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SEDIMENT TRANSPORT PROCESSES IN RIFFLE-POOL SEQUENCES AND THE EFFECTS OF RIVER REGULATION FOR HYDRO-ELECTRIC POWER WITHIN THE NORTH TYNE.

by

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Sediment Transport processes in riffle-pool sequences and the effects of river regulation for hydro-electric-power within the North Tyne.

Abstract

This study examines the effects of 10 years of river regulation on the sediments and sediment transport processes within the gravel-bedded River North Tyne. The North Tyne was regulated following the closure of Kielder dam in 1981. Since 1984, the releases from Kielder reservoir have been dominated by the generation of hydro-electric-power.

The work combines a long term review and re-survey of pre-regulation sediment and bathymetric databases, with measurements of contemporary sedimentological and sediment transport processes. This has involved the application of a range of techniques designed to characterise the bed morphology and sediments. These included two new techniques for determining the structure and strength of gravel-bed surfaces. The results of these surveys revealed subtle changes in the grainsize composition of riffle sediments, characterised by an increase in the frequency of coarse particles at the surface, and the accentuation of bed structure and particle compaction. This has resulted from a process of hydraulic winnowing sustained as a result of the high shear stresses experienced on riffles during the passage of the hydropower release wave.

Direct measurements of sediment transport using a range of tracing and trapping techniques identified a sediment flux divergence between riffles and pools. During rising discharges, sediments are selectively restrained by bed structure on riffles, whilst pool sediments become competent in the order pool-head, mid-pool, pool-tail. This generates a queuing system for sediments culminating at high discharges in the evacuation of the pool-tail to the downstream riffle. The presence of bed structure on riffles presents a surface of higher particle entrapment probability; the net result of which is lower particle velocities over riffles than in pools, and a subsequent choking of riffles with pool sediments.

The interaction of the regulated flood waves and the riffle-pool morphology produces riffle degradation and pool-tail aggradation, although at rates much lower than in a neighbouring regulated river. Hydropower releases retard the rates of aggradational channel change caused by the reduction of flood magnitude. However, historical evidence suggests that catchment sediment supply is variable through time, and should new supplies be accessed, major channel changes should be anticipated, particularly at the tributary junctions.

The results of this study have direct implications for the management of game fisheries in regulated rivers, and for understanding the relationships between flood waves and sediment transport in morphologically diverse channels.

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Chapter 1.0
Introduction and subject perspective

1.1 Introduction: Aims and objectives of the study

This thesis endeavours to assess the impact of 10 years of river regulation for hydroelectric power on the sediments and sediment transport within riffle-pool sequences. The aims as outlined in the title reduce to 3 tasks:

quantification of the factors affecting sediment transport which have changed as a result of river regulation, these include hydrological regime and sediment supply

the quantification of the effects that a changing hydrological regime has upon the transport and character of sediments within the North Tyne

the effect of a specific gravel-bed morphology (the riffle-pool sequence), on the routing and transport of sediment under these conditions.

These objectives require consideration of temporal and spatial changes in a range of parameters which result in a complex pattern of process interaction; a characteristic of sediment transport in gravel-bed rivers.

This study could be viewed as a comparison between theoretical and empirical approaches to an engineering problem since a full theoretical study of the effects of Kielder reservoir on the sediment transport and morphology of the North Tyne already exists (Brierley 1983). However since the conception of the initial theoretical study by Brierley the political agenda has changed, and for the North Tyne this has meant a change in emphasis from an engineering concern for river instability, to an environmental concern for biota and specifically Salmonids. As a result this study does not aim to compare the theoretical prediction with the empirical observation but rather to give an independent overview of the nature and rates of environmental change with particular regard to the biotically important riffle-pool sequence.

1.2 Approaches to the study of sediment transport in gravel-bed rivers.

The study of sediment transport in gravel-bed rivers, is approached from three avenues of research;

theoretical analysis based on force balancing

empirical Froude modelling using sand and small gravel in flumes

empirical analysis of sediment transport in natural, uncontrolled conditions within rivers.

The synthesis of this knowledge into an overall understanding of river processes reflects the very different objectives of river engineers and research scientists. Indeed the perpetual dichotomy between the two major knowledge users has arguably hindered the ideal situation of mutual learning advocated by Newson (1986) and Hey (1990). The situation to date leaves the river engineer (and dam designer) designing dams and "stable" channels based on a range of sediment transport formulae that are consistently updated by the research scientist. The resulting plethora of formulae is perhaps the most fitting testimony to the lack of understanding of the interaction of processes in gravel-bed rivers that prevents a generally applicable prediction capability for sediment transport. Given the enormous margins of error associated with most sediment transport formula, (errors of 100% are to be expected, Meigh (1987)) it is inevitable that empirical studies should be required to gauge the actual response of a natural channel to an engineering solution/design.

The lack of success in predicting sediment transport within gravel-bed rivers is in part due to oversimplification of the complex interactions of a variable bed morphology, heterogeneous substrate and 3-dimensional flow field. A characteristic of gravel-bed river studies is the tenuous extrapolation of relationships developed under uniform conditions to solve problems in a system that clearly functions on non-uniformity (Gomez and Church 1989). A recent study of the causes and consequences of river channel engineering in England and Wales has highlighted the financial ramifications of this lack of understanding of sediment transport amongst practising river engineers (Sear and Newson 1991).

The increase in field-based studies of sediment transport in gravel-bed rivers has greatly improved our understanding of the processes involved. Field-based studies are a necessary pre-requisite for the development of flume simulations that can be targeted to solve "real" problems which exist in the natural channel. Recent examples include the work of Wolcott (1989) on the development of bed surface structure, Ashworth et al (1992) on braided channel dynamics, Carling et al (1992) on the motion of individual grains, and Lisle et al (1991) on the development of alternate bar morphology. As Wolcott (1989) concludes, "The interplay between theory and observation and between field and flume is both complex and necessary".

