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SEDIMENT TRANSPORT PROCESSES IN POOL–RIFFLE SEQUENCES

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ABSTRACT

This paper reviews the published data for sediment transport in pool–riffle sequences which suggests that a velocity or shear stress reversal hypothesis does not explain all of the published evidence of sediment transport. This conclusion is explored in more detail using observations of sediment transport from the regulated River North Tyne. Sediment transport rates at discharges of <30 per cent bankfull are initially highest on riffles. As discharge increases, sediment transport rates in pools rise sharply, and values locally exceed those on riffles. Tracing experiments using a combination of magnetic and painted tracers are used to show the downstream dispersal of fine and coarse sediments through the pool–riffle sequence. Coarser particles experience longer transport paths and faster virtual rates of travel in pools during bankfull floods. Analysis of entrainment data reveals evidence for additional restraint operating on riffles and causing higher dimensionless entrainment thresholds. An appraisal of the possible mechanisms controlling sediment entrainment, transport and deposition in pool–riffle sequences is made which reveals evidence for the operation of a combination of hydraulic, sedimentological and interactive processes. A descriptive model of sediment transport processes in pool–riffle sequences is presented.

KEY WORDS pool–riffle; sediment transport; bed structure; entrainment threshold; virtual rate of travel

INTRODUCTION

The pool–riffle sequence is a mesoscale bedform characteristic of gravel and mixed load rivers of moderate gradient (<5 per cent). Useful reviews of the hydraulics, sedimentology and morphology of the pool–riffle sequence can be found in Carling (1991), Clifford and Richards (1992) and Sear (1992a). Awareness of the importance of the pool–riffle sequence is rising as society demands more sustainable river restoration policy from river management authorities (Sear, 1994). To achieve such sustainability, however, requires knowledge of the function of geomorphological features at the fundamental level of form and process.

To date, over 100 scientific papers have discussed the pool–riffle sequence. This work can be categorized into six research themes:

1. the formation of the pool–riffle sequence
2. the maintenance of the pool–riffle sequence
3. the definition/characterisation of the pool–riffle sequence
4. the hydraulic function of the pool–riffle sequence
5. the sedimentology of the pool–riffle sequence
6. sediment transport through the pool–riffle sequence.

The transport of sediment through pool–riffle sequences has been quantitatively determined in relatively few published studies. Of these, only seven involve measurements in pools, and only five of these actually measure the transport rate in the pool, the others concentrating on the movement of tracer particles seeded in units of the pool–riffle sequence (Table I).

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Table I. Documented studies of sediment transport in pool–riffle sequences

Source	River	Method	Observations
Keller (1971)	Dry Creek	Painted tracers	Riffle tracers move further than those in pools over two floods.
Milligan *et al.* (1976)	Capehorn and Knaphorn Creeks	Bedload in pools and riffles	Bedload transport variable across pool sections. Transport rates in pools as great or smaller than riffles.
Leopold (1982)	East Fork	Bedload in pools and riffles	Bedload transport rates in pools exhibit an asymmetric cross section with maximum rates on alternate bar.
Meade (1985)	East Fork	Bedload in pools and riffles	Sand-sized bedload moves from pool to pool as discharge rises.
Campbell and Sidle (1985)	Bambi Creek	Bedload at riffles	Bedload transport rates monitored at two riffles with movement from pool inferred. Interstorm variation in grainsize and transport in and out of pool.
Ashworth (1987)	Alt Dubhaig and River Feshie	Painted tracers Bedload in pools and riffles	Transport distances greater in pool-heads and mid-pools than on riffles in floods > bankfull. Bedload transport greater in pools than riffles during bankfull floods.
Petit (1987)	La Rulles	Painted tracers	Competence in pool-head greater than riffle or pool-tail
Sidle (1988)	Bambi Creek	Bedload at riffles	Bedload transport rates into and out of a pool dominated by antecedent flood magnitude.
Sear (1992a)	North Tyne	Bedload in pools and riffles. Painted/ magnetic tracers	Bedload transport rates higher on riffles at low flows but rising more rapidly with discharge in pools. Tracer distances higher in pool-head and pool-tail than on riffles at bankfull flow.
Lisle and Hilton (1992)	Trinity River Tributaries	Fine sediment volume survey	Fine sediments collect in pool-tails in quantities determined by sediment supply, local hydraulics and residual pool volume.
Hassan (1993)	Nahel Hebron Nahel Og	Magnetic tracers	Riffle sediments remain static during large floods, pool sediments mobilised during small floods.

The conventional model of sediment transport in pool–riffle sequences envisages the removal of fine sediment from riffles at low flows into pools since velocity (or shear stress) is at a maximum over riffles (Hack, 1957, Keller, 1971; Lisle and Hilton, 1992). As discharge rises the concept of a section average velocity or shear stress reversal is evoked (*sensu* Keller, 1971; Lisle, 1979) whereby near-bed velocity or shear stress in the mid-pool exceeds that over associated riffles. Correspondingly, sediment transport capacity and competence are considered to become maximized in the pools, providing a mechanism for the routing of coarse particles from the pool to the riffle. Sedimentologically this purports to account for the observed coarsening of the stream bed at riffles and aggradation of riffles after floods (Keller, 1971; Andrews, 1979; Sidle, 1988). The evidence for the operation of this model is conflicting; Campbell and Sidle (1985), for example, document the evacuation of coarser bedload from a pool for only 15 per cent of floods sampled and during only one bankfull flood over a period of six years of observation. Furthermore, a ‘competence’ reversal occurred during flood events of only 26 per cent bankfull (Sidle, 1988) which is well below the 80 per cent condition recorded for a velocity/shear stress reversal (Andrews, 1979). In the absence of hydraulic data, Sidle (1988) identifies antecedent flood history as the dominant factor in explaining sediment transport budgets in a pool. The important role of upstream sediment supply in conditioning the sediment transport regime in a pool–riffle sequence has been accepted by recent process-based studies (Clifford, 1990; Clifford and Richards, 1992). To date, however, the response of the pool–riffle unit to changes in upstream sediment supply remains unclear, although for finer sediments (< 8 mm) the response appears to be one of temporary storage in pool-tails (Lisle and Hilton, 1992; Sidle, 1988).

The measurement of shear stress within pools and riffles by Lisle (1979), Ashworth (1987), Petit (1987), Carling (1991), Clifford (1990) and Sear (1992b) reveals conflicting evidence for a shear stress (or velocity) reversal. Of these studies only those of Ashworth, Clifford and Petit actually record a shear stress reversal. Their data were collected from discrete points, and no section-integrated reversal was established. In the former case, even point reversals were not always evident at each site (Ashworth, 1987). The remaining studies present evidence for shear stress and velocity equalization at flows approaching and exceeding bankfull. In a reappraisal of the Dry Creek pool–riffle velocity reversal data, Keller and Florsheim (1993) utilized hydraulic modelling to illustrate a section-integrated velocity reversal at around bankfull flow. However, as with other studies, not all subunits of the pool experienced a reversal at the same discharge, particularly the pool-tail which did not experience a reversal with the riffles. Carling (1994) utilized a similar modelling procedure to examine those morphological factors which could account for a velocity reversal. Carling concluded that the main controls on the model values for pool–riffle reversal were differential bed roughness (pools needed to be hydraulically rougher at bankfull flows to produce a shear stress reversal at the bed) and a smaller cross-section area to produce a section-averaged velocity reversal at bankfull. There remains a body of evidence which suggests that not all pool–riffle sequences experience velocity or shear stress reversals and that not all pool subunits experience a reversal at the same time. In particular the pool-tail remains under-competent relative to the pool-head, mid-pool and riffle sections. This presents problems for the operation of the section-averaged velocity reversal model in explaining the maintenance of the pool–riffle sequence.

FIELD SITE AND METHODOLOGY

The data for this study were collected from two sources: field data from the River North Tyne and additional tracer data collated from a range of gravel-bed rivers. The River North Tyne is located in northwest Northumberland, UK (Figure 1). The North Tyne is a regulated cobble-bed river exhibiting a sequence of well defined pool–riffle sequences (Sear, 1992b). The headwaters of the North Tyne were impounded in 1981–1982 by the construction of Kielder Dam and Reservoir. The current hydrological regime is dominated by the production of hydroelectric power which involves stage changes of 0·56 m at confined sections of channel and discharge increments from 1·3–16·0 $m^3 s^{-1}$ over 2 h. Since regulation, bankfull floods have been eliminated in the reach between the dam site and the significant unregulated tributary inputs of the Tarset and Chirdon Burns (Figure 1). Downstream of these tributaries, bankfull floods still occur but at a reduced frequency. Further catchment characteristics are detailed in Table II.

