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# PHYSICAL HYDRAULIC MODELLING OF WIDTH REDUCTION AND BED LEVEL CHANGE IN BRAIDED RIVERS

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## ABSTRACT

To study the effect of width reduction on the rate of change of mean bed level of a braided river, a characteristic Froude law rough-turbulent flow hydraulic model of a medium-sized braided river was developed. This was then subjected to imposed width reductions to as little as 35% of its unconstrained width, under various sediment input regimes. The response of the model was complicated, but *all* width reductions increased the bedload transport capacity of the river; whether or not this caused the rate of aggradation (bed level rise) to increase depended on the sediment input rate. At high sediment input rates, width reduction increased the aggradation rate, whereas at low input rates the reverse occurred. Hence, width reduction alone is not a suitable means of controlling aggradation in a braided river; in some cases, indeed, troublesome degradation could be thus induced. Bed width reduction alone cannot cause aggradation where none was originally present.

## INTRODUCTION

Until recent years, the control strategy adopted for many of New Zealand's wide, braided gravel-bed rivers has been to confine them laterally (by training banks) to much less than their natural, unconfined width (Nevins, 1969; Acheson, 1968, Grant, 1948). The purposes of this strategy were to induce degradation, thus reducing the tendency of the river, in flood, to leave its 'normal' bed and flow through adjacent farmland, eroding the land or depositing gravel; and to reduce the area of land occupied by the active bed of the river, which could be of the order of 1 km wide. It was apparent that many of these rivers were 'unstable' (i.e. liable to change their courses) because of long-term aggradation of the bed resulting from gravel deposition; lateral confinement was expected to reduce this problem by increasing the mean flow depth at a given flow rate, increasing mean bed shear stress and bedload transport capacity (Nevins, 1969; Henderson, 1966). This philosophy was encouraged by the experience of European river engineers who had succeeded in controlling originally wide, braided rivers (such as the upper Rhine) by lateral confinement.

To a large extent this strategy has been successful, insofar as many laterally-confined rivers in New Zealand have to date presented no major problems. In a small, but worrying number of cases, however, including for example the North Ashburton River (Laronne, Duncan and Rodeley, 1986) lateral confinement has been associated with an increase in the rate of aggradation of the river bed, a situation which is embarrassing because the corresponding reduction in flood capacity requires the training banks to be heightened at frequent intervals. In the long term this cannot continue; eventually the river bed will lie some metres above the surrounding land, and the consequences of a breakout then become very serious. The only practicable remedial measure in such a case is mechanical removal of gravel from the river-bed between floods; this has become necessary to maintain the stability of the lower Waimakariri River where it threatens the city of Christchurch. It is not everywhere economic, however.

There is thus some doubt as to whether, as a general principle, reducing the bed width of a braided river will reduce or increase the rate of aggradation. To clarify this point a hydraulic model study was carried out by the second writer (Lee, in prep; Lee and Davies, 1986) at the Department of Natural Resources Engineering (formerly Agricultural Engineering), Lincoln College under a Research Contract with the National Water and Soil Conservation Authority of New Zealand.

## BACKGROUND

A physical hydraulic model was chosen to investigate this problem because the common alternatives, field or analytical studies, appeared to be impractical (Carson and Griffiths, 1987a; Davies, 1987a).

In this unpromising scene the attraction of a hydraulic model is obvious; if the necessary similarity laws can be fulfilled, the model will reproduce the behaviour of its prototype, to calculable scales. In practice, there are difficulties—modelling the initial geometry of a braided river, for example, and obtaining prototype data to prove that the model is behaving correctly. It is, however, encouraging that recent attempts to model both general (Ashmore, 1982, 1985) and more particular (Ashmore and Parker, 1983; Mosley, 1976, 1982) aspects of braided river behaviour have been conspicuously successful. In order to show, using a hydraulic model, the effect of width reduction on bed aggradation, it is not necessary to exactly model a specific reach of a specific braided river; it is sufficient that the characteristics of the model river, for example, the complexity of braiding and the size distribution of bars relative to the channel width, are similar to those of a prototype river. This obviates the necessity for exact modelling, and hence for the collection of detailed prototype data. Since no detailed method for characterising a braided river has yet been proposed, the "realism" of the present model was assessed in terms of its visual similarity to a prototype at various flow stages, and this subjective assessment was checked by a large number of river engineers and scientists, fishermen and lay people. This is obviously acceptable only in the context of a preliminary study, but the nature of the problem is sufficiently general that no more precise demonstration of the model's ability to represent prototype behaviour is needed at this stage.

Given this lack of precision in testing the ability of the model to reproduce large-scale river behaviour, predictions of the behaviour of full-scale rivers from the model's performance will be similarly imprecise. In this project, however, only the relative capacities of a river to transport bedload at various imposed channel widths are studied. Since the model is designed to be dynamically similar to a prototype, the behaviour of the model will adequately represent that of a visually similar full-scale river.

