (e.g. bank erodibility and the width/depth ratio) and may exert a strong influence. An important conclusion from this work was the need for more detailed studies of braided river channel patterns and dynamic similarity over a range of streams sizes using a refined modelling apparatus.



$Wr = (b_1 + b_2 + b_3) / B$

$P = (l_1 + l_2 + l_3 + l_4 + l_5) / L$

Brice Index 2 $(a_1 + a_2 + a_3 + a_4) / L$

Figure 2 Definition sketch of braided stream descriptive parameters Wr, P and the braiding index of Brice. Wr is the width ration or the proportion of the bed width occupied by water and P is the sinuosity or the total length of channel per unit length of river bed. Modified from Hong and Davies (1979).

Lee and Davies (1986) carried out a series of steady and unsteady (hydrograph) flow experiments in a model braided stream designed to find the steady flow equivalent to a naturally varying hydrograph flow series. Hydrographs were simulated using a computer flow control system which selected at random one of ten step function hydrographs designed to produce flows capable of moving bed load. Results demonstrated that there was a steady flow for which a braided stream could widen at the same rate as a stream experiencing a hydrograph series representative of a natural flow. This flow corresponded to a flow which exceeded the threshold discharge for sediment movement for 22% of the duration of active bed load movement. Using this approach a 'dominant discharge' could be defined for a model braided stream. However, as it was unlikely that the model stream had reached an 'equilibrium or steady state' condition, it was not clear whether steady flow would result in the same equilibrium width as the stream subject to naturally varying flow. In a related investigation Davies and Lee (1988) modelled the effect of width reduction on the rate of change of mean bed level of a braided river. The investigation was undertaken because of the doubt surrounding the engineering principle that reducing the bed width of a braided river would increase or decrease the rate of bed aggradation. Using the North Ashburton as a prototype, a 1:50 Froude law rough turbulent hydraulic model was constructed (Table 1). In a series of experiments widths were reduced by up to 35% of the unconstrained width, and sediment input was varied. Results demonstrated that reducing the bed width of a braided river increases bed load transport capacity. However the relationship was by no means simple. For example, reducing bed width will increase the rate of aggradation if bed load sediment input rate to the reach is more than 2.3 times the bed load transport capacity of the unconfined river. If input rate is less than 2.3, a reduction in bed width will decrease the aggradation rate. Further, reducing bed width will not cause aggradation in a river where there was none originally. Therefore width reduction alone is not a suitable method for controlling bed level changes in braided rivers. Clearly these experiments demonstrated aspects of braided river behaviour which were much more complicated that originally appreciated. However, due to the limited number of runs the behaviour patterns were not clearly defined, and the dynamics in the model cannot be easily related to the dynamics of prototype rivers due to insufficient data to verify the relationship between model and prototype.

Using a similar 1:50 scale hydraulic model of the North Branch of the Ashburton, Young and Davies (1990) undertook experiments using steady and quasi-unsteady flow to investigate the relationship between various combinations of discharge, slope and bed load transport capacity. In particular the effects of flow abstraction on bed load transport capacity were quantified. Two predictive bed load transport equations, those of Bagnold (1980) and Schoklitsch (1962), were evaluated using the data from the steady and unsteady flow experiments. It was found that overall, good hydraulic similarity was achieved between the model and the prototype. The Schoklitsch (1962) bed load transport equation underpredicts bed load transport rates in the model by 34% for steady flows and 17% for unsteady flows. The Bagnold (1980) equation also underpredicts but is more accurate in both steady and unsteady flow conditions; it underpredicted by 18% and 1% respectively. Excess stream power proved a useful predictor of bed load transport rates in braided channels and when used as a descriptor reliably predicted relative reductions in bed load transport capacity due to flow abstractions. A theoretical relationship between bed load transport capacity reduction (V_R) and a reduction in the available energy caused by modification of the flow regime (E_R) was developed (Fig. 3)

$$V_R = 1 - (1 - E_R)^{1.5}$$

An empirical (best fit regression) relationship derived from the experimental data yielded

$$V_R = 1 - (1 - E_R)^{1.54} \qquad (R^2 = 0.99)$$

Because excess stream power was a good predictor of bed load transport rate, assessing the reduction in available energy caused by a modification in the flow regime was a useful means of predicting changes in bed load transport capacity (Fig. 3).

