Journal of Hydrology (NZ) 35(2): 259-285, 1996

Active braidplain width, bed load transport and channel morphology in a model braided river

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Abstract

There is considerable inherent error in equations for predicting width in gravel-bed rivers, and the relationship between width and bed load transport is poorly understood. Eight experimental runs were undertaken to investigate the influence of braidplain geometry on bed load transport and channel dynamics in a 1:50 braided river model. The experiments were carried out in a 20 × 3m tilting flume with constant discharge and sediment supply. The initial geometry of the flume bed was varied by cutting a rectangular channel into the deformable sediment. Seven combinations of initial width and depth were used. For six of the runs depth was set at 0.025m and width at 0.31m, 0.5m, 0.7m, 1.1m (two runs) and 1.4m. In two other runs width was set at 0.7m and depth at 0.015m and 0.005m. Total bed load transport was measured at 5 minute intervals throughout the run and channel morphology and planform were measured at the end of each run. Bed load transport was greater in the narrower channels and, for runs of equivalent width, channels with an initially shallower cut depth had slightly higher bed load transport rates. Time series analysis of the bed load transport data shows a gradual, almost exponential, decline in the autocorrelation function and significant partial autocorrelation function values at lags 1, 2 and 3. Wider channels are characterised by small short duration sediment pulses, but shallower and narrower channels show greater variation in transport rate. Most runs are aggradational; braidplain storage increases with width. In response to the imposed flow and sediment regime the narrowest channels enlarge whilst the wider channels maintain their overall width. The narrowest channels have mid-channel bars dominate with some tendency to an alternate pattern, but the wider channels have a more braided pattern, with the flow divided into many smaller channels. The relationship between braiding and bed load transport is complex but suggests bed load transport is lower in the more braided systems. This contrasts with other recent results.

Introduction

Gravel-bed braided rivers commonly consist of multiple channels which constantly traverse a bare gravel 'braidplain' composed of old bar surfaces and abandoned channels. The maximum lateral extent of braiding defines the active braidplain width. The limit of the active braidplain is usually defined by cut-banks or, in managed rivers, by artificial stop banks or levees. The maximum width of the active braidplain and the stability of the river within its confines is of considerable interest to river managers and engineers.

For many years an important strategy for controlling New Zealand's braided gravel-bed rivers has been to confine them laterally between training banks (Nevins, 1969; Davies and Lee, 1988). The idea behind this practice was that confining a river would increase mean bed shear stress in the channel, increase bed load transport capacity and prevent aggradation. This was thought to be desirable because it would reduce the flood risk (by reducing water surface elevation) and protect agricultural land from the damaging effects of erosion and deposition over an extensive braided floodplain. However, it is now recognised that conversion to single-thread channels may not always have been appropriate (e.g. the North Ashburton River) and that the floodplain habitat is important and must be conserved (e.g. for nesting birds). Furthermore, recent studies of sediment storage in gravel-bed rivers have begun to recognise the importance of valley and floodplain geometry in regulating sediment transport and controlling bed load transport rates (Church and Jones, 1982; Hoey and Sutherland, 1991; Hoey, 1994). In the same way that natural variations in valley width influence floodplain geometry, so artificial training works alter braidplain width and sediment dynamics.

It is therefore timely that these practices be re-evaluated. However, this demands a more thorough understanding of the processes involved in maintaining the active braidplain at a particular width. In particular it raises the question of whether there exists a preferred or equilibrium stable width for a given river system or whether a fluvial system can exist at several stable widths. A second closely related factor is the depth or degree of entrenchment of the braidplain, which is responsible for confining the channel. These problems can be investigated in a number of ways including the use of engineering case studies, computer models (Pizzuto, 1990) and physical hydraulic models (Fujita and Muramoto, 1982). All three methods have their advantages and disadvantages but hydraulic modelling offers the most promise because it is direct, it allows complex flow patterns and sedimentary relations to be readily reproduced, and controlling variables can be easily manipulated. This study uses a 1:50 physical hydraulic model to investigate the influence of braidplain geometry on bed load transport and channel behaviour in a small braided river. The principal objective is to determine whether bed load transport increases or decreases as active braidplain width increases.

Background

In establishing what factors determine the width of a river braidplain three points need to be briefly considered. These are the relation between gravel transport and channel width, the conversion of braided rivers to single-thread channels and the importance of braiding in bed load transport. In the short review which follows, much of the material is based on the very useful account of gravel transport rates and yields related to channel width by Carson and Griffiths (1987a). It is important to note that channel width is distinct from the active braidplain width; channel width is defined by a wetted perimeter whereas active braidplain width is defined by the presence of banks at the margin of the gravel fairway. During very large floods the two may be the same.

River engineers are particularly interested in the design of a channel of the narrowest possible width but with a stable (non-mobile) bed - this is known as a *threshold channel* (Henderson, 1966; Carson and Griffiths, 1987a). Many equations have been proposed to predict threshold channel width. For cohesionless sediment and a cross-section with a constant depth mid zone, Henderson (1966) suggested that width (B) or wetted perimeter (P) can be determined by

$$B \approx P = 2.07\, Q\, S^{1.167} / d^{1.5} \qquad (1)$$

where Q is discharge in $m^3\ s^{-1}$, S is water surface slope and d is a representative grain size in m. Griffiths (1981) derived an alternative expression.

$$B = 5.28\, Q\, S'^{\,1.26} / d_{50}^{\,1.5} \qquad (2)$$

where S' is the mean water surface slope and d_{50} is the surface grain-size for which 50% of the clasts are finer. This equation predicts a two to five times greater threshold channel width than equation (1) depending on the representative grain-size used in equation (1). Assessing the usefulness of these equations is difficult for two reasons. Firstly, in natural channels where discharge is variable, a single value representing the dominant discharge needs to be selected. Unfortunately there is no consensus about what value to use e.g. bankfull discharge, the two-year flood, etc. Secondly, equations developed using field data for gravel-bed channels yield expressions very different from equations (1) and (2). For example Griffiths

(1981) using data from Kellerhals produced an equation of the form:

$$B = 21.2\, Q_d\, S'^{\,1.25} / d_{50}^{\,1.44} \qquad (3)$$

where Q_d is the dominant discharge. Further testing by Griffiths (1981) of equations (1), (2) and (3) using data from coarse gravel-bed channels in North America indicates that all three equations show discrepancies but equation (1) performed the best. Also, because most of the variance in the relationships was between data sets and not within them, this suggests that the equations are valid but the coefficient varies between river systems. This led Griffiths (1981) to propose a general relationship which incorporated a general stability index (L) to predict 'near' threshold conditions for a range of river system types:

$$B = (L / g^{0.5})\, Q\, S^{1.26} / d_{50}^{\,1.5} \qquad (4)$$

An alternative prediction of channel width comes from *regime theory* which assumes a long-term equilibrium channel morphology where the rate of sediment transport balances the rate of sediment supply. This approach was pioneered by Lacey (1929) and has been popularised in the training of New Zealand braided rivers by Grant (1948) and Nevins (1969). Lacey's (1929) equation is

$$B \approx P = 4.84\, Q_d^{\,0.5} \qquad (5)$$

However this equation was developed for silt-bed canals and has been shown to be inappropriate for gravel-bed rivers (Carson, 1986). Fortunately (or unfortunately) regime theory has been extended to gravel-bed channels (Simons and Albertson, 1960; Bray, 1982; Carson and Griffiths, 1987a). Bray (1982) produced the expression

$$B = 4.75\, Q_d^{\,0.53} \qquad (6)$$

which is remarkably similar to Lacey's equation (equation (5)). But again the application of such equations to New Zealand rivers is limited because the source data set used in developing the equation is dissimilar to New Zealand rivers.

