Journal of Hydrology (NZ) 35(2): 213-237, 1996

Sediment dispersion and duration of storage in a model braided river

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Abstract

Repeated measurements were made of sediment transport and sediment storage changes in a self-formed braided river model. Dyed sediment was introduced to the model for one hour after 25 hours of the experiment and its redistribution noted during a further 25 hours. Only 37% of the total input had been exported from the model by the end of the experiment, and the output appeared to have reached an asymptote. The sediment within the river bed was considered in terms of four storage reservoirs (active, semi-active, inactive and passive). Conventional residence time estimates for each of these show how changes in the residence times primarily reflect the sediment transport rate. A method is described for separating sediment exchanges into dynamic (where the sediment moves) and static (where the sediment changes classification as the reservoir boundaries move) components. The relative proportions of these components vary with the sediment transport rate and reflect the same channel and bar processes which are responsible for the fluctuations in transport. The dynamic component of sediment exchange is used to re-estimate residence times. These show greater variation in response to changes in the distribution of material between reservoirs than with the earlier technique. These results show that the peak of a mega-scale bedload pulse in the model was predominantly associated with the export of material from the active reservoir. As the transport rate fell, increasing amounts of the output sediment were derived from the inactive and, more importantly, the semi-active reservoirs. The separation of sediment exchanges into static and dynamic components will be an important development in the modelling of sediment storage in braided rivers.

Introduction

The development of bedload pulses in braided stream models has been demonstrated in a number of recent studies (e.g. Ashmore, 1988; Hoey and Sutherland, 1991; Young and Davies, 1991), and they have been explained with reference to changes in channel morphology (Ashmore, 1991; Hoey and Sutherland, 1991). Various scales of pulsed sediment output from these models have been recorded, with most attention focused on those classified as macroforms and megaforms (Hoey, 1992). Direct measurement of bedload pulses in prototype streams has been possible only at small scales, but several studies report pseudo-cyclic macroscale variations in sediment storage along the channels of braided and wandering gravel-bed rivers. In some cases these are independent of valley topography (Griffiths, 1979), whereas in others topography clearly determines the location of sediment accumulations (Church, 1983). These zones of sediment accumulation have been described as 'sedimentation zones' by Church and Jones (1982), and are separated by 'transfer reaches' within which there is little sediment storage.

Although bedload pulses are easily identified in braided stream models, relating them to specific processes within the channels has proved more difficult. For example, Ashmore (1991), Hoey and Sutherland (1991) and Young and Davies (1991) each concentrate on different aspects of channel morphology as being predominant in causing bedload pulses. While there are similarities between their descriptions, there are enough differences to suggest that different processes predominate under different sediment and hydraulic conditions. Statistical similarity of bedload transport time series in the different experiments is indicative of a form of equifinality (Hoey, 1992). In prototype studies, localised sediment accumulations (bed waves) have been described in comparatively few studies, and their identification often relies on surrogate measures of channel pattern (e.g. Beschta, 1983; Davies, 1987). Discussion of how bed waves form, translate downstream and are modified through time has often been speculative.

The understanding of the mechanisms by which bedload pulses develop, and the history and development of sedimentation zones are dependent on detailed description of the processes of sediment transfer within braided river beds. The experiment described below aimed to provide such description and to begin to quantify the pathways taken by sediment as it is transferred through a braided stream. In order to do this sediment storage within braided stream beds is considered in terms of storage reservoirs.

Reservoir Theory Applied to Sediment Storage

Different sedimentological zones can be identified in the beds of braided streams. Williams and Rust (1969) identified four such zones, differentiated on the basis of elevation. In the present study the bed is divided according to the relative mobility of the sediment, rather than by elevation, although these two measures are highly correlated. The approach taken follows that of Kelsey *et al.* (1987) who divided the bed of a gravel stream into four units, named active, semi-active, inactive and stable. Kelsey *et al.* differentiated the reservoirs according to the recurrence interval of the flow under which each was mobilised. In the present work, total water discharge is held constant, so the definition of the reservoirs is based on the presence and intensity of bedload transport. These definitions are only readily applicable to laboratory channels, and alternative classifications may be required in the field (e.g. Wathen, 1995). The four reservoirs are defined as:

Active:	sediment stored within bedload transporting channels
Semi-active:	sediment stored within submerged bars and channels which do not have appreciable bedload transport over and through them
Inactive:	sediment stored within bars which are emergent from the water
Passive:	sediment which remained within the undisturbed banks of the channel formed prior to the experiment.

Apart from the name "passive reservoir", these are the definitions used previously (Hoey and Sutherland, 1991). The potential transfers of sediment are illustrated by Figure 1. With the given definition of the passive reservoir, no sediment can be transferred into that state. These reservoirs can be used in the investigation of both the redistribution of sediment delivered to the river reach from upstream, and the transfers of sediment both within a reach and out of that reach.

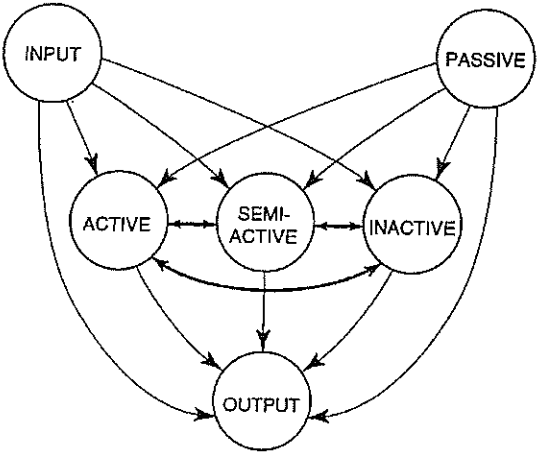

Figure 1 Schematic representation of the exchanges of sediment within the sand tray. Potentially bi-directional transfers are shown with bold arrows.

There are two ways in which sediment can change storage reservoirs, *static transfers* and *dynamic transfers*. The former occur when a change in the water surface elevation relative to the sediment necessitates reclassification in terms of the above reservoir definitions. The sediment does not move during this process. Dynamic transfers involve the physical movement of sediment from one reservoir to another. Static transfers are frequent in active gravel-bed rivers; for example, if a channel migrates across its floodplain, some sediment gradually becomes further removed from the channel and thus becomes part of a less active reservoir without moving.