Young and Davies (1991) used the same experimental data to investigate bed load transport processes. They confirmed that bed load transport rates were highly variable, varying between zero and ten times the mean rate, with relative variability being inversely related to mean bed load transport rate. There was also evidence of cyclicity in the bed load transport time series, thought to be related to the migration of bedforms. Bed load transport rates were higher under steady flow conditions than under unsteady flows (Fig. 4). It was suggested that this came about because channel form tends to evolve so that bed load transport is maximised for the current flow. For steady flow the maximum transport condition, once achieved, will result in a fairly stable channel configuration with a sediment transport capacity. Under unsteady flow conditions the channel boundary changes constantly and energy is dissipated in channel adjustments rather than contributing to a greater sediment throughput. This can explain the convergence of the steady and unsteady flow bed load transport at higher stream powers: a greater proportion of the energy is expended on channel readjustments under lower energy regimes. Average transport rate varied with channel form, and under a given slope-discharge regime several relatively stable channel structures with differing hydraulic conditions can be identified, although the exact nature of their relationship could not be determined.

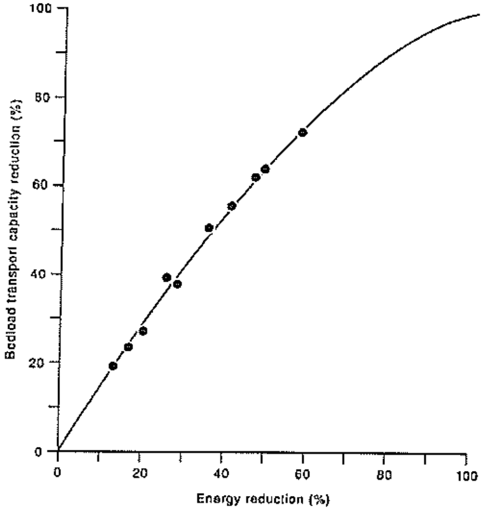
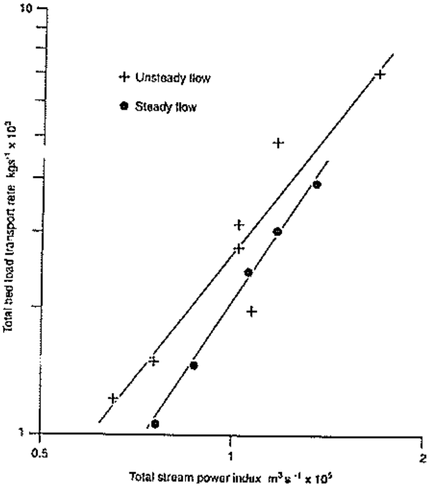


Figure 3 Percentage reduction in bed load transport capacity plotted against energy reduction showing the experimental data and the theoretical relationship explained in the text. From Young and Davies (1990).

Figure 4 Comparison of bed load transport rate (kg s^{-1} x 10^3) versus total stream power index (m^3 s^{-1} x 10^5) in the model of Young and Davies (1991). Data from steady flow experiments are shown as crosses and from the unsteady flow experiments as dots.



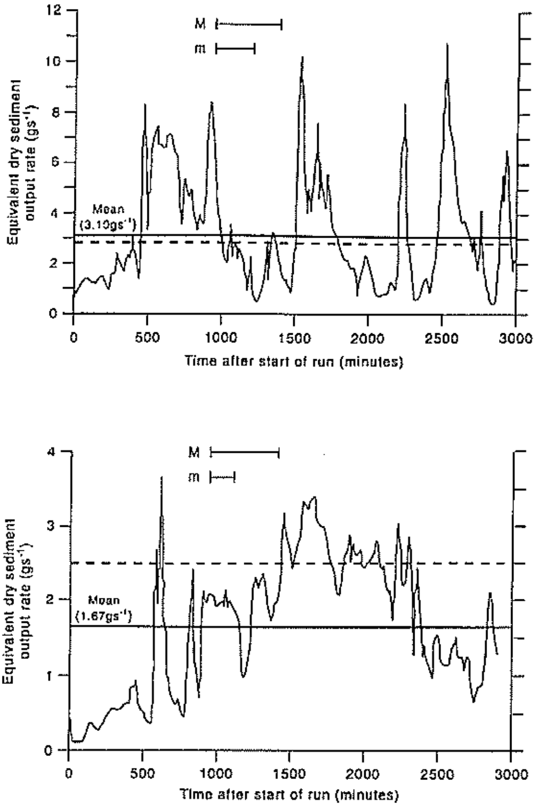


Figure 5 Sediment input and output rates for the experimental data of Hoey and Sutherland, (1991). (a) = Run 1, (b) = Run 2. Vertical scales are different and the dashed lines represent mean sediment input rates at the upstream end of the tray. The bars marked m and M indicate the duration of minor and major oscillations in sediment output, respectively.

