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# PREDICTION OF BEDLOAD TRANSPORT RATES IN BRAIDED RIVERS: A HYDRAULIC MODEL STUDY

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## ABSTRACT

A 1:50 scale hydraulic model was designed based on Froude Number similarity using hydrological and sediment data from a braided gravel-bed river. Experiments using both steady and quasi-unsteady flows were conducted to investigate relationships between discharge-slope product and bedload transport, and changes in bedload transport capacity resulting from flow abstractions. The model showed good hydraulic similarity to the braided North Branch of the Ashburton River, South Island, New Zealand.

Two equations for predicting bedload transport were assessed: the Schoklitsch (1962) equation and the Bagnold (1980) equation. The Schoklitsch (1962) equation gave reasonable predictions, however the Bagnold (1980) equation was more accurate, with the experimental data closely adhering to the empirical 3/2 power-law dependence of bedload transport on excess stream power. Data from the unsteady flow experiments show that stream power is a reliable basis for predicting reductions in bedload transport capacity caused by flow abstractions from braided rivers.


## INTRODUCTION

The major braided rivers of New Zealand are valuable water resources, with potential for further development for irrigation and hydro-electric power generation. Such developments modify the river flow regime by either abstracting or regulating flow. A major problem in the protection of environmental values is the unpredictability of changes to the river environment induced by flow regime modifications. Of primary interest is prediction of changes in channel form, especially widths, depths, and the number and total area of bars and islands, as these determine the available habitat for fish and bird life. Since channel form is a direct result of bedload transport a first requirement is the ability to predict the rate of bedload transport for a given discharge. This study deals with the relationship between discharge (or the discharge-slope product) and bedload transport.

Because of current deficiencies in analytical methodology, and the practical difficulties of extensive field work, the investigations of this study are based on hydraulic modelling. The ease of control and the speed of channel evolution in mobile-bed models make them a powerful research tool. The present study used available hydrological and sediment data to design a scale-model of one of the smaller braided rivers of Canterbury, New Zealand: the North Branch of the Ashburton River (hereinafter designated North Branch).

This study employs hydraulic modelling to investigate the relationship between discharge-slope product and bedload transport rate in self-formed braided channel systems for both steady and varying flows, and to quantify changes in bedload transport rate resulting from flow regime modifications.

## EXPERIMENTAL METHOD

The experiments were carried out in the 20 m x 3 m x 0.3 m tilting flume housed in the Soil and Water Laboratory of the Department of Natural Resources Engineering, Lincoln University, New Zealand. The flume employed a water recirculation system and a dry sediment feed device. Heating elements in the return tank allowed hot water to be used, affording some control over fluid viscosity. Outflow from the flume was into a sediment collection drum suspended from a 350 kg load cell, which was calibrated to $\pm$ 50g under static (steady flow) conditions. Flow control and bedload transport data collection were automated using a data acquisition and control device linked to a micro-computer.

The Froude law rough turbulent flow model was designed following the theory expounded in Yalin (1971). Dynamic similarity is achieved if:

$$\lambda_l > \left( \frac{70}{\left[ \frac{v_* D}{\nu} \right]_p} \right)^{2/3}$$

where $\lambda_l$ = length scale, $v_*$ = shear velocity, D = grain size, $\nu$ = kinematic viscosity and the subscript 'p' denotes prototype values. Using typical North Branch values in this equation (slope S = 0.0115, depth d = 0.4 m, $D_{90}$ = 150 mm, and $\nu$ = $1.3 \times 10^{-6}$ m² $s^{-1}$, and employing this $D_{90}$ grain size as representative of the bed roughness, gave $\lambda_l$ = 0.02; thus indicating a scale of 1:50 as the optimum obtainable. In the available 3.0 m wide laboratory flume, this scale meant that a total channel width of somewhat less than 150 m could be modelled without sidewall interference. The North Branch in its steeper reach averages between 150 m and 300 m wide, while in its flatter confined reach it averages 80 m to 90 m wide. The 1:50 length scale was acceptable for the model, with the knowledge that stream width development was likely to be limited by sidewall interference. This limiting condition was reached in several experiments, and therefore at the 1:50 scale the flume facility could adequately model only the narrower, confined reaches of the North Branch.

A representative braided stream grain-size distribution was established, based on the data of Laronne and Duncan (pers. comm., 1987) for bar sub-surface sediments (excluding sands) in the North Branch (Fig. 1). The model bed material was based on this distribution, since exclusion of North Branch sand sizes ensured that no cohesive material was introduced into the model. The mineral density of the sediment was 2650 kg $m^{-3}$, and the bulk density of the mixture was approximately 1800 kg $m^{-3}$, both values corresponding well with North Branch sediment densities.

The flow rates used in the model were restricted to the set of discrete values obtainable with the flow control system used. For the steady flow experiments, three different flows were used, corresponding to above-threshold exceedence