Sedimentological, hydraulic and sediment transport data were collected over a three year period (1987–1990) and during a 45 $m^3 s^{-1}$ controlled release from Kielder Dam in November 1992. Hydraulic data were collected at three pools and four riffles over a range of discharges from 1·3 $m^3 s^{-1}$ up to bankfull flow at 151 m^3/s^{-1}. Figure 1 illustrates the morphology of each of the three main riffle–pool–riffle sequences. The Smales riffle–pool–riffle sequence is located 5·2 km downstream of the Kielder Dam. Flows are dominated by regulation, but experience periodic unregulated discharges from the Smales Burn. Bankfull flows were not experienced during this study. Bankfull width does not vary between riffle or pool (35 m); however, flows in the pool are on average 39 per cent deeper than over the upstream riffle. Velocity profiles, bedload transport measurements and painted tracers were monitored at two sections, riffle 1 (SMR) and in the mid-pool (SMP) for discharges up to 45 $m^3 s^{-1}$.

The riffle–pool–riffle site at Tarset is strongly influenced by the confluences of the Tarset and Chirdon Burns. Deep tributary scour pools and bar morphology affect hydraulic and sediment transport routing through this reach (Sear, 1992b). Velocity profiles, sediment transport and painted tracer experiments were conducted at two riffles upstream and downstream of the tributaries (TR1 and TR2) whilst hydraulic data and sediment transport were monitored at an intermediate pool section (TP). All real-time monitoring

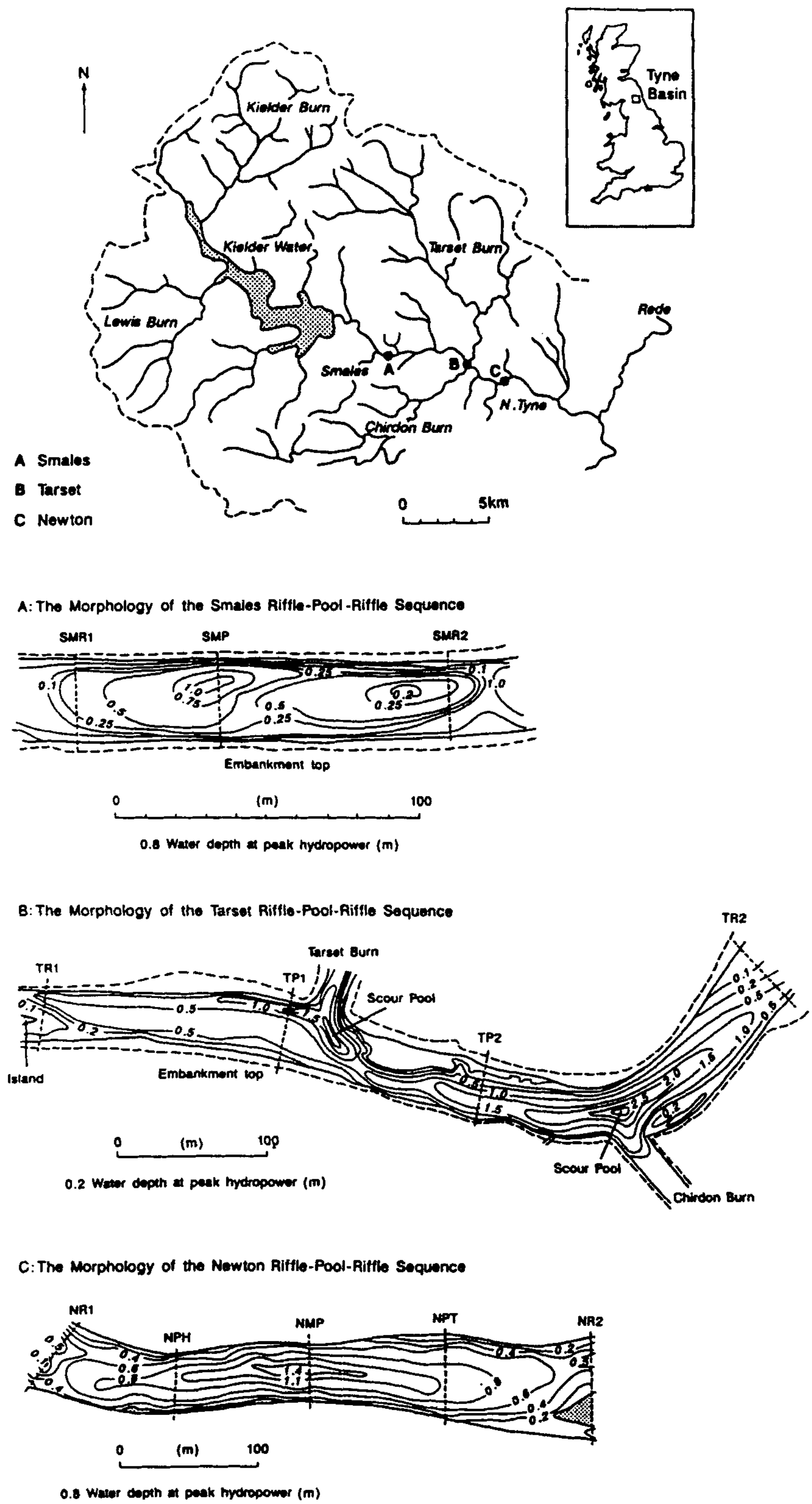

N
Tyne Basin
Kielder Burn
Kielder Water
Tarset Burn
Lewis Burn
Rede
Smales
A
B
C
N. Tyne
Chirdon Burn
A Smales
B Tarset
C Newton
0 5km
A: The Morphology of the Smales Riffle-Pool-Riffle Sequence
SMR1
SMP
SMR2
Embankment top
0 (m) 100
0.8 Water depth at peak hydropower (m)
B: The Morphology of the Tarset Riffle-Pool-Riffle Sequence
TR1
TP1
Tarset Burn
Scour Pool
TP2
TR2
Island
Embankment top
Scour Pool
Chirdon Burn
0 (m) 100
0.2 Water depth at peak hydropower (m)
C: The Morphology of the Newton Riffle-Pool-Riffle Sequence
NR1
NPH
NMP
NPT
NR2
0 (m) 100
0.8 Water depth at peak hydropower (m)

Table II. Catchment characteristics of the North Tyne

Catchment area	1118 km^2 (40% afforested)		
Reservoir area	10 km^2 (75% afforested)		
Geology	Lower Carboniferous Limestone (20%), Lower Carboniferous Sandstone (71%), quartz and dolerite outcrops (9%)		
Drift	Glacial boulder clay, peat, terrace gravels, alluvium		
Channel length	42 km	Bankfull width	31 m
Bankfull depth	3 m	Bankfull discharge	167 $m^3 s^{-1}$
Operational discharge	1·3–16·0 $m^3 s^{-1}$	Riffle spacing/width	6·7
Pool length	410 m	Slope	0·0018

Values given are averages for the North Tyne downstream of Kielder Reservoir

was conducted during discharges up to peak hydropower flows. Tracer movements were recorded for discharges up to 151 $m^3 s^{-1}$. No measurements were conducted at this site during the 45$m^3 s^{-1}$ test release.

The Newton site represents the main focus for sediment transport monitoring. The reach is on a gentle curve, with the right bank abutting a wooded valley side contact. The pool-bed is floored with boulders adjacent to this right bank between the pool-head and mid-pool. Velocity profiles and bedload transport were monitored at the upstream riffle (NR1), mid-pool (NMP) and downstream riffle (NR2) for discharges up to 45 $m^3 s^{-1}$. In addition, velocity profiles were measured at peak hydropower flows at the pool-head and pool-tail. Magnetic tracers were emplaced at the upstream riffle during low summer flows and monitored as they passed through the pool. Painted tracers were inserted at both riffles as well as at the pool-head (NPH) and pool-tail (NPT). Movement of painted tracers was documented for discharges up to bankfull, and in a separate survey during the 45 $m^3 s^{-1}$ test release.

Sedimentological data were collected for subunits of the pool–riffle sequences monitored for sediment transport. These data were supplemented by sedimentological surveys of riffles and pools in other catchments. Counts of 100 pebbles were made according to the method outlined in Wolman (1954). Particle shape was determined from measurements of the three primary axes of 100 stones per bedform at six pool–riffle sites including Smales, Tarset and Newton. An additional measure was made during the grid sampling procedure which attributed each stone to a structural category based on a review of the sedimentological literature (Sear, 1992b). These categories include pebble cluster components (obstacle clasts, stoss particles and wake particles), imbricated particles, open-bed and loosely clustered particles, particles infilling spaces between clasts, interlocked particles, and isolated and unprotected particles. These categories were subclassified into stable or unstable positions with respect to sediment entrainment using three variables: theoretical pivot angle, degree of sheltering and grain size (Sear, 1992b). Thus unstable particles are those in open-bed positions with no interlocking, isolated unprotected particles, and particles infilling the pockets between surface gravels. An additional measure of the strength of particle packing was determined using dynamic penetrometering of the surface gravel layer. This technique involves the application of a known force on a standard penetration point. The number of blows taken to advance the point a given distance is recorded (Sanglerat, 1979). The distance used in the North Tyne was taken as 0·05 m which approximates the D_{50} of surface gravels. The values recorded by this method reflect the composite effect of the weight of surrounding particles, packing density and degree of particle interlock. Overloose gravels record values of less than 10 blows/0·05 m, whilst concreted gravels record values of over 50 blows/0·05 m. Measurements of bed strength were determined at ten points across a section, and at four places around each point; the mean value of these four readings was taken as representative of bed strength at that point.