1.3: Experimental methodology

The critical rationalist approach of this study is based on the iterative solution of problems by the acceptance/rejection of empirically based hypotheses from which theoretical models are generated. This approach reflects the reality of the task required, namely the resolution of the effects of hydropower generation on sediment transport in riffle-pool sequences within the North Tyne. The important objectives as far as the managing authorities are concerned are the nature, spatial scale and time scales of the cause and effect. These cannot simply be determined by conventional theory, since much of the information on sediment transport operates in one or two dimensions (Naden 1987; Clifford 1990) and the interactions in three and four dimensions are not well understood. The riffle-pool sequence is three dimensional and variable in the fourth dimension of time consequently, an empirical approach designed to investigate the complexities of a problem is preferred as the basis to producing realistic landform models (Richards 1988).

Physical scale modelling in flumes was not practical in this study, and although feasible in gross morphological terms, it is impossible to replicate in entirety the complexity of the natural environment by using grades of sediment much finer than that experienced in the field. The empirical critical rationalist approach can however, identify areas where physical models can be adopted to improve the understanding of individual components of the total process.

Although the use of empirical field data encompasses the scale and complexity of the environment under scrutiny, there are inevitable logistical problems. To mitigate against this problem a sampling strategy is adopted in order to maximise the information collection whilst not compromising the reality of the situation in terms of complexity and scale. Sampling in a large river like the North Tyne over a period of only 3 years, requires subjective sampling decisions based on previous research. Correspondingly it was evident that tributary junctions would be important sites to monitor for rapid changes to regulation, and yet this realisation must be built into the framework of the project objectives which were concerned with the riffle-pool sequence.

The structure of this thesis is based on two approaches;

an extensive approach which draws on previous studies and databases and seeks to develop a wider, longer view of the study objectives

an intensive, reductionist approach which seeks to develop general hypotheses from small samples.

The latter approach is largely dictated by time and logistics together with the operational constraints of Water Authority release policy.

In practice the thesis develops the background to the Kielder water scheme, and attempts to investigate the historical stability and sediment storage within the North Tyne prior to regulation. The data generated for this approach is applied to the total river length downstream of the current dam site. The extensive approach is applied to records of flow discharge, in order to quantify the pre-regulation discharge regime and the effects of regulation on the North Tyne hydrology.

A suite of databases are utilised in order to determine what (if any) the changes have been on the North Tyne since regulation. This is again an extensive approach which focuses on the North Tyne upstream of the River Rede and produces evidence of morphological and sedimentological changes post-regulation.

A contemporary survey of sediments and coarse sediment transport is developed around three main study sites. In addition, these sites provide the hydraulic and sediment transport data required to investigate sediment transport processes during discrete hydropower events. Further sedimentological data was collected from sites within the North Tyne upstream of the River Rede, and within unregulated tributaries. The extension into unregulated tributaries was considered necessary to extend the pre-regulation database by substitution of space for time.

The rationale behind the choice of sites was based on the longitudinal distribution of unregulated tributaries and previous study sites. Previous experiments in regulated rivers had shown that unregulated tributary discharges and sediment supply were important for determining the effects and rate of change in the regulated channel. Correspondingly, the North Tyne was divided into two sections, separated by the junctions of the Tarset and Chirdon Burns. Upstream of these tributaries, discharge in the North Tyne is dominated by regulated flows, whilst downstream, the North Tyne experiences periodic unregulated floods up to bankfull capacity.

In addition to the division based on the Tarset and Chirdon burns, a decision was made to concentrate on the channel processes operating within the North Tyne upstream of the River Rede. Three reasons exist for this decision, first the effects of regulation are known to be most evident in the reach of channel closest to the dam site, second the majority of pre-regulation and contemporary biological sites were concentrated in this reach, and finally, the logistics of working on the channel downstream of the Rede proved too difficult to sustain. A site was set up at the Countess Wood gorge, but the channel width and the complexity of the bed made measurements of sediment transport including painted tracers, impossible.

Further considerations in the location of monitoring sites are accessibility and absence of the public. The latter point is important when leaving painted tracers or automatic sampling equipment, whilst the former is necessary for the haulage of equipment. Permission from the relevant landowners and angling interests is also a consideration, since the opposition of either party will jeopardise the experiments.

The decision on the actual riffle-pool-riffle sites was determined by accessibility, representativeness, inaccessibility to the public and position of contemporary biological experiments. Correspondingly, the Tarset site encompasses the boundary between the regulated North Tyne and the North Tyne experiencing flood unregulated events, as well as incorporating potentially reactive tributary confluences. The Smales site is representative of the dominantly regulated channel upstream of the Tarset/Chirdon Burns, and was accessible from the road. The possibility of a site at Ridley Stokoe was investigated but rejected on the grounds of public and angling accessibility and scale.

The Newton site was accessible but located on private land, and was associated with a former FBA site and contemporary biological experiments. In addition the reach ended in a former sedimentation zone, the supply of sediment to which was considered important to monitor with respect to the future stability of the site.

The structure of the thesis builds on the historical databases to present a picture of the pre-regulation North Tyne and identifies the post regulation effects on morphology, sedimentology and discharge regime. The changes are then examined in terms of the hydraulic and sediment transport processes operating during three hydropower releases. This information is supplemented by the monitoring of morphological changes at discrete cross sections and the movement of coarse and fine sediment through riffle-pool sequences. The objective is to identify those processes operating in the riffle-pool sequence during hydropower regulation which account for the observed changes in the North Tyne system. These are subsequently combined to present a model of riffle-pool development and maintenance, from which future changes in the North Tyne can be inferred. In as much as this study entails an investigation of the riffle-pool sequence under semi-controlled conditions it has a greater external validity than the North Tyne. The riffle-pool sequence is a fundamental unit of gravel-bed rivers and an important component of the aquatic habitat. Correspondingly the model of riffle-pool dynamics and detail contained within this study is built into a more general picture of gravel-bed river dynamics.

Throughout this dissertation, each subject area is introduced by a discussion of the existing theory and observation. The methods of investigation are outlined and the results described and discussed. Many of the conclusions of this dissertation are included in the body of the work, but a summary of important contributions is developed at the end.