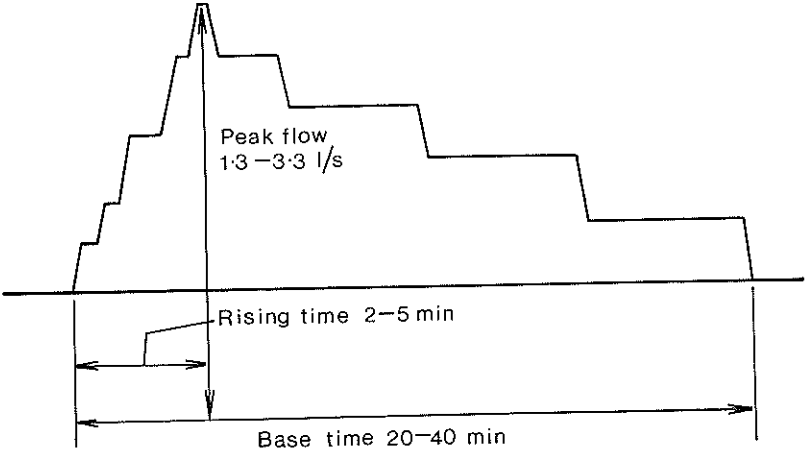


FIG. 1—Typical step-function hydrograph input to model stream.

## MODEL DESIGN

A comprehensive treatment of the theory of hydraulic modelling is to be found in Yalin (1971).

Assuming the prototype river (North Ashburton) has the following conditions:

mean width = 100 m
mean depth = 1.0 m
mean slope = 0.01
sediment $D_{50}$ = 25 mm
$D_{90}$ = 100 mm
flow rate = 35 m³/s at 1 % exceedence
viscosity $\nu$ = $1.3 \times 10^{-6}$ m²/s (corresponding to a temperature of 10°C)

and if model and prototype both run at 10°C then $\lambda_\nu = 1$ and

$$\lambda_l \gtrsim \frac{70}{24{,}000}^{2/3} \simeq 50$$

Then using a 1:50 scale model, the model quantities following the procedure of Yalin (1971 pp 152-156) would be:

mean width = 2 m
mean depth = 0.02 m
mean slope = 0.01
sediment $D_{50}$ = 0.5 mm
$D_{90}$ = 2 mm
Flow rate = 2 l/s

In some parts of the model, as in the prototype, flow depths and water surface slopes will be much less than their mean values, and $(Re_*)_m$ will be much less

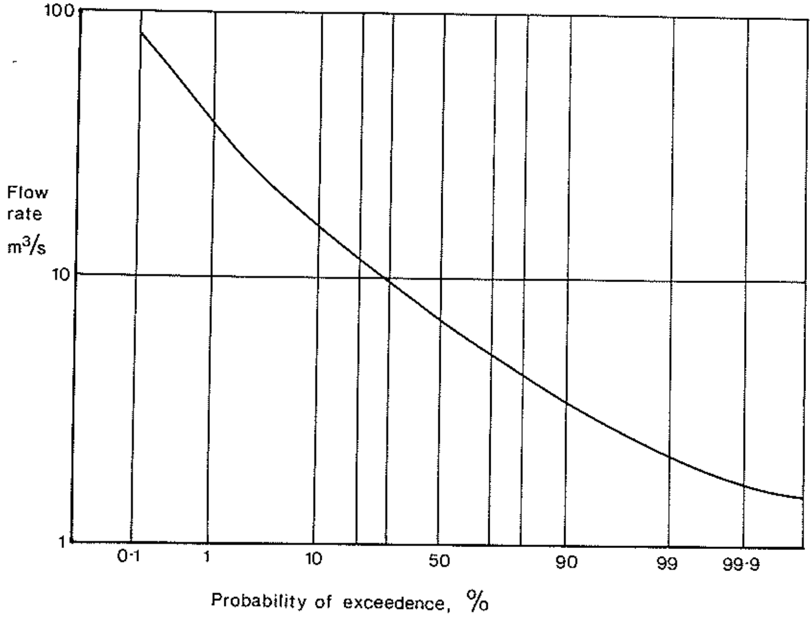


FIG. 2—Flow duration curve of North Ashburton River.

than 70, indicating locally transitional turbulent flow, whereas in the prototype, flow at a corresponding position would be rough turbulent. As long as such gross dissimilarities do not occur in regions where substantial bed load is moving, the behaviour of the model will be acceptable. Because bed load moves only over a relatively small proportion of the total bed width at a section (Davies 1987a), usually in regions of moderate to large depth, this criterion should be fulfilled.

The model flow regime comprised a set of 10 step-function hydrographs (Fig. 1) chosen in random sequence and designed to match the active bedload-moving part of the flow duration curve of the North Ashburton River (Fig. 2). The time-base of the model hydrographs (20 to 40 minutes) was chosen to ensure that convective shear stresses due to varying flow were negligible, while producing a large number of hydrographs in a typical experimental run of about 100 hours, so that the correct flow duration curve was experienced by the bed and reflected in the results.

At an early stage of planning the use of hot water as the model fluid was contemplated, in order to increase the obtainable scale ratio by reducing the fluid viscosity. In the event, time constraints prevented this from being done, but the technique is being evaluated in a subsequent project.