For discharges less than 46 $m^3 s^{-1}$, detailed velocity profiles were measured in the bottom 20 per cent of flow depth, at five to seven points above the bed, and at 1–2 m intervals across riffle and pool sections using an Ott C320 current meter. The velocity profile data were collected simultaneously with bedload transport

Figure 1. Individual riffle–pool–riffle sequences used in the North Tyne study

measurements as well as at points on the bed at which a tracer particle was emplaced. Velocity profiles were constructed and the shear stress at a point calculated according to the methodology outlined by Bathurst (1979) and Ashworth and Ferguson (1989). Inspection of the velocity profile data indicated that a log-linear model was appropriate for those readings associated with the highest near-bed velocities (r^2 range 0·67–0·98, $\sigma = 0{\cdot}237$) but departed from log-linearity in regions of low near-bed velocity associated with dead zones in pools and towards channel margins (r^2 range 0·1–0·54, $\sigma = 0{\cdot}154$). For the purposes of bedload transport estimates this did not prove problematic since the lower near- bed velocity regions did not experience bedload transport. Nevertheless, for those velocity profiles where r^2 values were less than 0·7, values for shear stress were calculated using the gradient for which the r^2 value was at a maximum. This was always constructed from three or more velocity readings.

In order to establish if a shear stress or velocity reversal occurred for flows $> 45\,m^3\,s^{-1}$, shear stress data were derived from the depth/energy slope product (calculated using sectional average velocity) after Allen (1977). The latter method has been shown to reduce the errors associated with using surrogates for the energy grade line such as water surface or bed slopes which rely on assumptions of uniform flow (Magilligan, 1988). However, the values obtained will contain an element of both form and grain shear stress. Recent studies by Carling (1991), Flintham and Carling (1988) and Hey (1979) suggest that for single thread gravel channels with high width:depth ratios, the values for the ratio of form:grain shear stress approach unity. However, Prestegaard (1983) has found considerable variance in the proportion of grain shear stress at bankfull flows (75–57 per cent of total shear stress). She identified no consistent variance between the proportion of grain and form shear stress between pools or riffles. In the subsequent discussions, movements of tracer particles associated with discharges $> 45\,m^3\,s^{-1}$ are related to estimates of shear stress calculated using this latter method, whose limitations should be borne in mind.

Sediment transport rates were measured at the three pool–riffle sites used in the determination of hydraulic data. Bedload transport was sampled at four positions across each pool and riffle during hydropower flows 1·3–20·7 $m^3\,s^{-1}$ (Smales, Tarset, Newton) and at every metre during 40–45 $m^3\,s^{-1}$ (Smales, Newton). A 150 mm hand-held Helley-Smith bedload sampler (modified after Newson) was used for discharges 1·3–20·7 $m^3\,s^{-1}$ while a 76 mm Helley-Smith was lowered from a boat by rope during flows of 40–45 $m^3\,s^{-1}$. The use of two different aperture sediment samplers was conditioned by the inability of the hand-held 150 mm Helley Smith to be effectively controlled at the higher discharges. Evidence from the tracer movements at $45\,m^3\,s^{-1}$ indicated that few particles > 64 mm were transported, which suggests that the sampler could accommodate the majority of the particles in transit. Bedload transport rates were based on sampler dimensions, sample weight and sampling time which in all cases was 3 min. Replicate measurements were made at each point during hydropower discharges but single sample measurements were made during the $45 m^3\,s^{-1}$ event though with greater spatial resolution. The sediment transport rates recorded at each point were assumed to be representative of the local near-bed hydraulics monitored simultaneously at the time. This has been shown by Meigh (1987) to be a realistic assumption, particularly for the largest particles sampled.

To determine the routing of fine sediments (< 22 mm) through the Newton riffle–pool–riffle site, 229 kg of North Tyne sediment was taken from the upstream riffle (NR1) and 'toasted' for 2 h at 300°C (Arkell, 1985; Sear, 1992b). The magnetically enhanced sediment was returned to the riffle site and trodden into the bed over a full 40 m riffle crest section. Field measurements of magnetic susceptibility were made using a Bartington MS1 Field Coil, every 2 m across sections located at 5, 10 and subsequent 20 m intervals from the emplacement site as far as the crest of the downstream riffle (NR2). Re-surveys were made on eight occasions over a period of 280 days in relation to prevailing hydrological conditions. Grain-size sampling for the magnetic material was attempted on only one occasion, and resulted in the recovery of 5 per cent of the total emplacement material by weight.

Coarse sediment transport was recorded through three pool–riffle sequences using painted tracers (Sear, 1992a). In total some 700 tracers were emplaced and monitored over a period of two years during which time flood events of up to $151\,m^3\,s^{-1}$ were recorded. The distance moved by each tracer was recorded after each flood event. Typical recovery rates were between 85 and 100 per cent, falling to 35 per cent after the bankfull flood. In addition, 150 tracers were inserted in structurally stable positions and 150 in open-bed, no interlocking positions in the Newton pool-head, pool-tail and downstream riffle (NR2). The particles were surveyed following hydropower flows when first movements had occurred. Their movement was then recorded after a 45 $m^3 s^{-1}$ release. Shear stress over each emplacement site was recorded by velocity profiling during discharges of 45 $m^3 s^{-1}$.

The tracer movement data were supplemented by a reanalysis of the datasets from the Dry Creek Flood 1 (Keller, 1971), River Severn (Hey, 1975; Thorne, 1978), River Swale (Thorne, 1978) Allt Dubhaig and Feshie (Ashworth, 1987). For each of these datasets the emplacement sites were classified according to riffle, pool-head, mid-pool and pool-tail (after Ashworth, 1987). The mean transport lengths of all particles that moved (L) were calculated and, where available, the transport length of individual particles.

The critical shear stress at 'initial transport' (*sensu* Carling, 1983, p. 2) was estimated for the largest particle caught in the Helley-Smith sampler and for each tracer particle that had moved <2 m during a 45 $m^3 s^{-1}$ test release from Kielder Dam. The latter criterion assumes that low transport distance is a function of a grain shear stress at or lower than the critical entrainment threshold for the particle and not the result of rapid incorporation into bed structure. A similar assumption was employed by Hey (1975). As will be revealed later, this assumption is realistic for pools but clearly subject to error on riffles. Consequently, the criterion for riffle tracer motion was reduced to <1 m.

A value for the dimensionless Shields parameter was calculated from the critical shear stress according to the formula:

$$\theta = \frac{\tau_c}{(\rho_s - \rho) g D_i} \tag{1}$$

Where θ is the Shields entrainment function (Shields, 1936), τ_c is the critical shear stress for initial transport, ρ_s and ρ are the densities of the sediment and water (2·65 and 1·0 $t\,m^{-3}$) respectively, g is gravitational acceleration and D_i is the diameter of a given particle. The value for τ_c was taken to be equal to the maximum field measure of shear stress made either at the point of bedload sampling (largest particle sampled taken to be associated with the maximum shear stress) or calculated over the point of painted tracer emplacement.

Recent analysis of particle tracing data by Hassan and Church (1992), Church and Hassan (1992) and Hassan *et al.* (1992) has suggested that a relationship exists between the maximum excess stream power of a flood and the mean distance moved by tracer particles. To facilitate comparison, the maximum excess stream power was calculated from the critical transport criterion for D_{50} particles determined for each site based on Bagnold's (1966) estimation of critical threshold of general bedload motion used by Hassan *et al.* (1992). This latter method was used for the datasets from the North Tyne, Dry Creek and the River Severn.

RESULTS

Bedload transport rates for Q < 30 *per cent bankfull*

The real-time monitoring of sediment transport in pool–riffle sequences during hydropower discharges (< 15 per cent bankfull) reveal a dominance of Phase 1 type bedload characterized by sands moving over a static armour (Jackson and Beschta, 1982). A similar observation has been reported for a regulated river by Beschta *et al.* (1981). Quasi-continuous bedload sampling at mid-pool and riffle cross-sections during these events revealed an unsteady bedload transport regime on the riffles characterized by fluctuating transport rates and an increase in competence with increasing discharge. In the pools, competence similarly increased with discharge, but bedload transport rates exhibited less variation than was experienced on adjacent riffles. Particles up to 8 mm *B*-axis were entrained in pools, whilst riffles experienced frequent movements of particles up to 22 mm and sporadic entrainment of particles of 45–64 mm calibre.