The sediment stored within a reservoir at a particular time can be described in a number of ways. The most useful are the distributions and averages of the age of sediment stored within the reservoir, and the distributions and averages of transit times of the sediment leaving the reservoir. The transit time is the time which a particle spends within a particular reservoir, and its average is often referred to as the residence time for the reservoir (Dietrich *et al.*, 1982). It is also possible to look at the sediment in terms of its origin (i.e. the reservoir which it occupied immediately prior to entering the present reservoir). Accurate determination of any of these properties and of the exchange between reservoirs is dependent on being able to trace a significant number of particles through the system, although in some cases accurate estimates can be obtained from the age distribution of vegetation or lichens on different deposits (e.g. Everitt, 1968; Dietrich *et al.*, 1982; Nakamura, 1986; Macklin and Lewin, 1989) or from repeat field mapping (Kelsey *et al.*, 1987).

In a model study the volumes of sediment in different reservoirs can be accurately determined. The following study uses dyed sand introduced into a model stream to determine sediment transfer pathways. By making assumptions about the nature of sediment evacuation from the modelled stream it is possible to quantify the residence times for different reservoirs. These results are then used to assess the likely sources of sediment involved in producing bedload pulses, and in the phases of aggradation which occur between pulses.

Methods

The experimental run used for this experiment is Run 2 of Hoey and Sutherland (1991). The run used the 14.2 × 3.0m University of Canterbury sand tray and was of 50 hours duration. The sediment forming both the bed and the feed material was unimodal sand with median size (D_{50}) of 0.57mm and σ_g ($=(D_{84}/D_{16})^{0.5}$) of 2.7. This distribution was not based on a specific prototype, but suggests a model length scale (λ_L) of 1:30 to 1:50 relative to a range of New Zealand braided rivers. The related scales for time (λ_T) and discharge (λ_Q) are 1:5.5 to 1:7, and 1:5 000 to 1:18 000 respectively. The initial bed slope was 0.01, and the constant water discharge was 1.9×10^{-3} $m^3 s^{-1}$. Sediment was fed in every 15 minutes at the top of the channel at a rate equal to the mean output rate from an earlier run with identical initial conditions (2.5 g s^{-1}). A braided channel pattern became established during the first 20 hours of the run, after which the flow was shut off every 4 hours for surveying and sediment sampling (more frequent shut-downs would have improved data resolution, but could have disturbed the bed). Surveyed cross-sections were located 1m apart, and vertical photographs were taken both when the flow was running and shut off. After 25 hours of the run the sediment feed for the following hour was replaced by fluorescently dyed sand, with the same grain size distribution as that used for the feed in the remainder of the experiment. This injection procedure represents a compromise between an ideally instantaneous injection and the need to have a reasonably large volume of dyed sediment for ease of relocation. Dispersion throughout the sand tray was rapid, although initially concentrated within the two most active reservoirs.

The median bed material size was 0.57mm, and material was divided into > 0.6mm and < 0.6mm fractions which are discussed separately. This separation is based on the closest available sieve size to the median grain size. Samples were taken from the collected bedload material at the end of the tray, and from within the tray. The concentration of dyed sand in these samples was measured using different techniques for the >0.6mm and <0.6mm size fractions. A sub-sample of the collected sediment was sieved through a 0.6mm sieve, and all the dyed grains in the larger fraction removed. These were then weighed to a precision of 1×10^{-7} kg. The finer fraction was further sub-sampled until a sample of about 1000 grains remained. The number of dyed grains within this sample was counted, and the percentage by mass obtained by assuming that each of these grains had the mass of the median size of the <0.6mm part of the size distribution (this median is 0.322mm having a mass of 4.63×10^{-8} kg for a spherical grain).

Results and Analysis

Output of Dyed Sand

Following the input of the dyed sand there was a period of slowly decreasing sediment transport rate (Fig. 2a). The output of the dyed sand

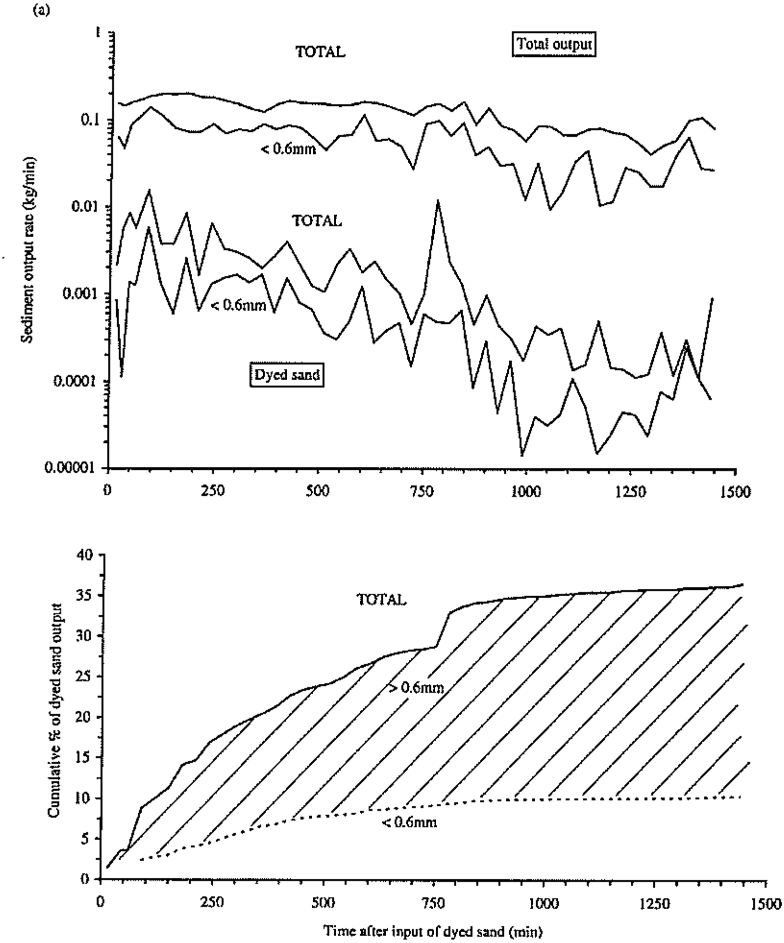

Figure 2 Output of sediment from the sand tray. (a) output rates for total sediment (dyed plus un-dyed) and dyed sediment. The total sediment output rate is described by the equation $G_b = 0.203e^{-7.60\times10^{-4}t}$ [r^2= 0.68; $p<0.001$], where G_b is the sediment output rate (kg min^{-1}), and t is the time after the input of dyed sand (min). There is no significant change through time in the proportion of total output which is <0.6mm (0.44 ± 0.042). The decline in the dyed sediment output rate with time is given by $G_b = 0.0074e^{-2.70\times10^{-3}t}$ [r^2 =0.73; $p<0.001$]. Again the relative proportions of sediment in the two size classes show no significant change through time, and the proportion in the lower class is taken as 0.33± 0.064; (b) output of dyed sediment as a percentage of the total volume of dyed sand introduced (transit time function).

from the tray also declined through time, following a negative exponential trend. A significant residual at 780 minutes is caused by a rise in the output rate of dyed sand >0.6mm which lasted for four 30-minute time periods. The cumulative transit time function (Fig. 2b) also shows the declining output of dyed sediment with time, the apparent asymptote being at about 37% of the total input. The episode of increased output of dyed sand at about 780 minutes suggests that more than 37% of this material would have eventually been output from the tray. Although the outputs of both dyed sand and total sand follow similar trends, the correlation between them is relatively weak ($r^2=0.37$) indicating that the processes generating peaks in the total transport rate are not necessarily those generating the peaks in the transport of dyed sand.