Therefore there appears to be no consensus about what relationship should be used to determine channel width in braided gravel-bed rivers. This stems from the fact that there is no satisfactory description of the mechanisms which determine the regime width of channels (Bettess *et al.*, 1988).

Both the threshold and regime approaches to channel design have been used to provide guidelines for training of gravel bed rivers (Henderson, 1966; Nevins, 1969; Carson and Griffiths, 1987a). A major assumption of the regime method was that by concentrating the flow into a narrower channel the sediment transport capacity of the channel would be increased. Nevins (1969) describes the assumptions involved in the single thread concept: by halting bank erosion the amount of sediment reaching the river will be reduced; by concentrating flow into a single channel transport capacity will be increased and bed scour will result; by directing and controlling flood overflows eroded material will be deposited to enhance bank protection; and sorting of the alluvial gravels during flood will lead to bed armouring and a stable channel configuration. The single channel is produced progressively by flood flows and following excavation of a 'pilot cut'.

Carson (1986) provides a New Zealand perspective on the design of stable channels in active gravel-bed rivers. He makes three important points. Firstly, a narrower channel may be less efficient as a transporter of gravel than a wide braided river. Secondly, existing equations (e.g. Lacey (1929)) used as a basis for training rivers do not appear valid. Finally, results from river systems different from those in New Zealand are likely to be unreliable. Carson and Griffiths (1987a, 1987b) argued that the traditional view, that transport capacity increases as width decreases, is flawed. Furthermore an optimum transport channel intermediate between a very wide and a very narrow channel may exist (the maximum transport channel; Carson and Griffiths, 1987a, p.100).

However, both Parker (1979) and Bagnold (1980) have argued that wider channels have higher bed load capacities. Overall however the question as to whether a narrower channel transports more or less bed load is still undecided. This stems from the fact that there is no comprehensive description of the processes involved. A full process description would need to include: particle size, slope, channel shape, bank resistance, flow resistance and a representative sediment transport relationship - and must be specified for varying discharges. Such a solution is complex and not easily conceptualised or modelled mathematically. This is especially true of braided channels where the flow breaks up into many smaller channels which divide and rejoin. Carson and Griffiths (1987a) cite these reasons as the principle barriers to predicting channel width in braided systems.

Nevertheless, some progress has been made using hydraulic model studies. Davies and Lee (1988) carried out a physical hydraulic model study of width reduction in braided rivers. Channel width was reduced to as much as 35% of the unconstrained width under various sediment input regimes. The response of the model was complicated in that aggradation and degradation was dependent on both the width reduction and sediment feed rate, although all reductions in width increased the bed load transport of the channel.

Therefore there is still considerable confusion over the importance of width in controlling bed load transport in braided gravel-bed river channels. However, in trying to predict the relation between width of a braided river and bed load transport, a useful starting point is to consider the case of a single channel. Gilbert (1914) demonstrated *"When identical discharges are passed through troughs of different width and are loaded with debris of the same grade, and the loads are adjusted so as to establish the same slope, it is usually found, not only that the capacity varies with width, but some intermediate width determines a greater capacity than do the extreme widths."* (Gilbert, 1914, p.124). In other words the relationship between sediment transport and channel width is parabolic. A similar relationship has been defined by Griffiths (1989, p.71) who used a set of design equations to determine the characteristics of a single thread gravel-bed channel with a water and sediment discharge equivalent to a given braided gravel-bed river. Griffiths demonstrates that two different stable gravel-bed braided channels are possible, and that in theory braided rivers do not always maximise sediment transport capacity.

In summary, it is clear there is still considerable scope for studies of the relationship between width and bed load transport in braided rivers. In particular there is uncertainty whether bed load transport should increase or decrease as width narrows, and this uncertainty stems from a basic lack of understanding of the processes involved. Flume studies of braided river behaviour offer the best hope of success since they can reproduce the complex behaviour of braided river systems. For example Warburton and Davies (1994) note that sediment transport correlates with braiding, which implies that as braiding increases, sediment transport capacity also increases. However, for the reasons just quoted this may occur over only a restricted flow range.

Modelling and Experimental Procedure

In order to study the effects of width more closely a 1:50 hydraulic model was constructed. Bed load transport and channel morphology were monitored for differing sets of initial conditions. The principles and design of mobile-bed hydraulic models have been covered at length by Yalin (1971) in general and by Ashmore (1988) and Davies and Lee (1988) in terms of braided river systems. The model used in this study has also been described previously by Warburton and Davies (1994). A small model braided channel developed in a poorly sorted coarse sand and a prototype braided gravel-bed river are assumed to obey the Froude scaling laws and the flow is rough-turbulent in both. Similarity is met when the model Froude number (Fr) is the same as that in the prototype and the particle Reynolds' number (Re_p) in the model is > 70. Warburton and Davies (1994) demonstrated that the model and prototype river showed reasonable hydraulic similarity. This study is concerned with the general behaviour of gravel-bed rivers, so it is not necessary to exactly reproduce the details of behaviour of a specific river. Rather it is sufficient that the model parameters correspond to a representative prototype.

