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Future prospects for the use of hydraulic models in the management of New Zealand braided gravel-bed rivers

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Abstract

As development pressures on New Zealand's water resources increase, hydraulic models are likely to have an important role in understanding and predicting the behaviour of braided gravel-bed rivers. Based on a qualitative assessment of past research, future research on hydraulic models will give a high priority to hydraulic similarity and model verification and to investigations into the relationship between bed load transport, channel morphology and equilibrium. Direct applications of model results to engineering studies have been relatively few and this will continue unless the philosophy of model use changes. The range of research themes remains broad, suggesting that hydraulic models are widely applicable to a range of

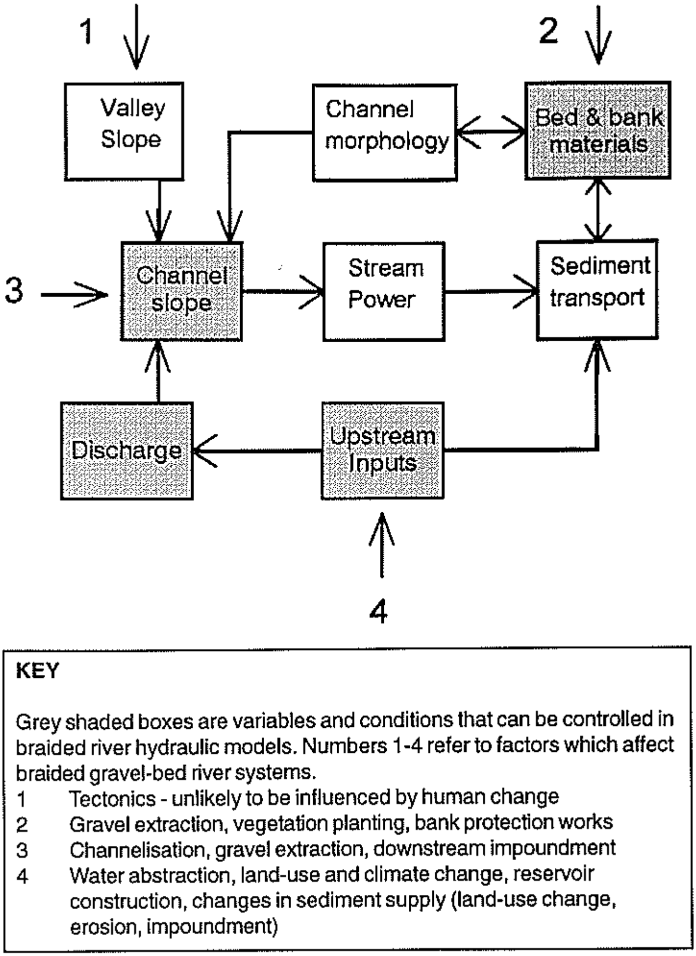
braided river management problems and that important questions remain unresolved. Given the current limitations of hydraulic modelling, more work is required to define the minimum scale for effective modelling and the scope for using fine-grained materials. The effects of model distortion on sediment transport and the channel morphology need to be investigated. A consistent procedure is needed for model verification in general, and experimental verification of time scaling in particular. Future model studies should aim to produce larger undistorted models and collect data over a wide range of model and prototype scales, so that models can be calibrated and verified.

Introduction

To forecast future trends in the use of hydraulic models in the management of New Zealand braided gravel-bed rivers is a difficult task. However, it can be said with certainty that hydraulic modelling will continue to have an important role in understanding, predicting and managing the behaviour of New Zealand braided rivers

As development in New Zealand increases, pressure on braided river water resources will intensify. Demand for water for irrigation, community use and hydropower will increase and the quality of fisheries and aquatic ecosystems, recreation, wildlife and the environment will be threatened. Sustainable management of this resource requires an ability to predict how the river will respond to engineering works, flow modifications and changes in the river sediment budget (Henderson, 1986) (Fig. 1). Flood hazard management, with strategies to control channel positions and prevent flood overflows and breakouts onto the floodplain, where assets are located, are needed. Reliance on the results of overseas research can be misleading, given the unique character of New Zealand braided rivers (Carson and Griffiths, 1987).