The relationship between channel morphology and bed load transport rate was also investigated by Hoey and Sutherland (1991) at the University of Canterbury. A generic model of a small braided gravel-bed stream was used to evaluate the relationship between bed load transport averaged at a particular downstream cross-section and changes in channel morphology measured upstream. Bed load output was gauged every 15 minutes and bed geometry was surveyed every four hours during the 50 hour runs. The results showed that bed load transport rates depended on whether or not the channels in the measurement reach were in equilibrium with the water flow. The production of macro and mega-scale bed load pulses was a result of the morphology of the braided river channels. Bed load transport time series showed considerable variability, indicating minor and major fluctuations in the bed load transport rate (Fig. 5). The Bagnold (1980) bed load transport equation generally overpredicted bed load transport rates in channels which were in equilibrium or aggrading but underpredicted when the channel was degrading. Changes in the number of channels in a particular reach can serve as a useful indicator of potential storage in the reach. Aggradation is associated with an increase in the number of channels and degradation with a decrease in the complexity of the channel pattern. Bed load transport increases as the channel pattern is simplified. Complex spatial feedbacks and the existing floodplain morphology determine the impact of bed load pulses on channel morphology and the location and specific timing of periods of aggradation and degradation. A simple correlation between bed load transport rates and channel morphology is apparent but is difficult to define quantitatively.

In an earlier paper, Hoey and Sutherland (1989) compared model channel geometries with those predicted from the river regime method of White *et al.* (1981). In the Froude scaled model, channels were generally wider and shallower than the predictions. It was concluded that although the model showed qualitative similarities to braided gravel-bed rivers, quantitative predictions using sand trays were unlikely to yield predictive models of channel form.

The variability of bed load transport and channel morphology was further investigated in a braided river hydraulic model study carried out by Warburton and Davies (1994). Using 11 replicate experimental runs of 90 hours duration, the replicability of experimental runs was assessed to determine to what extent braided river morphology is a single-valued response to a particular set of controlling variables. The results demonstrated that for a given set of controlling variables, bed load transport and channel morphology can be approximately replicated. Within-run bed load transport rates varied from close to zero to three or even four times the mean rate. Several phases of irregular bed load transport activity could be identified in the bed load transport time series. Small differences in channel behaviour produced a weak relationship between time-averaged bed load transport rate and braiding intensity measured at the end of the run (expressed as the braiding index - Brice (1964)) (Fig. 6). When compared with prototype river data the model showed good dynamic similarity in the main model channels but poor similarity in the subsidiary (small) channels. Further work is required to test whether these conclusions hold for other combinations of slope and discharge and to better define the relationship between bed load transport and channel morphology.

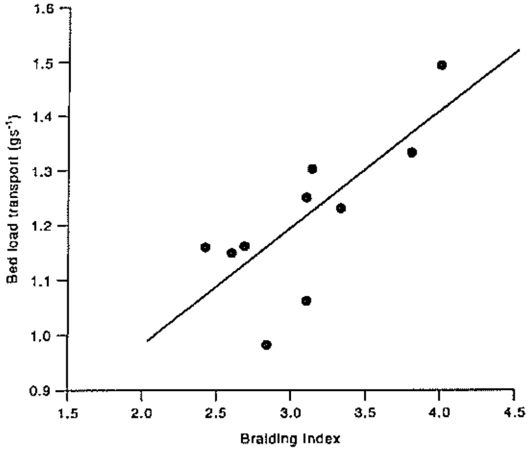


Figure 6 Relation between braiding index (Brice, 1964, Figure 2) and mean bed load transport rate. From Warburton and Davies (1994).

Summary of Research Themes

From the various contributions to research on the hydraulic modelling braided gravel-bed rivers in New Zealand several important themes have emerged and evolved.