As discharges increased above 20 $m^3 s^{-1}$ fine sediment (<16 mm) transport rates in pools attained and locally exceeded those on adjacent riffles. This is reflected in Figure 2 which relates the sediment transport rate recorded at adjacent riffles and pools with the local stream power calculated from:

$$\omega_p = \tau_p u \tag{2}$$

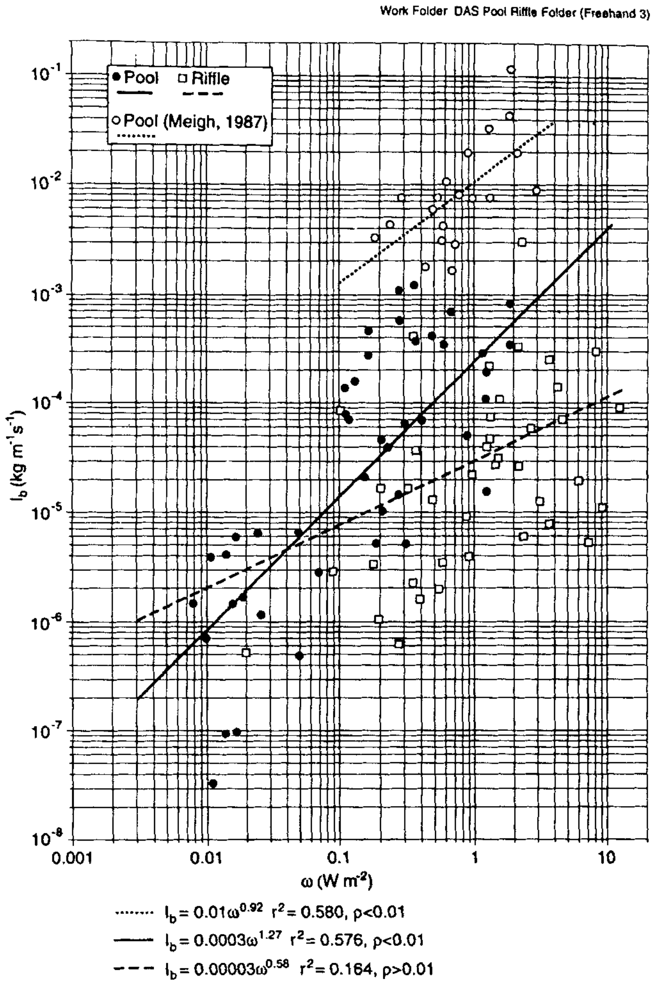


Figure 2. The relationship between local stream power and bedload transport for pools and riffles illustrating transport exceedance operating in pools. The data of Meigh (1987) for a mid-pool is shown for comparison

where ω_p (W m^{-2}) is the stream power at a point on the bed, τ_p is the point shear stress (calculated from velocity profile N m^{-2}), and u is the vertically averaged mean velocity (m s^{-1}). The use of this figure permits comparison with the data of Meigh (1987) for a pool in the gravel-bed River Severn. The dataset combines all the data available from the North Tyne pool–riffle sites.

Meigh (1987) and Sear (1992b) found that local stream power explained more of the variance in local bedload transport rate than local shear stress. Curves were fitted to the three datasets using SPSS statistical software which permited a range of functions to be tested simultaneously and the most statistically significant curve to be defined. Sediment transport in each case is best fitted by a power function. The slopes of the curves given in Figure 2 indicate how fine sediment transport rates in pools increase and exceed those on associated riffles for a given local stream power. The sediment transport 'reversal' exhibited in Figure 2 is considered to reflect the difference in transport thresholds for particles in riffles and pools as a result of structural restraint (fine sediment was still available as ostler lenses and as infill between and beneath larger particles) and the presence of more unrestrained or unprotected sediments in the pools (see Lisle and Hilton, 1992). The effect of sediment supply is also apparent in the contrast between the sediment transport rates

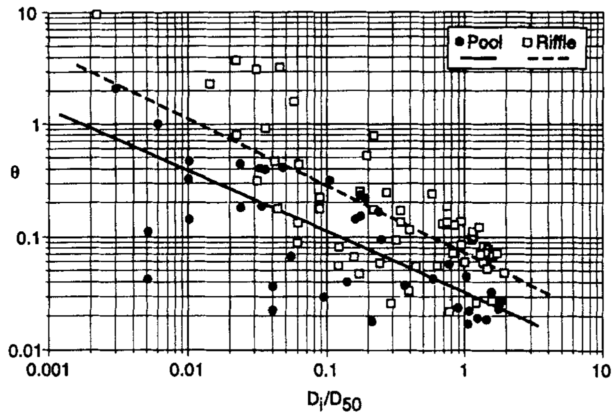


Figure 3. Dimensionless Shields' entrainment function for pool and riffle data collected in the North Tyne showing the higher entrainment thresholds required to initiate sediment transport on riffles. The equations for the curves are given in the text

measured in a pool by Meigh (1987) and those for pools in the North Tyne for the same local stream power. The bedload sediments from the River Severn pool contain significantly higher proportions of fine sediments (< 16 mm) than the North Tyne bedload at these discharges. Superficial interpretation of the bedload transport data suggests that the supply of available material for transport is greater in the pool and therefore the volume of material in motion at a given value of stream power will always be greater than that on the riffle. This is evident from grain-size analysis which reveals larger quantities of fine gravels and sands in the bedload from pools during discharges < 30 per cent bankfull.

Thresholds of transport for particles in pools and riffles

The threshold of transport as defined by Carling (1983) is plotted in Figure 3. The curves fitted are those which best accounted for the variance in the dependent variable. The equations for the two curves are:

$$\theta = 0{\cdot}034 D_i/D_{50}^{-0{\cdot}535} \quad \text{(pools)} \quad n = 40, \quad r^2 = 0{\cdot}623, \quad p < 0{\cdot}01, \quad SE = 0{\cdot}097 \tag{3}$$

$$\theta = 0{\cdot}072 D_i/D_{50}^{-0{\cdot}595} \quad \text{(riffles)} \quad n = 60, \quad r^2 = 0{\cdot}502, \quad p < 0{\cdot}01, \quad SE = 0{\cdot}061 \tag{4}$$

The slope terms in both equations indicate that the relationships depart from the $-1{\cdot}00$ required for equal mobility to dominate the transport process (Parker and Klingeman, 1982). On this basis sediment transport in both pools and riffles is characterized by size-selective transport. Although the data show some overlap, the populations predicted by the regression equations are significantly different at the 95 per cent confidence limit in a Mann–Whitney U-test. In general, particles in pools have a lower critical threshold of transport than particles on riffles. The values predicted by the regression equations for the surface sediment grain-size range 1–150 mm are $4{\cdot}1$–$41{\cdot}7\,\mathrm{N\,m^{-2}}$ in pools compared with $11{\cdot}2$–$84{\cdot}9\,\mathrm{N\,m^{-2}}$ in riffles, which results in a narrower critical shear stress range for pool sediments.

Sediment routing in pool–riffle sequences

Tracing of magnetized sediments < 22 mm *B*-axis was conducted at the Newton riffle–pool–riffle sequence in order to elucidate the routing of fine tracer material at low to moderate discharges. Table III records the centroid position of tracer material which equates to the point where the concentration of magnetic tracer is equal upstream and downstream (Crickmore, 1967; Arkell, 1985). Arkell (1985) and Sear (1992a) argue that the position of the centroid reflects the subtleties of tracer release and dispersion. The position of the centroid

Table III. Sequential centroid positions of magnetically enhanced tracer material (<16 mm) Newton riffle–pool–riffle sequence

Date	Centroid position downstream of emplacement site (m)	Movement (m)	Previous Peak Q (m^3/s)
08/03/89	17·9	17·9	5·6
09/03/89	74·1	56·2	18·7
30/04/89	56·8	−17·4	33·1
21/05/89	95·6	38·8	17·5
17/11/89	77·2	−18·4	30·2
14/01/90	118·2	41·0	21·0
24/05/90	214·8	96·6	151·0

is calculated using the sample-based formula:

$$\frac{\sum x_i S_i}{\sum S_i} \tag{5}$$

Where x_i is the distance downstream of the emplacement site at which a given tracer concentration S_i is found.