The equation for the output rate (G_b; kg min^{-1}) of dyed sand through time can be used estimate the mean transit time, the time to total flushing of the dyed material from the sand tray and the time for various percentiles of the dyed material to be output. In general terms the equation takes the form

$$G_b = ae^{-bt} \qquad (1)$$

in which a and b are constants and t = time (min). The total output of material is obtained from

$$\Sigma G_b = \int_0^\infty G_b.dt = \frac{a}{b} \qquad (2)$$

The time taken, t, for a proportion, p, of the total output to have occurred is determined from

$$\int_0^t G_b.dt = p\int_0^\infty G_b.dt \qquad (3)$$

which from equation (2) is equal to pa/b. Re-arranging, time t is given by

$$t = \frac{-1}{b}\ln(1-p) \qquad (4)$$

The values of $a=7.36 \times 10^{-3}$ and $b=2.70 \times 10^{-3}$ were obtained by regression analysis. As the time is known without error this is equivalent to a functional relationship and it is valid to re-arrange the regression equation as required by equation (4).

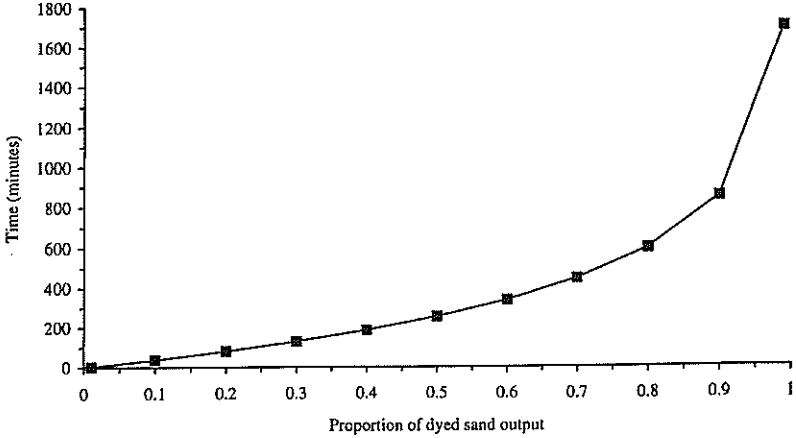

Figure 3 Time required for a given proportion of the total dyed sand to be output. Note the rapid increase in time for $p > 0.9$, which indicates the length of measurement period required for sediment tracing experiments to yield reliable results.

The total output of material (equation (2)) is 2.73kg or 30.4% of the dyed sand which was input to the tray. The peak in dyed sand output (Fig. 2) between 750 and 780 minutes indicates brief accelerated flushing which may occur irregularly. The total output will therefore exceed the 30.4% figure as is suggested by the apparent asymptote at 37%. If flushing of this 30.4% of material is assumed complete when 99% of it has been evacuated ($p=0.99$), equation (4) gives a value of about 1710 minutes. Applying equation (4) to $0.01 \leq p \leq 0.99$ (Fig. 3) shows how the percentiles of the transit time distribution function increase rapidly, above about $p=0.8$. This provides an indication of the time required for sediment tracing experiments to yield comprehensive results.

Redistribution of Dyed Sand within the Tray

The redistribution of the dyed sediment within the tray was observed and assessed by sediment sampling when the flow was shut down every 4 hours. Samples were taken to a depth of 10mm every 2m along the tray. Each channel and semi-active bar on a sampled cross-section was sampled separately. During initial dispersion (Fig. 4a) sediment was deposited within bedload transporting channels and on the surfaces of those bars over which some bedload transport was occurring. The density of dyed sand decreases downstream and is greater in the channel towards the left bank side of the active bed than in the right side channel through which

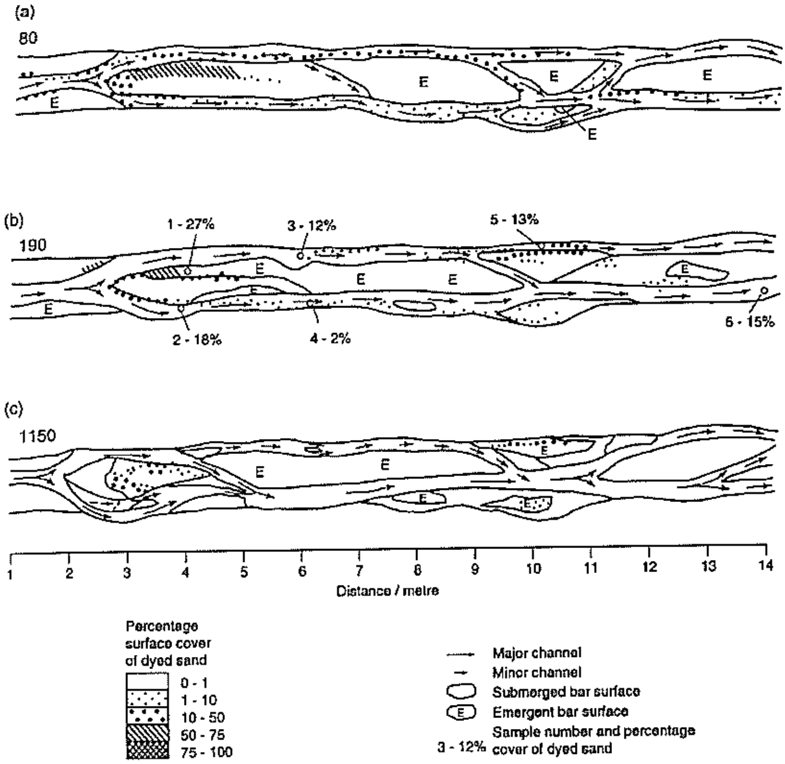

FIGURE 4

Figure 4 Distributions of dyed sediment at: (a) 80; (b) 190; and, (c) 1150 minutes after input.