1. Relationship between Bed Load Transport Rate and Channel Morphology

A number of studies (Davies and Lee, 1988; Young and Davies, 1991, Hoey and Sutherland, 1991; Warburton and Davies, 1994) have all suggested a relationship between bed load transport rate and channel morphology (Fig. 6). The exact form of this relationship has not been established due to problems in accurately determining bed load transport rates and, more importantly, defining a single value to characterise the complex channel morphology. As Davies and Lee (1988) have demonstrated, a particular bed load transport rate can be associated with very different channel configurations and a particular channel configuration may have varying bed load transport rates.

2. Accuracy of Predictions using Bed Load Transport Equations

Relatively few bed load transport equations have been tested in hydraulic model studies but of those investigated so far, predictions are reasonable (e.g. Young and Davies, 1990 - for Schoklitsch (1962) and Bagnold (1980) equations). In channels which are in equilibrium or aggrading the Bagnold (1980) equation generally overpredicts whilst in a degrading channel the equation underpredicts. Results for time-averaged transport are considerably better than for short-term periods. It is important to carefully define the limitations of such equations because of their importance in channel design (Griffiths, 1989).

3. Variability in Bed Load Transport Rate

Bed load transport rates have been carefully monitored in several of the hydraulic model studies e.g. Young and Davies, 1991 (1 minute); Hoey and Sutherland, 1991 (15 minutes); Warburton and Davies, 1994 (5 minutes). Within the bed load time series, several irregular phases of transport intensity can be observed, but time series analysis of the data show little underlying structure. An AR(1) or AR(2) autoregressive model indicates weak statistical dependence on the previous measurement values (Hoey and Sutherland, 1991; Warburton and Davies, 1994).

4. Quantification of Braided River Channel Morphology

Davies (1987) identified the description and analysis of braided rivers as the most challenging problem facing river engineers and scientists. Some very limited progress has been made in describing braided rivers, but in reality this has advanced little since early flume work. Research by Hong and Davies (1979) in deriving parameters to describe braided rivers and their application of Parker's stability analysis in predicting the number of channels has been advanced little in the subsequent years. Many studies still rely on relatively crude measures such as the number of channels and braiding intensity (Warburton and Davies, 1994) to describe the channel pattern. One promising approach is that of Hoey and Sutherland who define reservoirs of sediment storage within the braided floodplain.

5. Equilibrium between Channel Flow and Sediment Transport

Applying equilibrium concepts to braided river channels is fraught with difficulty due to the unsteady nature of discharge and the rapidly varying supply of sediment. Stable channel morphologies are rare in flume studies (Hoey and Sutherland, 1991) and few experiments have been allowed to evolve to a point where braided river width is stable (Lee and Davies, 1986). Even under conditions of constant discharge and sediment supply bed load transport rates fluctuate widely, although time-averaged bed load transport rates and cumulative (end-of-run) channel morphologies evolve to common conditions (Warburton and Davies, 1994). However, other experiments (e.g. Ashmore, 1985, Run 4), in which the channel changed from braided to nearly straight, demonstrate that there is more than one stable configuration for a given channel system. In attempting to define equilibria in braided rivers the approach used by Lee and Davies (1986) could be adopted, although it is probably best to accept that, due to the complexity of braided channel dynamics, only general tendencies of channel behaviour are likely to be established (Davies and Lee, 1988). For example more than one equilibrium condition may exist and separate definitions may need to be determined for morphology and process variables.

6. Model Verification and Dynamic Similarity

With modelling scales of the order of 1:50, parts of the braided river channel, especially areas of shallow depth and low velocity, do not always appear to satisfy criteria for hydraulic similarity (Warburton and Davies, 1994). Certainly the critical values used to define hydraulic similarity are in some doubt (Ashworth et al., 1994) and there is a need to try to define, through experimentation, exactly what these are. Although model studies have been verified by prototype data, often the data are not accurate enough for full model verification.

7. Inadequacies of the Field Data Base

Lack of understanding of braided river processes has often been identified as a factor limiting effective management (Carson and Griffiths, 1987). The reasons for this have usually been the difficulties in collecting adequate field data. This in turn has been used to justify employing model studies (Davies, 1987). However, if model studies are to be of use, field data is required for verification. This seems to be a circular argument. However, by approaching braided river dynamics through hydraulic modelling the field data requirements are generally precisely defined. Nevertheless there is still considerable scope for collection of better field data sets.

The research summarised here clearly demonstrates the progressive development of hydraulic models of braided gravel-bed rivers. Studies have focused on all aspects of braided river processes and have tried to refine modelling techniques. Although much progress has been made there is still considerable scope for further experimentation and refinement of modelling procedures.

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