Laboratory models of braided rivers provide new insights into braided river behaviour (Ashmore, 1991). They provide an overview of the system as a whole and allow observations of local processes unhindered by suspended sediments (Mosley and Zimpfer, 1978; Novak and Cabelka, 1981). Measurements can be made for scales, frequencies and conditions (e.g. flood) for which measurements cannot be undertaken in the field. Novel and innovative engineering structures can be tested in conditions of safety and control. Braided rivers can be observed at scales that cannot be comprehended in the field. Models provide a way of visualising complex dynamic geomorphic processes. Time scales of channel evolution are compressed and the periods of inactivity associated with low flows can be removed, permitting measurements on rapidly evolving systems (Jaeggi,



KEY

Grey shaded boxes are variables and conditions that can be controlled in braided river hydraulic models. Numbers 1-4 refer to factors which affect braided gravel-bed river systems.

1 Tectonics - unlikely to be influenced by human change
2 Gravel extraction, vegetation planting, bank protection works
3 Channelisation, gravel extraction, downstream impoundment
4 Water abstraction, land-use and climate change, reservoir construction, changes in sediment supply (land-use change, erosion, impoundment)

Figure 1 Flow diagram illustrating the interrelations in the braided river system and those variables that can be controlled in hydraulic models. Sources of human-induced change and their potential impacts on the system are also indicated. Diagram modified from Thornes (1987).

1989). Variables (e.g. slope and water discharge) can be controlled and experiments can be replicated. Several processes can be combined into a single model and various boundary conditions can be set. Precise measurements can be made. In correctly scaled hydraulic models the behaviour of a prototype river can be reproduced to calculable scales. In the field, changes are generally episodic or too slow for direct measurement;

when changes do occur, fluvial features may form rapidly then disperse. Relevant data for large rivers is difficult and expensive to collect. Natural conditions can rarely be controlled or replicated. Field observations are limited to point measurements, and limited in time. Water is often turbid and bed conditions cannot be observed. Field vantage points are often unfavourable. There are irregular and unknown water and sediment inputs. However, it should be remembered that field data are necessary to calibrate and verify hydraulic models, and therefore fieldwork cannot be abandoned completely in favour of laboratory models. A balance and integration of the two approaches is needed.

For many problems hydraulic models offer the only feasible way of obtaining a solution or at least showing what is impracticable or unworkable (i.e. they confine the solution set). For many problems prototype trials are out of the question environmentally and economically, and theoretical/numerical modelling is inadequate given the complexity of the physical situation and the initial boundary conditions, even when these are known. Hydraulic modelling can deal with multi-faceted problems e.g. flood flow in a braided gravel-bed river overtopping or bursting a stopbank, and then scouring around a structure on the floodplain, or sediment transport in the steep gravel-bed rivers of the West Coast, South Island (New Zealand) which experience severe bridge scour problems.

Hydraulic models therefore have a significant role in the management of braided rivers. The remainder of this paper will discuss that role. By providing a qualitative assessment of past research and the research described in this issue, and a brief discussion of the main limitations of hydraulic models, it is hoped a consensus on future directions can be established.

Past Research

Some guidance can be gained from the review of hydraulic modelling of braided gravel-bed rivers in New Zealand by Warburton (this issue) which summarises key research themes (Table 1). The review identified seven themes: 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 (Table 1). Many of the papers reviewed by Warburton (this issue) made specific calls for further work. Hong and Davies (1979) called for more detailed studies of braided river channel patterns and conditions for dynamic similarity. Davies and Lee (1988), almost ten years later, still identified a lack of data describing full-

Table 1 Summary of research themes in the hydraulic modelling of braided gravel-bed rivers in New Zealand.