Table III shows that some local movement of tracer material occurred immediately after emplacement during flows of only 5·6 $m^3 s^{-1}$. This is to be expected since the fine tracer material would be 'overloose' (*sensu* Church, 1972) and susceptible to entrainment in the high shear field experienced on riffles. The position of the centroid in Table IV actually moves upstream after two events of around 30 $m^3 s^{-1}$. This occurs due to the re-exposure of infiltrated tracer at the emplacement site which illustrates the dynamic nature of the infiltration/flushing process for fine sediments at riffles (Sear, 1993). After 311 days, the position of the tracer centroid had moved 118 m downstream, almost to the mid-pool region. The front of the tracer 'cloud' had

Table IV. Summary data for tracer movement in pool–riffle sequences

River	Bedform	D_{50} (mm)	L (m)	Per cent Recovered	Mean shear Stress ($N m^{-2}$)	Source
Allt Dubhaig	Riffle*	62	7·3	69	25·6†	Ashworth (1987)
	Pool-head*	56	16·7	77	47·3†	
	Mid-pool*	57	14·0	77	43·6†	
	Pool-tail*	51	12·9	76	41†	
Feshie	Riffle	62	5·7	89	66†	Ashworth (1987)
	Pool-head	87	73·0	60	69†	
	Mid-pool	68	89·0	32	45†	
	Pool-tail	54	55·0	41	39†	
Dry Creek	Riffle	42	16·0	20	37·7	Keller (unpublished)
	Pool	11	87·0	15	21·9	
Swale	Riffle	62	1·4	86	–	Thorne (unpublished)
	Mid-pool	45	5·3	86	–	
Severn	Riffle	35	11·7	40	10·1†	Thorne (unpublished)
	Mid-pool	38	23·0	79	5·5†	
	Pool-tail	37	12·2	54	6·3†	
North Tyne	Riffle*	50	11·8	60	200	Sear (1992a)
	Pool-head*	45	56·1	38	257	
	Pool-tail*	32	16·1	48	54	

* Values are averages of $n > 2$
†Velocity profile estimates

reached the downstream riffle after 73 days and a peak discharge of $33{\cdot}1\,\mathrm{m}^3\,\mathrm{s}^{-1}$. Following a bankfull flood event, the position of the tracer centroid moves almost 100 m to 215 m downstream to the pool-tail. The tracer front probably extends beyond the downstream riffle crest following this event, but tracking coil malfunction prevented further analysis.

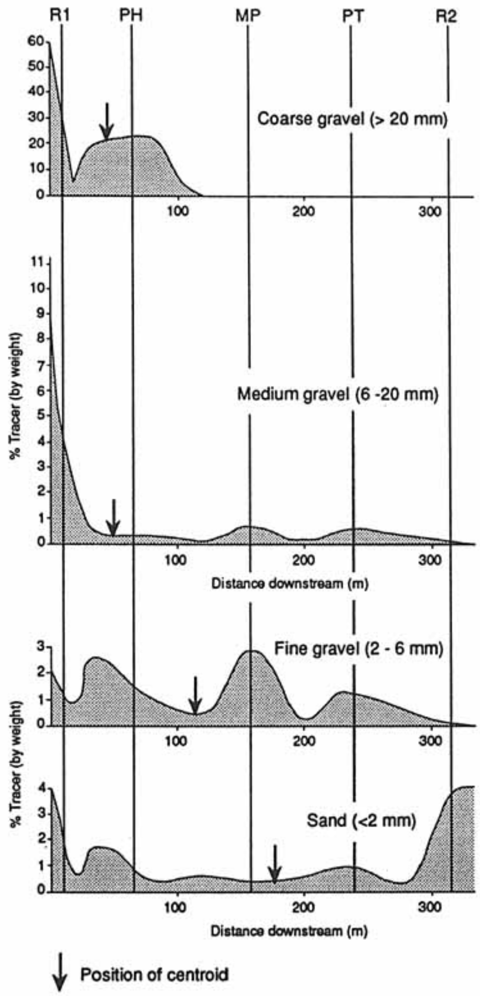


Figure 4. Downstream distribution and centroid location of magnetic tracer on a grain-size basis, Newton riffle–pool–riffle sequence

The downstream distribution of tracer material according to grain size was recorded after 120 days ($Q_{\max} = 33{\cdot}1\,\mathrm{m}^3\,\mathrm{s}^{-1}$). Size-selective transport results in a distinct downstream fining through the pool with the position of the tracer centroid increasing as grain-size decreases (Figure 4). Broadly, coarse gravel (> 20 mm) is stored in the pool-head and riffle whilst material between 2 and 16 mm is stored in the mid-pool and pool-tail regions. Sand is distributed throughout the riffle–pool–riffle sequence and concentrates on the downstream riffle as infiltrated fines and wake deposits (Sear, 1992b). The pool-head to mid-pool region is depleted in fine tracer < 20 mm whilst the downstream region of the pool receives fines from the upstream riffle. The preferential removal of fines from the pool-head region is supported by grain-size measurements which reveal coarser pool-head and finer pool-tail regions in North Tyne (Sear, 1992b).

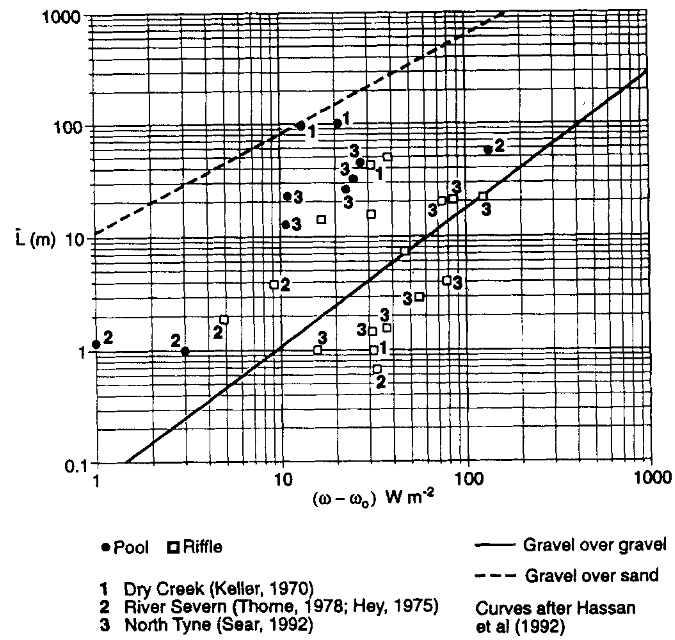


Figure 5. Mean distance (L) travelled by particles (>20 mm) in pools and riffles, expressed as a function of excess stream power ($\omega - \omega_0$)

The movement of gravel tracers

Table IV documents the summary data collated from six gravel tracer experiments specifically associated with pool–riffle morphology and during which discharges occurred at or near bankfull. The data for each survey have wherever possible been categorized in terms of the morphological subunit of the pool–riffle sequence. The values of shear stress refer to section averages for maximum flow conditions. Mean transport distance of coarse gravel tracers is shorter on riffles, and tends to decrease in the order PH > MP > PT > R, though exceptions to this pattern occur in the Allt Dubhaig streams. Shear stress hierarchies do not support this observation, with riffles frequently exhibiting higher values than pool subunits. Exceptions to this include the pool-head region which is characterized by high shear stress and long transport distances, and the Allt Dubhaig experiments of Ashworth (1987) which display a shear stress hierarchy in phase with the transport distances of tracers.

Hassan *et al.* (1992) and Hassan and Church (1992) consider the motion of tracer particles that were not influenced by morphological controls such as pool, riffle or bar forms. It is interesting, therefore, to compare their relationships with tracing data that were influenced by pool–riffle morphology. Figure 5 depicts the curves of Hassan *et al.* (1992) developed for the conditions of gravel moving over gravel and for gravel moving over a sand bed. Considerable variation is evident within pool and riffle data, which is a recognized phenomenon of particle tracing (Hassan and Church, 1992). Nevertheless, riffle data plot closer to the curve for gravel moving over gravel, whilst pool data plot more closely to the curve for gravel moving over sand. The Dry Creek pool data of Keller (unpublished) plot closest to the curve for gravel over sand. Reference to Table IV reveals that Dry Creek pool had a D_{50} of 10 mm in comparison with the other pool data. This would support the observation that transport lengths over smooth beds are greater for a given excess stream power (Iseya and Ikeda, 1987; Ferguson *et al.*, 1989; Hassan *et al.*, 1992).

