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Principles and practice of hydraulic modelling of braided gravel-bed rivers

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Abstract

Hydraulic modelling permits the forms and processes of braided rivers to be studied under closely monitored and controlled experimental conditions. The advantages of this approach stem from the degree of control available, the reduced physical size in the model, and the increased rate of geomorphic evolution. This paper outlines the principles of the hydraulic modelling of braided gravel-bed rivers, describes the practical limitations of this approach and compares model and prototype characteristics. Modelling procedures are based on the principles of hydraulic (dynamic) similarity. Models of braided river systems involve mobile bed modelling of complex two-phase flow. However, restrictions imposed by scaling ratios for gravitational acceleration, fluid viscosity and fluid density make it impossible to achieve full dynamic similarity, except with a length scale of unity. Therefore model experiments use *approximate dynamic similarity*, which to be satisfied only requires similarity of relative depth between the model and prototype. Practical limitations of flume size, sediment management and cost often limit model scales; because of the requirement of rough-turbulent flow in Froude-law models, it is seldom possible to use models smaller than 1:50 linear scale ratio. Modelling is therefore usually restricted to modelling typical reaches of smaller braided rivers or a group of prototype rivers. Because prototype rivers cannot be described adequately to carry out a detailed assessment of hydraulic similarity, quantitative prediction using these models is limited. Nevertheless, hydraulic modelling is a very attractive method for investigating braided river processes, and given careful design, a wealth of valuable data and information can be obtained with relative ease.

Introduction

Hydraulic modelling is a way of studying the forms and processes of braided rivers under closely monitored and controlled experimental conditions. Mosley and Zimpfer (1978) reviewed the advantages and disadvantages of experimental research in geomorphology; the main advantages they identified can be summarised for braided river modelling.

(i) Modelling permits the identification, isolation, manipulation and precise measurement, under controlled conditions, of processes and variables that cannot be easily investigated in the field.
(ii) Modelling permits the study of evolving braided river systems, of the differences between equilibrium and non-equilibrium systems, and of the implications of stage of evolution on the distribution of energy and matter within a system.
(iii) Modelling allows several processes or aspects of braided river systems to be examined simultaneously.
(iv) Modelling allows the study of the effect of varying boundary and initial conditions.
(v) Modelling allows easy quantitative observation of braided river forms and processes, and thereby can aid understanding and education.

The advantages of scale model studies thus stem from the degree of control available, the reduced physical size of the models, and the increased rate of geomorphic evolution. Furthermore, hydraulic models can be used to generate or test hypotheses about river behaviour, or they can be used for prediction and description (Schumm *et al.*, 1987). In the past, model studies were commonly used for descriptive studies of braided river forms and processes (e.g. Hong and Davies, 1979). Contemporary studies are often concerned with predicting future river form and behaviour following some change to the system, from the perspective of engineering or management rather than science (Young and Davies, 1991). Hydraulic models are invaluable for verifying computations made by empirical equations and obtaining solutions to problems that cannot be solved analytically (Foster, 1975).

From an engineering perspective models may be used for prediction of future 'river behaviour'. Change to the fluvial system implies a change in one or more controlling variables, such as channel slope, water discharge, and sediment size and discharge. Changes to these variables due to activities such as gravel extraction, irrigation water abstraction, river impoundment or lateral confinement of the channel may be anticipated. A change in the flow regime could also be caused by climate change. For instance, changes in rainfall patterns may result in larger or more frequent extreme events.

Humankind needs to co-exist with and use rivers; the most important aspect of river behaviour is the time-varying boundary shape and location of the channel (Davies, 1987). Typical questions about future river behaviour are:

(i) What is the likely future position of the channel?
(ii) Can general or localised erosion or deposition be expected?
(iii) Can an increase or decrease in the channel width be expected?

The aims of this paper are firstly, to outline the principles of hydraulic modelling and briefly discuss the procedure for choosing an appropriate model scale; secondly, to compare model and prototype braided river characteristics; and finally, to discuss the limitations of a modelling approach. The review is by no means a comprehensive treatise on hydraulic modelling; it concentrates on aspects relevant to braided rivers.

Principles of Hydraulic Modelling

Hydraulic modelling is a means of experimentally investigating a hydromechanical phenomenon, and is commonly used in many civil and mechanical engineering studies, as well as in geomorphological studies (Ashmore, 1991; Warburton and Davies, 1994). The procedures involved are based on the principles of hydraulic similarity which are well established, although for the mobile-bed models used in geomorphological studies the complexity of modelling two-phase flow of the water and sediment often requires approximations to be made (Yalin, 1971; Kobus, 1980). The results from mobile-bed models are therefore usually less definitive that those from fixed boundary models, but can nevertheless provide valuable information about complex natural and engineered systems at a relatively low cost (Foster, 1975).

To provide reliable information, a model must be correctly designed according to the rules of hydraulic similarity. A hydraulic model study may be viewed as a way of 'asking nature a question'. As pointed out by Davies (1987), the answer from a flume study will always be true, the difficulty lies in asking the question correctly. Applying the rules of hydraulic similarity enables you to pose the correct question. A laboratory channel (Fig. 1) is a real-world system that can be studied in detail; the usefulness of such a study comes from translating the qualitative and quantitative results to larger real-world systems (Novak *et al.*, 1990).

Three degrees of similarity can be defined between a model and its prototype. Geometric similarity requires only a constant ratio of length dimensions. Kinematic similarity requires constant ratios for both length and time dimensions, thus giving similarity of velocity. Dynamic similarity