RESEARCH THEME	STUDIES UP TO 1994								THIS ISSUE					LEVEL OF RESEARCH ACTIVITY
	1	2	3	4	5	6	7	8	9	10	11	12	13	
Bed Load Transport & Channel Morphology			○	○		○	○	○				○	○	High
Bed Load Transport Equations				○	○		○				○			Low
Variability in Bed Load Transport Rate						○	○	○				○	○	Medium - high
Braided Channel Pattern Description	○						○	○				○	○	Medium - high
Equilibrium Concepts		○	○				○	○			○	○	○	High
Hydraulic similarity and Model Verification	○	○	○	○	○	○	○	○	○	○	○			Very high
Engineering Applications					○	○					○			Low

KEY

1	Hong and Davies 1979
2	Lee and Davies 1986
3	Davies and Lee 1988
4	Hoey and Sutherland 1989
5	Young and Davies 1990
6	Young and Davies 1991
7	Hoey and Sutherland 1991
8	Warburton and Davies 1994

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9	Young and Warburton
10	Peakall and Warburton
11	Davies and Griffiths
12	Hoey
13	Warburton

scale rivers and measures to adequately describe braided river geometry. They also suggested further experiments were needed on the reaction of a braided stream under confinement. Young and Davies (1991) recognised that more flume experiments were required to verify the relationship between bed load transport and channel change at different discharges. Warburton and Davies (1994) suggested that their experiments should be extended to other combinations of slope and discharge. They identified the need to investigate the influence of sediment supply on braided channel forms and bed load transport rates. Most of these topics remain ongoing concerns, and point to the need for a more co-ordinated approach to complementary field and laboratory studies.

The research papers in this special issue continue some of the themes identified in earlier work (Table 1). Young and Warburton (this issue) in their review of braided gravel-bed river hydraulic modelling procedures, outline the principles and advantages and limitations of the approach. Flume size, sediment management and cost, together with the requirements for hydraulic similarity, impose limits on model scale which usually restrict modelling to small braided river systems (~1:50 scale). Peakall and Warburton (this issue) define critical conditions (Weber numbers) for surface tension effects in small hydraulic models. They conclude that although the potential influence is great, there is no consensus on a single critical condition. They suggest a series of experiments to determine the critical Weber number, the basis of which could be a flume study of surface wave propagation for various combinations of velocity and depth. A second experiment is also required to examine the changes in planform characteristics and sediment transport rates of a simple model reach, above and below the critical Weber threshold.

Hoey's observations of sediment transport and sediment storage (Hoey, this issue) provide a valuable insight into the role of storage reservoirs in controlling sediment release from braided channels. In an experiment using dyed sediment as a tracer, Hoey demonstrated that sediment dispersion consisted of continuous throughput at a declining rate and episodic pulses of sediment. Hoey's approach of classifying the river bed sediments in terms of storage reservoirs allows residence times to be estimated. The distinction between dynamic sediment movement and changes in reservoir classification provided further refinement of residence times and reflects the rate of sediment transport and associated changes in channel morphology. Hoey identified the further need for laboratory modelling, field verification, and small-scale field process studies to improve understanding of the mechanics and evolution of bed waves.

Davies and Griffiths (this issue) described a novel experiment in a distorted rough turbulent flow, Froude-law model of the passage of a flood hydrograph through the Waimakariri River Gorge and its impact on the stage-discharge curve at this river gauging site. Intrinsic variability of ± 300 $m^3 s^{-1}$ and ± 500 $m^3 s^{-1}$ (scaled) on the rising and falling limbs (respectively) of the >1000 $m^3 s^{-1}$ flood wave were measured. A theory was developed to extend the stage-discharge relationship to flood flows which cannot normally be measured directly. Although there were problems in determining bed slope and time scales in the model, hydraulic modelling in conjunction with theoretical analysis was found to be a valuable method in determining the variability in the stage-discharge relationship in a braided river gorge during high flows. However, clarification of the nature of sediment transport in flow constrictions and careful calibration of bedload formulae are required before further progress can be made.

Warburton (this issue), in his investigation of the influence of bed width on bed load transport and channel morphology, showed that bed load transport capacity is greater in narrower braided systems. Formulae designed to predict the width of shallow rectangular gravel-bed channels are unsound because of uncertainty about the relationship between bed load transport and width in braided channels. Wide braided systems are characterised by small short-duration sediment pulses. Most experimental runs were aggradational, and floodplain sediment storage increased with width. In response to the imposed flow and sediment regime the narrowest channels enlarged, whilst the wider channels maintained their overall width. The relationship between braiding intensity and bed load transport was complex, but suggests bed load transport is lower in the more braided systems, a finding which contrasts with the recent results of Warburton and Davies (1994) who found greater bed load transport where the channel was more braided. These results support the general conclusion of Davies and Lee (1988) that transport capacity increases as width decreases.