1.4 Sediment transport in regulated rivers: an overview and appraisal of the subject relevance.

River regulation in the UK has been thoroughly reviewed by Petts (1978; 1980; 1988) and a further review of the history and development is considered unnecessary in the context of this study. The relevance of this study is however linked to the increasing number of rivers that are affected in some way by river regulation. In the context of this study river regulation means the management of natural water supply for the generation of hydropower which in the USA would be termed Peaking Power regulation (Gore et al 1989). Peaking power regulation is the term used to describe the control on a rivers hydrological regime based upon the daily demand for electricity (Gore et al 1989). The use of reservoirs for peaking power production has advantages over coal-fired or nuclear power stations in that the time to "come-on-line" is considerably quicker, therefore enabling a more rapid response to demand. Peaking hydropower schemes differ from other types of river regulation in that they alter the pattern of seasonal and daily flows by reducing flood peaks, augmenting low-flow periods and increasing the frequency of events associated with the hydropower generation. Hydropower regulation rather than determined by the natural distribution of rainfall over a basin is governed by the economic, demand-led control of daily flows (Nestler et al 1986).

Petts (1988) using data based on the 1310 gauging stations in operation in the UK in 1976 documents 31 stations affected by river regulation solely for hydropower; the majority of these located in Scotland. The rate of dam building for hydropower within the UK has decreased since its peak in the 1960's (Petts 1988), however the increasing pressure on politicians to advance environmentally sensitive methods of power generation may lead to the development of more schemes at the small community level. On a Global scale river regulation for hydropower is a major source of cheap electricity which is particularly favoured in developing countries. Petts (1989) puts the numbers of peaking power schemes proposed for developing nations in the thousands. The relevance of this project in as much as the conclusions can be extended to other river systems is clear.

The environmental impacts within a river experiencing river regulation involve changes in 5 interelated categories:

1. water quality
2. stream biota
3. channel morphology
4. sediments
5. discharge/sediment regime.

Adjustments to the channel morphology and sediment character are important both for the transmission of water and sediment as well as the structure of floral and faunal communities within the channel (Haile et al 1989).

The adjustments within a channel brought about by regulation occur as a result of the changes in discharge regime and sediment supply (Petts 1988; 1979; Carling 1988; Brookes and Gregory 1989). The nature, magnitude and evolution of a given channels response are conditioned by changes in the discharge regime, sediment supply, sediment load and the relative sediment/water inputs from unregulated tributaries all reacting within the pre-regulation channel environment (Petts 1979; 1980). Petts (1987) correlates the type and timescales of a channels adjustment to river regulation with the pre-regulation channel morphology, sediment character, bank stability and rate of vegetation colonisation, whilst Schumm (1977) proposes that the position of a channels response to a change in discharge/sediment regime will be determined by the location of thresholds of change. Schumm (1977) proposed that river channels exhibit different conditions of stability, therefore positions within a given channel will exhibit different reaction times to a change in sediment supply or discharge regime. It was this concept that enabled Petts (1980) to identify the important and rapid adjustments to regulation at unregulated tributary confluences and meander belts and to emphasise the relatively localised nature of degradation.

Implicit within these observations is the need to identify pre-regulation conditions within the channel in order to assess likely post-regulation adjustments (Patrick et al 1982; Newson 1982; Church 1982).

Petts (1979;1983) emphasised the complexities of river channel adjustments to regulation based on the conditions above; and identified the spatial and temporal variations of adjustment scale. Carling (1988) remarked on the uniqueness of each regulation impact in terms of channel response whilst recognising that certain tangible adjustments occur but considered that to date no general predictive model could be applied to a given scheme.

Base on the above discussion, it is apparent that any assessment of the impact of a regulation scheme will be:

* effected with recourse to the database of existing knowledge derived from studies of the impacts of other regulation schemes, coupled with a knowledge that

* any specific response is likely to occur at positions of potential instability within the former channel, but that

* rates of adjustment and the magnitude of change will be unique to the conditions within a specific post-regulation channel.

Petts (1984) identifies three major adjustments to a river subsequent to regulation:

1. bed degradation
2. bed aggradation
3. channel metamorphosis

A fourth response is accommodation, which Petts (1988b) suggests is the major response of gravel-bed channels in the UK. Indeed Petts goes on to state that in most cases of river regulation within the UK the post-regulation channel has accommodated the regulated flow regime with little or no adjustment.

Although Carling (1988) and Petts (1988b) produce a picture of unique response (if any) to river regulation within gravel-bed channels, there nevertheless exist certain typical responses which are discussed below with particular emphasis on gravel-bed rivers. Each response represents a change in the sediment transport capacity and competence of the post-regulation channel and as such are important to consider as indirect measures of change in sediment transport.

1.4.1 Channel Degradation

Channel degradation occurs wherever competent flows occur in the absence of sediment supply. Degradation below dams was until recently considered to be the dominant and primary affect of regulation, associated with proximity to the dam and viewed as a migrational erosion front the progression of which is controlled by slope, roughness and the rate of armouring (Kellerhals 1982). Degradation in sand-bed channels is at a maximum between the dam tailwater and 69 channel widths downstream (Wolman 1967); however both Petts (1979) and Kellerhalls (1982) conclude that in gravel-bed channels little if any degradation will result owing to the presence of an armour layer in the pre-regulation channel. Carling (1979) and Brierley (1983) concluded, on the basis of theoretical considerations of the threshold of median particle motion for the North Tyne, that little if any change in channel morphology was to be expected as a result of the reduced discharges. Despite these considerations Petts and Pratts (1983) have described degradation in the gravel-bed river Ter up to 17km downstream of the Leigh reservoirs. This regulation scheme, though not equivalent to hydropower regulation, is also characterised by flow augmentation. The implication being that degradation in gravel-bed regulated rivers requires an increase (or maintenance) of competent flows. Thorne (1982) describes the increased bank erosion and local degradation on the River Severn below Clywedog dam. His observations, supported by the tracer movement studies of Hey (1975; 1986) and Leeks and Newson (1989) suggest that degradation within gravel-bed rivers will be localised to reaches of channel that are near the threshold of instability described by Schumm (1977). Boles (1980) describes the preferential degradation of riffles below reservoirs in the USA, whilst Cowx et al (1981) document the erosion of spawning gravèls below Llyn Clywedog in Mid-Wales.