The model bed material was Birdling's Flat sand, a medium sand with a grading curve similar to that of the prototype, though slightly more narrowly graded (Fig. 3). The model grains were quite angular by contrast with the rounded river

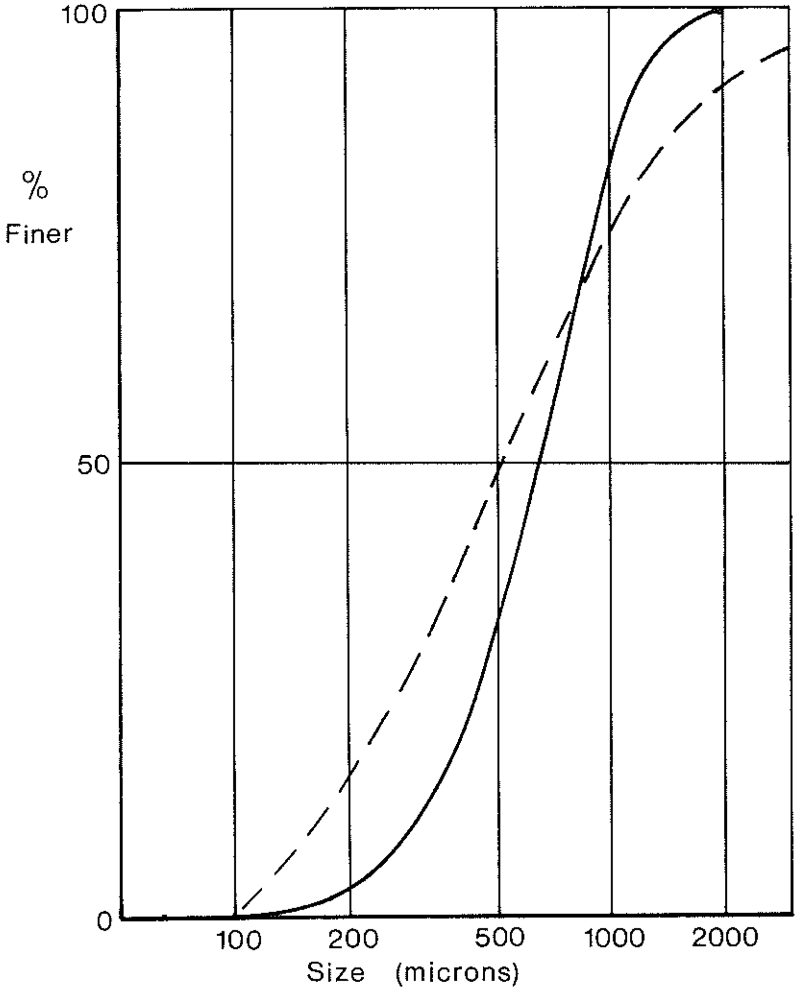


FIG. 3—Grading curve of model sediment (solid line) and of North Ashburton River (scaled down) (dashed line).

gravels, but this was considered to have a minor effect on the aggradational behaviour of the river.

The effect of vegetation was not studied, as it is very difficult to scale down prototype vegetation (willow trees, scrubby bushes, etc.), so that its role in strengthening the bed and bank materials and increasing the resistance to flow is properly represented in a model (Marsden, 1981). In a medium-sized river like the North Ashburton, vegetation may inhibit bank erosion and provide semi-permanent nucleii for in-channel bars to form.

## EXPERIMENTAL PROCEDURE

The experimental procedure was to choose a flow regime and slope and to allow the channel to widen to its equilibrium width from an initially straight, narrow form while feeding dry sediment into the upper end of the channel at a constant rate of 80 g/min, so as to cause neither aggradation or degradation there. Thus the independent variables determining the channel behaviour were flow regime (i.e., the time-varying flow series), slope and bed material. The bedload transport capacity of the equilibrium channel $G_{sa}$ was measured by collecting the bedload output from the lower end of the channel over a period of 5 hours (or about 10 hydrographs) and was equal on average to the sediment input rate. The channel planform was a shown in Figure 6 (a).

The "equilibrium" channel had probably not completely ceased widening its bed by bank erosion; the "equilibrium" state was assumed to have occurred when the rate of mean bed width increase had decreased to near zero. There might still have been some bank erosion occuring, however, which explains the difference between the sediment input rate of 80g/min while the "equilibrium" output was 92g/min.

With the same flow regime, the channel was then reduced to 90% of its equilibrium width, and the bedload output rate $G_{so}$ measured again at various rates of sediment input $G_{si}$ . The reason for varying the sediment input rate to the confined channel is that many braided gravel-bed river reaches are aggrading in their natural state, and it seems possible that the effects of confinement will depend on the rate of aggradation of the original unconfined channel. The width was reduced by positioning straight, sand-roughened galvanised steel strips into the sand bed at an angle of 60° to the vertical at the required spacing. Each measurement of $G_{so}$ was made following 100 to 200 hours of run time to allow the time-average value of $G_{so}$ to be properly evaluated. Subsequently the channel width ratio $W_r$ was reduced successively to 0.70, 0.60, 0.50 and 0.35, where $W_r$ is the ratio of confined width to original unconfined width (channel width is defined as the mean distance between the extreme edges of the sometimes active bed). Figure 6 (b), (c) and (d) show typical channel patterns resulting from confinement.