The maintenance of the pool–riffle sequence during sediment mobilizing floods requires the evacuation of material from pools at a greater rate than from riffles. This is to some extent reflected in the tracer distances recorded above; however, a more useful indicator is the virtual rate of travel of particles which is directly

Table V. Virtual rates of travel for particles in pool–riffle sequences in the North Tyne

Site	L (m)	Q ($m^3 s^{-1}$)	T (h)	V_b ($m h^{-1}$)
NRiffle1	22·1	48	55	0·402
NPool-head	87·8	52	50	1·756
NPool-tail	24·1	74	19	1·268
NRiffle2	25·0	46	59	0·424
TRiffle2	16·3	53	56	0·291
SMRiffle	1·0	70	10	0·100
SMPool	1·2	93	3	0·400
Pool (<16 mm magnetics)	96·6	–	36	2·700

related to sediment discharge. The virtual rate of travel of particles (V_b) is estimated from the distance travelled in relation to the duration of flow above the critical entrainment threshold (Einstein, 1937; Sear, 1992b; Hassan *et al.*, 1992). The critical transport thresholds developed for particles in pools and riffles were combined with information on tracer distance and bankfull flood duration to provide an estimate of virtual rate of travel for North Tyne pool–riffles after the method of Hassan *et al* (1992). Table V shows that for 22–125 mm grain-size particles, the virtual rates of travel in the Newton pool-head and pool-tail are 4·2 and 3·0 times faster respectively than for associated riffles. Virtual rates of travel in North Tyne pools are generally 3·8 times faster than associated riffles. The data for the magnetic tracer material < 16 mm indicate that very fine sediment sizes ($\ll$16 mm) once entrained achieve higher virtual rates of travel than coarser particles through the pool, which indicates size-selective transport.

DISCUSSION

The scatter in the datasets presented above is typical of bedload transport in mixed sized gravel-bed rivers. However, the results do suggest that despite this variability, sediment transport processes in pools differ from those operating on riffles. It is therefore important to explore the possible causes of this, and to determine if this condition has any ramifications for the maintenance or formation of the pool–riffle sequence.

The controls on sediment transport in pool–riffle sequences alluded to in the literature can be categorized under five headings:

- Hydraulic variation between pool and riffle both in terms of sectional average differences and in terms of turbulent boundary-layer conditions (Keller, 1970; Clifford and Richards, 1992).
- Grain-size variation between subunits of pool and riffle (Keller 1970; Milne, 1982).
- Differences in the frequency of loose and restrained particles between pools and riffles (Lisle, 1979; Sear, 1992b; Clifford, 1994).
- Different probabilities of particle entrapment within pool and riffle (Bluck, 1987).
- Variation in the degree of particle interaction during transport in pools or riffles (Langbeim and Leopold, 1963; Iseya and Ikeda, 1987).

Recent reviews of the hydraulics of the pool–riffle sequence confirm that sectional average differences may or may not occur and that equalization of velocity and/or shear stress also occurs. The role of the bankfull flood event is also queried by data from Bambi Creek (Sidle, 1988) and the North Tyne, which indicate higher rates of bedload transport in pools at discharges lower than 50 per cent bankfull. Analysis of the subunits of the pool–riffle sequence provides conflicting hydraulic evidence to explain the observations of tracer movement. Clifford and Richards (1992) conclude from their study of a single pool–riffle unit that the complexity of flow dynamics probably precludes any sensible interpretation of sediment transport from sectional average data alone. The data reported in this analysis confirm that sediment transport in the pool–riffle sequence is not explained by sectional average hydraulic variables in all cases.

Table VI. Values of roughness height (k) and spacing (h) for pools and riffles

Site	D_{50} (mm)	h (mm)	h_{echo} (mm)	k (mm)	k_{echo} (mm)	h/k	d/k
Pool-head	45	–	858	–	32·0	27·3	42·8
Mid-pool	51	872	952	33·0	29·0	23·2	50·3
Pool-tail	32	–	936	–	14·0	57·4	87·1
Riffle	60	320	–	54·0	–	5·9	17·2
Boulders	252	–	1049	–	202·5	2·6	6·1
QuarmeR1*	41	131	–	24·6	–	5·3	–
QuarmeR2*	41	221	–	29·9	–	7·4	–
QuarmeR3*	32	134	–	21·4	–	6·3	–

* Riffle data from Clifford *et al.* (1992)
$n = 72$ (riffle), $n = 40$ (pool) for field observations of h and k

Recent investigations of near-bed hydrodynamics have identified a link between local roughness spacing, roughness element protrusion (k), flow resistance, near-bed velocity and sediment transport (Davis and Barmuta (1989); Hassan and Reid, 1990; Carling, 1992; Clifford *et al.*, 1992). Davis and Barmuta (1989) identify four hydraulically rough–turbulent flow types for Reynolds numbers > 70, based on the work of Morris (1955) and Smith (1975):

- isolated roughness flow
- wake interference flow
- skimming flow
- chaotic flow

Chaotic flow describes the flow conditions when $d/k < 3$ whilst the remainder can only occur when $d/k > 3$, where d is the local flow depth in metres. Hassan and Reid (1990) identify the transition between near-bed flow types in terms of h/k where h = roughness spacing in metres and k is the height of the roughness elements. Isolated roughness flow occurs at $h/k > 35$, wake interference at $35 > h/k > 10$ and skimming flow at $h/k < 10$. Davis and Barmuta (1989) identify similar transitions on the basis of h/d, whereby the transition between wake-interference and skimming flow occurs at $h = d$.

The relevance of these near-bed flow types to the transport of sediment in pool–riffle sequences stems from their effect on near-bed velocity and sediment transport. Sediment transport rates are known to decrease once skimming flow is attained, due to the development of low-velocity, quasi-stable vortices in between the roughness elements (Davis and Barmuta, 1989). Hassan and Reid (1991) have observed a reduction in sediment transport rate as h/k decreases and flow resistance increases. At the point of maximum flow resistance ($h/k \geqslant 17$) bedload transport is characterized by sporadic movements resulting from powerful eddying around the roughness elements. Where chaotic flow conditions prevail, Smith (1975) suggests that near-bed flow will be complex, with velocities locally accentuated by acceleration between roughness elements.

To quantify the possible flow types experienced at pools and riffles and across individual pool cross-sections, values for h and k are needed, together with local flow parameters u (near-bed velocity) and d (local flow depth). Near-bed velocity and flow depth were obtained from velocity profile data taken at $Q = 40\,m^3\,s^{-1}$. Values of h and k in pools were obtained from detailed echo-soundings, with a resolution down to 0·001 m (see Sear (1992a) and discussion of Ergenzinger (1992)) supplemented by direct field measurements. Values of h and k for riffles were obtained from direct field measurement using tapes and rulers. Individual roughness elements were easily identified at riffles where they projected through the water surface at low flows and in pools as isolated particles standing $\geqslant D_{84}$ bed material size above the local bed surface (Wiberg and Smith, 1991). It should be noted that values of h for pools and riffles were made after the $43\,m^3\,s^{-1}$ releases and velocity profiling had been recorded. Supplementary data from echo-soundings taken during the period of sediment transport experiments confirmed field observations of h and k (Table VI). The values of h/k obtained for riffles are within the same order of magnitude as those documented by Clifford *et al.* (1992) using detailed bed microprofiling (Table VI). Roughness spacing in pool subunits is longer and values of k are shorter than in riffles, resulting in larger values for h/k and d/k.

On the basis of h/k and d/k values, the near-bed flow types over pool and riffles can be categorized. During low discharges when d/k values on riffles are <3, riffles experience largely chaotic near-bed flows while pools ($d/k > 3$) experience isolated roughness element or even hydraulically smooth near-bed flows. Sediment transport on riffles is likely to be characterized by sporadic pulses associated with vortex shedding around the roughness elements. This describes the sediment transport regime observed during hydropower flows in the North Tyne. As stage rises over riffles a rapid transition is envisaged from chaotic flow to quasi-skimming flow conditions ($h = d$ and $h/k < 11$). In contrast, at the pool bed, high values of h/k and d/k suggest that near-bed flows are characterized by isolated roughness or wake interference flow. At this point contrasting flume and field observations make interpretation of sediment transport processes difficult. The flume studies of Hassan and Reid (1990) suggest a reduced sediment transport rate due to quasi-skimming flow occurring on riffles relative to the higher sediment transport rates associated with isolated roughness or wake interference flows characterizing the pool. In contrast, field observations of transient high near-bed velocities associated with turbulence suggest increases in mean transport rate although the near-bed flow typology of these conditions is not known (Hammond *et al.*, 1984). Clifford (1994) presents data which suggest that near-bed turbulence in a pool–riffle sequence increases with discharge but that the variance between pool and riffle reduces almost to equality by bankfull. The variance between pool and riffle is therefore much greater at lower discharges when sustained sediment transport is confined to the smaller grain-sizes.