Characteristic model and run conditions are summarised in Table 1. Eight experimental runs were undertaken in a 20 × 3m tilting flume. Using a 1:50 scale it is possible to model a small braided gravel-bed river of approximate maximum width of 150m and a 0.9 km reach length. Each run lasted a minimum of 90 hours or until the channel touched the side wall of the flume. As far as possible runs were continuous, with interruptions only for emptying a sediment collection drum. Water was fed to the flume over a 250 mm wide sill onto a layer of pebbles and cobbles (used to dissipate the initial flow energy). Dry sediment was introduced directly onto the inflow sill from an inclined rotating tube which was connected to a large sediment storage hopper. Feed rate was 1.53g s^{-1} (+/- 0.005g s^{-1}) with no apparent sediment sorting during feeding. The sediment used as the model bed material was a poorly sorted gravely sand truncated at 0.1 mm to prevent grain cohesion and flotation (D_{50} = 0.5 mm, D_{90} = 2.2 mm). Outflow from the flume was over a flat-topped metal tail weir which fixed the bed elevation at this point. On leaving the flume, water and sediment entered a sediment collection drum which was connected to a 350 kg load cell. The sediment settled out and the water was routed by an overflow back to a $6m^3$ return tank. Maximum errors determined during the calibration of the load cell under steady flow conditions were +/-100g. Maximum errors caused by drift between successive calibrations was less than 3%. Because of these errors cumulative bed load was measured at 5 minute intervals. Water was recirculated by two centrifugal pumps from the return tank, which had a float-controlled inlet valve and overflow pipe so that a constant pumping head could be maintained. The return tank was fitted with three thermostatically-controlled heating elements (total capacity 4 kW) which allowed warm (30°C) water to be circulated. Warming the water reduces its viscosity and thereby increases the particle Reynolds number ($Re_p = u_* D_{90}/\upsilon$, where u_* is the shear velocity, D_{90} is the grain diameter than which 90% of the grains are finer and υ is viscosity) so that rough-turbulent flow could be maintained. Mean flow depth was approximately 0.007m. The Reynolds number ($Re_F = u\ d\ /\ \upsilon$, where u is the mean velocity and d is mean flow depth of the channel cross-sections) varied between 2230 and 3400, and the Froude number ($Fr = u/(g\ d)^{0.5}$, where g is acceleration due to gravity) between 0.68 and 0.9 with local maxima as high as 1.5, dependent on individual channel morphology and flow.

The initial geometry of the flume bed was established by cutting a rectangular channel into the sediment. Seven combinations of initial width and depth of cut were used. For six of the runs cut depth was constant at 0.025m and width was set at 0.31m, 0.5m, 0.7m, 1.1m (two runs) and 1.4m. In two other runs width was set at 0.7m and cut depth adjusted to 0.015m and 0.005m. The decision to constrain the channel by cutting into the deformable bed was prompted by observations that many natural channels (excluding bedrock gorges) are confined by erodible banks. In many engineering schemes channels are confined by levees and stopbanks constructed of deformable sediments (although additional protection is often added). This approach contrasts with other experiments that control cut width using non-erodible banks - Davies and Lee (1988) used sand-roughened galvanised steel strips. Bed slope was set at 0.0114 m m^{-1}. Space requirements for the apparatus for water and sediment supply and collection at the entrance and exit from the flume restricted the active experimental flume length to approximately 17.5m.

Channel morphology was mapped using vertical photography and a point gauge mounted on a carriage above the flume. Bed slope was estimated as the regression of 34 values of thalweg elevation measured at 0.5m intervals along the flume. Bed topography was surveyed before the start and at the end of each run with channel photographs taken immediately after the end of each run. Transects were measured at nine cross sections at 2m intervals down the flume.

Results

The results from the flume experiments are summarised in Table 1.

Bed Load Transport and Width

Figure 1 shows a plot of initial channel width against mean bed load transport rate. Trend lines are fitted by eye to the lowest data points on the graph. For this set of flume conditions bed load transport is greater in the narrower channels. For the runs of equivalent width but with shallower channels, bed load transport is slightly higher due to easier erosion of the low banks. Comparison of widths before and after runs reveals an interesting pattern (Fig. 2, Table 1). Firstly, all end-of-run widths were greater than the initial widths, indicating a general increase in width of between 3 and 103% (Table 1). Most widening occurred in the earlier parts of the runs. The narrowest channels showed the greatest percentage change in width. Some channel widening is inevitable, even in the widest channels, given the passage of the initial flood wave at start-up and the piecemeal nature of bank erosion. However, the results could perhaps suggest that the very

Table 1 Characteristics of the experimental runs. All runs had a steady flow of $1.43\ \mathrm{l\ s^{-1}}$.

RUN	WIDTH m	DEPTH m	W/D	RUN TIME h	BED LOAD TRANSPORT $\mathrm{g\ s^{-1}}$ *	BRAIDING INDEX	SLOPE "	END WIDTH m *	% CHANGE IN WIDTH
JW01	1.1	0.025	44	47	0.78 (0.34)	3.32	0.0114	1.16 (0.01)	6
JW02	1.1	0.025	44	135	0.87 (0.50)	2.82	*0.0126*	1.15 (0.04)	5
JW07 +	0.7	0.025	28	91	1.23 (0.46)	3.30	*0.0124*	0.87 (0.15)	24
JW13	0.5	0.025	20	89	1.36 (0.52)	1.28	0.0115	0.60 (0.09)	21
JW14	0.31	0.025	12.4	70	1.75 (0.71)	1.35	*0.0122*	0.63 (0.13)	103
JW15	1.4	0.025	56	68	0.43 (0.30)	5.22	0.0113	1.45 (0.02)	3
JW17	0.7	0.015	47	90	1.34 (0.57)	2.23	0.0113	0.84 (0.15)	19
JW18	0.7	0.005	140	20	1.59 (0.77)	2.00	0.0114	0.90 (0.33)	28

\+ Run JW07 was selected from 11 replicate runs as the most representative because the bed load transport rate was nearest to the average bed load transport rate of all runs (Warburton and Davies, 1994)

* Standard deviation shown in brackets

" Values in italics represent slopes which are significantly different from the initial bed slope

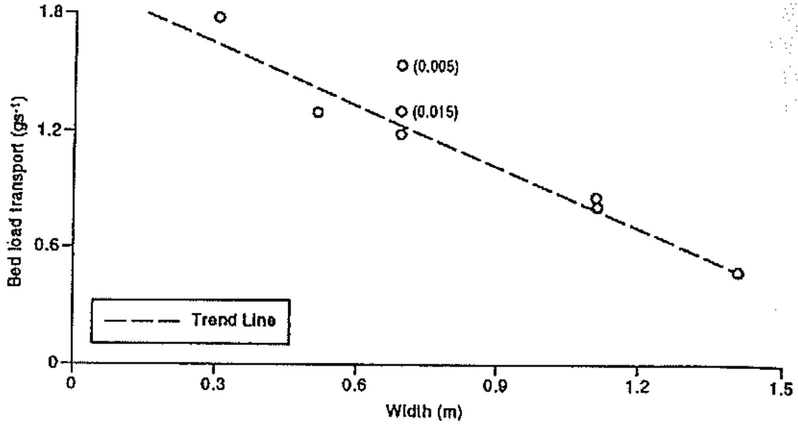

Figure 1 Plots of width versus bed load transport rate. Trend lines are fitted by eye to the lowest data points.

narrow channel (0.31m) widens to attain a more stable channel configuration at around 0.5m (Fig. 2). Evidence in support of this tentative hypothesis can be seen in the bed load transport time series for run JW14 (initial width 0.31m, end width 0.63m) which changes trend at around 2700 minutes, with the mean transport rate diminishing (Fig. 3). The bed load transport rate from 2700 minutes to the end of the run has a mean rate of 1.43 g s^{-1} (standard deviation 0.6 g s^{-1}) which is similar to the transport rate for JW13 (initial width 0.51, end width 0.6m) of 1.36 g s^{-1}, indicating a very similar channel configuration.