## RESULTS

The experimental data are shown in Fig. 4.

These data points were obtained using a time-varying flow series with characteristics corresponding to those of the active (i.e., bedload-moving) part of the flow duration curve of the North Ashburton River; they are thus the result of just one flow regime. Other flow regimes would give rise to a different data set. Until different flow regimes are tested, one must assume that the observed behaviour pattern is representative of a range of flow regimes and sediment types.

There is a generally consistent pattern to the data in Figure 4. For each sediment input rate $G_{si}$ a reduction in $W_r$ (by artificial confinement of the flow) increases sediment output rate from the channel. However, the rate of increase of mean bed level $\dot{y}$ depends on both the difference between sediment input and sediment output, and on the area of bed over which this difference is effective:

$$\dot{y} = \frac{G_{si} - G_{so}}{\gamma L W_o W_r} \qquad (1)$$

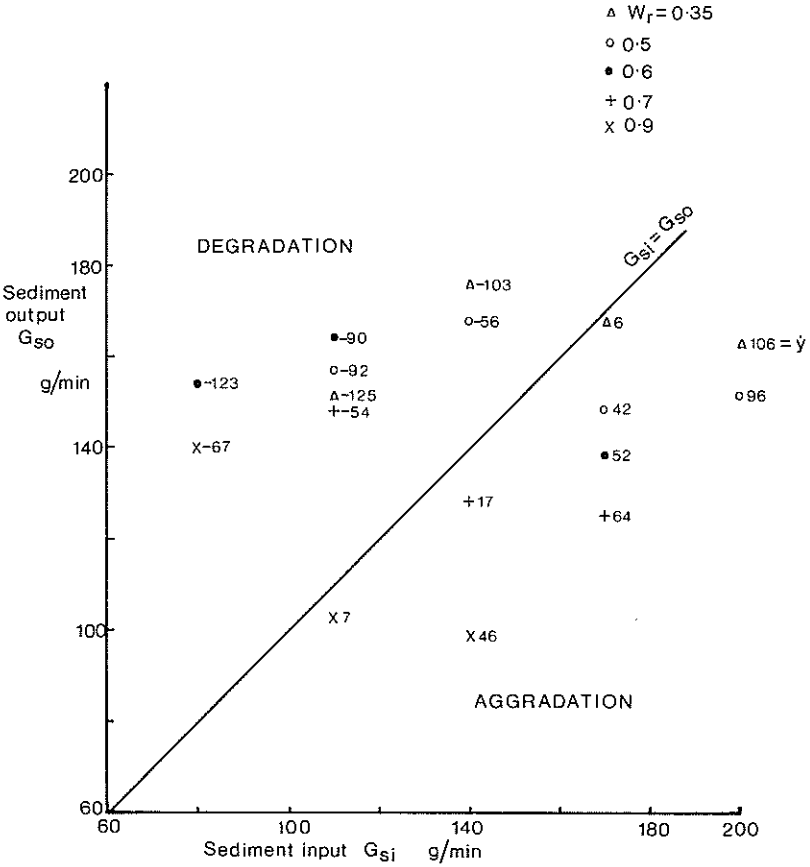


FIG. 4—Experimental data from aggradation tests. ($\dot{y}$ in arbitrary units).

where $\gamma$ is the bulk density of the sediment, L is the channel length over which measurements of $\dot{y}$ and $W_o$ are averaged and $W_o$ is the original unconfined width. Gsi and Gso are in units of mass per unit time. For a specified initial channel and experimental reach $\gamma$, L and $W_o$ are constant, hence

$$\dot{y} = K \frac{(G_{si} - G_{so})}{W_r} \tag{1a}$$

where K is a constant of proportionality = $1/L\ W_o\ \gamma$. Eq. (la) was tested experimentally and found to be correct, implying that the measurements of $\dot{y}$, $G_{si}$, $G_{so}$ and $W_r$ were satisfactory. The value of K has been arbitrarily put equal to 1.0, hence values of $\dot{y}$ are arbitrary but self-consistent; since the objective of the work is to study *relative* aggradation or degradation rates, this step is justified.