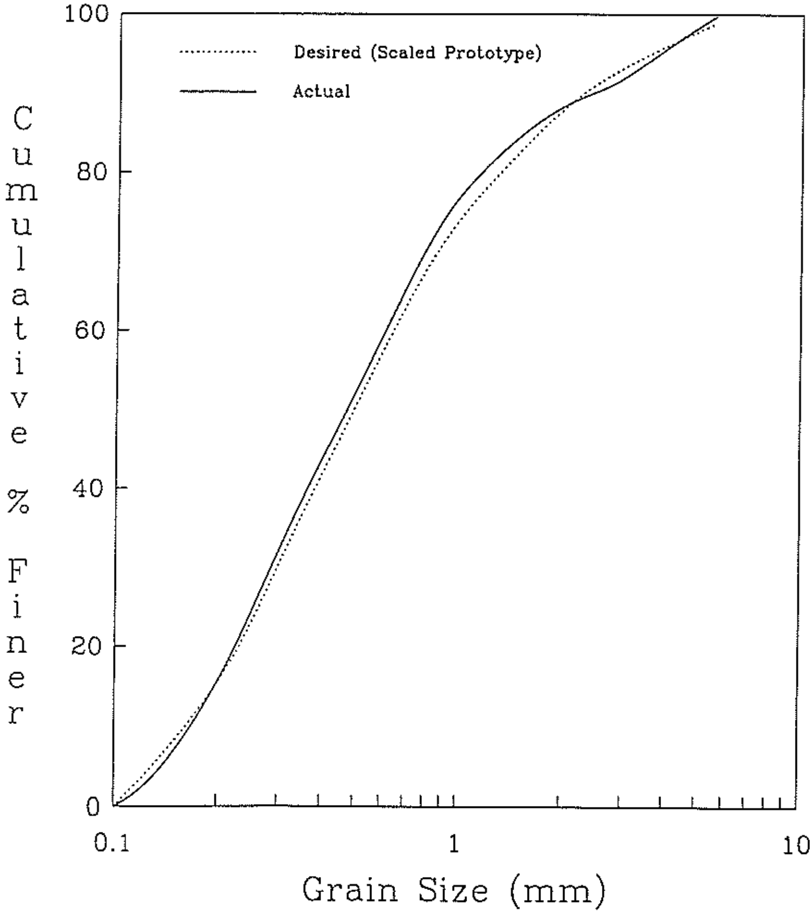


FIG. 1—Grain size distribution.

values (for S = 0.74%) of 58%, 42%, and 18%. Above-threshold exceedence values are obtained from the above-threshold flow series — flows capable of moving bedload. The exceedence value of a particular flow within the series gives the percentage of time that this flow is equalled or exceeded for that series. For the unsteady flow experiments a synthetic hydrograph series was designed consisting of ten hydrographs with identical shapes, but different time-bases (Fig. 2), chosen so that the resultant flow duration curve matched the above-threshold flow duration curve of the North Branch as closely as possible (Fig. 3). The hydrograph shape was based on inspection of hydrographs of events from the North Branch. These above-threshold flows were delivered together with an independently pumped base-flow of $0.7 ls^{-1}$, which was equivalent to the estimated threshold flow of $12\ m^3s^{-1}$ for the flatter confined reach of the North Branch

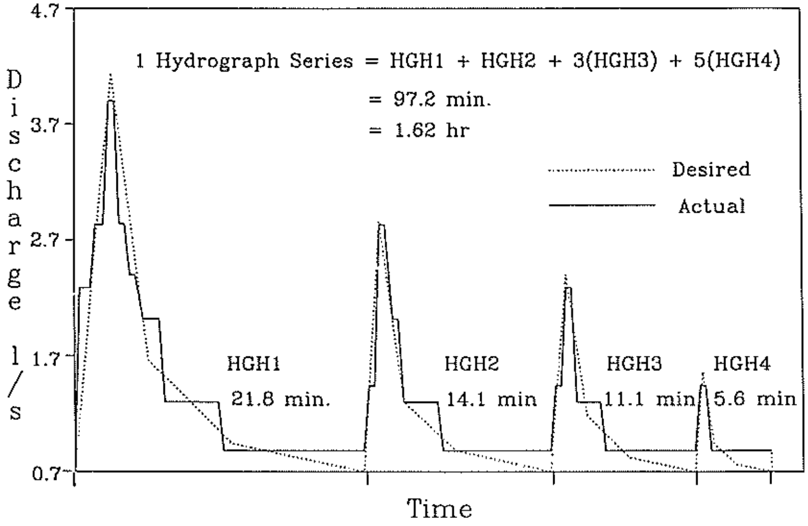


FIG. 2—Model hydrograph series.

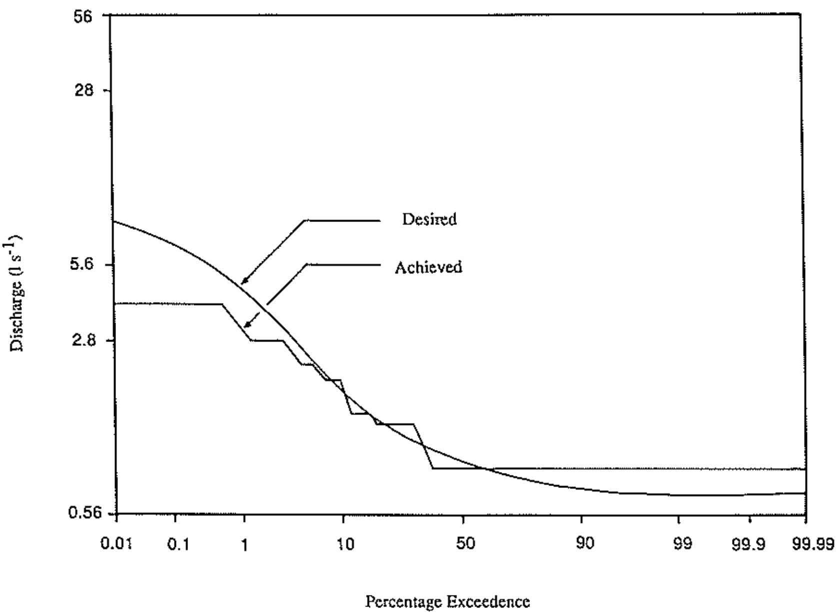


FIG. 3—Model flow duration curve.