Bed Load Transport Time Series

Because of the differing lengths of some of the experimental runs, it is difficult to compare bed load transport series directly. In the analysis which follows results are presented as a graph of cumulative sediment transport rate plotted against run time, and time series analyses are carried out on continuous segments of the runs. In selecting the time series segments for analysis, the first 10 hours of each run was disregarded (5 hours in the case of JW18) and the largest remaining unbroken segment was used. Both autocorrelation and partial autocorrelation functions were calculated for each of the series (Fig. 4). The randomness of the series was initially tested using a two-sided runs test. All series were significantly different from random therefore time series analysis was undertaken. The autocorrelation function provides a measure of the correlation between

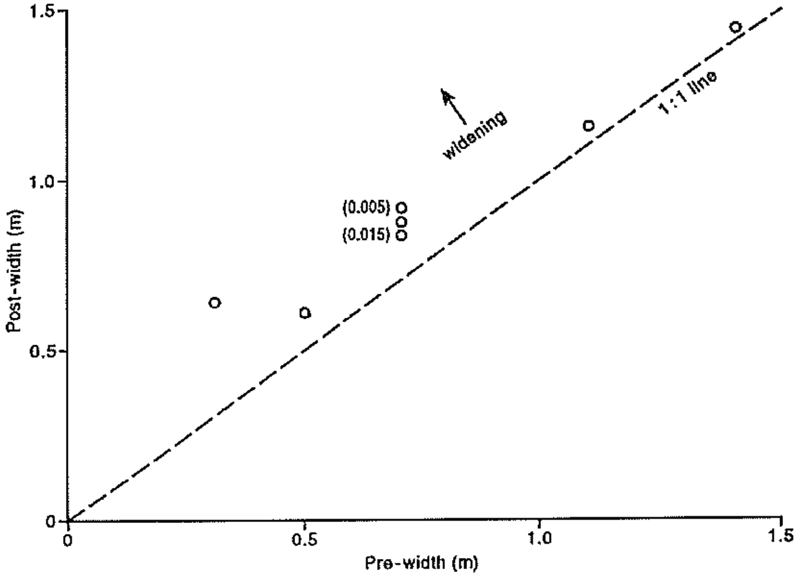

Figure 2 Plot of initial cut channel width and width at the end of the channel runs. Points plotting above the 1:1 line indicate a widening channel.

transport rates in the series at positions separated by a time interval along the series.

Time series analysis of the sediment transport data shows a gradual, almost exponential, decline in the autocorrelation function and significant partial autocorrelation function values at lags 1, 2 and 3 (Fig. 4). This is common in many bed load transport series derived from other braided river models (Ashmore, 1988; Hoey and Sutherland, 1991; and Warburton and Davies, 1994). This simply indicates that there is some statistical dependence on the previous transport rates, measured in the previous 10 to 20 minutes of run time. Observations from time lapse video recordings indicate that this corresponds to the scale of sediment transport associated with the movement of small bar forms and sediment lobes down channel (Warburton and Davies, 1994).

Two summary statistics describing the bed load transport series were calculated. These were the standard deviation (σ) of the elevation series and a characteristic 'decay' dimension (S) estimated from the autocorrelation function ($\rho(s)$) (Fig. 4). Most bed load transport series display a distinctive autocorrelative structure defined by:

$$\rho(s) = \exp(-\alpha \mid s \mid) \quad . \quad (7)$$

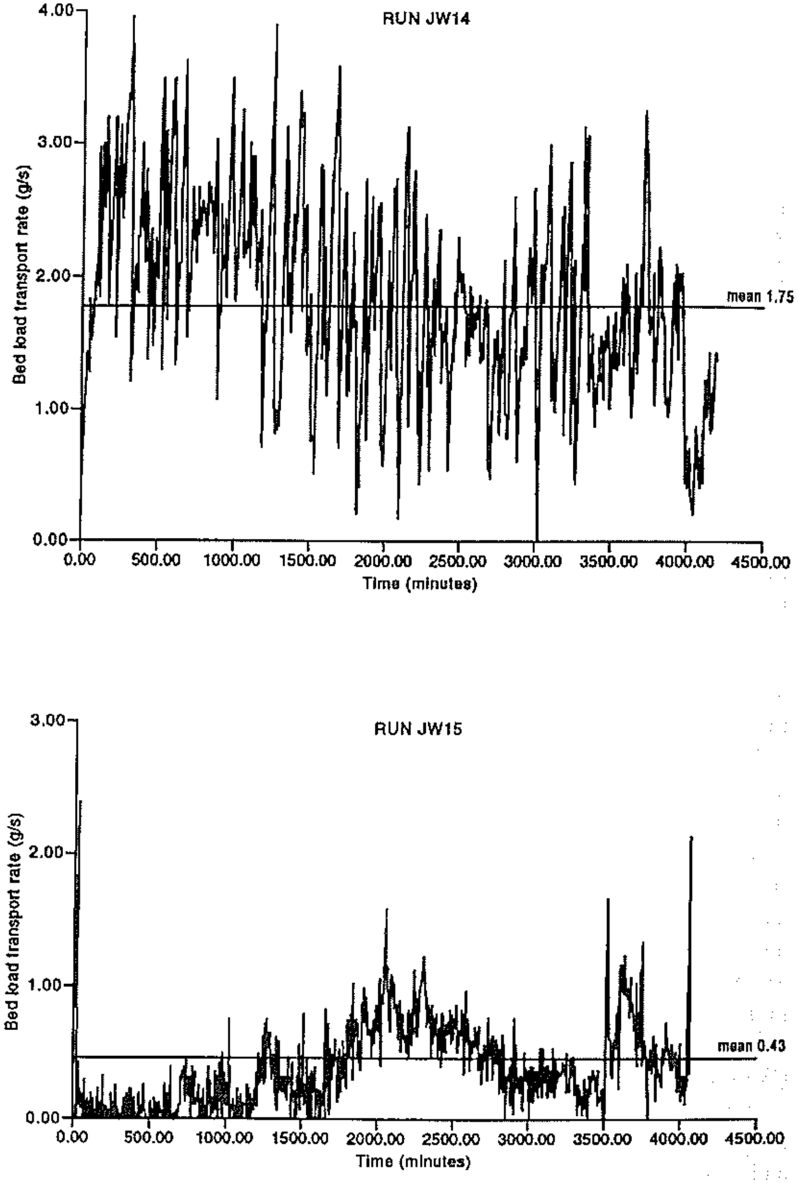

Figure 3 Bed load transport series from runs JW14 (initial width 0.31m) and JW15 (initial width 1.4m). Time refers to the time elapsed since the start of the run.