The themes explored in this recent work continue established areas of research and add new information to the growing data base. Table 1 summarises this information for the work undertaken so far and indicates the major themes investigated in 13 papers. The first six themes are identified from Warburton (this issue) ('Inadequacies of the field data base' is not included) but a seventh theme 'Engineering applications' is added. Clearly some themes are given higher priority than others. For example, hydraulic similarity and model verification, particularly at the start of modelling, is a major preoccupation. Similarly the relationship between bed load transport and channel morphology and the related ideas of equilibrium are also major themes. Variability in bed load transport rate and description of braided river channel patterns have also been carefully considered, but the level of research activity is slightly less than for the other major themes. Direct application of model results to engineering studies have been relatively few and the use of bed load transport equations has been low, which is surprising given the vast amount of flume work undertaken to calibrate these equations. From this assessment it is clear that the range of research themes remains as broad as it has always been, which leads to two conclusions. Firstly, hydraulic models are widely applicable to a range of braided river management issues and secondly, important questions remain to be resolved in all these areas.

Limitations of Hydraulic Modelling of Braided Gravel-bed Rivers

The limitations of braided gravel-bed river hydraulic modelling can be theoretical - mainly relating to scaling problems; physical - relating to modelling materials e.g. the fluid and sediment; and practical - limits imposed by cost, space and available equipment. These produce a number of problems including model scaling, morphological modelling, model grain sizes, scale distortion, dynamic similarity and time scales. The hydraulic principles that under-pin scaled modelling have been reviewed in detail on numerous occasions (e.g. Yalin, 1971; Foster, 1975; Sharp, 1981; Novak and Cabelka, 1981; Ackers, 1990). Our aim is to realistically appraise current modelling techniques and discuss the future role of hydraulic models in braided river engineering.

Model Scaling

When deciding on the scale of a hydraulic model, the upper limit is usually controlled by practical constraints and the lower limit by physical laws. Practical constraints refer to limits imposed by the modelling apparatus and the long duration of runs. Typical examples are the size of the flume facility, water pumping capacities and sediment feed apparatus, logistics of mixing bed material sizes, facilities to dry large volumes of sediment, and the ability to measure representative variables. These constraints can be overcome by applying a bigger budget but in reality this is not always possible. Typical problems include boundary problems of input and exit conditions and side-wall effects. The latter is a particular problem in braided river models where the flow is usually laterally unconstrained. Bed material tends to be the major limiting factor and should be selected on the basis of its availability and the ease with which it can be handled and controlled. The modelling of braided gravel-bed rivers requires models of a large size so that model grain-sizes can be scaled correctly and the braided channel can developed fully i.e. all boundaries are deformable. Sand and fine gravel are the most common materials used. Generally speaking the model should be as large as economics permit so that scale effects are minimised and the credibility of predictions is increased.

Experience shows that Froude models can give representative results for alluvial gravel channels as long as the scale is not less than 1:40-50 and the prototype sediment is large enough to be represented by fine gravel. *More work is required in defining the smallest scale at which braided rivers can be effectively modelled.*

Morphological Modelling

The scale limitation of about 1:100 on dynamically similar modelling of gravel-bed braided rivers restricts the information available from them to the reach scale - i.e. up to about a 2 to 3 km length of prototype river. This is quite a serious limitation in that, using a model, the effects of proposed changes to a river cannot be assessed for more than a few kilometres away from the site of change. It would appear, therefore, to be worthwhile investigating the ability of smaller models to represent prototype behaviour with a much reduced degree of dynamic similarity, i.e. at scale ratios much smaller than 1:100. Hong and Davies (1979) found significant behavioural similarity at a scale of about 1:2000 in spite of dissimilar force ratios. If this behavioural similarity were better understood, the predictive limitations of such models could be defined. Small-scale models could be used to represent longer reaches of rivers, over longer time periods and interacting with more of the surrounding landscape. *Investigations using smaller models are needed.*