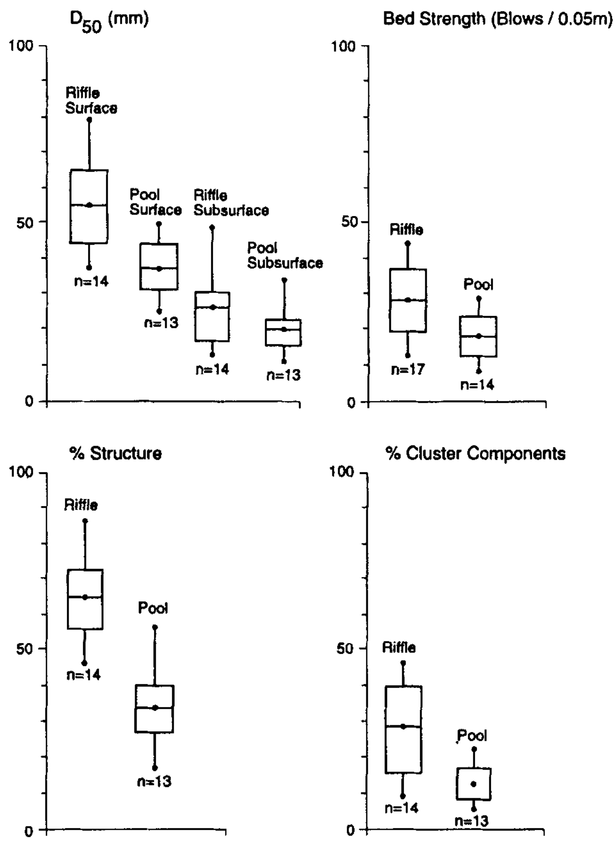


Figure 6. Summary sedimentological data illustrating the coarser, more structured and stronger riffle surface sediments

Recent studies suggest that fundamental sedimentological differences between pool and riffle might explain some of the observations of sediment transport behaviour (Clifford and Richards, 1992; Sear, 1992a). Differences in grain size, shape and packing between riffles and pools result in differential critical entrainment thresholds for particles in each bedform. The resulting higher entrainment thresholds for riffle sediments maintain these units as topographic highpoints in the river bed, whilst the pools are scoured at discharges below those necessary to mobilize the bed at riffles.

Sedimentological differences between the pools and riffles used in this study are documented in Figure 6. Mann–Whitney tests for population difference were significant at the 0·1 per cent level for all categories of sedimentology with the exception of subsurface D_{50}. This confirms that pool surface sediments are dominated by finer, loosely interacting particles that are more frequently in structurally unstable sites. Riffle surface sediments are coarser, tightly interacting and more frequently in structurally stable positions. The structural stability of riffles is not dominated by pebble cluster components (although these are significantly more abundant on riffles) which suggests that structural surveys based solely on these sedimentological features may over-emphasize their role in specifically delaying entrainment (De Jong, 1991; Reid *et al.*, 1992). Rather, these features may affect sediment transport through their influence on near-bed flow structure (see above).

The subsurface sedimentology of pools and riffles is not so well discriminated by summary statistics of grain size, suggesting that the populations are in fact broadly similar. Indeed the range of grain sizes is often wider in pools due to the presence of large boulders. Direct comparison between surface and subsurface grain-size populations is not possible, however, due to the different sampling strategies. Nevertheless, the lack of a significant difference between subsurface populations suggests that size-selective transport most profoundly affects the surface grain-size distribution, a condition which is most evident during high frequency, low magnitude events when turbulence intensity and shear stress over the bed is at maximum discrimination between pools and riffles. Clifford (1994) suggests that sorting via particle shape may be more significant than sorting on the basis of particle size. However, the data presented to date are inconclusive and tend to suggest that shape differentiation between pools and riffles is subordinate to grain size. Information on particle shape was available for six riffles and six pools in the North Tyne catchment, but statistical analysis revealed no significant difference between the sphericity, flatness or Zingg classifications of surface sediments in pools and riffles (Sear, 1992b). The sedimentological evidence suggests that it is the surface particle arrangement that best discriminates between pool and riffle. The higher proportion of larger particles displayed on the surface of riffles together with the presence of enhanced bed structure and bed strength is reflected in the higher thresholds required to initiate sediment transport.

A theoretical explanation for the difference in critical threshold for particle transport observed in riffles and pool subunits in the North Tyne can be explored through the consideration of particle geometry. In a recent study, Kirchiner *et al.* (1990) and Buffington *et al.* (1992) examined the relationship between critical shear stress for entrainment of particles from heterogeneous gravel beds (both artificial and natural) and particle friction angles and relative exposure. Buffington *et al.* (1992) showed that the critical shear stress for individual particles on a gravel bed was characterized by a probability distribution rather than a single value, although noting that the lower tail of the distributions for a range of particle sizes converged to similar values, hinting at equal mobility.

The formula developed by Buffington *et al.* (1992) for predicting the frequency distribution of friction angles was applied for two particle sizes (32 and 64 mm) which are smaller than and larger than the D_{50} of pool and riffle surface sediments respectively. The formula was applied to pool and riffle subunits as defined by:

$$\Phi_n = (25 + 0{\cdot}57n)(d_i/D_{50})^{-(0{\cdot}16+0{\cdot}0016n)}(\sigma)^{-(0{\cdot}21+0{\cdot}0027n)} \tag{6}$$

where Φ_n is the nth percentile friction angle, d_i is the particle size (32 or 64 mm in this case), D_{50} is the 50th percentile of the bed surface sediments and σ is the sorting coefficient of the bed surface sediments. The resulting friction angle distributions were used to calculate the critical shear stress for entrainment according to the formulae derived by Carling *et al.* (1992):

$$\tau_c = \frac{2V(\rho - \rho_s)g}{\psi C_d \pi (a_2 b_2 c_2)^{2/3}} \frac{\sin(\Phi - \beta)}{\cos\Phi} \frac{1}{[5{\cdot}75 \log(30z_p/k_s)]^2} \tag{7}$$

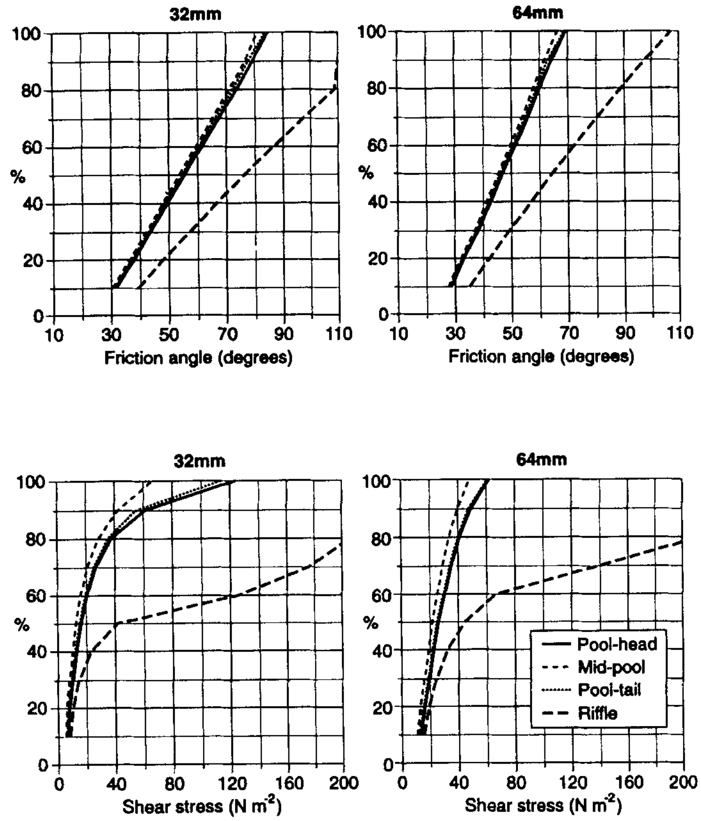


Figure 7. Calculated friction angle and critical shear stress distributions for riffle and pool subunits, using the methods of Buffington *et al.* (1992) and Carling *et al.* (1992)

where V = particle volume, β is the local bed slope (degrees), ψ is an exposure factor (0·5 for coplanar beds, 0·87–0·9 for exposed particles), C_d is the drag coefficient (values of 1·10–1·20), $(a_2b_2c_2)^{2/3}$ equates to the particle area exposed to flow, z_p is the vertical distance between centre of bed and entrained particles and k_s is a value for hydraulic roughness. This formula was developed under controlled conditions using grain size and roughness values similar to those found in the pools and riffles in the North Tyne. The result is a critical shear stress distribution model for pools and riffles (Figure 7).

Figure 7 reveals a similarity of friction angle distribution between pool subunits, despite a general down-pool fining and increased sorting coefficient. This similarity is reflected in the shear stress distributions, although the effect of a positive bed slope in the pool-tail effectively increases the values of critical shear stress above those for the mid-pool section. The values of the critical threshold for sediment transport calculated using Equations (6) and (7) are shown for comparison.