(Duncan, 1987). The available pump capacity limited the maximum flow in the model to a 1.8% above-threshold exceedence value, and the stepping nature of the flow control meant that even the derived simple hydrograph shape could only be approximated; the resulting flow regime was therefore only 'quasi-unsteady'. The ten hydrographs were run in a computer-generated random order to avoid any cumulative effects of sequence on channel development.

To model flow abstractions, energy dissipation analysis was used to design two flow regimes with 20% and 40% less energy available for sediment transport (Young, 1989). These reductions could be approximated by using the original hydrograph series with base flows reduced by 0.15 l $s^{-1}$ and 0.25 l $s^{-1}$ respectively.

Preliminary experimental runs showed that, during low flow conditions, depths and velocities were such that in many areas grain Reynolds' numbers were below the accepted limits of rough turbulent flow. Subsequent runs therefore used water heated to 30°C, thus reducing the fluid viscosity and increasing grain Reynolds' numbers. With grain sizes and flow rates set, the geometric scale was set, and changing the viscosity ratio altered only the grain Reynolds' number values.

The experimental programme consisted of two series of experiments, using steady and unsteady flow conditions. All experimental runs started with an initial rectangular channel of 1.1 m × 0.025 m cross section. Sediment feed rates were selected to ensure that the system was neither overloaded nor limited by supply.

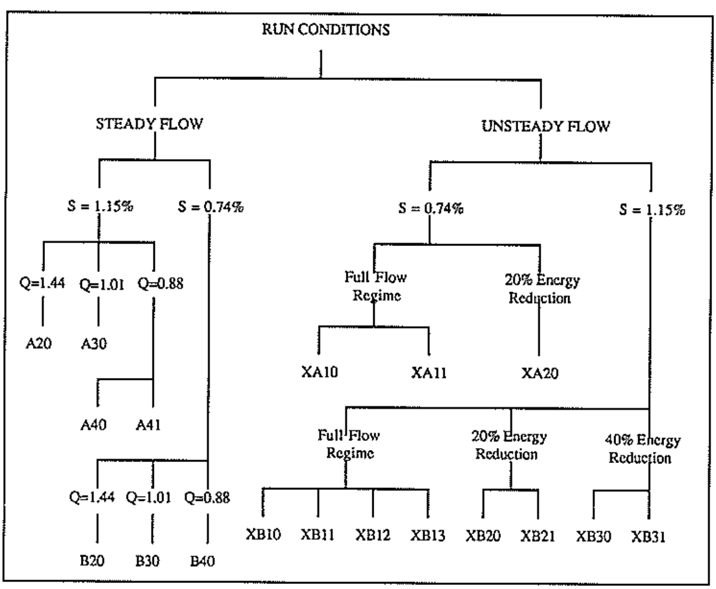


FIG. 4—Experimental programme structure.

The sediment feed rate was adjusted to maintain a constant bed level at the head of the channel, and as the bed level was also fixed at the flume outlet, channel slope remained constant. The independent variables for the system were grain size (D), flow rate (Q) and overall channel slope (S). With Q and S as independent variables the flume system is comparable to a natural river channel in the short term, where channel slope does not have time to adjust to rapid fluctuations in discharge (Davies and Sutherland, 1983). The model is thus limited to predicting river behaviour in the short term.

For the seven steady flow experiments (Fig. 4) the weight of collected sediment was logged every minute. Photographs and hydraulic data were collected twice during each run without interrupting the flow. Flow depths were measured with a carriage-mounted point gauge, and surface velocities estimated by timing polystyrene beads over a distance of 0.3 m. These measurements were made across five cross sections at 6 m, 8 m, 10 m, 12 m, and 14 m from the head of the flume.

For the eleven unsteady flow experiments the weight of collected sediment was logged at the end of each hydrograph only when the flow was essentially steady. As shown by Figure 4 several of the eleven runs were replicas. Run lengths varied, as they were determined by the rate of channel development. Hydraulic measurements and photographic records were taken in the same manner as for the steady flow runs, however for unsteady flow runs it was necessary to interrupt the experiment and set a standard steady flow to collect data. The flow used was 0.7 l $s^{-1}$, the estimated threshold flow for the lower slope. Experiment durations and the extent of the data collected for all runs are shown in Figure 5.

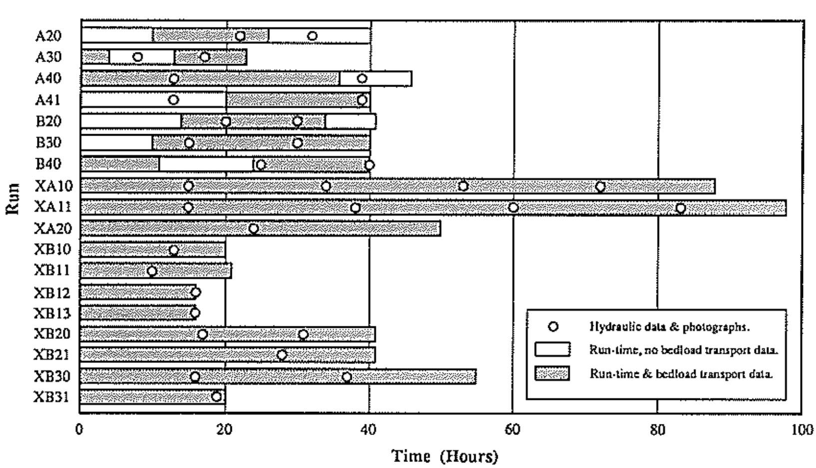


FIG. 5—Experimental run times.

## MODEL VERIFICATION

To verify the model it was necessary to show that the hydraulic modelling criteria had been fulfilled. A Froude law model requires:

(i) that the flow conditions in the model are 'rough-turbulent',
(ii) general Froude similarity of the flow between model and prototype, and
(iii) similarity of relative roughness (d/D) between model and prototype (equivalent to similarity of grain Froude number, $Fr_*$).