Petts and Thoms (1987) have described localised degradation at the confluence of the North Tyne and the Tarset Burn in association with the development of a tributary confluence bar. The degradation of tributaries is also a feature of gravel and sand-bed streams and results from local bed degradation in the main channel or where the base level is lowered in the main channel through channel widening or reduced water levels at times of tributary flooding (Petts and Lewin 1979; Germanoski and Ritter 1988). The degradation of tributaries in response to a base level change in the main channel increases the sediment yield from the stream leading to aggradation in the regulated main-stream.

1.4.2 Channel Aggradation

Aggradation occurs where sediment supply exceeds sediment transport at a site. In the North Tyne and many other regulated gravel-bed rivers these conditions occur at tributary confluences or downstream of areas experiencing bank or bed erosion. The extent of aggradation is conditioned by the balance between sediment supply and the frequency of competent flows. The rate of aggradation is conditioned by the effectiveness of tributary floods and the supply from these sources,(often enhanced by rejuvenation).

Petts and Thoms (1987) proposed a model of aggradation below unregulated tributaries whereby continued supply of sediment, coupled with increased flow competence in the narrowed mainstream, will effectively allow the downstream routing of additional material once the sediment sink is filled. This sediment sink, corresponds to the separation shear zone identified by Reid and Best (1985), and is related to the angle of tributary confluence to the mainstream together with the ratio of tributary:mainstream discharges. Aggradation at tributary confluences is generally localised although Kellerhalls (1982) documents effects up to 8 km below tributaries.

Aggradation also occurs as a result of the redistribution of sediments within the regulated channel. Riffle degradation and an increase in fine sediment transport has reportedly caused the infilling of pools (Petts 1980), whilst Petts (1977) documents the development of extensive marginal berms within the regulated River Derwent. The latter phenomenon results in a positive feedback of fine sediment siltation encouraging the establishment of riparian vegetation, with the subsequent increase in fine sediment trapping efficiency. Northrop (1965) concludes that the development of in-channel riparian vegetation can cause the development of new aggradational barforms and islands, and documents a 66% reduction of channel capacity resulting from riparian vegetation incursion. Aggradation of channel margins can also be effected by bank collapse, as a result of lower water levels within the regulated channel (Petts 1978).

1.4.3 Channel Armouring

The armouring process within gravel-bed rivers is well documented, if not well understood (Bray and Church 1980; Parker and Klingeman 1987; Willetts et al 1992; Lamberti and Paris 1992). Armouring is a condition of most unregulated gravel-bed rivers and consequently some studies argue that armouring subsequent to regulation will not be dramatic (Petts 1982; 1988a; Kellerhalls 1982), indeed where fine sediments are released into a regulated gravel-bed river, "anti-armouring" may result as in the River Chew (Petts and Thoms 1986), or below tributary confluences (Petts 1983). The stabilisation of rapids is mentioned as a response of a gravel-bed river to a reduced frequency of competent flows, with stability related to the size and frequency of large immobile elements in the surface sediments (Graf 1980).

More recently Gore et al (1989), have argued that peaking hydropower regulation, "can result in more substantial downstream changes in physical habitat than a non-hydropower operation". They go on to describe increases in bed scour and armouring as a result of the reduced sediment loads in the presence of competent discharges. The effect of peaking hydropower regulation is variable downstream depending upon the initial release hydrograph (specifically the rate of rise/fall) and the amount by which the release wave is attenuated downstream. Gore et al (1989) describe increased armouring and bed degradation near to peaking hydropower dams and the sedimentation of eroded material in regions below the dam where the release wave attenuates. The impacts of a release wave from a hydropower operation are related to the rate of rise which promotes higher near-bed velocities as the rate of rise increases (Petts et al 1985; Gilvear 1989). Brierley (1983) in a mathematical modelling approach to the effects of proposed hydropower generation in the North Tyne found that the rate of armouring following competent floods, strongly influenced the degree of morphological change in the system, but failed to assess the changes to the armour layer grainsize as a result of the predicted increase in competent flows.

1.4.4 Channel Siltation

Channel siltation is largely associated with regulation schemes that result in prolonged periods of low flows and a greatly reduced frequency of discharges capable of gravel-bed mobility. The siltation of streams associated with hydropower regulation, is documented in association with prolonged periods without a peaking power demand (Reiser et al 1989) or where the competence of the hydropower releases are below the value of surficial armour layers. Siltation is directly related to the supply of fine sediments which in turn links it with unregulated tributary confluences and areas downstream of eroding sections of channel. Siltation in gravel-bed channels is associated particularly with inputs from unregulated tributaries the effects of which are generally localised (Petts 1988b; Petts and Thoms 1987). Petts and Thoms describe the development of a flow separation bar downstream of the Tarset Burn confluence on the North Tyne. Siltation of gravels occurs up to 200m downstream of the confluence. Siltation within the regulated gravel-bed river Daer exhibited preferential development in association with wake deposits in the lee of large particles up to 2.5km downstream of a tributary input (Petts 1988b). In extreme cases where fine sediment supply is enhanced, detrimental siltation of gravels can occur along large sections of a channel. Cave (1985) documents the development of a 30cm thick deposit of fine sediments over spawning gravels during construction of the Kielder Reservoir whilst Doueg et al (1987) showed that construction related siltation of gravels was spatially and temporally varied, and decreased with distance from the dam site.

The changes in gravel composition within regulated rivers is significant for the development and maintenance of biota and particularly stocks of game fish. Siltation can seriously affect the survival of salmonid eggs if permeability and dissolved oxygen levels are reduced (Cave 1985), although recent experiments suggest that alevins are capable of penetrating through sand and filamentous algal matts of up to 10cm depth (Haile et al 1989).

The accentuated development of a dense matt of filamentous algae containing a "cocktail" of heavy metals is a characteristic of regulated gravel-bed rivers experiencing periods of prolonged low flows (Haile et al 1989). Gilvear (1988) identifies these deposits as a major source of suspended solids in regulated rivers, in the absence of bed mobilising flows which would release the trapped inorganic fines. Nevertheless, the effects of this "mousse" are not known although it is a source of seston load within the North Tyne (Petts et al 1985).