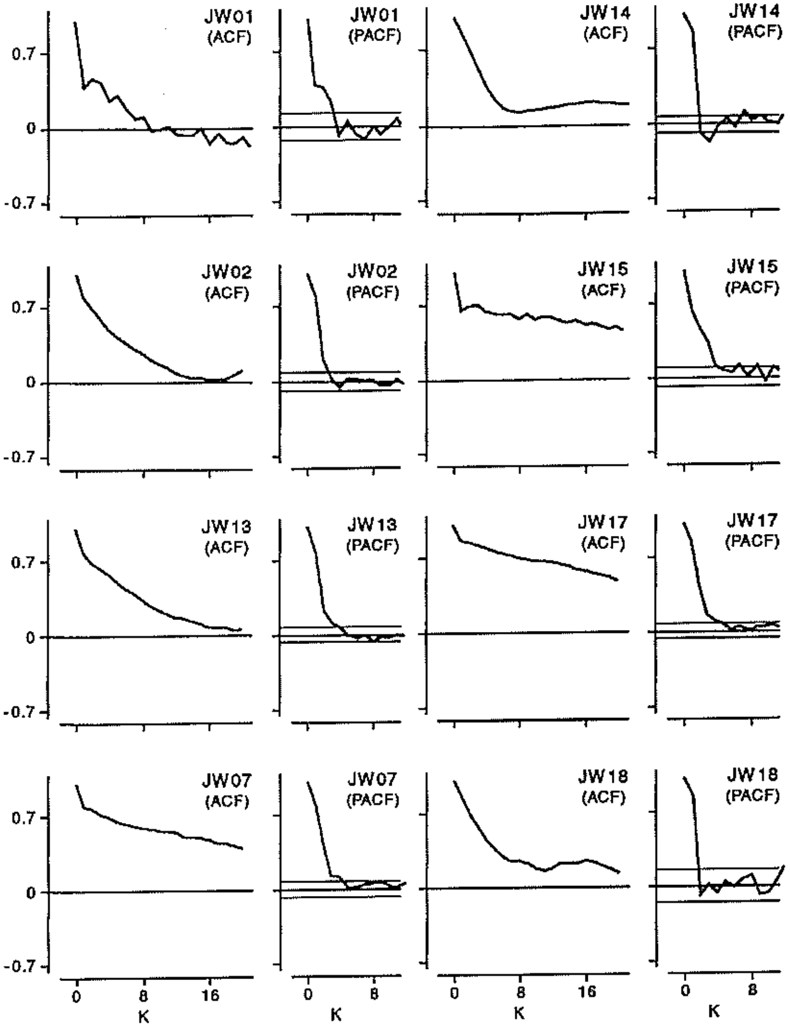

Figure 4 Autocorrelation functions (ACFs) and partial autocorrelation functions (PACFs) of the original bed load transport series. Each lag (k) is 5 minutes and the confidence limits (shown by the dashed lines) are +/-2/n$^{0.5}$, where n is the sample size.

where $\rho(s)$ is the autocorrelation function of the bed load transport series and $\alpha = 1/S$ where S is a characteristic constant. The value S is calculated from the integral length which is best estimated from the lag one value of the autocorrelation function

$$S = -\alpha / \ln \rho(s)(1) \qquad (8)$$

S is a measure of predominant 'pulse' size in the sense that bed load transport rates separated by time intervals less than S are correlated and intervals greater than S are uncorrelated. Estimates of S varied between 5 and 30 minutes, corresponding to the same time scale as suggested by the significant lags in the partial autocorrelation function. Generally, the wider channels had smaller standard deviations and shorter S values, indicating a series of short duration small sediment pulses (e.g. Run JW15, Fig. 3). The initially shallower and narrower cut channels (e.g. Run JW14, Fig. 3 and JW17 and 18, Fig. 5) showed greater variation in transport rate (higher standard deviations) and S values were of greater duration. These differences could be explained by differences in sediment delivery from small braided channels with many stable bars (e.g. JW15, Fig. 3), as opposed to a narrower channel with large mobile bars where bank erosion is greater and therefore sediment supply is higher (e.g. JW14, Fig. 3). In other words the sediment transport dynamics largely depend on the channel configuration. For example in the two replicate runs of 1.1m width, in the less braided channel JW02 standard deviation is great and S is larger (Fig. 5). For the shallower channels the argument is less convincing, although braiding is not very well developed and sediment supply from banks tends to be fairly high.

Sediment Transport and Channel Form

Figure 6 shows five cross-sections surveyed at the midpoint of the flume at the end of runs JW01, 07, 13, 14 and 15, for initial widths varying between 0.31 and 1.4m. The initial channel dimensions are indicated by the dashed scale bar. The pattern of behaviour is very clear; the narrowest channel enlarges whilst the wider channels maintain their overall width. In the wider channels sediment accumulates and bars develop. Because these examples are from single sections, the cross-section for 0.31 and 0.5m are slightly misleading inasmuch as section JW14 contains a bar whilst JW13 is a scour hole, although mean differences in width (Table 1) are consistent with the general pattern. This suggests that the narrow channels enlarge to a greater width and wide channels deposit sediment.

By reducing depth of the braidplain, the overall channel capacity is reduced and the potential for sediment storage decreased. For the combinations of flow and braidplain depths studied, flow was less than channel capacity

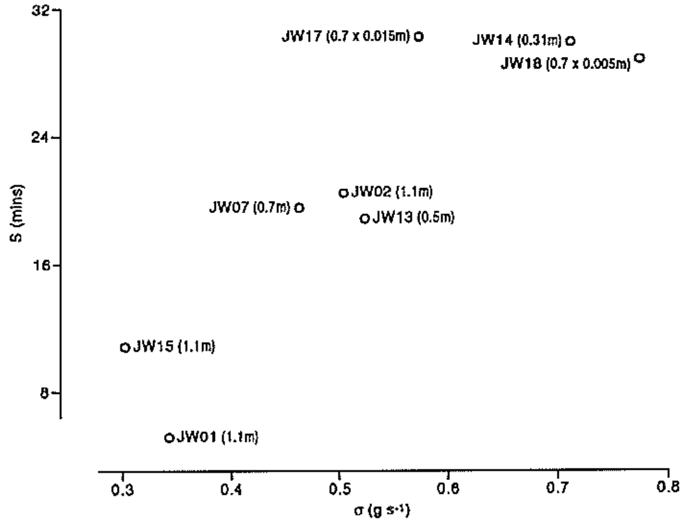

Figure 5 Statistical characteristics of the sediment transport series. Scattergraph of the standard deviation and 'S' value (see text) of the bed load transport series.

and overbank flows were rare. The influence of floodplain depth on bed load transport is generally less than the influence of width. However, for the runs at three different depths, the shallower initial channels showed greater widening and bank erosion, over-bank flows became significant and channel patterns were more braided (Fig. 7).