both water and bedload discharges were greater. After a further 110 minutes (Fig. 4b) the concentrations visible on the surface had been considerably reduced. Concentrations measured within the uppermost 10mm of the sediment reveal considerable local variability, which was also reflected in the grain size distribution of the dyed sediment at the different sites. Five of the samples (numbers 1,2,3,5, and 6) have concentrations in excess of 10% (Fig. 4b). Each of these has been subject to a particular sequence of deposition and erosion which account for these concentrations. Sample 2 has a concentration of 18% of which 99% is coarser than 0.6mm. Most of this sediment was deposited within this channel soon after the input of the dyed sand, but was then buried by some of the subsequent sediment feed material. A short-lived phase of degradation within this channel re-exposed the dyed material, from which any finer sediment had been winnowed, as it was by this time located close to the thalweg of the major channel. It is notable that the concentration of dyed sand in the next sample downstream (sample 4; 1.9%) is low. Sample 1 has a high concentration (27%), of which 52% was <0.6mm. This area of bar was subject to shallow flows during the 2 hours after the input of the dyed sediment. The dyed sediment in the sample was transported onto the bar at this time, and deposited by the shallow flows which were not competent to move bedload once on the bar surface. No burial occurred as the volume of water moving across the bar surface was reduced. Samples 3 and 5 lie in a channel into which a considerable amount of dyed sand was moved soon after its input, and the concentration remained high due to the progressive reduction in flow through this channel by this time. Finally, sample 6 was from a location recently re-activated by the main channel. Some dyed sand was deposited in this channel soon after its input to the tray. The channel then widened as it eroded its left bank, and the area from which sample 6 was taken became occupied by a shallow submerged bar. This bar was removed by the channel becoming straighter prior to the time of sampling.

Within the subsequent 760 minutes the dyed material dispersed considerably, and there were no concentrations measured at over 2%. Some higher surface concentrations remained, notably in the left bank channel at about 10m (Fig. 4c). That these areas exist after such a time is again a consequence of changes in the active channel. Note especially the change through time in channel positions in the uppermost 4m of the tray. The changes in channel position and shape here left some of the dyed sediment from this area unaffected while remobilising other parts of it.

Volumes of Stored Sediment and Residence Times

After the input of the dyed sand there were three general phases of sediment output. For the first 270 minutes there was net degradation within the sand tray as a whole, followed by a period with little net change which lasted until 840 minutes. A phase of aggradation then followed until the conclusion of the experiment after 1500 minutes (Fig. 2). The degradational phase involved net output of 8.2kg of sediment, equivalent to 0.3 mm of degradation across the entire bed. The aggradational phase involved 59.5 kg, equivalent to 2.2 mm of uniform aggradation. Although these averaged figures conceal considerable variation within the sand tray, averaged data can be used to characterise the net changes in the individual sediment storage reservoirs (Hoey and Sutherland, 1991). The phase of this experimental run after the input of the dyed sand is consistent with the generalised relationships between net sediment storage changes and the relative volumes stored in individual reservoirs identified in Table I of

Hoey and Sutherland (1991). During the degradational phase the inactive reservoir gains material from the active and semi-active reservoirs by both static and dynamic transfers of material. Aggradation sees the reverse occurring, such that by the end of the run no inactive reservoirs remained.

Direct computation of the residence time for a reservoir depends on having the transit time distribution function (Dietrich *et al.*, 1982). In the absence of information from natural or artificial tracer materials this can only be approximated by assuming that the residence time is a function of the volume and flux of sediment from the reservoir. These volumes can be readily measured, but the fluxes require long term measurements. For all but the active reservoir there are no true fluxes as these are not significantly greater than zero by definition. Kelsey *et al.* (1987) resolve this by assuming that the residence time depends on the sum of the volumes in a particular reservoir and all less active reservoirs. This is an implicit way of incorporating the reduced flux for the reservoirs other than the active. That these reservoirs have a flux at all is dependent upon the transfer of sediment between reservoirs. Residence times are calculated as follows:

$$\begin{aligned}
RT_a &= v_a / \overline{Q_t'} \\
RT_s &= (v_a + v_s) / \overline{Q_t'} \\
RT_i &= (v_a + v_s + v_i) / \overline{Q_t'} \\
RT_p &= (v_a + v_s + v_i + v_p) / \overline{Q_t'} \qquad (5)
\end{aligned}$$

where RT_j = residence time for the jth reservoir (min), v_j = volume of sediment stored in the jth reservoir at time t (m^3), and $\overline{Q_t'}$ = mean net flux rate for the time period t to t+Δt ($m^3 min^{-1}$). The net flux is the total output rate minus the throughput rate of sediment fed into the tray during the time period. Variations in residence times during an experiment can be attributed to either the changing volumes of material in storage or to the changing flux (Fig. 2). This can be allowed for by calculating the residence times using the flux from the first time period considered and assuming that these provide a direct measure of the impact of the stored volumes on the residence time. The material output from the sand tray can be divided into the proportions derived from each of the four reservoirs (ϕ_j) by using

$$\phi_j = (1 / RT_j) / \Sigma(1 / RT_j) \qquad (6)$$

Residence times for the three non-passive reservoirs were calculated and scaled by the residence time for the active reservoir in the first time period considered (Fig. 5). The residence times inevitably become longer as reservoir activity decreases, with minor alterations in their relative values occurring in response to changes in the sediment storage pattern within the tray. Between 900 and 1000 minutes the mean output rate from the tray fell by over 50%, producing an increase in residence time for all reservoirs. This stabilised more rapidly for the active reservoir than for the others. The separation of residence time into volume effects and flux effects (Fig. 5) indicates that these increases are largely due to the change in output rate, although the exchanges of sediment between the active and semi-active reservoirs associated with degradation and aggradation have minor effects during the first and last measurement periods.