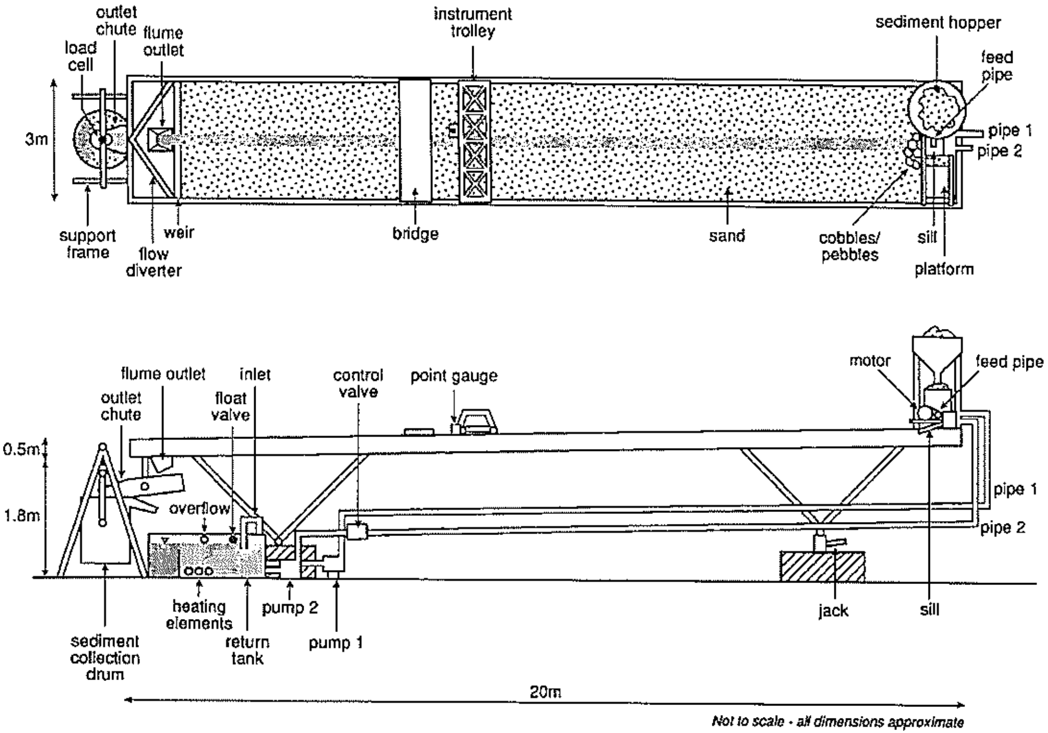

Figure 1 Typical hydraulic model flume facility. Department of Natural Resources Engineering, Lincoln University, Canterbury, New Zealand.

requires constant ratios for length, time and mass, thus ensuring similarity of forces. Because hydraulics is concerned with the forces that govern fluid and sediment motion, hydraulic similarity requires dynamic similarity between model and prototype. Using dimensional analysis, the parameters which describe a given system can be combined into dimensionless groups. For mobile-bed models the two-phase motion (assuming cohesionless granular material) can be completely described by:

(i) the nature of the fluid: its dynamic viscosity μ and density ρ
(ii) the nature of the granular material: its density ρ_s; grain diameter D; grading coefficient ϕ; and shape factor f;
(iii) the nature of the flow: the slope S; the flow depth d, and the acceleration due to gravity g.

This gives a set of seven independent parameters which, after the useful substitution of g for $\gamma_s = g(\rho_s - \rho)$, where γ_s is the specific weight of the granular material, and $v_* = \sqrt{Sgd}$ where v_* is the shear velocity, can be arranged into the four following dimensionless groups (Yalin, 1971):

$$X_1 = \frac{v_* D}{\upsilon}$$

which is the ratio between viscous and inertial forces (where υ is kinematic viscosity), and is called the grain-size Reynolds' number (Re_*),

$$X_2 = \frac{\rho v_*^2}{\gamma_s D}$$

which is the ratio between gravity and inertial forces, and is called the grain-size Froude number (Fr_*),

$$X_3 = \frac{d}{D}$$

which is the relative depth, and

$$X_4 = \frac{\rho_s}{\rho}$$

which is the relative sediment density.

Commonly, however, the scale ratios for gravitational acceleration g, fluid viscosity μ and fluid density ρ are all unity. With these constraints it is impossible to satisfy full dynamic similarity, except with a length scale of unity. That can only be satisfied with a full-scale model!

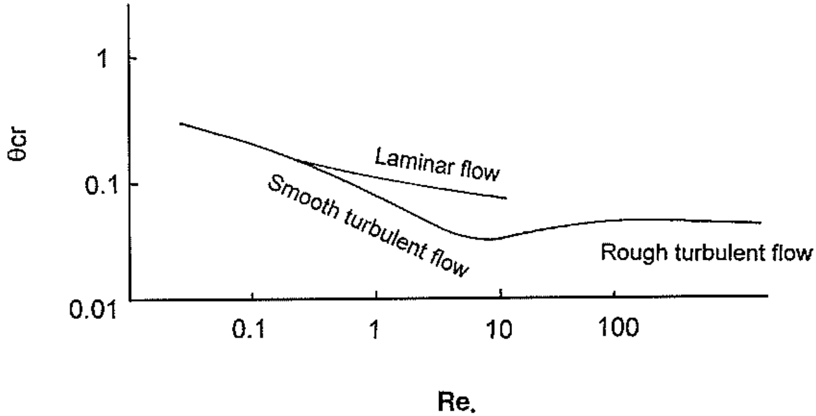

Figure 2 Shields diagram - modified from Dingman (1984). Relation between critical dimensionless shear stress ($\theta cr = rv_*{}^2 / g_s D$) and grain-size Reynolds' number (Re_*) for laminar and turbulent flows.

While the fluid viscosity can be decreased by using heated water, it is not possible to achieve useful scale ratios by this method alone. The usual solution is to relax the condition of grain-size Reynolds' number similarity. If Re_* is greater than a certain critical value, grain detachment and motion are independent of the fluid viscosity and hence of Re_* itself (Fig. 2). This condition is, however, only met in rough-turbulent flow. In modelling using sand bed channels, the small grain sizes do not ensure rough turbulent flow near the bed, and small bedforms atypical of gravel-bed rivers may form.

When modelling braided rivers, it is usual to use water as the fluid and a quartz sediment as the bed material. This fulfils the condition $\lambda_{x4} = 1$. The criterion $\lambda_{x3} = 1$ implies that the sediment grain sizes should be scaled directly by the length scale, and given this, and that ρ, γ_s and g all have scale ratios of unity, the criterion $\lambda_{x2} = 1$ can be reduced to $\lambda_s = 1$. That is, the slope in the model should be the same as the prototype. Therefore, if the following conditions are met:

(i) sediment density is equal in model and prototype,
(ii) grain sizes are scaled directly by the length scale,
(iii) water is used as the model fluid,
(iv) flow is rough-turbulent in the model,
(v) bed slope is equal in a model and prototype

then to fulfil 'approximate dynamic similarity' only requires similarity of relative depth. This has rarely been evaluated in model studies.