Examination of channel planforms for the same runs clearly shows major differences in pattern. In all the channels mid-channel bars dominate, with some tendency to an alternate pattern in the narrower channels. In the wider channels a more braided pattern is evident, with the flow divided into many smaller channels (Fig. 7). This is reflected in the braiding index (Table 1). Along-bank flows are prominent in all the runs and are associated with convexity in the cross-channel relief (Fig. 6).

The relationship between braiding (Braiding Index, Brice, 1964) and bed load transport is shown in Figure 8. The negative trend indicates that bed load transport is lower in the more braided systems. This contradicts the weak positive correlation between braiding index and mean bed load transport rate identified by Warburton and Davies (1994) for 11 replicate runs identical to JW07. In reporting this weak correlation Warburton and Davies stressed this was only a tentative conclusion because the exact mechanisms relating bed load transport to channel pattern are not fully understood. The results however agree with Davies and Lee (1988) who found that bed load transport was lower in wider (braided) channels.

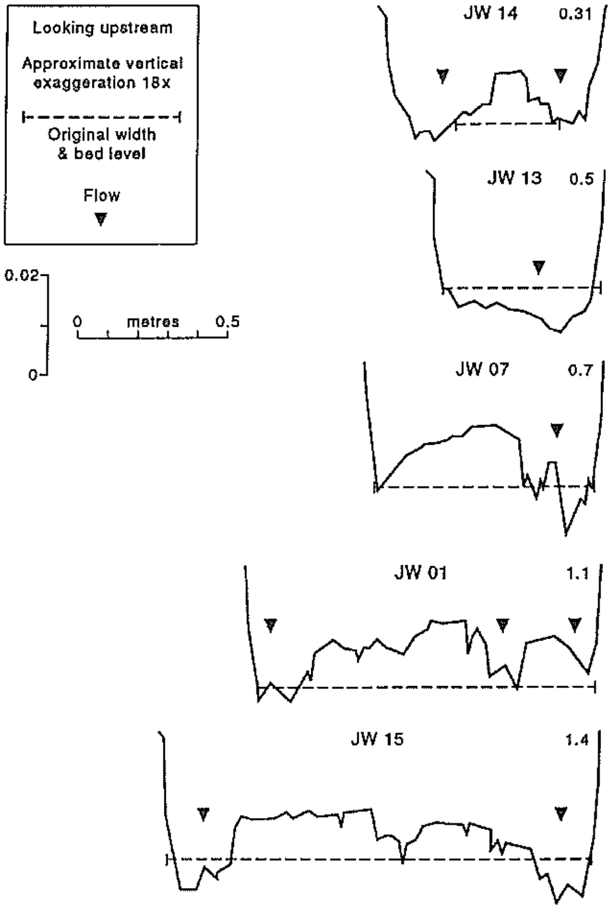

Figure 6 Active braidplain cross-sections at the mid-point in the flume. Original bed levels and width are indicated by the dashed bars.

Determining representative variables to characterise a particular fluvial system is fraught with difficulty. This is particularly true of braided river channels where variables are two-dimensional e.g. the Brice braiding index of planform or cross-section characteristics. Furthermore the physical significance of these measures, the planform ones in particular, has never been clearly established. The relationship between braiding index and bedload transport, although corroborated by Davies and Lee (1988), is considerably more variable than the data points in Figure 8 suggest. A measure as simple as a braiding index is insensitive to the variability in three-dimensional channel configurations and cannot characterise the channel evolution with time.

Only three out of the eight experimental runs had channel slopes significantly different from the initial slope (t-test p=0.05) and of these all were increases in slope. Slope increased for channel widths 0.31m, 0.7m and 1.1m and all tended to be associated with steep initial input slopes. Therefore although the slopes are significantly different, the differences do not correlate with width and are associated with local rather than general trends e.g. Runs JW01 and JW02 replicated width 1.1m and produced slopes of 0.0114 and 0.0126 - one significantly different from the initial slope and one the same.

In examining the interrelations between channel form and sediment transport variables, simple linear correlation was used (values greater than

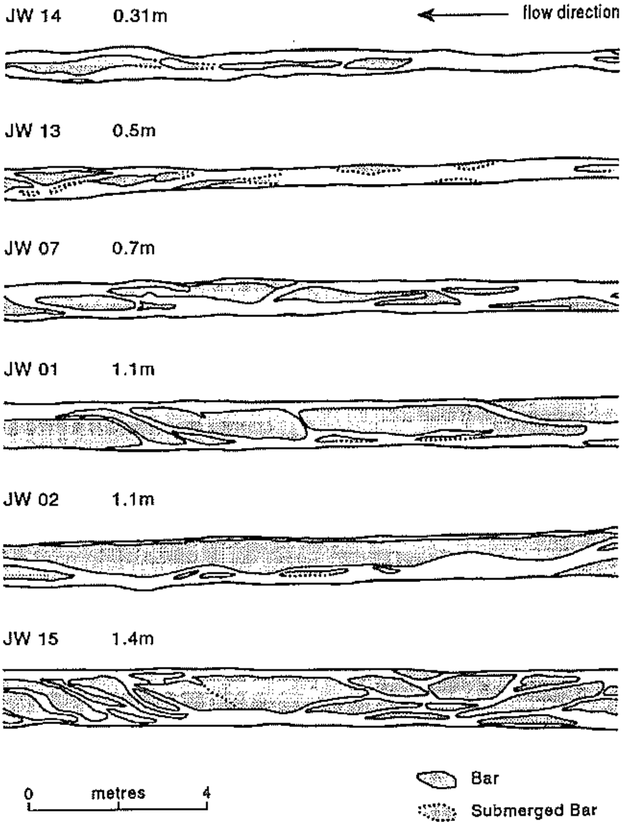

Figure 7 End-of-run channel patterns for various initial widths and a depth of 0.025m. Flow is from right to left.

0.8 significant at the p=0.05 significance level). These correlations include all data (n=8) and therefore scatter is increased by the inclusion of runs JW17 and JW18 where depth was varied. Figure 9 shows the interrelationships between significant variables in the hydraulic model for constant inputs of water and sediment and for fixed initial channel slope, width and depth. This represents a summary of many of the relationships described in the other figures and tables. The diagram has four main components relating bed load transport, braidplain width, braiding and bank erosion. Channels with large widths have low bed load transport rates, tend to be more braided and have lower rates of bank erosion. For a channel where bank erosion rates are low, the bed load transport series is characterised by low S values and a small standard deviation (i.e. sediment pulses tend to be smaller and less persistent). For narrow channels the opposite is true, which suggests a feedback loop controlling channel width. For example, the narrowest channels have the greatest bed load transport rates and rates of bank erosion. This implies the channel will widen and in doing so bed load transport will decline, as will bank erosion. Braiding will increase, in part to redistribute sediment from the banks.