The measured hydraulic data indicated that the first of these criteria was generally fulfilled, and that viscosity scale effects were minor and limited to areas where bedload transport was unlikely to occur (Young, 1989). To test for the remaining two criteria (and for general hydraulic similarity) the field data of Laronne and Duncan (pers. comm., 1987), from the North Branch were used. Although the flume dimensions imposed a limit on stream width development, the model showed good hydraulic similarity to the narrower confined 'Blands Reach' of the North Branch (Young 1989). A summary of these comparisons is given in Table 1; the measured velocities were considered as maximum values ($v_{max}$), and hence the average velocities quoted ($v_{av}$) represent values calculated as $Q/(W.d_{av})$.

TABLE 1—Hydraulic variable comparisons.

| | Model Values (Scaled) | | | Prototype Values | |
|---|---|---|---|---|---|
| Variable | Mean | Range | Error | Mean | Range |
| Discharge (Q) | 15.4 | 13.1–25.5 | ± 0.05 | 15.0 | 12.1–21.4 |
| Flow width (W) | 32.0 | 21.0–37.0 | ± 1.0 | 33.0 | 15.7–55.0 |
| Mean depth ($d_{av}$) | 0.45 | 0.35–0.65 | ± 0.05 | 0.41 | 0.29–0.54 |
| Mean velocity ($v_{av}$) | 1.0 | 0.6–1.6 | ± 0.1 | 1.23 | 0.82–1.57 |
| Max. velocity ($v_{max}$) | 2.2 | 1.8–2.6 | ± 0.1 | 1.8 | 1.5–2.1 |
| Froude number (Fr) | 0.5 | 0.3–0.6 | ± 0.05 | 0.61 | 0.40–0.73 |
| Aspect ratio ($W/d_{av}$) | 69 | 52–96 | ± 10 | 88 | 30–157 |
| Number of channels | 2.6 | 1.3–3.8 | ± 0.1 | 2.0 | 1–5 |

As no numerical methods for characterising braided rivers have yet been developed (Davies and Lee, 1988), it is impossible to quantitatively assess similarity of form between the model and the North Branch. The model stream exhibited a similar average number of channels to the prototype (Table 1), and their planforms were assessed to be 'visually similar'.

As well as hydraulic similarity, similarity of process was assessed. Comparisons with bedload transport rate data from the North Branch (Laronne and Duncan, 1987) and from the hydrologically and sedimentologically similar Elbow River,

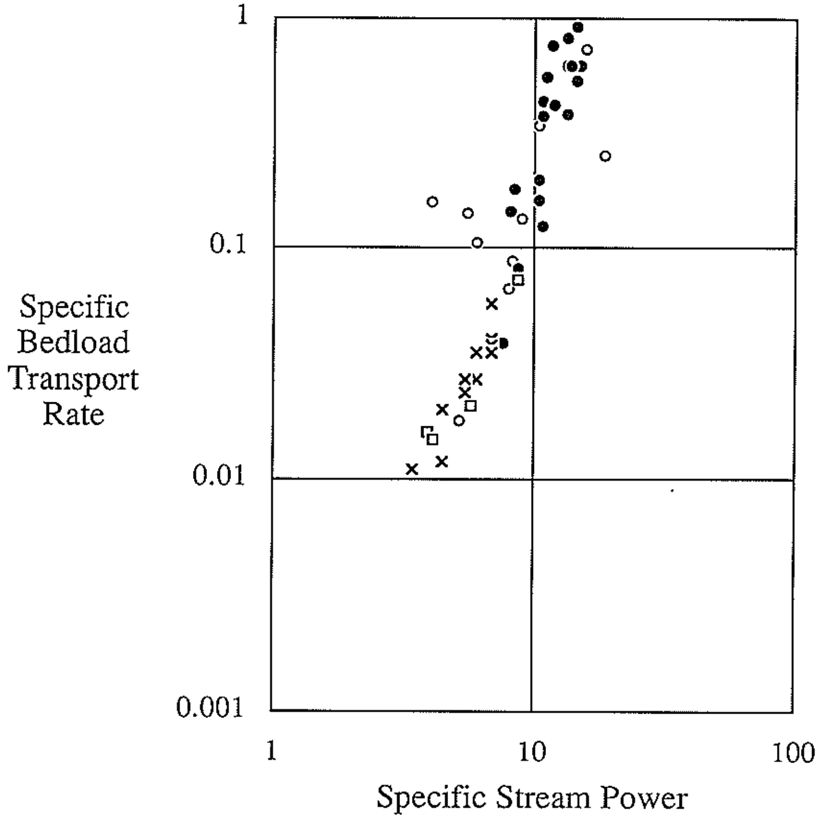


FIG. 6—Bedload transport rate versus stream power: field data and scaled model data in kg $m^{-1}s^{-1}$. (Key: circles = North Branch, Ashburton River, spots = Elbow River, boxes = steady flow experiments, crosses = unsteady flow experiments.)

Alberta (Hollingshead, 1971) indicate the model rates follow the general trend of field bedload transport rates (Fig. 6). This comparison suggests reasonable similarity of process rates.

Predictions of total bedload volumes based on the model results were approximately 60 to 80% below volume estimates based on field survey data. The equilibrium transport regime of the model did not adequately represent the North Branch which has an excessive sediment supply from a rapidly eroding upland catchment. However since hydraulic similarity was achieved the results from the model study can be applied at least qualitatively to full-scale braided rivers.