When modelling braided rivers, the model grain size must be large enough to ensure that at discharges sufficient to initiate sediment motion, Re_* is greater than 70. This usually necessitates the use of gravel and sand-sized material in the model. Where grain sizes are smaller, and rough-turbulent flow is not assured, the influence of viscosity cannot be neglected and a different approach is needed for the production of two-phase motion in a small scale model. Usually this involves using larger, lighter grains in a geometrically distorted model; that is, one with different horizontal and vertical length scales. Distortion poses problems for modelling braided rivers (moveable bed models) because it affects parameters such as the width/depth ratio of the channel, the velocity distribution across the channel, the slope of the channel banks, and scour hole geometry. Linear distortion should be as small as conditions permit (Foster, 1975), as little is known about how distortion affects model behaviour.

In distorted models, the length scale of dynamic similarity in the vicinity of the bed is λ_D, as it is this length which determines the fluid and sediment motion. This is different from both the horizontal and vertical scales, and leads to a distortion in the behaviour of the grains. It can be shown that grain motion is delayed with respect to the motion of the fluid. For these reasons, the time scales in distorted models are quite complex, with different times and scales applying to fluid motion, grain motion, and vertical and horizontal bed formation processes (Yalin, 1971). Davies and Griffiths (this volume) provide an example of a distorted gravel-bed river model.

In undistorted models these complexities do not arise. Since $\lambda_D = \lambda_l$ the time scale can be derived from the shear velocity scale ratio by $\lambda_t = \lambda_D/\lambda_{v_*}$. As $\lambda_g = \lambda_s = 1$, this leads to $\lambda_t = \sqrt{\lambda_l}$. This time scale applies to all motion, both of the fluid and of the grains in an undistorted model. With a density ratio (for both fluid and sediment) of unity, the mass ratio λ_m is equal to λ_l^3. With both the mass and time scales related to the length scale it is simple to determine the scale ratio for any quantity in terms of the length ratio. For instance, for flow rate Q, we arrive at $\lambda_Q = \lambda_l^{2.5}$

Limitations

Applying the above principles in a model study is not always a simple task. Theoretical, physical and resource limitations often combine to create problems in designing hydraulic models. Discrepancies between a model and prototype are usually termed 'scale effects' and generally arise due to imperfect modelling of geometric and kinematic conditions rather than a flaw in the basic theory of dynamic similitude (Sabersky and Costa, 1964). This section discusses some common problems associated with braided gravel-bed river hydraulic models. These include: ensuring rough-turbulent flow conditions; limitations on scale ratios; modelling the grain-size distribution; reproducing realistic flow series; and modelling specific river sites.

Rough-turbulent Flow

The choice of scale for a braided river model is restricted by the requirement for rough-turbulent flow. The lower bound of Re_* to ensure rough-turbulent flow is poorly defined (Fig. 2). Yalin (1971) suggests that the critical value lies somewhere between 70 and 150; however the considerable scatter of incipient motion values derived from different studies means that the Shields curve is ill-defined, and a lower figure could be acceptable. For example Ashworth *et al.* (1994) suggest transitional and rough turbulent flow conditions may still prevail at values as low as 15 (Fig. 2).

Using a critical value of $Re_* = 70$ for the model, a limiting criterion for the length scale can be established as follows:

$$\left[\frac{v_* D}{u}\right]_m \geq 70$$

$$\frac{\lambda_v \lambda_D}{\lambda_\upsilon} \geq \frac{70}{\left[\dfrac{v_* D}{\upsilon}\right]_p}$$

$$\lambda_l \geq \left[\frac{70}{[v_* D / \upsilon]p}\right]^{2/3}$$

If average values are used in this expression to determine λ_l, then in the model, the critical value of 70 will refer to average conditions, and there will be significant areas where Re_* will be less than 70 (Warburton and Davies, 1994). When choosing a grain diameter D for use in this expression it should be noted that it is the prototype grain Reynolds' number that is being estimated, and thus the grain diameter used should be that which best represents the bed roughness. [Note: in the original definition of the above formula, equivalent sand grain roughness replaced D]. For the wide grain size distributions characteristic of braided rivers, the bed roughness is largely determined by the largest particles, and hence the D_{90} percentile is often used to represent the bed roughness.

The variability of discharge is also important. If an average base flow depth from the prototype is used when estimating λ_l, then at transporting flows (with greater depths), the Re_* values will increase and a greater proportion of flow areas in the model will satisfy the criterion $Re_* \geq 70$. In wide braided rivers depth does not change markedly with discharge, and this effect may therefore be small. It is therefore wise to choose a critical Re_* as high as is practical. The practical limitations are usually the size of the available flume facility, or the limits of space, time or money available when constructing a new flume.

Scale Ratios

Typically, scale ratios range between about 1:20 and about 1:75, with flume dimensions ranging from 2 m to 5 m in width and from 10 m to 30 m in length. At these scales, a flume large enough to model the lower reaches of very large braided rivers such as the Waimakariri or Rakaia Rivers in New Zealand, where total bed widths are 1000 m or more, would be impractical or too costly. Generally one is therefore restricted to modelling narrower rivers, or accepting that lateral development of the braids will be limited by the flume width. For most braided rivers flow rarely fills the full width of the floodplain, so the 'active' width (where gravel transport is occurring) is usually much smaller than the full braidplain width (Warburton *et al.*, 1993). For such rivers failure to model the whole width is not always a major drawback, as the important changes are occurring over a small section of the braided floodplain. Table 1 shows an example of model scaling in a 1:50 model designed to reproduce the Waimakariri and Ashley Rivers. Even at this modest scale, a model channel width of over 6 m is required. Assuming a reasonable flume length/width ratio is in the order of 7:1 to 10:1 for braided stream processes to evolve naturally, the length of the flume would be approximately 40 to 60 m.

As well as the costs involved, large models typically require several tonnes of sediment, which leads to the practical difficulties in accurately modelling the prototype grain size distribution, and in handling the volumes of sediment required in the model.

River	Prototype				Model 1:50			
	Slope %	Mean width m	D50 mm	Mean flow m^{3}s^{-1}	Slope %	Mean width m	D50 mm	Mean flow ls^{-1}
Waimakariri*	0.29	320	20	116	0.29	6.4	0.4	6.56
Ashley*	0.38	300	20	14.6	0.38	6	0.4	0.83

*North Canterbury Catchment Board

Table 1 Scaling relationships between model and prototype for a 1:50 model of two North Canterbury rivers. Width estimates must be for the entire fairway, not the wetted channel area, because mean flows are very different in the two examples.