1.4.5 Morphological changes in regulated rivers

Accounts of morphological changes downstream of regulated rivers are dominated by the reduction in channel capacity identified through regional regression modelling, (Park 1977; Petts 1977; 1979; 1980b; 1987; Carling 1988). In addition the literature is replete with descriptions of the development of tributary flow separation bars (Petts 1983; Petts and Thoms 1987; Kellerhalls 1982). These reactions represent the result of a reduced flood frequency, augmented low flows and a corresponding stabilisation of channel side deposits by riparian vegetation (Petts 1984). Reduced channel capacity has important implications for flooding since rare high discharge events will tend to have higher stages as a result of reduced freeboard. This is translated into engineering problems in a number of regulated rivers resulting in tangible financial costs to the tax-payer (Sear and Newson 1991). Increased capacity as a result of bank erosion appears to be rare or at least poorly documented, although Hey (1986) indicated possible channel widening in association with the proposed Craig Goch regulation scheme, and Petts and Pratts (1983) document a 45% increase on the River Ter. Destruction of the riffle pool sequence is documented as a result of riffle degradation or pool infilling, however the spatial scales of these effects are not known (Trotzky and Gregory 1974). The morphological response of gravel-bed rivers is at present considered to be one of little or no adjustment with the bulk of channels accommodating the imposed flow regime.

1.4.6 Timescales of impacts

Petts (1980) derived a model of channel adjustment through time in which he identified the potentially rapid response of a system to regulation (reaction time) and the longer relaxation time to effect a new equilibrium. Petts (1979) identified rapid response within 10 years at sites associated with unregulated tributaries, and a period within 100 years for the rest of the channel affected by regulation to adjust to the imposed regime. In gravel-bed rivers the processes of adjustment may be triggered by extreme events, the probability of which increases with elapsed time since regulation (Petts, 1980; Carling,

Table 1.1 **Timescales associated with adjustments of gravel-bed rivers to regulation.**

Adjustment	Timescale	Source
Degradation	Riffles destroyed after 26 years	Trinity Scheme (Boles 1980)
	0.3m during 1 flood	Clywedog Dam (Thorne 1982)
	0.3-3.9 cm/yr 9 years (nearest dam)	River Ter (Petts & Pratts 1983)
	0.3-3.2 cm/yr 9 years (away from dam)	River Ter (Petts & Pratts 1983)
	Channel capacity doubled (67 years)	Camps Water (Petts 1978)
	Channel capacity doubled (87 years)	River Rede (Petts 1984)
	0.005-0.05 m/yr (1965-75)	Colorado River (Pemberton 1975)
	34% increase in capacity	Hodder (Petts 1984)
Aggradation	10 cm/yr (downstream of tributary)	Rheidol (Petts 1984)
	1.5 m/yr (downstream of tributary)	Peace River (Kellerhalls 1982)
	1.0 m per flood	Colorado (Dolan et al 1974)
	4.2 cm/yr (redistribution)	River Ter (Petts & Pratts 1983)
	12 cm/yr (redistribution)	Bistinta River (Radaone 1980)
	12 cm/yr (redistribution)	Bistula (Ichim & Radaone 1980)
	1.2 m per flood (tributary)	North Tyne (Petts & Thoms 1987)
	50% reduction in capacity (87 years)	River Rede (Petts 1984)
Armouring	34 years riffle armouring reduces fish stocks by 60%	Milhous (1982)
	D_{50} increased by 300% in 26 years	Colorado (Mostafa 1980)
	15 years for 50% increase in rapid stability.	Colorado (Graf 1985)
	16% increase in D_{50} in 15 years	Blackbrook (Pratts 1983)
Siltation	0.0157 kg/m^2 day^{-1} (pool/riffle) (unregulated upland stream)	Carling & McCahon (1987)
	500 m^2 year^{-1}	Daer/Derwent (Petts 1988)
	300% increase in fines (tributary)	Daer/Derwent (Petts 1988)

1988). The reaction time in this case is conditioned by the frequency of a flood of required competence to effect a change. The relaxation time can be considerably reduced by the rate of riparian vegetation colonisation; landuse therefore becomes an important issue through control on riparian corridors.

Table 1.1, depicts the timescales associated with the documented responses of regulated gravel-bed rivers to the imposition of a regulated flow regime. From the arguments above it can be anticipated that hydropower regulation will exhibit a more rapid reaction time for channel armouring and degradation although no quantitative data exists to confirm this.

Table 1.1 shows the relative rapidity of aggradation in response to regulation which is linked to the unregulated, flood based nature of the process. Degradation is a relatively slow process but again this will vary depending on the individual reach conditions and the type of regulation experienced. Rates of channel armouring are not well documented in the literature largely due to a paucity of pre-regulation databases. Documented adjustments over long reaches of channel occur within 35 years and constitute a rapid reaction process; this is discussed further in Chapter 5. Siltation is similarly difficult to quantify in terms of time but generally occurs rapidly in association with tributary inputs. Relaxation times are impossible to identify from the literature except for channel capacity adjustments which occur over periods of 100 years. Ecological reaction times are more rapid largely due to the mobility of the subjects involved. Thus effects on the invertebrate and salmonid populations of the North Tyne were evident after only 9 years of regulation, 4 years of which were dominated by hydropower generation (Hailes et al 1989).

1.4.7 Sediment transport in regulated rivers

Studies of sediment transport in regulated rivers have been dominated by considerations of seston dynamics, or the effects of unique, extreme events. The lack of studies concerning the transport of bedload is perhaps a reflection of the dominance of water supply regulation in the UK (Petts 1988). Instream flow methodology has recently focussed more attention on the transport of bedload in gravel-bed regulated streams through estimates of critical discharge for "flushing flows" (Milhous 1982; Reiser et al, 1985; Reiser et al 1989). However these studies are generally concerned with the initiation of motion of fine sediments from a stable gravel bed in relation to the regulated discharge regime.

Sediment transport experiments within gravel-bed regulated rivers are often associated with the testing of a scour valve (Thorne 1982; Petts et al 1985; Hey 1986; Leeks and Newson 1989) or a controlled release for flushing flow tests (Beschta et al 1981). In addition, studies of suspended solids transport have concentrated on water supply function reservoirs which lack the characteristic bi-modal discharge regime associated with hydropower generation. Nevertheless these studies have produced important evidence of the effects of river regulation on the sediment transport regime of regulated rivers, but the extent to which they can be used as analogs for other regulated systems is debatable.