These interrelationships are internally consistent and offer clues about the key mechanisms in channel behaviour, although they don't indicate the detail processes involved. For example there is a need to examine

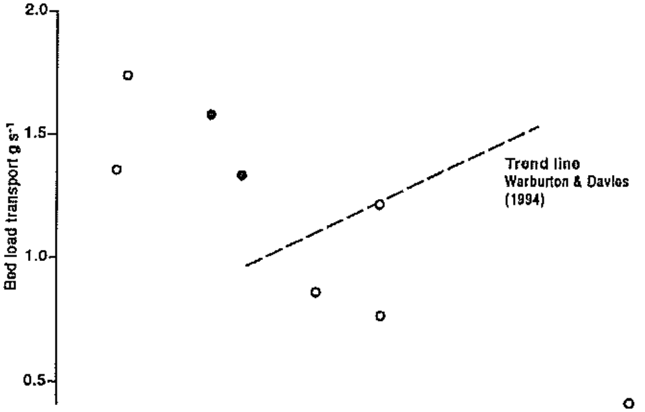

Figure 8 Scattergraph of the relationship between Braiding Index and bed load transport rate. Shaded points are runs of shallower initial depth. The trend line is from Warburton and Davies (1994); their models indicate a much different relationship between the two variables.

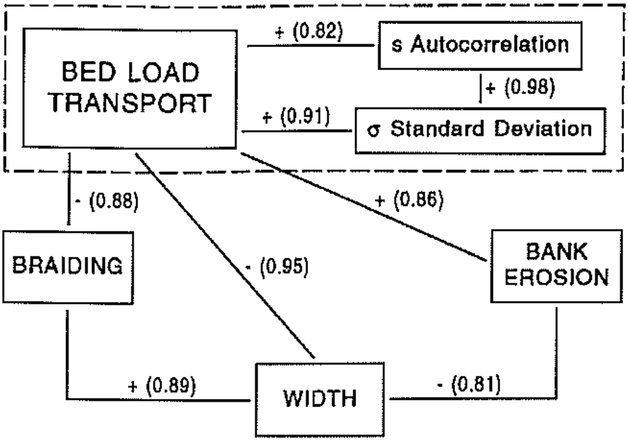

Figure 9 Interrelationships between sediment transport and channel form variables in the hydraulic model. The signs and correlation coefficients (all significant) are shown for each of the linkages.

spatial variability in flow and sediment transport in the model. However, this is not easily resolved at the model scale.

Sediment Budgets

Cumulative sediment output curves are shown in Figure 10. These curves indicate the sediment output histories for the duration of the flume runs. In runs that plot above the 1:1 line, sediment output is greater than input. This occurs in the narrowest (0.31m) and shallowest channels (JW17 and JW18), although during run JW17 sediment output declines after 3000 minutes to less than input. All other runs show sediment output is less than input for the duration of the experiments. The wider channels also show a lag in sediment output of approximately 600 minutes before appreciable sediment is registered at the outlet. This is associated with the movement of an initial sediment wave down channel (e.g. JW15, Fig. 10). For the narrower and shallower runs sediment transport is more immediate, reflecting contributions from bank erosion and the more rapid translation of the sediment wave downstream in a narrower channel (less storage potential) (e.g. JW14, Fig. 3). Many of the sediment transfer curves also show deflections. A downward deflection could be associated with increased bed stability, or an upward deflection may be associated with large-scale sediment pulses of the kind shown in run JW15 (Fig. 10).

The relationships expressed in the correlation diagram (Fig. 9) are consistent with the results of the sediment budget calculations (Table 2). Table 2 shows sediment budget calculations for the full duration of each run. Budgets were calculated from sediment balance between input and output (both of which were measured) and from cross-section surveys at the start and end of the run. Bank erosion is defined as the total amount of sediment eroded from the floodplain sidewalls and net bed deposition is the total sediment accumulated within the confines of the channel walls at the end of the experiment. The major source of uncertainty is at the flume head where cross-sections are few but adjustments are greatest. All values are expressed as a percentage of the total sediment input. This is done so that output is an indication of sediment delivery.

For the first 6 runs in Table 2 (omitting the runs where depth was varied, JW17 and JW18), in all cases except JW14, sediment output was less than input and, as width decreased sediment delivery increased. There was also a tendency for bank erosion to be greater and bed deposition to be less in the narrower channels, reflecting greater sediment mobility or at least increased sediment transfer. The budget calculations are approximate because of uncertainties surrounding the sediment balance at the head of the flume.

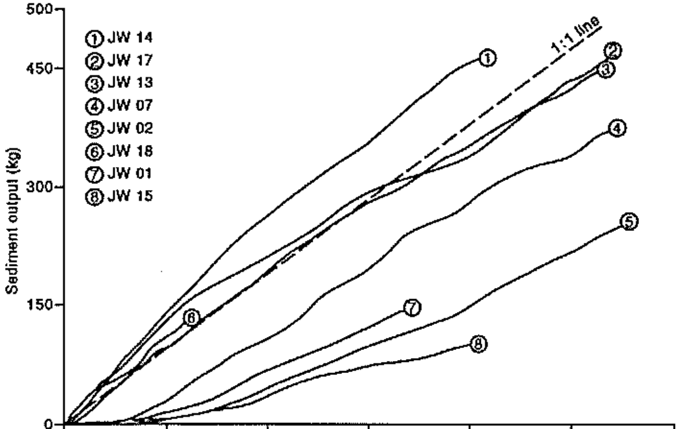

Figure 10 Cumulative sediment transport curves plotted with respect to sediment input rate (dashed line). Curves plotting above the 1:1 line indicate degradation; curves below the line indicate aggradation. Curves truncate at the end of each experiment.

Additional sediment is input due to bank erosion and changes in channel storage. All runs show evidence of changes in storage of both the bed and banks. Bank erosion and changes in channel storage tend to be greater in the initially narrower and shallower channels. This is generally confirmed by the cumulative transport curves shown in Figure 10 and the cross-sections in Figure 6. It should be recognised, however, that while bed levels may aggrade, channel capacity may increase through bank erosion and sediment derived from bank erosion contributes to aggradation of the bed; e.g. run JW14 (Fig. 6). Sediment budgets for entire runs are very general and must be carefully interpreted. Treating the run as a single sediment balance event disguises phases of sedimentation and erosion in the model. For example, trends in the cumulative sediment transport curves (Fig. 10) indicate changes in behaviour within runs. Interestingly all the runs were either aggradational or degradational, none were in equilibrium (i.e. none had zero change in storage over the entire run). This is important because theories of channel design are largely based on assumptions of equilibrium conditions.

For the runs where the initial depth was small, both for JW17 (depth 0.015m) and JW18 (depth 0.005m), sediment delivery was high. Bank erosion increased and deposition in the channel increased. Run JW18 in particular was characterised by massive bank erosion and lateral channel migration due to the lack of resistance afforded by the low banks. This resulted in a very shallow aggrading channel with significant over-berm flow and scour. This run had to be stopped prematurely when the channel reached the side-wall of the flume.