## PREDICTION EQUATIONS

Two bedload transport rate prediction equations were used in the present study; the Bagnold (1980) equation, and the Schoklitsch (1962) equation. The Bagnold (1980) equation is based on studies of the physics governing two-phase flow (Bagnold, 1956, 1966), which led to an equation describing the bedload transport rate as the product of the power available to do work in moving bedload, and the efficiency of the energy conversion. Being unable to establish a method for determining the efficiency parameter, Bagnold (1977) used empirical correlations to obtain a usable bedload transport equation. These correlations showed the specific bedload transport rate to be dependent on the 3/2 power of excess specific stream power. (Herein the term 'specific' refers to a 'per unit width' value, and the term 'excess' refers to a quantity expressed as the amount by which it exceeds a threshold value. Bagnold's convention of expressing stream power quantities in units of kg $m^{-1}$ $s^{-1}$ and kg $s^{-1}$ (i.e. true power units divided by the acceleration due to gravity) has also been used). The calibration of the Bagnold (1977) equation used only data from sand-bed channels; this limitation masked a considerable variation of bedload transport rate with grain size. Bagnold (1980) subsequently amended his earlier equation to include this factor, making the equation applicable to a wide range of rivers including gravel-bed rivers. In the present study, where flow abstractions were modelled by specified reductions in the available energy of the system, the stream power approach of Bagnold was of particular interest. Gomez and Church (1989), from an assessment of bedload transport equations for gravel-bed rivers, concluded that a stream power equation should be used when hydraulic data is limited, as is common in braided river studies.

The Bagnold (1980) equation may be expressed as:

$$i_b=(i_b)_* \left[\frac{\omega-\omega_o}{(\omega-\omega_o)_*}\right]^{1.5} \left[\frac{d}{d_*}\right]^{-0.66} \left[\frac{D}{D_*}\right]^{-0.5} \qquad (2)$$

where $i_b$ is the specific submerged mass transport rate, and $\omega$ is the specific stream power given by $\omega=\rho qS$, with the zero subscript denoting the threshold value. The asterisk subscripts note reference values for the respective variables, which Bagnold (1980) gives as:

$(i_b)_* = 0.1$ kg $m^{-1}s^{-1}$, $d_* = 0.1$ m, $(\omega - \omega_o)_* = 0.5$ kg $m^{-1}s^{-1}$, $D_* = 1.1$ mm

The Schoklitsch (1962) equation was developed from an earlier empirical equation of Schoklitsch (1934) based on sand transport data from his flume experiments, and sand and gravel transport data from the flume experiments of Gilbert (1914). For graded sediments the Schoklitsch (1934) equation calculates the bedload transport for each size fraction independently. A later version (Schoklitsch, 1962) which used an extended calibration data set of both flume and field data does not require calculation by size fraction. The Schoklitsch (1962) equation was developed as an empirical equation for engineering use, rather than as a theoretical equation. The equation does not involve depth or shear stress explicitly. Applied originally by Schoklitsch to rivers with coarse sediments, it is investigated here to determine its suitability for braided gravel-bed rivers.

The Schoklitsch (1962) equation may be expressed as:

$$g_b = 2.5\ \rho\ S^{3/2}(q-q_o) \tag{3}$$

where $g_b$ is specific mass transport rate, $\rho$ is the density of water, and q is specific discharge (with the zero subscript again denoting the threshold value). This equation can be re-written for specific submerged mass transport ($i_b$) as:

$$i_b = \frac{2.5\ \rho\ S^{3/2}}{\rho_s/\rho - 1}(q-q_o) \tag{4}$$

where $\rho_s$ is sediment density. Using the form of equation 4 allowed direct comparison with the predictions of equation 2.

## STEADY FLOW RESULTS

Using the average bedload transport rates from the steady flow experiments both the Bagnold (1980) equation and the Schoklitsch (1962) equation were evaluated. To assess the 'long term equilibrium' bedload transport rate, data for the first ten hours in the 'A' series runs and for the first twenty hours in the 'B' series runs (Fig. 4) were omitted in calculating average bedload transport rates. This arbitrary truncation removed the high bedload transport rates associated with initial rapid width development.

The threshold condition in the flume was defined by the 0.7 l $s^{-1}$ flow that was observed to initiate bedload motion in the initial 1.1 m wide straight-cut channel at a slope of 0.74%. This condition corresponds to a threshold specific stream power of $\omega_o = 0.0045$ kg $m^{-1}$ $s^{-1}$, and threshold specific discharges of:

(i) $q_o = 0.58 \times 10^{-3}$ $m^2s^{-1}$, for S = 0.74%

(ii) $q_o = 0.38 \times 10^{-3}$ $m^2s^{-1}$, for S = 1.15%

Calculations for the Bagnold (1980) equation used the above value for $\omega_o$, the $D_{50}$ grain size and the measured average depths. The Bagnold (1980) equation predicts the magnitude of the measured bedload transport rates well, averaging an under-prediction of 18% and an average absolute error of 19%. The measured and predicted rates (Fig. 7) show that the Bagnold (1980) equation also predicts the trend in the experimental data very well. This is reflected in the regression for this plot:

$$i_b\ \alpha\ [\text{Bagnold (1980) prediction}]^{1.06} \tag{5}$$

The Schoklitsch (1962) equation on average under-predicted bedload discharges by 34% for the present study. The measured (actual) and predicted discharges are plotted on Figure 7. Although the under-prediction error could be corrected by adjusting the empirical coefficient in equation 4, the trend in bedload discharge is still considerably steeper than that predicted by the Schoklitsch (1962) equation.