These studies are discussed within the relevant sections devoted to considerations of sediment transport dynamics. This study concentrates on the movement of bedload, since it is this which will be most affected by the riffle-pool sequence and which contains the sediment sizes whose transport determines the morphology of a river (Leopold 1992).

1.5: The function of the riffle-pool sequence

This study is primarily concerned with the transport of sediment (under hydropower regulation) through the riffle-pool sequence. The theoretical and empirical discrimination of riffles and pools will largely be dealt with in the relevant Chapters, however it first necessary to identify their function within a river system.

Riffles and pools represent a meso-scale bedform which is inherent to gravel-bed channels with slopes less than 5% (Church and Jones 1982). At steeper slopes bed morphology is replaced by a sequence of step-pools whose composition is characterised by large boulders or bedrock exposures and whose formation is related to the development of antidunes (Whittaker and Jaeggi 1982).

Riffles are shallow reaches of channel characterised by rapid turbulent flow, whilst pools are the intervening deeper slower-flowing regions; these observations pertaining to low flow conditions. Inter-riffle spacing is typically pseudo-rhythmical, of the order of 3-10 times the channel width (bankfull) which can be of the order of a km or a few metres Keller and Melhorn (1978). ?

Knighton (1984) defines the function of riffles and pools within the broader context of channel development as:

1. significance for the attainment and maintenance of dynamic equilibrium

2. significance in the development of meandering

to which can be added their function as important components of the fluvial ecosystem (Lewis and Williams 1984) and as an amenity resource (Sear and Newson 1991).

Church and Jones (1982) differentiates between riffles and bars in terms of function; riffles functioning primarily as units of enhanced hydraulic resistance whilst bars function as units of sediment storage. The functional differentiation of riffles-pools and bars is complicated by the interaction between units so that bars are often attached to riffles as well as pools whereupon the question of whether the riffle is functioning as a storage unit or not becomes blurred. As a result of this interaction some studies perceive riffle-pool-bar morphology to represent a single functional morphological unit, with little differentiation considered between the individual components (Lewin 1976; Thompson 1986). The riffle in these cases is percieved as the leading edge of a diagonal bar, the proximal end of which develops within the pool (Church and Jones 1982). The differentiation between riffle-pool sequences and the riffle-pool-bar unit is a function of sediment supply since a channel accomodating a high sediment supply, will necessarily require a greater storage facility than one in which sediment supply is lower. Correspondingly, Church and Jones (1982) identify a sequence of riffle-pool-bar development downstream, whereby upstream sediment source areas exhibit braided bar-chute-pool morphology and areas receiving less sediment in relation to channel capacity, riffle-pool sequences with little or no sediment storage. Thus a major function of the riffle-pool sequence is as a moderator of sediment storage and release during mobilising floods, however the question remains how and why?

The teleological debate on the equilibrium theory for riffle-pool sequences appears to have been initiated by Leopold and Langbein's (1962) consideration of minimum variance theory by which rivers tend to adjust their morphology in such a way as to simultaneously minimise (as much as possible) the rate of power expenditure whilst equalising the power expenditure per unit discharge. Cherkauer (1973) points out that in order to satisfy the second condition the uniform flow must exist over a uniform bed. Dolling (1968) suggested that this was achieved through greater stream power expenditure at riffles in low flows, balanced by a lower power expenditure in pools. This was subsequently advanced by Yang (1971) who like Dolling, used the slope differences between riffle and pools at low flow to propose that an undulating topography satisfied the "law of least time rate of energy expenditure" better than a uniform bed slope. The use of low flow slope data caused Richards (1982) to conclude that this principle was least relevant at the high flows when the bed profile is developed, and that extremal hypothesis cannot replace explanations based on physical mechanisms. This point has been subsequently challenged by Clifford (1990) who suggests that extremal hypothesis and physical mechanisms are not always incompatible. Clifford cites the concentration of macro-turbulence at riffles, (as predicted by Yalin (1972) in association with the physical bed response of increased particle structure. However, a major problem still exists in proving extremal hypothesis in the field; Ashmore (1977) asks the pertinent question, to what extent are the patterns of energy expenditure, sediment structure, and flow structure a function of the bed morphology already in existence? whilst Carling (1990) concludes that support for the extremal hypothesis from field observation will be impossible to achieve.

The function of the riffle-pool sequence as an equilibrium form is based primarily on their ubiquitous nature (independent of substrate (Keller and Melhorn 1978; Dozier 1976)), apparent temporal stability (Dury 1971; Haile et al 1989), and their regularity of spacing (Richards 1976). Richards (1976) and Church and Jones (1982) have identified a pseudo-cyclic trend in the bed topography of gravel-bed rivers which corresponds to the riffle-pool sequence and which is best described by a second order auto-regressive model with a periodicity equivalent to **2pi** channel width. Richards concludes from this that the origin of the riffle-pool sequence lies in the similarly rhythmical distribution of macro-turbulence inherent within open channel flow and identified by Yalin (1972). Support from this comes from the streamplate experiments of Gorycki (1973) that suggested that some form of downstream variation in streamflow exists which is analogous to the riffle-pool sequence in scale. Recent observations by Clifford (1990) hint at macro-scale turbulent structure at the scale of the riffle-pool sequence. In this theory therefore, the riffle-pool sequence represents the morphological expression of an energetic imbalance inherent within flowing water.

Thompson (1986), following observations of secondary flow patterns in riffles and pools by Hooke and Harvey (1983), proposed a model for riffle-pool development based on anisotropic secondary flows. Accordingly, the interaction between open channel flow and the boundary of a channel induces counter-rotating secondary flow cells which in turn modify the bed profile into a sequence of pools and alternate bars. The interaction of these pool-bar forms generate a riffle-pool-bar sequence as an individual unit through their subsequent maintenance of secondary flow cells. This model in fact represents a modification of the Yalin (1972) macro-turbulence theory and supports, with inferred field evidence, the development of riffles and pools from an inherent variation in the flow field. The model does not satisfactorily explain the transport of sediment through the riffle-pool-bar sequence nor the sedimentological variations observed in the field. The spacing of riffles is also unexplained.