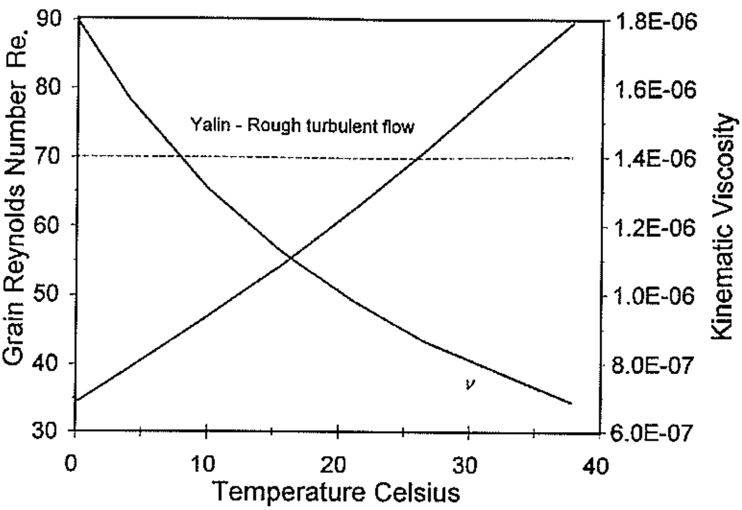

Figure 3 Variation in grain-size Reynolds number and kinematic viscosity with temperature. The Yalin (1971) criterion for rough-turbulent flow is plotted as a broken horizontal line.

Model Grain-size

Having selected a model scale, and used it to determine grain sizes and flow rates, one may, on running the model, find that grain-size Reynolds' numbers are below the critical value in too great a proportion of the model. The viscosity of the fluid may be reduced by heating, thereby increasing Re_* values (Fig. 3). Water heating elements may be placed in the water return tank (Fig. 1) so that hot water can be pumped into the flume. Given a reasonably warm ambient air temperature, the hot water will cool by only a few degrees as it flows over the flume bed. With grain sizes and discharges set, this does not alter the model scale, only the model Re_* values. This reduces the influence of viscosity-related scale effects, by ensuring that more of the flow meets the conditions for approximate dynamic similarity.

Most practical modelling problems are best dealt with on an individual basis, and solutions will vary with the exact nature of the flume set-up, model facility and resources available. However, most models of gravel-bed braided rivers will have a design similar to that shown in Figure 1. The greatest practical problems in running such a model are those associated with the handling of sediment. These include the mixing of sediment to achieve a model grain-size distribution, handling sediments during a run and avoiding boundary effects at the points where sediment enters and leaves the model.

Large models require large volumes of sediment, which are difficult to handle. For example in the flume shown in Figure 1, approximately 15 tonnes of sediment are required to prepare the bed, and during a run of 90 hours (assuming a moderate sediment feed rate of 1.6 g s^{-1}) approximately 518 kg (over half a tonne) of sediment is fed into the flume. Therefore, for a particular grain-size distribution, approximately 16 tonnes of sediment are required. Mixing this volume of sediment is not a trivial task and usually requires semi-automated techniques e.g. rotary sieves, and automatic feed hoppers.

When modelling the grain-size distribution of the bed material, the prototype grain-size distribution is usually truncated to avoid problems created by very fine sediment. Fine sediments are often cohesive; when dry they can float on the fluid due to surface tension, and they can cause ripple formation on the bed (Fig. 4). Restricting the grain-size curve to the coarse sand fraction avoids these problems. However, if in a 1:50 model the grain-size distribution is truncated at 0.1 mm this excludes all sediments finer than 5 mm in the prototype, which is a significant proportion of the grain-size range in some gravel-bed rivers. The sensitivity of model results to changes in the grain-size has not been adequately evaluated in studies of gravel-bed rivers.

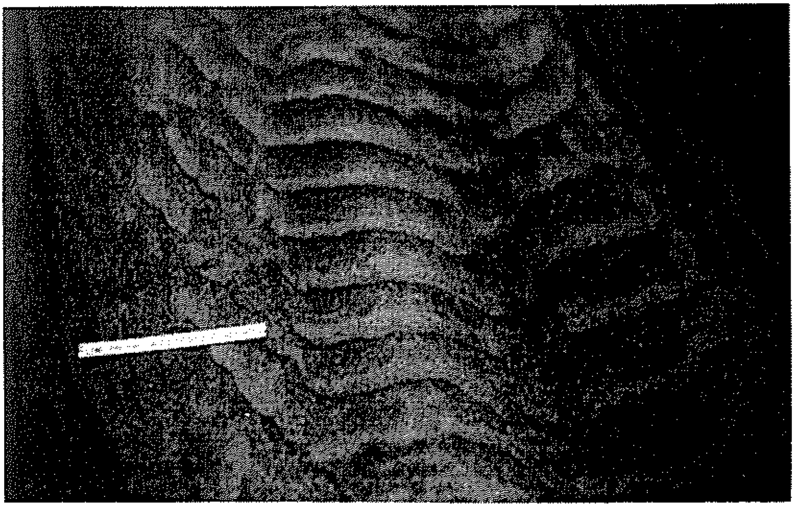

Figure 4 Small ripples formed on the channel bed of a braided river hydraulic model. Flow is from top to bottom and the scale bar is 100 mm.

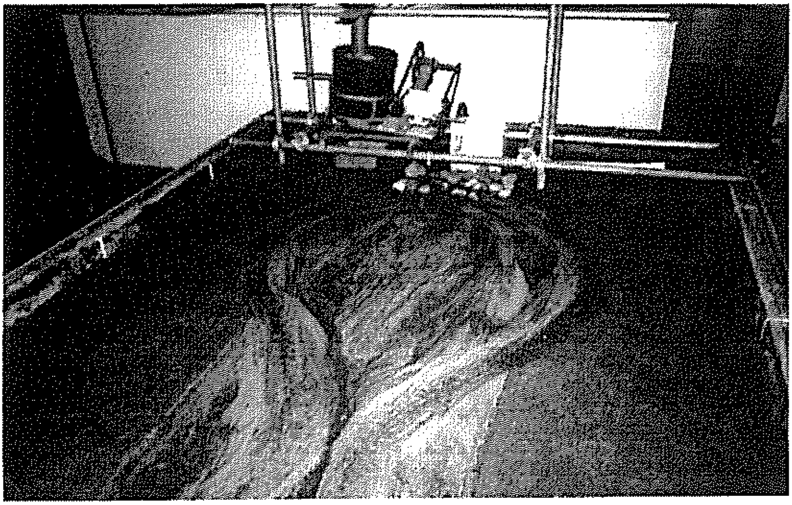

Figure 5 Photograph showing slight bed aggradation at the head of a flume. Sediment is delivered to the flume via a rotating tube connected to a drum and hopper. Dry sediment falls on to a sill which is discharging water. The water and sediment fall onto the cobble bed and then flow out onto the flume bed. Sediment feed rates can be adjusted to prevent sedimentation problems during sediment delivery.