Applying eq. (I) to Figure 4 gives the rates of bed level increase noted below

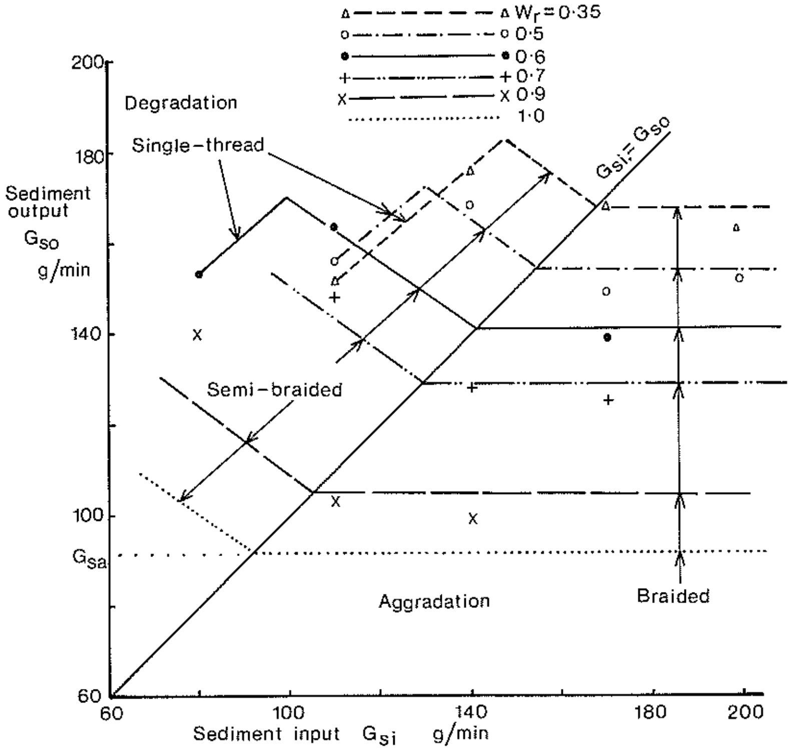
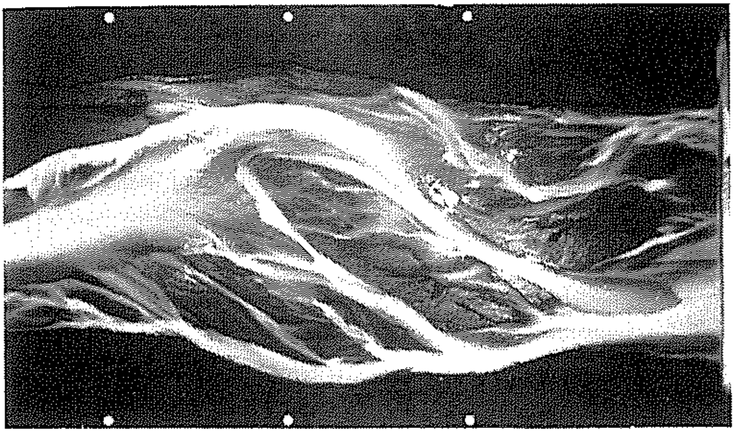


FIG. 5—Behaviour pattern inferred from data points of Fig 4.

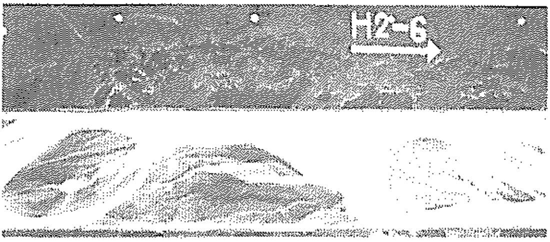
the points. Reducing the channel width generally reduces $\dot{y}$ if $G_{si}$ is less than about 200 g/min., and increases $\dot{y}$ if $G_{si}$ is greater than this. In order to explore this behaviour further, it is necessary to infer the general behaviour pattern which the data points on Figure 4 represent. The simplest satisfactory pattern found is that shown in Figure 5, in which lines of constant $W_r$ have similar slopes in the same regions, but are displaced diagonally relative to each other.

In the right-hand part of the plot, below the $G_{si} = G_{so}$ line, $G_{si} > G_{so}$ and $\dot{y} > 0$ hence aggradation occurs. Here the lines of constant $W_r$ are horizontal, indicating that the sediment transport capacity of a channel of given width does not vary with changes in sediment input rate. In the degradation region (Fig. 5), however, $G_{si}$ strongly influences $G_{so}$, causing it to either increase or decrease at constant width. These variations in behaviour suggest that the sediment transport processes vary strongly between the regions shown in Figure 5, and vertical photographs of the channel under various experimental conditions indicate different channel patterns for each region on Figure 5. Typical examples of these patterns are shown in Figure 6; in the aggrading region (Fig. 5) the channel is usually fully braided, in the region where degradation is strongest the pattern is essentially that of a single channel with alternating bars, while in most of the degrading region the pattern is semibraided, i.e., with a less obviously braided appearance.

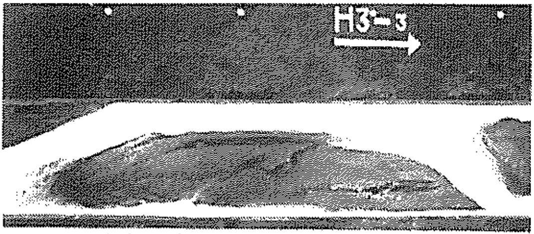


(a) Braided unconfined, $W_r$=1.0

(b) Braided $W_r$ = 0.6



(c) Semi-braided $W_r$ = 0.6



(d) Single-thread $W_r$ = 0.6

FIG. 6—Examples of channel pattern.