Langbein and Leopold (1968) developed a theory for the maintenance of riffle-pool sequences based upon kinematic wave theory. According to kinematic wave theory the movement of a random influx of particles soon adopts a semi-constant zonation of particle concentrations and dispersion as a result of the inverse relationship between particle concentration and particle velocity. These are considered to maintain riffles and pools through the balance of particle input:output at a site, which promotes the apparent stability of a dynamic bed. Richards (1976a) criticises the theories inability to satisfactorily explain the spacing and sedimentological variability of riffles and pools; neither does it allow for the development of alternate or point bars. Nevertheless it is important as a model of the interaction of individual particles and incorporates the variability of sediment supply (concentration) which is omitted from the extremal hypothesis and macro-turbulence theories. Furthermore, supporting evidence for the kinematic behaviour of particles is available from the field in the from of observations of collections of coarse particles at regular spacing on ephemeral sand bed channels, (Leopold et al 1964; Langbein and Lepold 1968;) and from the movement of large sand waves through a stable gravel bed channel (Meade 1985). The application of kinematics to explain the maintenance (and formation) of the riffle-pool sequence is developed further in Chapter 14.

The riffle-pool sequence is considered to function as an important element within the development of meandering (Yang 1971; Keller 1970; Hooke and Harvey 1983; Thompson 1986). Indeed the extremal hypothesis of minimisation of energy expenditure proceeds from the formation of riffles and pools to the development of meandering, the two morphological features being viewed as components of the same teleology. The link with meandering provides evidence for the sedimentological requirement for full development of the riffle-pool sequence since meandering is found in silt and sand channels as well as in unbounded stream flows where riffles are not (Goryki 1973; Friedkin 1945). This leads to the conclusion that the development of riffles and pools as a morphological feature, is dependent upon some property inherent within flowing water but which is only fully expressed through some property of heterogeneous bed material containing a dominant gravel mode. Models of meandering involve secondary flow patterns and generally proceed through erosion of the outer bank of the meander apex associated with the pool (Hooke and Harvey 1983), although elongation of the straight meander arm is an alternative proposed by Thompson (1986). In reality a variety of meander developments are possible which are not specifically related to riffle-pool morphology (Hooke and Redmond 1992).

Carling (1990) comments on importance of riffle spacing for determining the discharge at which a shear stress maximum is achieved at the riffle. This spacing of the downstream riffle in relatión to channel slope determines the rate of upstream propagation of the backwater curve, which in turn conditions the moment at which the upstream riffle is drowned out and the rate of increase of shear stress falls. Carling (1990) notes that the effect of meanders is to increase the rate at which upstream riffles are drowned out therefore tending to lower the shear stress maximum over the riffle. Quite how this relates to the maintenance of the riffle-pool sequence or the development of meanders is not known, however a rapid drowning out of riffles upstream of meander bends may well lead to the rapid development of secondary flow patterns which erode meander bends (Thorne et al 1979) thereby enabling progression of the minimisation of energy expenditure through meander development.

The riffle-pool sequence is increasingly recognised as a fundamental component of gravel-bed river habitat (Lewis and Williams 1984; Holmes 1983; Purseglove 1988). The function of the riffle-pool sequence in this context is variable depending upon the species concerned. Thus salmonids require unconsolidated gravel riffles for spawning and deep pools for resting in their journey upstream or for feeding in the case of Trout. Similarly oyster catchers utilise exposed gravel bars for nesting whilst kingfishers and herons use pools and riffles for hunting. Scullion et al (1982) record distinctive variations in the invertebrate fauna of riffles compared to pools. Higher proportions of fine sediments in slower flowing pools supports greater abundances of oligochaetes and chironomids, whilst the riffles exhibited higher densities of ephemeropterans and simuliids whose physionomy is more suited to higher velocity flow and stable substrate. This pattern, though consistent (Minshall and Minshall 1977), is clearly disrupted by regulation for hydropower (Gore 1977; Haile et al 1989).

The riffle-pool sequence is also important for the low flow management of water quality, a function which is particularly important in regulated rivers dominated by prolonged periods of compensation flow (Petts 1984). Riffles act as low flow weirs reducing upstream slopes and promoting large deadwater regions with potential for increased residence time for pollutants (Carling pers comm). Similarly riffles are important functionally for the aeration and mixing of water generated by the turbulent flow conditions (Purseglove 1988).

Linked to the habitat function of riffles and pools is the increasing awareness of their function as an amenity in the river corridor (Lewis and Williams 1984; Purseglove 1988). Riffle-pool sequences are now considered as necessary features to retain or reconstruct in streams undergoing channelisation, primarily for amenity and habitat reasons (Brookes 1992; Petersen et al 1992), although Sear and Newson (1991) have recommended their reinstatement/preservation from considerations of sediment transport and channel stability.

The relevance of this study therefore extends beyond considerations of river regulation, encroaching upon theories of dynamic equilibrium and the preservation of a valuable component of the highly sensitive fluvial ecosystem.

Chapter 2.0

Background Details

2.1 The North Tyne: Background to the Study Area

The North Tyne is a gravel/cobble-bed river with a catchment area of 1118 km^2. There are many tributary streams feeding the main channel of which the River Rede, Tarset, Chirdon, Houxty and Wark Burns are the dominant. The North Tyne catchment is part of the larger Tyne basin,(catchment area 2927 km^2) which is includes the rivers South Tyne, East and West Allens and Derwent.

Maximum recorded flow on the North Tyne at its lowest gauging station at Barrasford (NY920733) was 730 cumecs in 1955. In 1980 the head-waters of the North Tyne were impounded by an earth core dam at Yarrow, and since 1984, the discharge in the North Tyne has been dominated by river regulation for hydro electric power.

2.2 Geology and Physiography

The geology of the North Tyne can be described as a South Easterly tilted block of folded and heavily faulted Carboniferous sedimentary rock, intruded by igneous dykes and sills, and overlain by a blanket of glacial drift and Holocene alluvium and peat. At the gauging station at Reaverhill (Catchment area 1007 km^2) the geology for the catchment is comprised of 61% Scremerstone Coal Series, 20% Lower Carboniferous limestone, 10% Fell Sandstone and 10% other rocks, largely associated with the igneous intrusions of the Carboniferous and Tertiary.