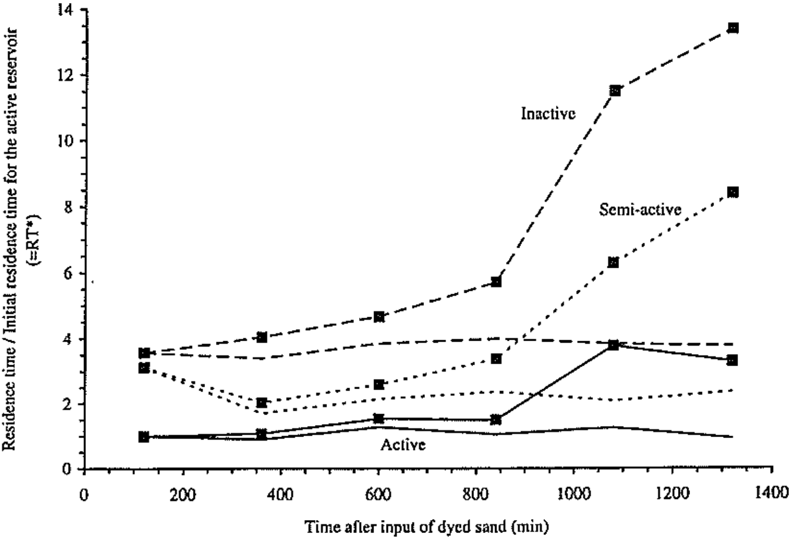

Figure 5 Relative residence times for different storage reservoirs. RT* is the residence time for reservoir j at time t, scaled by the residence time for the active reservoir at the first time period. Two lines are shown for each reservoir. The upper line (with symbols) shows the calculated residence times. The lower line (without symbols) shows the estimated residence times assuming that the sediment output rate had remained constant for the duration of the experiment at the value measured during the first time period. The space between the two lines provides an indication of the importance of the changing flux rate to the overall residence time.

The source of material which was being output underwent little change during the experiment. The active reservoir contributed an average of 48% (95 % confidence interval ±2.6%) of the output with 27 (±2.6)%, 18 (±0.8)% and 7 (±0.2)% coming from the semi-active, inactive and passive reservoirs. The throughput of feed material is not considered here. For the first time period this is known from the dyed sand to represent about 15% of the total, but how this changed through time cannot be assessed.

Exchanges of Sediment between Storage Reservoirs

The concept of a residence time for reservoirs other than the active reservoir implies the exchange of sediment between reservoirs. The differentiation of these exchanges into static and dynamic components would assist in developing a more reliable definition of what is meant by a residence time. An estimate of the relative magnitudes of these two transfer types can be derived as follows. Firstly, the cross-sectional surveys for two consecutive times are plotted together (Fig. 6), and the minimum depth recorded at either time is taken as the local depth of bed activity. The reservoirs, defined as above, are superimposed on this plot and used to identify sectors of the bed which were subject to particular transfers of material. Within each of these sectors, the area of sediment above the local depth of bed activity ($A_{j,1}$) was calculated for each of the two surveys. The

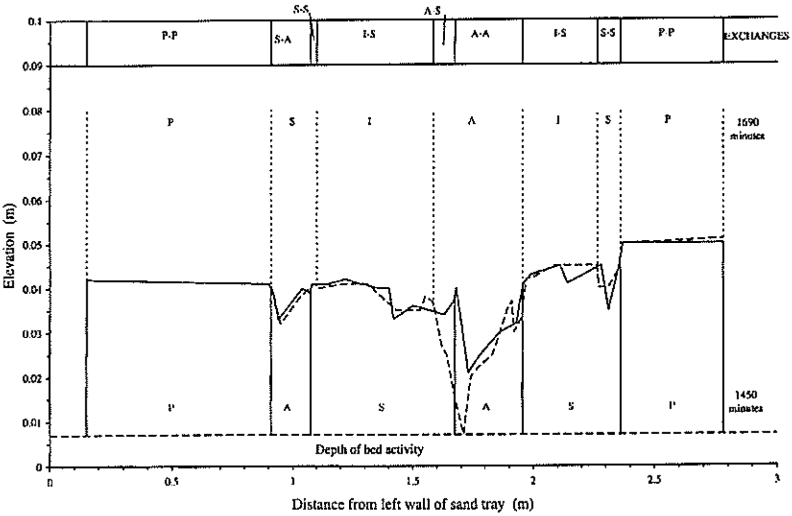

Figure 6 Identification of static and dynamic sediment transfers from cross-section survey data. A - Active reservoir; S - Semi-active reservoir; I - Inactive reservoir; P - Passive reservoir.

net change in sediment storage area ($=A_{j,t+1} - A_{j,t}$) provides a minimum estimate for the volume of dynamic sediment transfer. This is necessarily a minimum because the data allows only net changes to be recorded; phases of scour and fill which contribute to these net changes cannot be identified. Where a particular sector underwent a change from one reservoir to another, the volume of static sediment transfer is then estimated as the lesser of the two areas, $A_{j,t}$ and $A_{j,t+1}$. The assumption that the minimum bed elevation represents the depth of bed activity for the entire cross-section is thus important in these calculations. This is justified in cases such as the present experiments where the main channel(s) migrate laterally across the entire braidplain, but may be less applicable where channels are less active.

This procedure was applied to each of the twelve surveyed cross-sections for six time periods. The different sections have different histories of aggradation and degradation and are changing in different ways at the same times. It is thus difficult to relate these results directly to the rate of sediment output from the sand tray as a whole. The proportions of the different types of transfer have therefore been related to the change in sediment storage area at each individual cross-section. These changes are functions of the position of the section through a cycle of aggradation and degradation, and so have been scaled using the mean area of stored sediment during a time period, giving the parameter $A^* = (A_{j,t+1} - A_{j,t})/((A_{j,t} + A_{j,t+1}) * 0.5)$. This method yields an approximation which requires a degree of aggregation for patterns to become evident. The mean proportion of the total sediment transfer due to dynamic processes has been calculated for different values of A* grouped into categories representing 5% of the total storage (Fig. 7). The mean proportion of dynamically transferred sediment ranges between 0.27 and 0.55. Thus, static transfers are usually more significant, but this is in part an artefact of the definition of the depth of bed activity. If the method used defines a depth too close to the bed surface, the importance of static transfers will be underestimated. The inverse is also true, added to which is the fact that the estimates of dynamic transfers are known to be minima. Thus it is difficult to draw a conclusion about the absolute values shown for the relative importance of the two types of transfer. The pattern of changes in these absolute values with respect to bed aggradation and degradation can be more reliably interpreted. Figure 7 shows the expected result that dynamic transfers are least important when there is little change in bed elevation or slight degradation. Dynamic transfers are most important with a low rate of aggradation.

Figure 7 is best explained in terms of channel processes during phases of aggradation and degradation. Using the results of Hoey and Sutherland (1991), the four regions of this graph can be associated with different dominant processes. These are:

Moderate-high degradation (A<-0.1):* high sediment transport rate [dynamic transfer]; degradation, concentrated in one or two main channels [dynamic transfer]; main channels often migrate laterally, with transfer from inactive and semi-active reservoirs to the active [static transfer];

Little net change (-0.1<A<0.05):* moderate sediment transport rate [dynamic transfer]; small scale localised changes in channel and bar shape [dynamic transfer]; occasional reduction in flow through a channel transferring it to the semi-active reservoir [static transfer];

Moderate aggradation (0.05<A<0.1):* channel infilling and bar accretion [dynamic transfer]; little change in reservoir boundaries [static transfer];

High aggradation (A>0.1):* channel infilling [dynamic transfer]; spilling of water over bar surfaces transferring sediment from inactive to semi-active reservoir [static transfer]; reduction of flow in main channels, transferring from active to semi-active reservoir [static transfer].