The range and 50th percentile values for both friction angle and critical shear stress are higher at riffles than at associated pools. In addition, Figure 7 shows that the predicted values for the range and 50th percentile critical shear stress are close to those observed from the field, although the upper limit for riffle sediments is poorly defined owing to the inability to account for negative particle exposure in the shear stress calculations. The relatively narrow range of critical shear stress values predicted for pool subunits may explain how sediment transport rates in pools increase more rapidly than for riffles. The narrow range also suggests that the mechanism for entraining pool sediments should more closely approximate to the equal mobility condition than evident in the field data. More datasets are required to confirm or reject

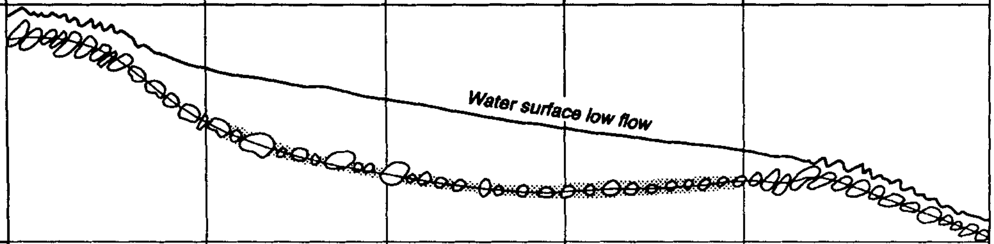
BEDFORM	RIFFLE	POOL-HEAD	MID-POOL	POOL-TAIL	RIFFLE
LONGITUDINAL VIEW					
BED STATE	$\boxed{\text{Congested}}$	→	$\boxed{\text{Smoothing}}$	→	$\boxed{\text{Congested}}$
SEDIMENTARY STRUCTURE OF SURFACE	Tightly packed. High frequency of particles in stable structures. Armoured. Open-work	----------→	Loosely packed. High frequency of particles in unstable positions in bed. Armoured. Increasing matrix		
SURFACE D_{50}					
ENTRAINMENT THRESHOLD	High	Decreasing	→	Low	High
DISTRAINMENT OPPORTUNITY	High	Decreasing	→	Low	High
BED SLOPE	+ High	Gentle	→	- ive →	+ High
PARTICLE MOVEMENT	Short L Low V_b	High L High V_b	→	Mod L → Mod V_b →	Short L Low V_b
BEDLOAD BALANCE	Aggrading		Degrading	→	Aggrading
RELATIVE EXPOSURE D_{50} RIFFLE PARTICLE	Low	Increasing	→	High	Low

Figure 8. A descriptive model of sediment transport processes in pool–riffle sequences adapted from Iseya and Ikeda (1987)

this observation. Riffle sediments, by contrast, require a wider shear stress range to achieve general bed mobility and might be expected to display size-selective entrainment. At any given shear stress, therefore, the number of particles entrained in pools is likely to be higher than for riffles, though the hydraulic and structural discrimination between bedforms will act to modify the calibre of the material in motion.

Despite the apparent success of this model in predicting the observed differences in critical entrainment thresholds, there remains a distinct difference between the field observations of increasing shear stress with increasing particle size, and the converse situation as predicted by grain geometry and relative exposure. This was noted by Kirchiner *et al.* (1990) and Carling *et al.* (1992) in the flume and by Buffington *et al.* (1992) in the field. The latter accounted for the variance by suggesting that what in fact is represented by the critical shear stresses is not entrainment but 'distrainment' or the opportunity for grain trapping since the measurements of friction angles in all three studies refer to grains resting on the bed surface and not within the surface. The effect of packing on the entrainment of grains within the river bed should result in higher critical shear stresses. Conceptually, therefore, the results of friction angle modelling suggest that riffles possess a greater capacity for trapping particles in high critical entrainment sites on the gravel surface, whilst the opportunity for such trapping in pools is more limited. The behaviour of this model is similar to that defined by Bluck (1987) for bar–pool systems where sorting is a function of the selection/rejection of particles on the basis of the pore size of bar/riffle surfaces and the lower energy environment in pools.

A model proposed by Iseya and Ikeda (1987) describes sediment transport and sedimentological variations similar to those identified in this study for the pool–riffle sequence. Their flume experiments identified a relationship between the sedimentological status of the bed and the mobility of sediments based on relative exposure and the development of rythmically spaced zones of different sediment discharge.

According to their model, regions of tightly packed gravel (termed congested bed state) are characterized by steep slopes, low particle velocities, low frequency of particles in motion and high frequency interchange between mobile and static particles. The bed is characterized by net aggradation during conditions of bed mobility. This is similar to those observed on riffles in this study. A smooth bed state which in the flume experiments was dominated by sand is characterized by high velocity transport of particles, gentle slopes and high rates of sediment transport at the transition from smooth to congested bed. Sediment transport discharge is at a minimum at the downstream end of a congested state. Iseya and Ikeda (1987) considered relative exposure and particle collision to be the main processes responsible for the observed sediment transport, though like the pool–riffle debate, the conditions were observed after the formation of the different bed-states. Lisle *et al.* (1991), conducting a similar flume study, related bar development to the longitudinal sorting of bed material into congested and smooth zones. The resulting pattern of differential bed-state resulted in the evolution of the alternate bar morphology. Figure 8 schematically compares the observations from the pool–riffle sequences with those determined by Iseya and Ikeda (1987). The downstream pattern of zones of different bed surface states and sediment transport conditions at bed mobilizing flows is similar to the flume model. The mechanics of the sediment transport may be interpreted from the discussions above. Riffle surface sediments are coarser, rougher and more tightly packed and exhibit a higher frequency of stable sediment structures than pool sediments. This results in a zone of high critical transport thresholds, higher frequency of particle entrapment in higher critical entrainment positions, lower particle velocities and aggradation during bankfull floods. Pools exhibit a downstream fining of surface sediments which are loosely packed, relatively low in structure, and which have lower critical transport thresholds than similar grain sizes (and possibly shapes) on riffles. The frequency of entrapment sites of high critical entrainment thresholds is lower, and particle velocities are generally higher through the pool. The pool is characterized by degradation, though the pool-tail may aggrade.

CONCLUSIONS

Sediment transport through the pool–riffle sequence does not require a section-averaged or local shear stress or velocity reversal to explain the patterns of scour, fill and sedimentology in pool–riffle sequences. Rather, during low magnitude, high frequency flows, the riffle surface is subjected to chaotic, turbulent flows that develop structure through *in situ* particle vibration and sporadic particle motion. The bed surface becomes tightly packed and interlocked. In contrast, the pool sediments are not subjected to turbulent flows, and sediment transport is limited to the routing of sands over a static bed. An explanation for the lack of bed structure in pools, despite high near-bed shear stress during floods, may come from the relatively narrow critical shear stress field required to entrain pool sediments as observed in the field and as predicted on the basis of friction angle calculations. Rapidly rising shear stress during floods quickly mobilizes most of the pool bed , preventing the local *in situ* vibrations and short distance particle movement experienced on riffles. The transport of fines through pools towards the pool-tail and the high sorting coefficients in the pool provide a bed of relatively lower (and narrow distribution of) entrainment thresholds, decreasing roughness and decreasing compaction which encourages faster particle velocities (Ferguson *et al.*, 1989). Once mobilized, there is greater opportunity for finer particle entrapment (pocket geometry is smaller in pools) which enables coarse particles to be routed through the pool to the downstream riffle in accentuated frequency, similar to the selection/rejection model of Bluck (1987). Against this trend, the local reach morphology tends to produce a downstream reduction in shear stress through the pool. Particles therefore maintain a high velocity throughout the pool but decelerate through the pool-tail. Scouring of pool sediments should therefore progress from pool-head to pool-tail, with the evacuation of the pool-tail being associated with larger concentrations of initially fine sediments as the low-flow carapace of fines is mobilized, and subsequently, coarser particles as transport sorted sediments arrive from upstream pool subunits. This is similar to the observations of Iseya and Ikeda (1987) and Lisle *et al.* (1991).

Tracer studies from a range of sources and rivers confirm that pool sediments travel further per flood event than riffle particles. Sediment transport path lengths are of the order of one pool–riffle unit in distance per bankfull flood event, with little linkage between upstream and downstream riffles. As Lisle *et al.* (1991) and Clifford (1994) observe, the transport of sediment is from pool to pool with storage on riffle surfaces. The longevity of this storage is probably related to the rate of development of bed structure and compaction.

The nature of the formation of the pool–riffle sequence is still unknown, although it is clear, at least in flumes, that a mechanism for downstream sediment sorting exists which results in alternating zones of particle congestion. Further research is needed to validate the observations made in this study and to examine in more detail the interaction between particles and the nature of the particle exchange within the bed. However, a conclusion from this and similar studies is that bedforms should be interpreted on the basis of their sediment transport characteristics and not simply on stage-dependent morphology or basic grain-size distribution. Spatial patterns of bed structure and compaction, accentuated at low to moderate discharges, can continue to influence sediment transport patterns during floods through the development of regions of high and low particle velocities and differential near-bed flow types. These in turn may cause local concentration of particles with positive feedbacks to the local hydraulics and particle velocity in a manner akin to Iseya and Ikeda's (1987) theory. Application of grain geometry analysis appears to provide an opportunity for the modelling of sediment transport at the reach scale.

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