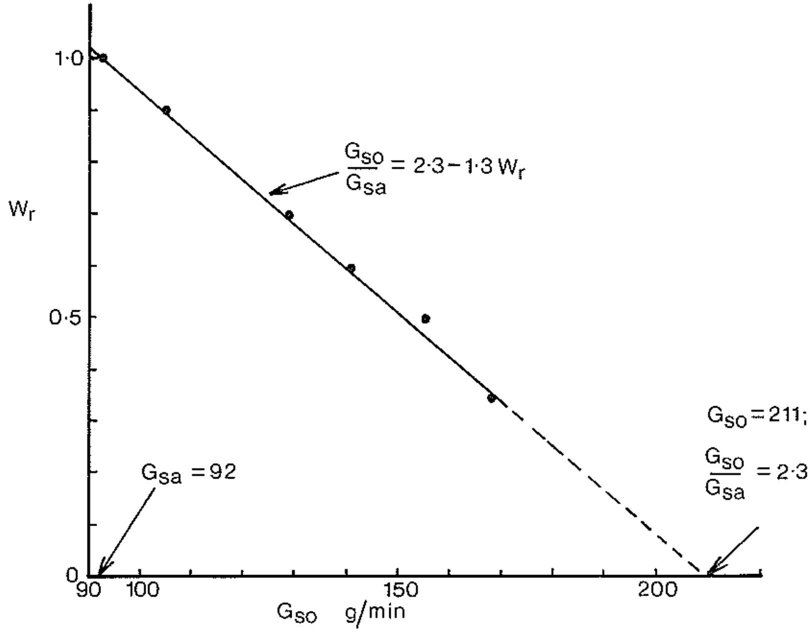


FIG. 7—Variation of bedload output rate ($G_{so}$) with channel width ratio ($W_r$).

Clearly a more quantitative description of the channel pattern is needed, but development of such a system is beyond the scope of this project. There are other ways of matching the experimental data to families of trend lines. One variation would be to slope the lines of constant $W_r$ down to the right, with $G_{so}$ decreasing slightly as $G_{si}$ increases in the aggradation region; the effect of such a modification is discussed later.

If the pattern of Figure 5 is accepted as a preliminary description of the response of a braided river to lateral confinement, eq.(1) can be used to calculate $\dot{y}$ at any point on the graph. First, however, it is appropriate to plot the sediment transport capacity $G_{so}$ of the channel in the aggrading region against the width ratio (Fig. 7); the relationship is linear ($r^2 = 0.998$) and of the form

$$G_{so} = G_{sa}\,(2.3 - 1.3\,W_r) \qquad (2)$$

where $G_{sa}$ is the value of $G_{so}$ at $W_r = 1.0$.

Combining eqs. (1) and (2) gives the following expression for $\dot{y}$ in terms of $G_{si}$ and $W_r$:

$$\dot{y} = \frac{G_{si}}{W_r} - G_{sa}\left(\frac{2.3}{W_r} - 1.3\right) \qquad (3)$$

in the aggrading region of Fig 5.

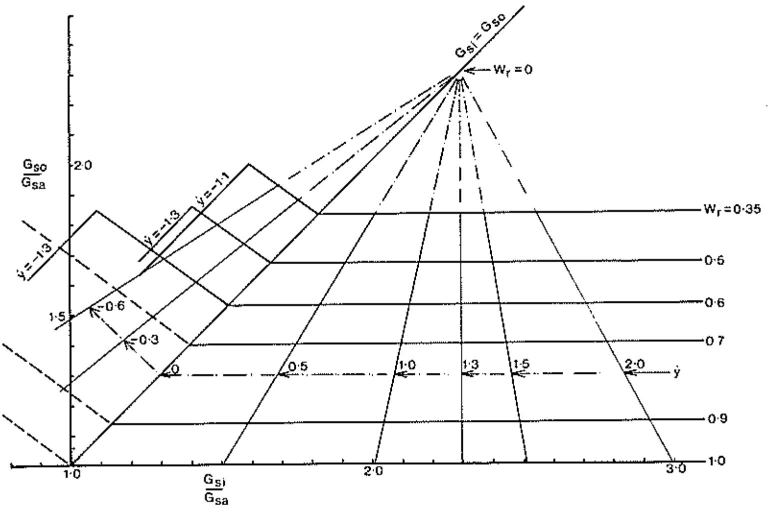


FIG. 8—Aggradation rate contours. All quantities non-dimensionalised with respect to the bedload transport capacity of the equilibrium channel ($G_{sa}$).