This association of dominant process and sediment exchanges suggests a possible cycle of sediment exchange processes in concert with the cycle of aggradation and degradation in this experiment (Fig. 8). The suggested

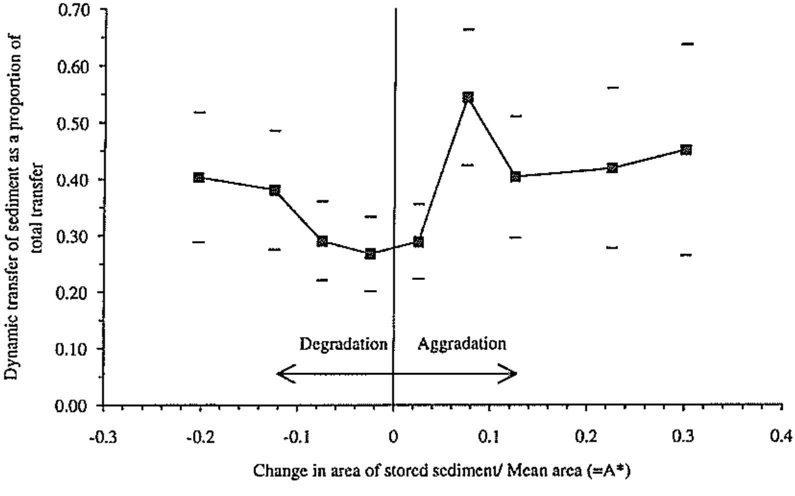

Figure 7 Relative importance of dynamic and static transfers as a function of changes in net sediment storage at a cross-section. Four regions of this graph are explained in the text [A* < -0.1; -0.1 < A* < 0.05; 0.05 < A* < 0.1; A* > 0.1].

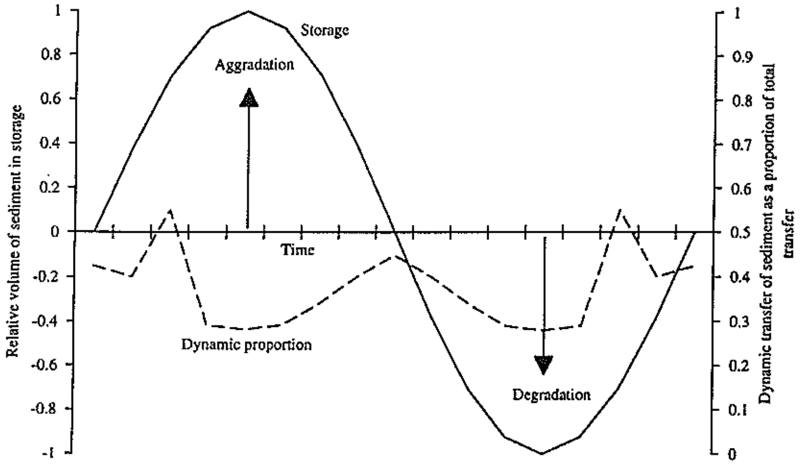

Figure 8 Idealised model for the changing importance of dynamic sediment transfer associated with a hypothetical sinusoidal cycle of aggradation and degradation (storage curve). The dynamic proportion curve was derived using the relationship of Figure 7. The timescale is arbitrary, but data from Hoey and Sutherland (1991) suggest a period of about 500 minutes for this experiment.

cycle is based on the data from Figure 7. A sinusoidal variation in sediment storage through time is assumed; as this is itself idealised, the cycle of change in sediment transfer is best considered as an idealised representation only. Figure 8 shows that dynamic transfers become most important at times of the most rapid change in sediment storage, and that this is especially pronounced during aggradation (Fig. 7).

Partitioning of Residence Times

The calculations of static and dynamic transfers of sediment allow mean residence times to be calculated directly from these known exchanges of sediment. This is a conceptual improvement over the method which relies on the mean sediment transport rate and the volume of each reservoir. The volume of material stored in each reservoir at each time period is divided by two fluxes to get separate estimates of the residence time. The first flux is the total volume of sediment dynamically exported from the reservoir within the observed time period. The second flux is the total volume of sediment statically transferred within the time period. The dynamic transfer estimate is a minimum and the residence times estimated

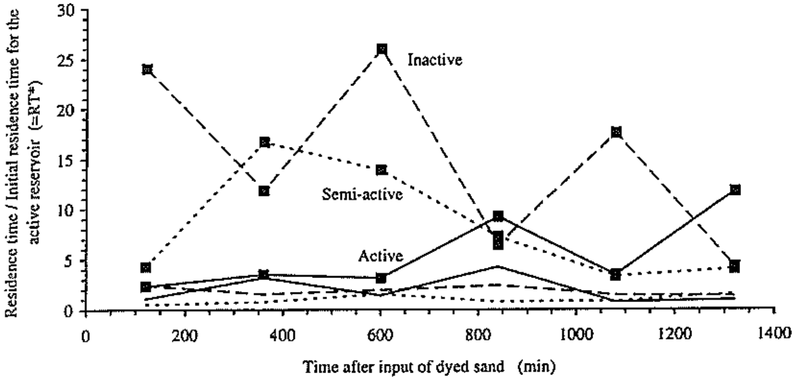

Figure 9 Dimensionless residence times for the three storage reservoirs under two assumptions. Lines with symbols are for residence times assuming that only dynamic transfers of sediment take place. Lines without symbols assume that only static transfers take place. All times have been non-dimensionalised using the same reference time as in Figure 4.

are maxima. To enable comparison with Figure 5, these times have been divided by the residence time of the active reservoir in the first time period determined using equation (5).

For all three non-passive reservoirs at all times the residence time assuming only dynamic transfers exceeds that assuming only static transfers (Fig. 9). This effect is less pronounced for the active reservoir, as this is the reservoir within which nearly all advection of material takes place. The dimensionless residence times assuming only static transfers are all less than 4, indicating the relative rapidity of sediment recycling by these processes. The especially low values for the semi-active reservoir are a direct consequence of its central position between the other two reservoirs. It exchanges material with both other reservoirs directly, whereas the others are effectively isolated from each other (although this does not preclude the direct transfer of material between the active and inactive reservoirs). The residence times for the active reservoir assuming only dynamic processes are relatively long compared to those reported in Figure 5. This indicates the extent to which the method of calculating dynamic transfers underestimates their actual magnitude for this particular reservoir. The semi-active reservoir undergoes a reduction in residence time as the net aggradation within the sand tray increases, indicating the increased significance of dynamic transfers to this reservoir during aggradation. This contrasts with the irregular pattern for the inactive reservoir which reflects the localised erosion of emergent bars.