Model Grain-size

Variation in bed material size in gravel-bed rivers necessitates the use of a fine gravel and sand mix in most models. The size distribution is commonly truncated to avoid complications caused by the finer fraction. Models using medium or fine sand often experience difficulties due to the formation of pronounced bed ripples, and it has been suggested that coarser, lighter materials may be preferable. In many models a significant fraction of the grain-size distribution is modelled with silt-sized material, especially at smaller scales. There are also fine-grained deposits in many braided river floodplains which can significantly alter the morphology and hydraulic properties of the gravel-bed. Fairly subtle differences in grain-size distribution between the model and prototype may lead to large discrepancies between model and prototype behaviour, for example in the armouring process and in locally enhanced bed load transport. Furthermore, if the full grain-size range is modelled, then reproduction of the bed morphology also implies reproduction of sedimentary structures. Differences between gravel and sand-bed systems (Simons and Simons, 1987) are often not recognised in modelling e.g. the mechanisms of armour formation and bed load transport over beds of varying roughness. Recent modelling work by Ashworth *et al.* (1994), suggests that non-cohesive silicates (fine grained silica of 1-20 mm) can be used to model the silt fraction of braided rivers. Ashworth *et al.* (1994) describe the physical modelling of a braided gravel-bed river and processes leading to deposition of fine-grained sediment. The model is a Froude scale model with the flow Reynolds number relaxed in order to achieve model-prototype hydraulic similarity. A case is made for operation of a Froude model at a grain Reynolds number as low as 15. The authors claim excellent hydraulic and morphological similarity between model and prototype. Although this is an interesting application, under dry conditions and in shallow flows very fine-grained material may float (surface tension). For example silica may dry out on bar surfaces then be re-entrained by flotation as channels are reactivated in the model. *Further investigation of the use of fine-grained materials in models is required.*

Distorted Scales

In Froude models with a mobile bed of sediment with the same specific weight as the prototype, the grain-size is scaled geometrically and the model is undistorted. The advantage of having an undistorted model is that sediment transport and channel form will both be correctly represented. However, for practical reasons the horizontal scale is often less than the required vertical scale. To ensure velocities high enough to transport material, vertical distortion is often needed - this increases slopes and reduces the width/depth ratio. This introduces linear distortion into the model and requires slope adjustment to compensate.

In distorted models bed forms must be absent or insignificant relative to grain size. In gravel-bed-rivers it is often assumed that bedforms are negligible, however form resistance (resistance from bars) is still a significant factor which must be taken into account in a distorted model. Distortion should be avoided in braided river models because it results in a departure from dynamic similarity which will affect velocities and channel form (width/depth ratio, channel bank slopes, etc.). Distortion is also significant where modelling has been used to characterise braided river sedimentary structures important in identifying reservoirs for oil exploration. The braided river situation is so complex that wherever possible the model should reproduce prototype conditions with as little distortion as possible. *The effects of even slight distortion on sediment transport and the channel morphology in braided gravel-bed river models need to be investigated in detail* (Davies and Griffiths, this issue).

Dynamic Similarity and Verification

In braided rivers where width/depth ratios are large and flows are shallow, scaling can create problems. To ensure similarity of model and prototype, scale effects must be minimised. In very small models viscous and surface tension forces may become important. Evaluating the magnitude of these influences by calculating the Froude, Reynolds or Weber numbers is an insufficient basis for making a judgement because critical values for these parameters have not been agreed on (Gehrig, 1980). In Froude models the underlying assumption is that viscous forces are relatively insignificant in the model and prototype. The reduction in the Reynolds number is relatively unimportant as long as the flow remains rough turbulent. The important characteristic is the flow adjacent to the boundary given by the particle Reynolds number. Young and Davies (1990) suggest that model verification in a Froude law model requires: flow conditions in the model are 'rough turbulent', general Froude similarity of the flow between model and prototype, and similarity of relative roughness (d/D) between model and prototype (equivalent to similarity of grain Froude number). Even if not dynamically similar, hydraulic models can still reproduce the geometry of braided rivers. Hong and Davies (1979) found significant geometric and hydraulic similarity between the Rakaia River and a self-formed laminar flow sand channel of a scale of approximately 1:2000. However, there are likely to be some scale effects in very small models or tributary channels in parts of larger models. *Guidelines and a consistent procedure for model verification need to be established.*