The effect of decreasing channel width, i.e.. decreasing $W_r$, is found by differentiating eq. (3) with respect to $W_r$:

$$\frac{d\dot{y}}{dW_r} = \frac{1}{W_r^2}(2.3\ G_{sa} - G_{si}) \tag{4}$$

Hence when $G_{si} < 2.3\ G_{sa}$, $\frac{d\dot{y}}{dW_r}$ is positive and decreasing the channel width reduces the aggradation rate. When $G_{si} > 2.3\ G_{sa}$ the converse is true, and reducing the channel width increases the aggradation rate. This behaviour is shown graphically on Fig. 8 in which sediment input and output rates are nondimensionalised with respect to $G_{sa}$, and the units of $\dot{y}$ are thus different from those shown in Figure 5. In the aggrading region lines joining points of equal $\dot{y}$ converge to meet the $G_{si} = G_{so}$ line at $G_{si} = 2.3\ G_{sa}$, which is where eq.(2) extrapolates to zero. Clearly a channel of zero width has $G_{so} = 0$, hence eqs. (3) and (4) cease to be valid as $W_r$ approaches zero. Extrapolation of the trends shown to $W_r$ values less than 0.35 is therefore not recommended.

In the degrading region (Fig. 5) the behaviour changes distinctly, and the channel pattern also becomes less strongly braided. As $G_{si}$ is reduced to become less than $G_{so}$, $G_{so}$ *increases* in this region, presumably because of channel pattern change; as $G_{si}$ becomes less than $G_{so}$, the channel pattern changes in such a way as to cause $G_{so}$ to increase. This is a kind of instability, which suggests that the change of behaviour as $G_{si}$ becomes less than $G_{so}$ might well be a sharp threshold (Fig. 8).

In the semi-braided region the aggradation rate $\dot{y}$ is given by

$$\dot{y} = \frac{1.75\ G_{si}}{W_r} - G_{sa}\left(\frac{4.025}{W_r} - 2.275\right) \tag{5}$$

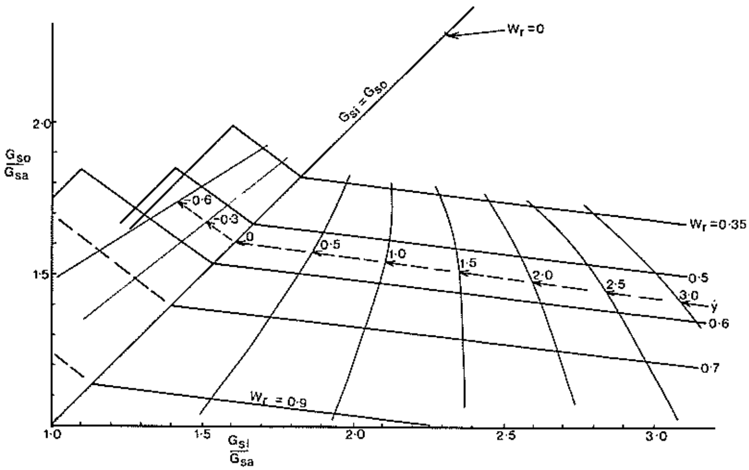


FIG. 9—Alternative behaviour pattern.

which is negative. Again the $\dot{y}$ contours extrapolate to meet $G_{si} = G_{so}$ at $W_r = 0$. In general the increase of $G_{so}$ as $G_{si}$ reduces continues until $G_{so}$ achieves a maximum, whereafter $G_{so}$ decreases at the same rate as $G_{si}$ in the single-thread region.

In the single-thread region (Fig. 5) the rate of aggradation $\dot{y}$ is the minimum achieved anywhere on the graph and is essentially constant irrespective of $G_{si}$, because a reduction of $G_{si}$ causes $G_{so}$ to reduce by the same amount. In the present tests this degradation rate was of the same order as the sediment transport capacity of the equilibrium, unconfined channel ($G_{sa}$).

Allowing the lines of constant $W_r$ to slope down to the right as the experimental data suggest does not change this pattern of $\dot{y}$ substantially (Fig. 9). The critical value of $G_{si}/G_{sa}$ separating reduced from increased aggradation remains 2.3 (by inspection) and the $\dot{y}$ contours distort rather more at $W_r = 0.35$ than is the case with Figure 8.

The experimental results of this study are thus self-consistent and follow a reasonably simple pattern. No doubt some details of the aggradational behaviour of braided rivers remain undiscerned, but it seems likely that the major aspects have been represented, perhaps approximately, but sufficiently clearly for their implications for river management to be discussed.

## IMPLICATIONS

It must be clearly understood that the behaviour observed in the present small-scale tests has not yet been confirmed by measurements of large-scale rivers; at the present state of technology, such measurements are not possible. Extrapolation of these results to field situations is thus based solely on the application of hydraulic modelling criteria. Some qualitative encouragement may be drawn from the opinion of New Zealand river engineers and scientists, that the model stream "looks right".

The most general outcome of the tests is that reducing the width of the model braided stream increases the sediment transport capacity, at least until $W_r = 0.35$. Whether or not the aggradation rate (rate of bed level increase) is thereby reduced depends on the sediment input; with low sediment inputs (less than 2.3 times the transport capacity of the unconfined equilibrium — i.e. non-aggrading and non-degrading — stream) a width reduction reduces the aggradation rate, whereas with greater sediment inputs than this a width reduction increases the aggradation rate.