Discussion

Processes of Sediment Redistribution

The dispersion of the dyed sand within the tray indicated that sediment dispersion in braided rivers can be considered as a two-stage process. The transit time distribution function (Fig. 2) can be approximated by an exponential curve which represents the first stage. This curve has an asymptote at only 30% of the input sediment indicating the aggradational nature of the part of the experiment reported here. The redistribution of material within the sand tray indicates a dispersive process, causing dyed sand concentrations to decrease downstream. Mosley (1978) and Pickup *et al.* (1983) have demonstrated these dispersive processes in the field. This can also be considered to be characteristic of the first stage of dispersion. The second stage is represented on the transit time distribution function by occasional peaks in sediment output. This is a stage where pockets of sediment change position within the tray as a consequence of channel and bar changes. These are irregular in time and space, leading to the development of a complex distribution of dyed sand within the tray. Once the second stage has commenced the observed patterns of dyed sand concentration must be explained in terms of the history of channel and bar development at the particular site. The residence time distribution within any particular sediment storage reservoir will thus be composed of a series of packets of sediment of different age. This becomes important when assessing the duration of storage, or examining, for example, the consequences of a change in the rate or calibre of sediment supply.

The observed patterns of sediment dispersion can be described in two ways. One way is to consider the channel as a whole and to regard sediment exchange as a stochastic process. This conforms to the observed stochastic nature of bedload transport rates in braided streams (e.g. Ashmore, 1988), and is a convenient way of identifying some regularity in sediment exchange processes (Hoey and Sutherland, 1991) and of enabling modelling of sediment transfers (Kelsey *et al.*, 1987). This concept of sediment exchanges is supported by the alternative approach, that of small scale process measurements (e.g. Ferguson *et al.*, 1992; Laronne and Duncan, 1992). These approaches are complementary, and both are required to interpret results such as the transit time distribution function of Figure 2. Process studies have shown how sediment is sorted by size within braided channels and over bars (e.g. Ashworth *et al.*, 1992a,b), but it is not yet clear how this partitioning affects the size distribution and mobility of sediment within different sediment storage reservoirs. If size sorting can be identified, then it becomes important to assess how this may affect the types and frequencies of sediment exchange between reservoirs. The present investigation has shown how the processes of sediment exchange vary between times of channel aggradation and degradation, and it is suggested that these occur in a quasi-regular way due to the existence of bed waves. Although different bar and channel development can occur under the different conditions, these have yet to be described in detail using field process studies. This issue is also important for the specification of sediment exchanges within river beds.

Estimating Sediment Residence Times

The specification of residence times is important when modelling changes through time in sediment storage using a reservoir-based method. Calculating these using equation (5) leads to the result being a function of the transport rate input to the calculation (Fig. 5). This will be adequate when the transport rate is averaged over the whole of a cycle of aggradation and degradation and is a true long-term mean. Residence times for less active reservoirs are simply indices of their volumes, which implies that a certain degree of exchange takes place between these reservoirs and the active reservoir. Separating residence time estimates into static and dynamic components is a way of evaluating residence times for periods of different transport rates and exchange processes within the bed wave cycle. The method used herein is open to criticism as it relies on the specification of a depth of bed activity which is held constant across the channel. It also ignores changes in bed geometry caused by cycles of scour and fill between measurement periods. Laronne and Duncan (1992) have demonstrated the importance of such episodes in braided channels. The evidence from Figure 9 is that, for net aggradation, static sediment transfers yield relatively short residence times. This implies that channel switching and bar evolution in active braided rivers are sufficiently rapid that the entire river bed is potentially active during a relatively short time period. Assuming that the constant high flow in the model is equivalent to the dominant discharge which occurs for about 2% of the time (Lee and Davies, 1986), the data on Figure 9 suggest a maximum residence time for static transfers of less than 5 years in a 50m wide prototype braided river. Because of this relatively rapid cycling of sediment through the different reservoirs, the flushing times (defined as the mean times for a particle from a given reservoir to enter the output reservoir in the terminology of Figure 1) for sediment from different reservoirs are approximately equal under certain conditions (Kelsey *et al.*, 1987).

The residence times estimated using dynamic transfers alone are somewhat longer and depend upon the rate of sediment transport. Thus for the active reservoir they reflect the decrease in transport rate through the experiment (Fig. 9). The impression is thus given of dynamic transfers being somewhat less significant in braided rivers than static ones, but in the prototype this will depend on the magnitude and frequency of high flow events. Although in terms of absolute volumes this appears true, there are cases where the movement of a relatively small amount of sediment by a dynamic transfer can cause a volumetrically more significant static transfer. For example, a plug of sediment may develop at the head of a branch channel (a dynamic transfer) which then leads to the sediment within that channel being transferred to the semi-active reservoir as flow and sediment transport decline. The two types of sediment transfer are thus inter-dependent.

The method described above to differentiate the two types of sediment transfer is a useful way of assessing the most important influences on residence time calculations. The relative importance of the two components of transfer is expected to vary with channel type (and in particular with the degree of lateral mobility of a channel), and has been shown to vary as a bed wave passes through a reach. The differences between this method and that of equation (5) can be illustrated using the calculations of the proportions of the output sediment derived from the different reservoirs. Results from using equations (5) and (6) can be compared with those obtained from the calculated dynamic transfers and equation (6), ignoring the relatively minor inputs from the passive reservoir and the input sediment (Fig. 10). As noted earlier there is little apparent change through the run using the method

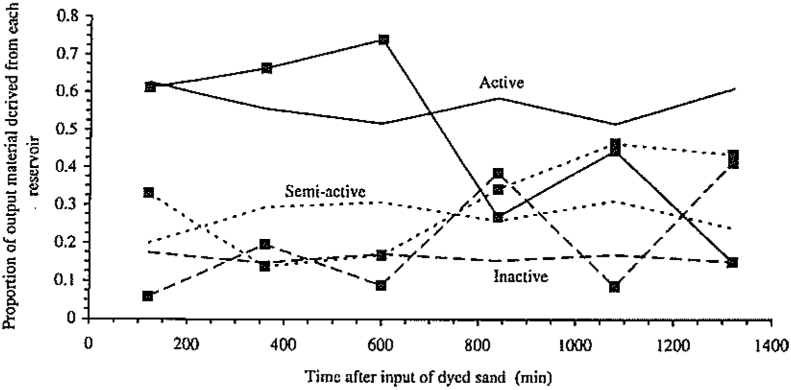

Figure 10 Sources of sediment output during the experiment. The relative contributions of the different source reservoirs are estimated directly from the residence time calculations. Lines without symbols use equation (5) and those with symbols use the measured dynamic sediment transfers. Note that throughput of material fed in at the upstream end of the sand tray and the passive reservoir are not included in these calculations.

of equation (5) whereas significant changes are apparent using the dynamic transfers, which change in their relative importance for the different reservoirs during the course of a run.