The inclusion of a significant proportion of fine sediment in the grain-size distribution or local sorting in the model can lead to ripple formation in the model (Fig. 4). The formation of ripples in the model is undesirable, as these small-scale bedforms typical of sand-bed alluvial channels have no equivalent in gravel-bed rivers. Furthermore the presence of ripples can considerably enhance form resistance and under some circumstances increase the transfer of bed material, leading to an overestimate of bedload transport rates.

A further problem relating to the handling of sediment is that of input and output conditions (Fig. 5). Adjusting sediment supply so that there are no adverse input effects is usually accomplished by 'trial and error'. For example the sediment feed rate can be adjusted to avoid excessive aggradation or degradation at the flume head. Alternatively, aggradation or degradation might be acceptable as long as the flume is large enough to accommodate 'natural' readjustments in the sediment balance i.e. there are no wall effects and sediment supply from the flume bed is not limited. In dry sediment feed systems, additional problems arise, especially when working with small grain-sizes. The sediment must properly mix with the

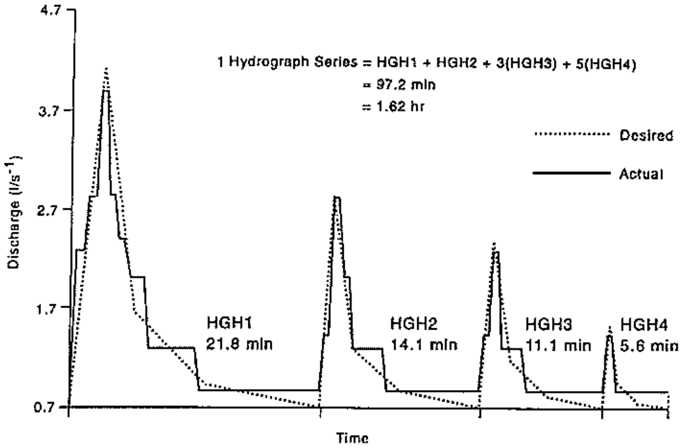

Figure 6 The model synthetic hydrograph series used by Young and Davies (1990) in their hydraulic model study of the North Ashburton.

fluid when it is added to the flume to avoid grain flotation; size-sorting must be prevented in the process of sediment feeding; and feed rates must be constant.

Realistic Flow Series

Reproducing a realistic flow series is also an important problem in hydraulic model studies. Lee and Davies (1986), Davies and Lee (1988) and Young and Davies (1990) have all used a computer to control the flow rate in the model. A stepper motor connected to the flow valve enables step function hydrographs to be generated. Young and Davies (1990) modelled unsteady flow (for the North Ashburton prototype) by designing a series of 10 synthetic hydrographs which were identical in shape but had time bases varying between 5.6 and 21.8 minutes (Fig. 6). These were chosen so that the resultant flow duration curve matched the above threshold of sediment motion flow duration curve in the prototype. The hydrographs were of sufficient duration to ensure that convective shear stresses due to varying flow were negligible (Davies and Lee, 1988). The computer randomly selected a hydrograph series, from a selection of ten step-hydrographs thus avoiding the possibility of a regular flow series influencing channel development. Although the synthetic hydrographs do not model the exact shape of prototype hydrographs (flow is said to be *quasi-steady*) the flow duration curves for the model and prototype are similar. With improved technology the flow rate could be controlled more precisely to produce more realistic synthetic hydrographs.

Modelling Specific Sites

When using mobile-bed models with self-formed channels, the modelling of problems such as the effects of a bridge or diversion structure is extremely difficult. In these instances, the actual channel planform will largely determine local changes such as scour or deposition. While the model may be statistically similar in planform geometry to the prototype, it is not possible to exactly reproduce the geometry of a given braided river reach. This may be overcome to some extent by making multiple experimental runs of the same phenomena. In this way an image of the range of possible outcomes can be assembled and 'worst', 'most likely' and 'best' scenarios established. Unfortunately with braided river models this has rarely been attempted (Warburton and Davies, 1994).

Armouring processes may also be dissimilar in the model and prototype, as their grain shapes differ. River cobbles and gravels can be flat and platy, while sands tend to be more angular and uniform in shape. This has implications for the formation of imbricated bed structures and the stability of the river-bed. This has not been investigated in detail in braided river hydraulic models.

As well as predictions for engineering purposes, models may be used to predict future environmental variables associated with the river system. This is an inherently more difficult task, as it is very difficult to measure environmental variables in the field, let alone in a model. For example the crusting of fine sediment surfaces by biological processes cannot be modelled in the flume at a reduced scale (Gehrig, 1980). Environmental factors that may be of interest to predict include habitat areas for fish species or water birds, or the extent of areas suitable for swimming or boating. With habitat variables, the predictive ability of scale models is limited, since aspects such as vegetation and bank stability are difficult to model, and flow velocity and depth are difficult to measure accurately. Measures such as total bar area and number of channels are, however, reasonably simple to obtain and may be useful habitat indicators. Nevertheless, it is recognised that the full environmental system cannot be reproduced in a scale model.

Model Verification and Comparisons with Prototype Rivers

No matter how carefully designed and constructed a hydraulic model may be, it is common practice to try to verify both the forms and processes in the model using prototype data. Verification involves adjusting the model to obtain satisfactory similarity between the model and prototype in terms of bedload movement and channel configuration (Foster, 1975). Without verification, it is impossible to assess how well the model represents the prototype, as inevitably approximations have to be made in the design, and various factors such as those discussed above, together with surface tension and capillary forces, can not be scaled (see Peakall and Warburton this volume). Gehrig (1980) suggests that model investigations with moveable beds require verification using prototype data more than other types of model.

Until recently hydraulic models were evaluated in terms of their visual similarity to equivalent prototypes (Davies and Lee, 1988) or by semi-quantitative comparisons using morphological and hydraulic data (Young, 1989; Warburton and Davies, 1994).