Discussion

The results reported here support the general conclusion of Davies and Lee (1988) and the view of Henderson (1966) that transport capacity increases as width decreases. This is contrary to arguments proposed by Parker (1979) and Bagnold (1980). Carson and Griffiths (1987b) suggest that both views are flawed and transport rate may be maximised at an intermediate width. In the present experiments neither view has been demonstrated unequivocally; although there is a negative relationship between width and bed load discharge, this only applies to a restricted range of widths e.g. very narrow widths were not tested. Furthermore, width is not static and channel adjustments, as demonstrated in these experiments, modified such a relationship.

Three factors are thought to reduce bed load transport capacity in the wider channels: (1) flows are generally shallower; (2) beds aggrade and paving may leave a coarser than average surface grain-size distribution;

Table 2 Sediment budget calculations for the experimental runs. All values are calculated as a percentage of the total sediment input into the model. The sediment balance is given by: $I - O = \Delta S$, *where* $\Delta S = \Delta Sb + \Delta Sc$.

RUN	WIDTH	DEPTH	INPUT I	OUTPUT O	CHANGE IN STORAGE ΔS	BANK EROSION ΔSb	CHANNEL STORAGE ΔSc
JW01	1.1	0.025	100	44	56	16	40
JW02	1.1	0.025	100	42	58	5	53
JW07	0.7	0.025	100	73	27	26	1
JW13	0.5	0.025	100	90	10	19	-9
JW14	0.31	0.025	100	120	-20	47	-67
JW15	1.4	0.025	100	25	75	12	63
JW17	0.7	0.015	100	93	7	19	-12
JW18	0.7	0.005	100	117	-17	102	-119

and (3) in wide channels there is less flow at the surface because underflow and seepage to groundwater through the bed is greater. However this third factor has been shown to represent only a small proportion of the total river flow, particularly at high discharges (van't Woudt *et al.*, 1979). These factors have not been proved because direct testing would require detailed measurements of hydraulic geometry in the different runs; comparison of grain-size distribution of the input and output sediments and a spatial survey of bed grain-size; and a comparison of input discharge and surface discharge in the channel.

Davies and Lee (1988) essentially used a sediment budget to assess changes in aggradation and degradation in their width reduction experiments. The major differences between this experiment and Davies and Lee's work was that width in this experiment was constrained laterally by deformable boundaries whereas Davies and Lee used rigid banks. In the present set of experiments, a combination of approximately 0.5m width and 0.025m depth (W/D = 24) produced a relatively stable channel. This has implications for channel design: maintaining width and bank height close to these values will minimise bank erosion and aggradation, resulting in a relatively stable channel design e.g. see Table 2 for bank erosion losses and Figure 10 for an estimate of aggradation (Runs JW13 and JW14).

From the small number of runs described, a channel width of approximately 0.5 m may represent the most likely stable configuration for the present flume conditions. It is interesting to compare this estimate with width estimates derived from the commonly used design equations. Table 3 summarises the estimates from five equations frequently applied to gravel-bed rivers and compares the estimates with a width of 0.5m. The value of 0.5m is estimated from run JW13, which shows the lowest net change in storage. It is clear that the Henderson (1966) equation comes closest to the 0.5m value (although this is sensitive to the grain-size used). However, this is not necessarily a suitable design formula because:

1. It must be accepted that the value of 0.5m is only suggested from the data; further experiments would be needed to confirm this value e.g. was the channel actually stable at the end of the run? Observations suggest that it was, as at the end of the run bank erosion was minimal and mean bed load transport rate was only slightly less than sediment input rate (Runs JW13 and JW14).
2. Comparison of flume data with empirically derived field data may not be valid. The model is assumed to be a scaled reproduction of a braided gravel-bed river and therefore the equations should apply. However, verification of hydraulic models is still an area which is being actively researched.
3. Even accepting that the model is a fair representation of a gravel-bed

prototype, the application of these design formulae is subject to the same criticisms as outlined by Carson and Griffiths (1987a) and described earlier.

4. The range of values in Table 3 (0.15 to 3.57m) hardly inspires confidence in the results.

It is clear that formulae designed to predict the width of shallow rectangular gravel-bed channels are unsound and are of little help in accurately determining width in braided channel systems. These should be abandoned in favour of experiments designed to enhance understanding of the mechanisms which determine the width of braided gravel-bed rivers. Past studies have concentrated on the use of regime-type equations to determine channel width rather than study the factors which determine braidplain width. In engineering of braided rivers the latter is a more sensible approach.

Conclusions

Formulae designed to predict the width of shallow rectangular gravel-bed channels are unsound because of uncertainty about the nature of the relationship between bed load transport and width in braided channels. Flume studies of braided river behaviour offer the best method for determining the nature of this relationship for complex braided river systems.

For the present set of flume experiments it is clear that bed load transport is greater in the narrower channels, and for runs of equivalent width, shallower channels have slightly higher bed load transport rates due

Table 3 Calculated channel widths for the present model study based on commonly used design equations (see text for the methods of calculation).

SOURCE	CALCULATED WIDTH	DISCREPANCY WITH 0.5m m	COMMENT m
Lacey 1929	0.18	-0.32	Qd = Q
Henderson 1966	0.51 (d_{75}) 1.43 (d_{50})	0.01 0.93	
Griffiths 1981	2.43	1.93	
Griffiths 1981	3.57	3.07	
Bray 1982	0.15	-0.35	Qd = Q

primarily to increased bank erosion. Time series analysis of the bed load transport data shows a gradual, almost exponential, decline in the autocorrelation function and significant partial autocorrelation function values at lags 1, 2 and 3 (Fig. 4). This indicates that there is some statistical dependence on the transport rates measured in the previous 10 to 20 minutes of the run time. This corresponds to a time scale associated with the movement of small bar forms and sediment lobes down channel. Generally speaking the wider channels have smaller, shorter duration sediment pulses (Fig. 5). The shallower and narrower channels (Fig. 5) showed greater variation in transport rate. The majority of runs are aggradational and have a sediment delivery ratio of less than unity, indicating sediment output is less than input. As width increases sediment delivery generally declines, indicating the importance of braidplain storage.

The narrowest channels enlarge whilst the wider channels maintain their overall width. The narrowest channels commonly have mid-channel bars with some tendency to an alternate pattern, but the wider channels have a more braided pattern with the flow divided into many smaller channels (Fig. 7, Table 1). The relationship between braiding and bed load transport is complex but suggests that bed load transport is lower in the more braided systems (Fig. 8). Some channel slopes increase, but these are associated with local rather than general trends.

These interrelationships are internally consistent and offer clues about the key mechanisms in channel behaviour, although the scale of the experiments does not permit investigations of the detailed processes involved.

Acknowledgements

This work was carried out in the Department of Natural Resources Engineering, Lincoln University, New Zealand whilst in receipt of a New Zealand University Grants Commission Postdoctoral Fellowship. Financial support was provided by a Lincoln University Research Grant, The Royal Society, New Zealand Hydrological Society and Durham University.

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