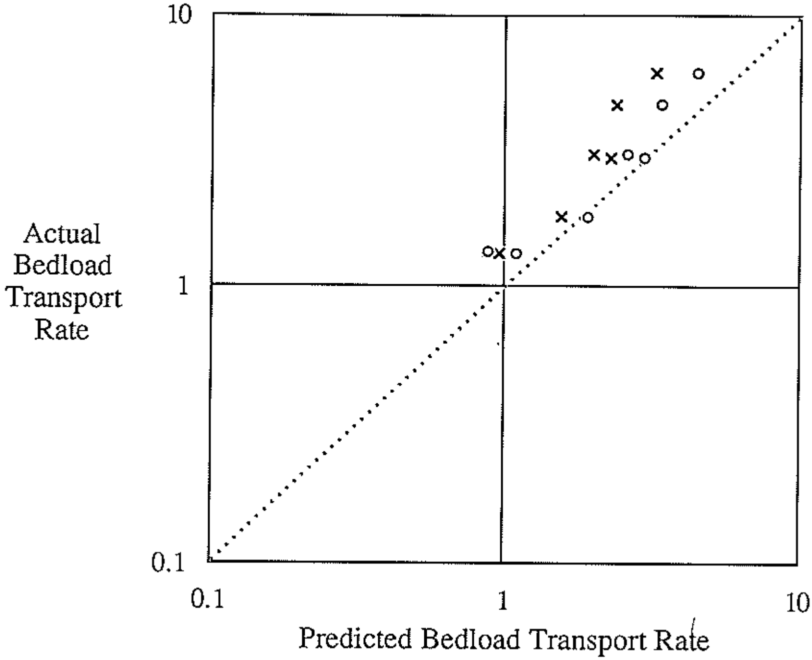


FIG. 7—Bedload transport rate predictions for the steady flow experiments. Open circles are for the Bagnold (1980) equation, crosses are for the Schoklitsch (1962) equation. Plotted values are specific submerged mass bedload transport rates in kg $m^{-1}s^{-1} \times 10^3$.

This is reflected by the greater than unity exponent of the regression equation for actual versus predicted bedload discharges:

$$q_b \propto [\text{Schoklitsch (1962) prediction}]^{1.29} \quad (6)$$

The 3/2 power-law dependence of bedload transport rate on excess specific stream power which is the basis of the Bagnold (1980) equation can be re-expressed in the following form:

$$\text{Bedload transport rate} \propto S^{1.5}\,(q-q_o)^{1.5} \quad (7)$$

Expressed in this form it is clear that the Bagnold (1980) equation predicts a stronger dependence on stream power than the Schoklitsch (1962) equation which has:

$$\text{Bedload transport rate} \propto S^{1.5}\,(q-q_o) \quad (8)$$

A separate regression of bedload transport rate on excess specific stream power yielded:

$$i_b \, \alpha \, (\omega\text{-}\omega_o)^{1.42}, \; R^2 = 0.89 \qquad (9)$$

From this regression and the previous regressions for the two prediction equations it is concluded that 3/2 power of excess specific stream power is a useful empirical basis for predicting bedload transport rates.

## RESULTS FOR UNSTEADY FLOW

The mean bedload transport rates for the eleven unsteady flow experiments are shown in Table 2. Considerable differences in the mean bedload transport rates were obtained for replica experiments, and non-parametric statistical analysis showed that for none of the replica experiments could it be stated with a sufficient degree of confidence that the data represented samples from the same population. Treating the data from replica experiments as samples from different populations implies that some factor other than the controlled variables (discharge, slope, sediment) is important in determining the bedload transport rate. The influence of channel morphology on bedload transport is well accepted if poorly understood, and this factor must be quantified to define the bedload transport condition (e.g. Ashmore, 1988). Braided channel form is difficult to quantify and in this study insufficient measurements were made to identify a relationship between bedload transport rate and channel form. Since bedload transport rate is dependent on hydraulic flow conditions, useful descriptions of braided rivers must quantify channel form rather than planform geometry.

Under a given flow regime a range of bedload transport conditions can occur, each associated with a different channel form and each of a different stability. In this study neither the range nor the stability of these different conditions were known, and thus the best estimate of the long-term average bedload transport rate for each regime was simply the mean of the different rates measured (Table 2). While the replica experiments show that channel form has a statistically significant influence on bedload transport rate, the percentage differences between run and regime average bedload transport rates (Table 2) suggest that, within a braided environment, the variations in channel form that occur in the medium term (order of years) cause changes in the average bedload transport rate of the order of only ±10%. Hence, from a river engineering perspective, variations in braided channel form in the medium term are not very important.

To describe excess stream power and excess discharge for the bedload transport data from the unsteady flow experiments, a representative discharge for each flow regime was required. Without prior knowledge of variation of the bedload transport rate with discharge it is impossible to determine what discharge represents the average bedload transport rate, so for simplicity the mean flow rate for each regime was used (Table 2).

Using these mean flow rates an assessment of the Bagnold (1980) and Schoklitsch (1962) bedload transport rate prediction equations were made as for the steady flow data. A representative flow width of 0.68 m, which corresponds to a flow of 0.7 $l \, s^{-1}$ was used, a simplification made in the absence of information of how flow width varied with discharge. Similarly a representative flow depth of 0.009 m was used in the calculations for the Bagnold (1980) equation. For

TABLE 2—Results from unsteady flow runs.

| Regime No. | Run No. | Mean Bedload Transport For Run (kg m$^{-1}$s$^{-1}$) | Mean Flow For Regime (l s$^{-1}$) | Mean Bedload Transport For Regime | % Difference Run/ Regime |
|---|---|---|---|---|---|
| XA1 | XA10 | 1.73 | 1.16 | 1.48 | + 17.3 |
| | XA11 | 1.22 | | | - 17.3 |
| XA2 | XA20 | 1.07 | 1.01 | 1.07 | – |
| XB1 | XB10 | 4.45 | 1.16 | 3.93 | + 13.2 |
| | XB11 | 4.00 | | | + 1.8 |
| | XB12 | 3.74 | | | - 5.0 |
| | XB13 | 3.54 | | | - 10.0 |
| XB2 | XB20 | 3.29 | 1.01 | 3.01 | + 9.5 |
| | XB21 | 2.72 | | | - 9.5 |
| XB3 | XB30 | 2.34 | 0.91 | 2.44 | - 4.1 |
| | XB31 | 2.54 | | | + 4.1 |

Average % difference = 9.2

these data the Bagnold (1980) equation under-predicted by an average of only 1%, while the Schoklitsch (1962) equation gave an average under-prediction of 17%. Measured and predicted values are plotted on Figure 8.