For example, Table 2 shows a comparison of a 1:50 hydraulic model and prototype hydraulic values for the North Ashburton River in Canterbury (Young, 1989). The values in the table indicate good hydraulic similarity between the model and prototype. Similarity of flow was good; the similarity of relative roughness (d/D) implied by the similarity of flow depth indicates similarity of Grain Froude numbers (Fr_*); the similarity of width, depth and form ratios implies similarity of channel shape; and some similarity of planform is suggested by comparable average numbers of channels.

Table 2 Comparison of hydraulic data for model and prototype - Blands Reach, North Branch of the Ashburton, Canterbury, New Zealand. Modified from Young and Davies (1990).

		Model Values (Scaled)			Prototype Values	
Variable	Units	Mean	Range	Error ±	Mean	Range
Discharge	$m^3 s^{-1}$	15.4	13.1 - 25.5	0.05	15.0	12.1 - 21.4
Flow Width	m	32.0	21.0 - 37.0	1.0	33.0	15.7 - 55.0
Average depth	m	0.45	0.35 - 0.65	0.05	0.41	0.29 - 0.54
Average velocity	$m s^{-1}$	1.0	0.6 - 1.6	0.1	1.23	0.82 - 1.57
Fr.		0.5	0.3 - 0.6	0.05	0.61	0.40 - 0.73
Width/Depth		69	52 - 69	10	88	30 - 157
Average number of channels		2.6	1.3 - 3.8	0.1	2.0	1 - 5

Forms

In comparing model and prototype braided gravel-bed river geometry, one is immediately faced with the problem of how to describe the braiding phenomenon. The geometry of braided rivers is so complex and variable that adequate descriptors do not presently exist (Davies, 1987). Models are therefore usually assessed in terms of their visual similarity to the prototype.

Comparing the form of models visually usually involves looking at the planform, cross-section and long profile characteristics. Recently, more quantitative measures based on bar geometry and the form of depositional niches have been suggested (Ashworth *et al.*, 1994). The examples given in Figures 7 and 8 clearly show the visual similarity between model and prototype. Figure 7 is a planform plot of the Blands Reach of the North Branch of the Ashburton River, Canterbury at low flow and a corresponding flume run of Young (1989) (slope 0.74%, steady discharge 0.88 l s^{-1}). Visually the two planforms are very similar in both overall dimensions (width) and channel complexity. They have similar total sinuosity values (total channel length/reach length): 2.5 for the prototype and 2.4 for the model. A comparison of cross-sections also reveals similarities. Figure 8 shows a comparison between a flume cross-section from Warburton and Davies (1994) and a field section surveyed on the Ashley River, North Canterbury. The two sections show overall similarity in that they are relatively confined, the highest relief tends to occur in the centre of the channel, and the lowest relief occurs towards the margins of the floodplain. Maximum relief difference for the flume and field is 1.6 m (scale adjusted) and 1.5 m respectively and the profile rugosity (channel width/profile length) is 0.83 for the field profile and 0.79 for the flume model. The largest channels in both cases occur at the base of cut banks on the outer edge of the braidplain (right bank in the field, left bank in the flume). Smaller channels bisect the higher areas leaving behind small hollows. Overall floodplain widths are dissimilar in that the flume width is proportionally 20% less than the field width. This is attributed to differences in bank strength, differences in flow history (time of model run duration) and the natural variation in braided river floodplain widths which can easily be ± 20%. Long profile data are very difficult to compare. In undistorted models overall slopes should be the same in the model and prototype, but smaller scale variations related to the movement of sediment waves should also be present (Hoey and Sutherland, 1991). There have been few attempts to compare slope between prototypes and models. Slopes are difficult to plot in a sinuous multiple-thread system and often flumes are too short to really evaluate such variation because of input and output constraints.

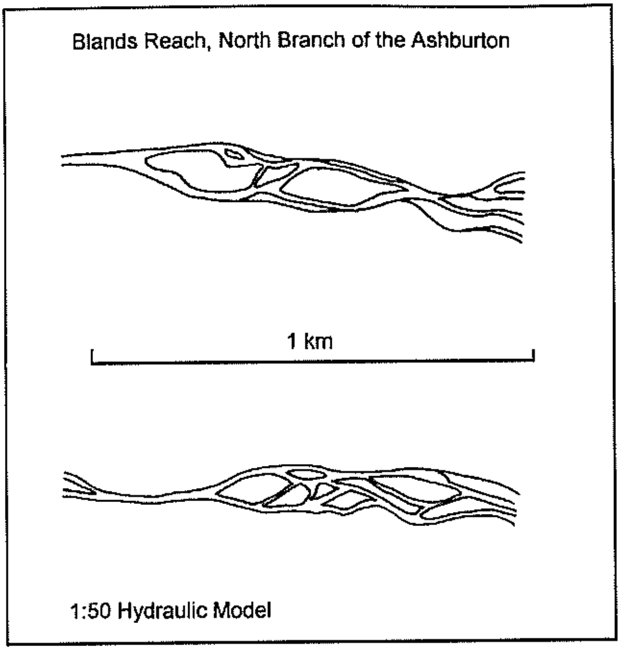

Figure 7 Comparison of river channel planforms of model and prototype - Blands Reach, North Branch of the Ashburton, Canterbury, New Zealand. Flow is from left to right.

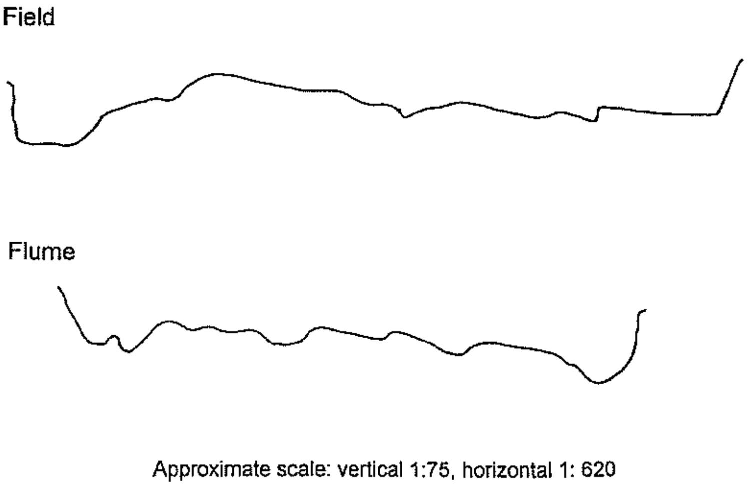

Figure 8 Comparison of river channel cross-sections of model and prototype - Ashley River, Canterbury, New Zealand. View is looking upstream.