Time Scales

In hydraulic models time scales are generally compressed by scaling, although the nature of the time scale is sometimes in doubt (Ashmore, 1987). This is particularly true when scaling bed load transport rates. Yalin (1971, p.182) suggests this scale is $\lambda_t = (\lambda_l)^{1.5}$ for specific bed load transport rates and $\lambda_Q = (\lambda_l)^{2.5}$ for volumetric transport rates; this agrees with Zanke (1978) who also suggests a scale of $\lambda_Q = (\lambda_l)^{2.5}$. Nevertheless errors in reporting model bed load transport rates appear in the literature. Alternatively, where time scales are unknown, a 'historical' test run of a known discharge series could be put through a model, then a comparison made between model and prototype bed configurations. Comparison of the results could be used to calibrate the sedimentation time scale. However this approach is weak because the quality of model calibration can only be as good as the quality of prototype data. There are also practical difficulties in running braided river models for long periods. Firstly it is costly in terms of effort e.g. recycling sediment, maintenance, etc. and secondly many braided rivers behave like fans and if they are not laterally constrained during long runs will eventually contact the side-walls. *Experimental investigation of time scaling is needed.*

The Role of Hydraulic Models in Braided River Engineering

In the future river engineering and river management will increasingly affect braided systems by altering upstream inputs of sediment and water, changing channel slopes and modifying channel bed and bank materials (Fig. 1). Because of feedback mechanisms in braided river mechanics, such interference may cause a variety of changes which cannot be reliably predicted by theoretical approaches (Fig. 1). Hydraulic models help bridge the gap between theory and practical design. Models verify empirical equations, e.g. bedload transport, and provide solutions to problems that cannot be solved analytically. In this respect they are useful for predicting prototype behaviour. Analytical models have been widely used in river engineering for approximate solutions and predictions about river behaviour. Unfortunately they only really represent equilibrium conditions and give little indication of the variability and rates of change of river processes. Hydraulic and numerical models offer more insight, but are expensive to run and time consuming to establish (White, 1987). As Klassen (1990) notes, where the bed and banks are not fixed the situation eludes mathematical modellers. Nevertheless significant developments have been made in this area, in terms of modelling both specific elements of the braided river system (Pizzuto, 1990 - river widening processes) and the system as a whole (Murray and Paola, 1994). Murray and Paola (1994) suggest, on the basis of a cellular model study, that braiding may be the fundamental instability of laterally unconstrained free surface flows over cohesionless beds. This conclusion is hardly surprising because this situation will always produce braided conditions. Calibrations of models of this kind have traditionally relied on field data. However, most field data sets are often expensive to collect, inaccurate, incomplete and unrepresentative, so data from physical models, particularly for high flows, provides a feasible alternative. Hydraulic models are, however, only one tool for studying braided gravel-bed rivers, and significant progress has been made in field measurement of braided river processes at the reach scale. Valuable recent reviews by Bridge (1993) and Ferguson (1993) have summarised geomorphological and sedimentological perspectives, and current understanding of reach-scale, braided river behaviour.

Hydraulic modelling allows testing of physical options that would not be practicable or whose environmental effects would not be tolerable in the prototype river. By manipulating variables such as channel slope, water and sediment flows, and bed and bank materials under controlled conditions (Fig. 1), model studies give engineers confidence and reduce the piecemeal approach to engineering of rivers and the need for pilot projects (Shen, 1979). For example, models would be useful in deciding on a defensive or aggressive strategy of river training. However, in engineering decisionmaking, hydraulic models are only one tool; they do not give a definitive answer in their own right. It is therefore surprising that they have not been used more in river engineering. Reluctance to use hydraulic models probably stems from realisation of the uncertainties and problems in model design, particularly the calculation of quantitative changes over scale. This is typified in two recent quotes, from Ferguson (1993, p.85) who suggests "... there have been fewer flume experiments on braiding than field studies, but they have contributed a great deal to qualitative understanding..." and from Bridge (1993, p.14) who states "Laboratory experiments have provided useful information about the nature and short-term evolution of braided rivers but direct application of this information to natural rivers must be treated with caution in view of simplified experimental conditions and scaling considerations". Davies (1987) suggested a comparison of models at different scales e.g. 1:10, 1:50, 1:100. The 1:100 scale is thought to be about the limit of model studies that can still have rough turbulent flow. Alternatively, Hoey and Sutherland (1989) suggested using prototype rivers with different grain sizes and hydraulic characteristics as models of one another. Future model studies need to assess the influence of model scale on the reproduction of fluvial processes. They should aim to produce larger undistorted models and collect data over a wide range of model and prototype scales so that models can be calibrated and verified. In view of the problems outlined above and the likely demands on braided rivers in the future, New Zealand investment in a large braided river hydraulic modelling facility would be money well spent. For example, the model used by Davies and Griffiths (this issue) and Warburton (this issue) would cost approximately the same as 100 metres of stopbank.