The data yielded the following regressions:

$$i_b \; \alpha \; [\text{Bagnold (1980) prediction}]^{1.03} \qquad (10)$$

$$q_b \; \alpha \; [\text{Schoklitsch (1962) prediction}]^{1.19} \qquad (11)$$

$$i_b \; \alpha \; (\omega\text{-}\omega o)^{1.53}, \; R^2 = 0.99 \qquad (12)$$

As with the steady flow data the stronger dependence on excess steam power that is implied by the Bagnold (1980) equation fits the data trend better than that of the Schoklitsch (1962) equation. The agreement with the empirical exponent found by Bagnold (1977) for many data sets is striking. The excellent agreement with the Bagnold (1980) equation was obtained using average flow parameters, as is usually necessary for braided rivers due to the difficulties of describing the hydraulic conditions for even a short reach. This encouraging result suggests that the use of the Bagnold (1980) equation for predicting braided gravel-bed river loads deserves further investigation.

## FLOW ABSTRACTIONS

One of the main objectives of the unsteady flow experiments was to investigate the effects of flow abstractions on the sediment transport capacity of a braided river system. Flow abstraction was simulated by reducing the input flow regime.

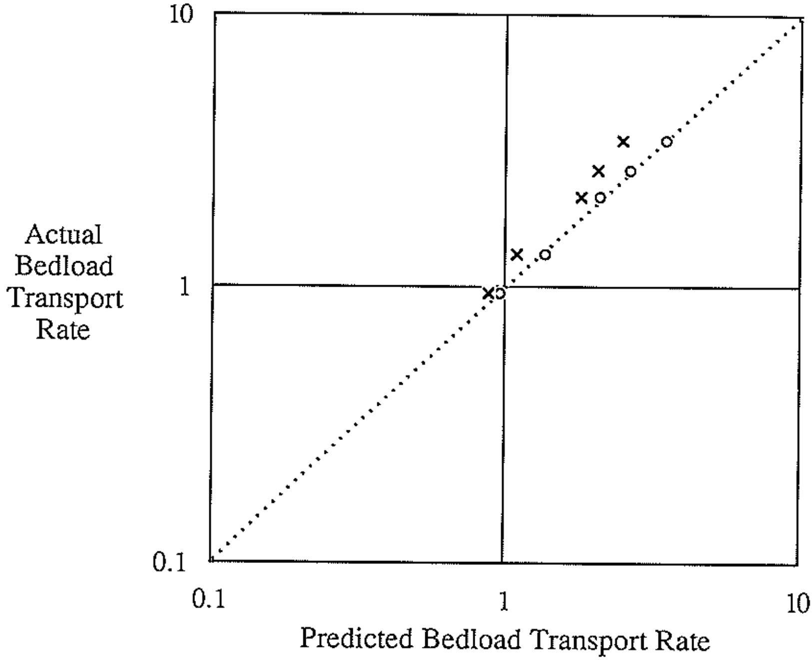


FIG. 8—Bedload transport discharge predictions for the unsteady flow experiments. Open circles are for the Bagnold (1980) equation, crosses are for the Schoklitsch (1962) equation. Plotted values are specific submerged mass bedload transport rates in kg $m^{-1}s^{-1} \times 10^3$.

Constant flow reduction values were derived by calculating percentage reductions in above-threshold (or available) energy dissipation. The energy reduction values used are comparable to those of abstraction rates proposed for the Rakaia River, New Zealand.

A theoretical relationship between reduction in sediment transport capacity and reduction in above-threshold energy dissipation was derived, based on the Bagnold (1980) equation.

Flow depth varies little with discharge in braided rivers, and for constant flow depth and grain diameter, the Bagnold (1980) equation can be written as:

$$i_b = K_1 (\omega-\omega_o)^{1.5} \qquad (13)$$

where $K_1$ is a constant. Multiplying by width gives an expression for total bedload transport rate:

$$I_b = K_1(\omega W-\omega_o W)^{1.5}/W^{0.5} = K_1(\Omega-\Omega_o)^{1.5}/W^{0.5}$$

if width is constant, then the equation can be reduced to:

$$I_b = K_2(\Omega-\Omega_o)^{1.5} \quad (14)$$

where $K_2 = K_1/W^{0.5}$. $\Omega_o$ is only a constant for a given constant width. Total stream power ($\Omega$) is taken herein as $\rho QS$, and is equivalent to the energy dissipation rate of flowing water per unit channel length. Hence if the above relationship is integrated with respect to time, the following is obtained:

$$V = K_3.E^{1.5} \quad (15)$$

where:

V = total volume of sediment moved, i.e. the bedload transport capacity,

E = total available (above threshold) energy, and

$K_3$ = a coefficient involving $K_2$, density factors to convert submerged mass to bulk volume, and the square root of the time period of integration.