Sedimentary features developed in hydraulic models have been frequently used as a basis for describing gravel-bed river processes and inferring mechanisms of channel change (Ashmore, 1991; Hoey and Sutherland, 1991; Ashmore, 1993; Leddy *et al.*, 1993). Figure 9 shows a section of channel developed after a 90 hour flume run. Water has been drained from the channel to reveal the bed which shows several features typical of gravel-bed rivers. A small white clay figure ('Barman') has been added for scale, flow is from left to right and the darker areas indicate zones of coarser sediment. The figure is standing at a bar head with the bar fining downstream. At the top of the picture is a low cut bank with a coarse basal lag deposit of gravel (equivalent to small boulders). In the foreground is the dry bed of the main channel which has a coarse lag deposit lining its base. Individual boulders in the channel show fines deposited on their leeward sides. This small scale sedimentary evidence provides compelling support for similarity of braided river form between model and prototype.

Processes

Hydraulic similarity between model and prototype is now frequently tested in hydraulic model studies of gravel-bed rivers. Non-similarity results when the physically meaningful dimensionless parameter values are not the same

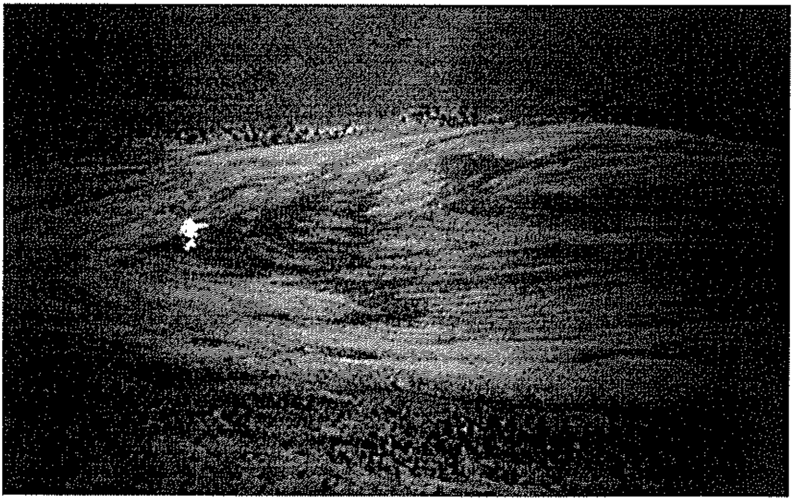

Figure 9 A small section of a dry 1:50 hydraulic model channel developed after 90 hours. Flow is from left to right. The small white figure ('Barman' - scaled height 1.7m) has been added to show the length scale and the darker areas indicate zones of coarser sediment. The figure is standing at a bar head.

in both model and prototype. This is usually caused by the small size of the model, which means that forces which are negligible in the prototype may become significant (Sabersky and Costa, 1964). This leads to scale effects which produce errors of modelling. Gauging the significance of these errors is crucial in interpreting the results of model studies (Novak *et al.*, 1990). The grain-size Reynolds Number and Froude Number are often compared. More recently the Weber Number, indicating the magnitude of surface tension effects, has also been suggested as a useful parameter for comparison, although definition of a critical value is difficult (Warburton and Davies, 1994). Most hydraulic model studies of gravel-bed rivers have small grain-size Reynolds Numbers and large ranges in both grain-size Reynolds' and Froude numbers (Fig. 10). The generally accepted criteria for these dimensionless parameters are that the flow should be rough turbulent (Yalin, 1971 - grain-size Reynolds' Number > 70) and that the Froude number should be the same in the model and prototype. For many studies the Reynolds' numbers are below this value, and the similarity of the hydraulic conditions must therefore be questioned (Fig. 10). This is especially true when it is realised that these calculations are based on 'average' conditions in the model, therefore in substantial areas of the model hydraulic similarity will be even more unrealistic.

Comparing process rates in model and prototype is also fraught with difficulties. Transport rates in braided rivers are extremely variable and hence it is seldom meaningful to compare instantaneous bedload transport measurements between model and prototype. Average bedload transport rates provide a better basis for comparison and these are indeed easier to measure in the model. Unfortunately estimates of average transport rates by direct measurement in the field are almost impossible over the full range of flows and in any river larger than a small stream. Fortunately, sediment budgeting techniques based on morphometric survey of control reaches or storage sites offer an alternative (Martin and Church, 1995). In one of the few attempts to relate field and laboratory data Young and Davies (1990) compared bed load transport rate data between a small (1:50) hydraulic model and two hydrologically and sedimentologically similar prototype rivers - the North Ashburton River (Canterbury) and the Elbow River (Alberta) (Fig. 11). When scaled all three data sets plot in the same general space, and the scaled model data follow the general trend of the field data sets. This suggests model rates reasonably approximate prototype rates.

Nonetheless, prototype data are seldom available and difficult to obtain, especially over the full range of transporting discharges. Comparisons are most useful if the full flow regime of the prototype is being modelled. This presents practical difficulties since braided rivers have widely varying

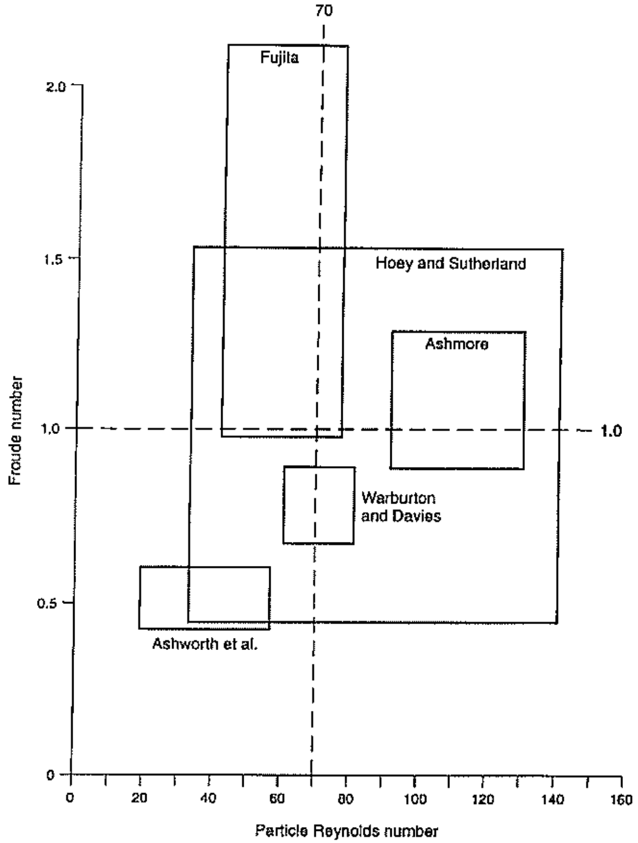

Figure 10 Plot of grain-size Reynolds number against grain-size Froude number for a number of gravel-bed river hydraulic model studies. Boxes indicate the range in values reported from these studies, the vertical and horizontal lines correspond to a Froude number of 1.0 and a Reynolds number of 70 (Yalin 1971 criterion for rough-turbulent flow).