Conclusion

The effort expended in braided river hydraulic modelling in New Zealand and elsewhere over the last 20 years has yielded significant new understanding of some of the fundamental processes operating in such rivers. Much of the most useful work has been based on empirical observations (often of a qualitative nature). As this special issue has shown , there has been less progress in theoretical understanding of braided gravel-bed rivers or in quantitative predictions which will be of direct use to river managers. A recurrent theme in the papers in this volume has been the tendency of braided river hydraulic models to raise as many questions as they solve, allied to which have been pleas for more and better field data for calibration. Further progress in the understanding of braided rivers requires integration of field, laboratory and theoretical approaches.

In flume modelling, the themes identified as requiring further research are generally technical in nature and may appear rather unstimulating, but need to be addressed if the maximum use is to be made of flume modelling in the future. Inevitably practical constraints and the need to provide answers to specific questions will influence future flume work. It will not be possible to answer all the technical questions before further modelling work is undertaken. Future braided river modellers should follow two basic guidelines: (1) to construct models carefully using experimental conditions, materials and procedures which are designed to produce reliable scale models; and (2), to report fully in detail experimental procedures, sediment characteristics and hydraulic conditions, to allow proper evaluation of scaling and verification.

If hydraulic models are to be accepted in New Zealand four steps must be taken.

1. Resolve the more pressing technical problems such as calibration and scaling.
2. Solve some river problems of real concern by means of hydraulic modelling so as to build-up or gain user confidence in the application of modelling approaches and solutions.
3. Promote education in modelling techniques with engineering students in particular and also with engineering and resources management professionals.
4. Seek resources from science funding providers to develop a dedicated modelling facility.

References

Ackers, P. 1990: Dimensional analysis, dynamic similarity, process functions, empirical equations and experience - how useful are they? In Shen, H.W. (Ed.) *Movable Bed Physical Models.* Kluwer Academic Publishers, Netherlands, 23-30.

Ashmore, P.E. 1987: Bed load transfer and channel morphology in braided streams. In Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G. and Swanson, F.J. (Eds.) *Erosion and Sedimentation on the Pacific Rim.* IAHS Publication 165, 333-341.

Ashmore, P.E. (1991) How do gravel-bed rivers braid? *Canadian Journal of Earth Science 28:* 326-341.

Ashworth, P.J.; Best, J.L.; Leddy, J.O.; Geehan, G.W. 1994: The physical modelling of braided rivers and deposition of fine-grained sediment. In Kirkby, M.J. (Ed.) *Process Models and Theoretical Geomorphology.* John Wiley, Chichester, 115-139.

Bridge, J.S. 1993: Interactions between channel geometry, water flow, sediment transport and deposition in braided rivers. In Best, J.L. and Bristow, C.S. (Eds.) *Braided Rivers*, Geological Society Special Publication 75, 13-71.

Carson, M.A.; Griffiths, G.A. 1987: Bedload transport in gravel channels. *Journal of Hydrology (NZ) 26 (1):* 1-151.

Davies, T.R.H. 1987: Problems of bed load transport in braided gravel-bed rivers. In Thorne, C.R., Bathurst, J.C. and Hey, R.D. (Eds.) *Sediment Transport in Gravel-bed Rivers.* John Wiley, Chichester, 793-828.

Davies, T.R.H.; Lee A.L. 1988: Physical hydraulic modelling of width reduction and bed level change in braided rivers. *Journal of Hydrology (NZ) 27 (2):* 113-127.

Ferguson, R.I. 1993: Understanding braiding processes in gravel-bed rivers: progress and unsolved problems. In Best, J.L. and Bristow, C.S. (Eds.) *Braided Rivers*, Geological Society Special Publication 75, 73-87.