Identification of Sediment Sources

The exchanges of sediment between reservoirs during aggradation and degradation have previously been described (Hoey and Sutherland, 1991). The relative significance of static and dynamic transfers of sediment have also been identified (Figs. 7 and 8). Degradation was previously related to the incision of main channels and their lateral migration which eroded some bar deposits. Figure 8 illustrates that during the time of maximum degradation dynamic transfers are relatively significant. This is due to the incision of one or more main channels. The reduced importance of dynamic transfers during the early and late stages of degradation is due to two different types of static transfer. During early degradation there is static transfer as minor channels are abandoned and shallow bars become emergent, thus transferring material to less active reservoirs. Late degradation is characterised by lateral migration of the main channels, leading to bar erosion and the incorporation of material into the active reservoir. This is associated with the dynamic removal of some material from the bars. Dynamic transfers were also noted as being significant during aggradation. This occurs despite low sediment transport rates during this phase because there is relatively little static transfer at this time.

During the phase of degradation and relatively high sediment output rates during the first three time periods, the output material was predominantly derived from the active reservoir (Fig. 10). The semi-active and inactive reservoirs each contributed similar amounts to the total output. As aggradation occurred (until the end of the run), the contribution of the active reservoir declined from over 60% to under 45%, falling to 15% by the last measurement period. This was accompanied by a rise in the contribution of the semi-active reservoir to 47% at its peak. During aggradation the semi-active reservoir consistently increased in significance whereas the active and inactive exhibited greater variability.

Figure 10 indicates how the sources of sediment during a bedload pulse can be identified. During the peak output time sediment output is largely material directly eroded from the active reservoir. The other reservoirs make minor contributions due to lateral migration of the main sediment transporting channels. As aggradation proceeds during the low transport rate phase, most of the output sediment is derived from the semi-active reservoir. This becomes more important due to frequent and widespread static transfers of sediment between this and the active reservoir. Sediment is eroded as these transfers occur, especially as semi-active sediment is

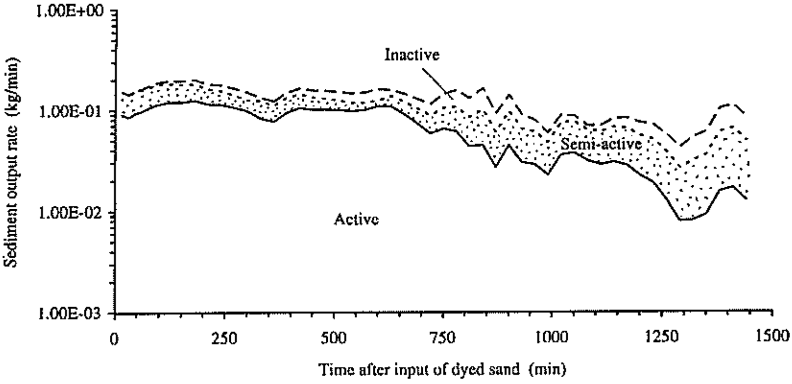

Figure 11 Partitioning of the sediment output into different source reservoirs. Lines for each reservoir are cumulative for all less active reservoirs. Note that the throughput of feed material and the passive reservoir have been omitted, and would represent up to 20% of the total sediment output at some times during the experiment.

transferred to the active which was often accompanied by incision of new minor channels. Figure 10 shows the relative amounts of sediment from the different reservoirs. When considered as absolute amounts (Fig. 11) it is apparent that the main cause of the fall in total output is a reduction in output from the active reservoir. Output derived from the semi-active reservoir increases during the low output phase, and there is a smaller increase from the inactive reservoir.

The predominance of the active reservoir in controlling sediment output is inevitable. The active reservoir is of overriding importance at the peak of the bedload pulse, and the semi-active reservoir increases in importance during the low output phase. This is another indication of the importance of static transfers during aggradation as these create the potential for dynamic removal of semi-active sediment.

Conclusions

The transit time distribution for dyed sand from the model river illustrated that sediment dispersion consists of a phase of continuous throughput at a declining rate, followed by a phase of episodic evacuation of material consequent upon changes in sediment storage within individual channels and bars. Although particular sites are subject to complex series of events which depend on the previous history of changes, some general patterns have previously been identified and related to overall channel aggradation and degradation (Ashmore, 1991; Hoey and Sutherland, 1991). These general changes in dominant process during passage of a bed wave are further reflected in the relative importance of static and dynamic transfers of sediment within that cycle. Although there are problems with the method used herein to differentiate these two, the changes in their relative importance can be explained in terms of known changes in channel and bar processes.

By considering the role of dynamic sediment transfers alone it is possible to produce better estimates for the residence time of material than those previously calculated from the volumes of sediment stored within particular reservoirs. The residence times change in response to changes in the channels which occur as a bed wave passes. They can be used to suggest that the peaks in sediment transport associated with a bed wave are caused primarily by evacuation of material from the active reservoir. During times of low sediment transport static transfers enable the dynamic transfer of more material from the semi-active reservoir which dominates total sediment transfer.

These results suggest that attempts to model sediment storage changes during the passage of bed waves should incorporate static and dynamic transfers of sediment separately, but allow for them to have some interdependence. The complexity of sediment exchange processes causes problems when attempting to model the pathways taken by particular packets of sediment or the age distribution of specific storage reservoirs. Although some success has been achieved in the modelling of bed waves (Kelsey *et al.*, 1987; Griffiths, 1993) there remains a need for further work in laboratory modelling, field documentation of bed waves, and field process studies to improve understanding of the mechanics and evolution of these features.

Acknowledgements

The experiment described herein was conducted during tenure of a New Zealand Commonwealth Scholarship. The project was assisted financially by the North Canterbury Catchment Board (now Canterbury Regional Council) and the University of Canterbury. Alex Sutherland assisted greatly in the formulation of many of the ideas contained herein, and further discussions with Burn Hockey and Bill Dietrich are appreciated.

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