discharges. The very infrequent large events are, however, very important in terms of total sediment load because of their high transporting capacity, and in terms of defining the channel form. Indeed, the very large events may be the only way to change channel form sufficiently to define a new transport regime (Young and Davies, 1991). The modelling of extreme discharges is difficult, since in such events braided rivers usually occupy the full bed width. In braided river models sidewall interference commonly occurs at these important transporting flows. For these reasons, it can be

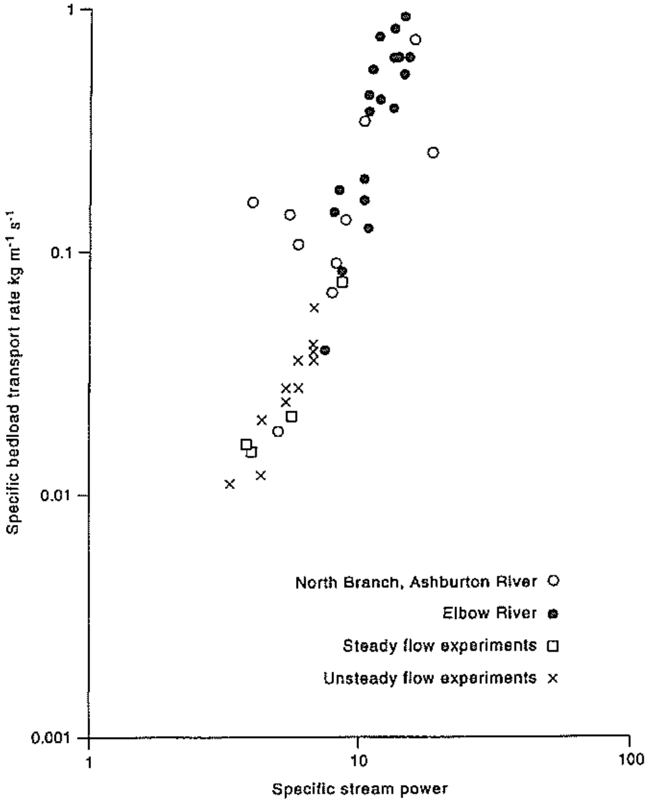

Figure 11 Comparison of model and prototype bedload transport rates. Stream power plotted against bedload transport rate. Redrawn from Young and Davies (1990).

difficult to get good agreement between model and prototype bedload transport rates. Flows below the threshold for bed movement are not usually modelled, yet they represent the majority of the time in the prototype, so one must be careful in defining what is actually meant by average bedload transport rate. One can either average over just the transporting flows, or average over all the flows. The latter approach gives the total annual load when summed over one year. When attempting to compare annual loads, one is confronted with the issue of time scaling, which has been an area of some confusion. For undistorted models the timescale for grain motion and fluid motion is given by $\lambda_t = \lambda_l^{0.5}$. However, Young (1989) showed that this approach has only met with limited success. In a comparison of annual bedload estimates between a 1:50 hydraulic model and the Blands Reach of the North Ashburton (New Zealand) model estimates were an order of magnitude less than bedload volumes estimated from survey data. The actual discrepency is probably even greater, given that survey data give only minimum estimates of bedload transport.

As well as allowing comparisons of longer-term sediment loads, scale models can be effectively used for investigating the variability of bedload transport. Because of the speed of evolution in scale models, prototype variability can be studied at the scale of years, as well as within and between events. Numerous researchers have used scale models to investigate variability of bedload transport, and together with observations and measurements of changing channel form, make inferences about the nature of bedload transport processes (e.g. Ashmore, 1988; Kuhnle and Southard, 1988; Gomez and Church, 1989; Hoey and Sutherland, 1991; Young and Davies, 1991; Warburton and Davies, 1994). Comparisons of bedload transport variability between model and prototype, and description of the mechanisms causing variability have often been confusing. Much of the confusion has arisen from uncertainty with regard to time scaling of transport processes. This, however, should not be a problem with undistorted models, since as already stressed, both sediment and fluid motion scale as the square root of the length scale.

Conclusions

Six main conclusions can be made:

1. Hydraulic models have been widely used in the study of braided gravel-bed rivers and the principles of hydraulic modelling are well established.
2. Because the scale ratios for gravitational acceleration, fluid viscosity and fluid density are all unity it is impossible to satisfy full dynamic similarity, except with a length scale of unity (full-scale model). Therefore in modelling braided rivers one can at best obtain approximate dynamic similarity.
3. Dynamic similarity is achieved when: sediment density is equal in model and prototype; grain sizes are scaled directly by the length scale; water is used as the model fluid; flow is rough-turbulent in the model; and bed slope is equal in a model and prototype. This implies that to fulfil 'approximate dynamic similarity' only requires similarity of relative depth.
4. Practical limitations of flume size or cost will often restrict the choices available to researchers. Because of the requirement of rough-turbulent

flow in Froude-law models, it is seldom possible to use models smaller than 1:50 scale ratio. At the opposite end of the spectrum, very large models are not only costly, but are difficult to manage in terms of sediment requirements. One is therefore usually restricted to modelling smaller braided river systems.

5. Models of braided rivers are most useful in qualitative and quantitative studies of braided river forms and processes, and in predictive river behaviour studies.
6. Because it is difficult to adequately describe prototype rivers and therefore to rigorously assess hydraulic similarity, these models are limited to representing a 'typical' river reach for a given prototype, or a reach typical of a group of prototype rivers. Nevertheless, hydraulic modelling is a useful method for investigating braided river processes, and given careful design, can yield a wealth of valuable data and information.

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