Foster, J.E. 1975: Physical modelling techniques used in river models. *ASCE Symposium on Modelling Techniques 1975, New York*, 540-559.

Gehrig, W. 1980: River models with movable bed. In Kobus, H. (Ed.) *Hydraulic Modelling*, Pitman Books, London, 49-70.

Henderson F.M. 1986: Introduction. In Smart, G.M. and Thompson, S.M. (Eds.) *Ideas on the Control of Gravel-bed Rivers.* Publication No.9 of the Hydrology Centre Christchurch, 1-5.

Hoey, T.B.; Sutherland, A.J. 1989: Self formed channels in a laboratory sand tray. *International Association for Hydraulic Research, XXIIIrd Congress, Proceedings: Technical Session B, Fluvial Hydraulics*, B41-B48.

Hoey, T.B.; Sutherland, A.J. 1991: Channel morphology and bedload pulses in braided rivers: a laboratory study. *Earth Surface Processes and Landforms 16*: 447-462.

Hong, L.B.; Davies, T.R.H. 1979: A study of stream braiding. *Bulletin Geological Society of America 90(11):* 1839-1859.

Jaeggi, M.N.R. 1989: Channel engineering and erosion control. In Petts, G.E., Moller, H. and Roux, A.L. (Eds.) *Historical Change on Large Alluvial Rivers*, 164-183.

Klassen, G.J. 1990: On the scaling of braided sand-bed rivers. In Shen, H.W. (Ed.) *Movable Bed Physical Models.* Kluwer Academic Publishers, Netherlands.

Lee, A.L.; Davies, T.R.H. 1986: Dominant discharge in braided streams. In Smart, G.M. and Thompson, S.M. (Eds.) *Ideas on the Control of Gravel-bed Rivers.* Publication No.9 of the Hydrology Centre Christchurch, 220-229.

Mosley, M.P.; Zimpfer, G.L. 1978: Hardware models in geomorphology. *Progress in Physical Geography* 2: 438-461.

Murray, A.B.; Paola, C. 1994: A cellular model of braided rivers. *Nature 371*: 54-57.

Novak, P.; Cabelka, J. 1981: *Models in Hydraulic Engineering: Physical Principles and Design Applications.* Pitman, London.

Pizzuto, J. 1990: Numerical simulation of gravel river widening. *Water Resources Research, 26 (9):* 1971-1980.

Sharp, J.J. 1981: *Hydraulic Modelling.* Butterworths, London, 242p.

Shen, H.W. 1979: Additional remarks on extremal floods, basic equations, river channel patterns, modeling techniques and research needs. In Shen, H.W. (Ed.) *Modeling of Rivers.* John Wiley, New York, 20.1-20.21.

Simons, D.B.; Simons, R.K. 1987: Differences between gravel and sand-bed rivers. In Thorne, C.R., Bathurst, J.C. and Hey, R.D. (Eds.) *Sediment Transport in Gravel-bed Rivers.* John Wiley, Chichester, 3-15.

Thornes, J.B. 1987: Environmental systems - patterns, processes and evolution. In Clark, M.J., Gregory, K.J. and Gurnell, A.M. (Eds.) *Horizons in Physical Geography.* Macmillan, Houndmills, 27-46.

Warburton, J.; Davies, T.R.H. 1994: Variability of bedload transport and channel morphology in a braided river hydraulic model. *Earth Surface Processes and Landforms 19*: 403-421.

White, W.R. 1987: Engineering aspects of fluvial morphology. In *Proceedings IAHR Congress, Lausanne*, 1987, 1-18.

Yalin, M.S. 1971: *Theory of Hydraulic Models.* Macmillan, London.

Young, W.J.; Davies, T.R.H. 1990: Prediction of bedload transport rates in braided rivers: a hydraulic model study. *Journal of Hydrology (NZ) 29(1):* 75-92.

Young, W.J.; Davies, T.R.H. 1991: Bedload transport processes in a braided gravel-bed river model. *Earth Surface Processes and Landforms 16*: 499-511.

Zanke, U. 1978: *Zusammenhang zwischen Strömung und Sedimenttransport.* Teil 2. Sonderdruck aus Heft 48, Mitt. des Franzius-Instituts, Univ. Hanover, Germany, 95p.