Using a prime to denote values for the modified regime, the relationship between proportional reduction in bedload transport capacity ($V_R$), and proportional reduction in available energy ($E_R$) can be obtained:

$$\frac{V - V'}{V} = \frac{E^{1.5} - E'^{1.5}}{E^{1.5}}$$

let: $V_R = \dfrac{V - V'}{V}$, $E_R = \dfrac{E - E'}{E}$

therefore: $V_R = \dfrac{E^{1.5} - E'^{1.5}}{E^{1.5}}$

and: $V_R = 1 - (E' / E)^{1.5}$

or: $$V_R = 1 - (1 - E_R)^{1.5} \quad (16)$$

Hence if the reduction in available energy caused by a flow abstraction can be assessed, then the above relationship predicts the reduction in the bedload transport capacity. The accuracy of such predictions will be affected by departures from the assumed constant flow width and flow depths and by deviations from the strength of dependence of bedload transport rate on excess stream power assumed by using the Bagnold (1980) equation. This explicit relationship is an improvement on the approximate method of Davies (1988) for predicting relative changes in bedload transport capacity.

The five unsteady flow regimes had equivalent flow widths and hence their bedload transport data can be used to obtain an empirical plot of bedload transport capacity reduction versus energy reduction. This plot is shown on Figure 9 together with the theoretical relationship derived above. Calculations are summarised in Table 3. Since the data set fits the Bagnold (1980) equation very well, the

TABLE 3—Flow abstractions

| Flow Regime Pair | Bedload Transport Rate % Reduction | Available Energy % Reduction |
|---|---|---|
| XA1 & XA2 | 27.7 | 20.4 |
| XA1 & XB1 | 62.3 | 46.6 |
| XA1 & XB2 | 50.8 | 35.8 |
| XA1 & XB3 | 39.3 | 25.7 |
| XA2 & XB1 | 72.8 | 57.7 |
| XA2 & XB2 | 64.5 | 48.9 |
| XA2 & XB3 | 56.1 | 40.9 |
| XB1 & XB2 | 23.4 | 16.8 |
| XB1 & XB3 | 37.9 | 28.1 |
| XB2 & XB3 | 18.9 | 13.5 |

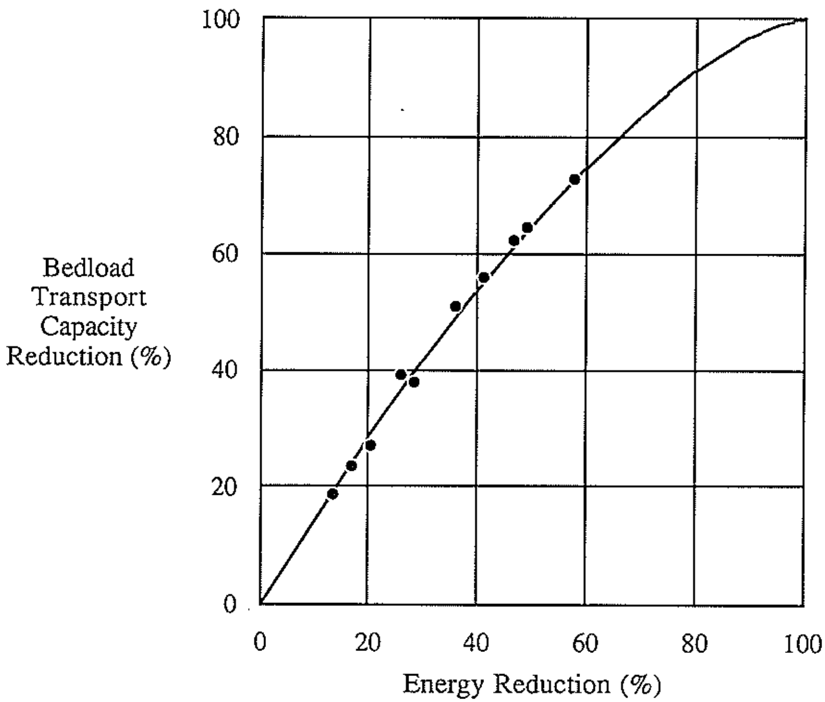


FIG. 9—Bedload transport capacity reductions; with both the experimental data and the theoretical curve plotted.

good fit to the derived relationship was not surprising. The best fit regression for the data is:

$$V_R = 1 - (1 - E_R)^{1.54},\ R^2 = 0.99 \qquad (17)$$

The abstraction modified flow regimes were designed on 20% and 40% reductions in available energy, but because the initial method employed was only approximate the actual reductions differed. The nominal 20% available energy reduction regime gave actual reductions of 20.4% for the lower slope, and 16.8% for the steeper slope. The nominal 40% available energy reduction regime in fact caused only a 28.1% reduction for the steeper slope. Excess stream power is a good predictor of bedload transport rate, so assessing the reduction in available energy caused by a modification to a river's flow regime allows a prediction of the likely reduction in the bedload transport capacity of the river.

## CONCLUSIONS

The following conclusions can be drawn from the investigations:

(i) it is possible to achieve good hydraulic similarity between real and model braided channel systems.

(ii) excess stream power is a useful predictor of bedload transport rates in braided channels, and the empirical 3/2 power-law dependence of Bagnold (1977) is reliable.

(iii) the Schoklitsch (1962) bedload transport rate prediction equation reasonably predicts bedload transport rates in laboratory braided channels, however the Bagnold (1980) bedload transport rate prediction equation is more accurate, even for unsteady flow conditions using averaged hydraulic variables. The Bagnold (1980) equation for predicting braided river bedload transport rates therefore deserves further investigation.

(iv) using the excess stream power descriptor of Bagnold (1977, 1980), it is possible to reliably predict relative reductions in bedload transport capacity of braided rivers caused by flow abstractions.

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