Clearly it is not convenient if a channel confined within control banks is aggrading, because the flood flow capacity of the channel will then reduce with time, requiring that the height of the control banks be increased from time to time. Ultimately this leads to the unacceptable situation in which the river bed is some metres above the surrounding land. Hence the consequences of channel confinement can be beneficial or otherwise, according as the aggradation rate is reduced or increased, depending on the sediment input to the river relative to its transport capacity.

In principle it is possible to evaluate this initial state by measuring the sediment input to a reach from upstream and comparing this with the theoretical bedload transport capacity. This latter property of the flow is, however, not yet amenable to realistic calculation (Carson and Griffiths, 1987a), while the former is susceptible to unavoidable errors of the order of 100% unless a total bedload trap such as a lake can be used (Davies, 1987a). Definition of the initial state is thus difficult. If a physical model of the type used in the present study were available, and could be shown to be characteristically geometrically similar to the prototype, then measured bedload transport rates in the model could be scaled up using conventional relationships (Yalin, 1971) to define the transport capacity of the river, and hence the upper bound of acceptable sediment input, so that confinement would not lead to increased aggradation. The problem of measuring the actual input remains.

In any river in which aggradation needs to be controlled, confinement is unsuitable as a control technique because the rate of sediment input will be high; conversely, where the sediment input rate is low enough for confinement to be beneficial, aggradation usually will not be a severe problem. Lateral confinement is thus *not* a suitable technique for control of aggradation, at least where the width ratio is greater than 0.35. Where $W_r$ values are lower than this, lateral confinement might reduce aggradation rates in heavily-aggrading rivers, but it is questionable whether such a degree of confinement could be achieved economically in this country. Where there are other reasons for lateral confinement of braided rivers, however, the present results could be of some use in anticipating troublesome aggradation.

There appears to be no circumstance in which confining a river laterally would induce aggradation where it was not originally present. Troublesome *degradation* could, however, be induced by width reduction, particularly if this caused conditions to change from an aggrading to a semi-braided state (Fig. 8). Care should therefore be taken in confining a river which is either stable, or slightly aggrading, or degrading. Model results (Fig. 8) give some indication of the relative severity of these effects; if an unconfined river of the type studied is aggrading at a rate of, say, 0.5 units, and its width is reduced to 50% of the unconfined width, the results will be to induce degradation at about 0.6 units. To use practical absolute units for aggradation and degradation related to sediment inputs and outputs, the length of the reach over which the bed levels are changing must be assessed — in the present tests this was about 10 times the width of the unconfined channel.

The results presented here apply only to cases in which the channel is confined for reaches of the order of at least several channel widths in length, rather than for short distances or at single cross-sections (e.g., for a bridge crossing). In the latter case flow convergence and divergence will dominate the channel response, which could be quite different from that of long confined reaches.

In terms of solving the problems of heavily-aggrading braided rivers the present results are not particularly encouraging. They do, however, show that, for confinement to be effective in reducing or reversing aggradation, the relative sediment input to the reach $G_{si}/G_{sa}$ must first be reduced. This can most easily be achieved, where possible, by augmenting the flow rate during freshes with clear water, hence increasing $G_{sa}$. Reducing $G_{si}$ is usually not feasible in the long-term unless gravel removal for sale is possible. The effects of such flow augmentations, however, should be monitored, as the path of behaviour from aggradation to degradation need not necessarily be a straight line; a long-term decrease in aggradation could occur by way of a shorter-term increase, which might be unacceptable. The timing of flow augmentation relative to the time of confinement, and to the passage of gravel waves down the channel (Griffiths, 1979; Carson and Griffiths, 1987) would be important.

## INDICATIONS FOR FUTURE WORK

With further experimental work it would obviously be possible to define the behaviour of a braided stream, and its reaction to confinement, much more accurately. The greatest obstacle to using this information for management purposes, however, is lack of data describing full-scale rivers, especially their sediment transport capacity (Davies, 1987a). Hydraulic model data can be scaled up to prototype situations only if the degree of geometric similarity between model and prototype can be assessed. Due to the geometric complexity of braided rivers this is not yet possible. For this and many other reasons, it should be a high-priority objective to adequately describe braided river geometry. Model apparatus such as that used in the present study would be useful for developing techniques which can subsequently be applied to full-scale rivers.

## CONCLUSIONS

This model study has produced self-consistent data on braided river behaviour from which the following conclusions can be drawn.

a. Reducing the bed width of a braided river increases its capacity to transport bedload.

b. Reducing the bed width will increase the rate of aggradation (bed level rise) if the bedload sediment input rate to the reach is more than about 2.3 times the bedload transport capacity of the unconfined, stable river.

c. If the bedload input rate is less than this, reducing the bed width will reduce the aggradation rate.

d. Bed width reduction alone will not control severe aggradation in a braided river; flow augmentation or gravel removal are also necessary.

e. Bed width reduction in a river which is not heavily aggrading, or is degrading, could induce severe degradation.

f. Bed width reduction cannot cause aggradation where none was originally present.

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