The head-waters of the North Tyne drain the South eastern slopes of the Cheviot Dome, locally rising to 500 m O.D. on Carter Fell. The strata dip gradually westwards away from the Cheviot volcanics towards the Rede valley which follows the line of a syncline between the Chevoit and Bewcastle Domes. The exposed geological series in the North Tyne catchment begins with Devonian Old Red Sandstone which is exposed on the Carter Fells above Carter Bar. These are succeeded by the Lower Carboniferous cementstones, Fell Sandstones and the Scremerstone coal series, which dominate the North Tyne and Rede valleys.

The igneous intrusions in the North Tyne catchment fall into two broad divisions; the Lower Carboniferous Cottonshope lava flows which are locally exposed on the Southern slopes of the upper Rede valley, and the Late Carboniferous and Tertiary intrusions which are dominated by the Whin Sill in the southern part of the North Tyne catchment, and a Dyke Swarm which outcrop above Kielder.

Overlying much of the North Tyne catchment is a thick deposit of glacial drift. The ice flow responsible for the drift deposits came from the southern uplands of Scotland and the Cheviot ice sheet. North of Bellingham the North Tyne valley contains large quantities of blue-grey boulder clay with local Carboniferous rocks within it. The present channel lies within Pleistocene glacial and fluvioglacial deposits and Holocene alluvium. The latter varies from gravel-cobble facies to fine-grained vertically accreted alluvium which comprises much of the present bank material.

Prior to the construction of Kielder Reservoir the North Tyne flowed through a wide alluvial valley floor, bounded by gravel terraces or haughs. Peel (1941) records the presence of two terrace levels throughout the course of the North Tyne until the confluence with the river Rede. The terraces are fluvial in origin, and occupy a height of between 7-8m and 12-14m above the present channel bed (Peel 1941).

Downstream of the current dam site at Yarrow (GR NY710880) the North Tyne flows South East along the line of strike in the direction of younging as far as the confluence with the river Rede. Brierley (1983) describes the channel upstream of the Rede as falling into the river classification categories of Charlton (1975) and Kellerhalls et al (1976) as "not obviously degrading or aggrading, occasionally confined by the valley wall, and topographically independent". The channel is only weakly sinuous (sinuosity = 1.05) but displays a prominent meander at Falstone (GR NY720877). In general the channel is a wandering gravel bed river, characterized by occasional islands, lateral bars, mid channel bars and a well developed riffle-pool sequence. Palaeochannels exist at several locations along the course, with a prominent example on the right bank at Snabdaugh farm (GR NY786849) dated as last active around c.2400 BP (Passmore, pers comm). The channel is bordered by trees along much of the course upstream of the Tarset and Chirdon Burns.

Between Bellingham and the Rede confluence Peel (1941;1949) identifies a significant knickpoint which he attributes to rejuvenation of the channel following isostatic readjustment after the glaciations. Valley slope steepens from 0.00174 for the North Tyne upstream of Bellingham to 0.00265 downstream of the knickpoint to the South Tyne confluence. Valley profiles downstream of the Rede confluence exhibit a marked reduction in floodplain width as the channel becomes confined by discrete gorges and rock bluffs of up to 46m height. The channel gradient is controlled by a series of rock bars and rapids. Peel (1941) identifies terrace remnants and palaeochannels within this reach, with terrace levels peaking at 25-30m above the present channel bed. Historically the reach downstream of the Rede confluence has been more laterally stable, with fewer and temporally less active storage of traction load.

The course of the North Tyne abruptly changes course downstream of the Rede confluence to flow due south, plunging through the Countess Wood and Warden gorges, before discharging into the South Tyne some 42 km downstream of the dam site.

2.3 Climate and Hydrology

The climate of the North Tyne catchment is profoundly affected by the western upland region of the Northern Penines. This produces a temperature and precipitation gradient across the North Tyne catchment. The temperature in the region is generally cool in comparison with the rest of England (July max 19.3 C, February min 0.4 C) and increases from the western uplands to the Tyne valley in the southeast.

Precipitation shows the effect of the western uplands, falling from 1275mm pa to 760mm pa at the confluence with South Tyne (Petts et al 1985). Mean annual runoff is 1026 mm pa, accounting for 82% of the mean annual rainfall, which in combination with the steep relief produces rapid runoff response times to rain events (Hall 1964). Archer (1981) detects little evidence of seasonality in precipitation distribution except for a tendency for a winter maximum in the west and a summer maximum in the east.

Rumsby (1991) in a review of the long term temperature and precipitation records for the Tyne basin identified periods of relatively high precipitation associated with 1898-1916, the 1925-1936, the late 1940's and the mid 1960's. A period of low rainfall is associated with the 1970's. Temperature recorded at the Durham observatory reveals cool periods in 1870-1890 and generally since the 1940's.

In association with the periods of above average rainfall, Rumsby (1991) records distinct periods of increased flood frequency within the Tyne basin during 1740-1790, 1860-1899 and 1940-1965. The intervening periods were characterised by low flood frequencies. The largest flood event in the Tyne basin occurred in 1771 with an estimated maximum discharge at Hexham of 3500-4000 cumecs (Archer pers comm) which compares to the largest recorded flood at the Bywell gauging station of 1586 cumecs in 1967.

2.4 Land-use change in the North Tyne

The North Tyne valley has always been a region of marginality, situated as it is some 50 km from the largest local industrial and commercial centres. This marginality has affected the development of the land, there has been a post-war emphasis on forestry, water resources and lately, tourism (Newson in press).

The historical development of the North Tyne valley began with isolated settlements of Mesolithic and later, with the improving climate, Neolithic farmers. In the North Tyne catchment settlement was probably restricted to isolated valley-side and floor-sites such as that found at Kennel Hall Knowe (Jobey 1978). Clearance of the forest cover began at this time but only became widespread towards the Iron Age and Romano British periods when settlements and cultivation became permanently established (Charlton 1987).

Following the abandonment of sites during the Saxon insurgences, much of the cleared land degenerated back to forest only to be restored to cleared agricultural land in the 12th-13th centuries (Charlton 1987). As a result of the North Tyne's proximity to the contentious Scottish borders, the settlement has always been subject to periods of decline and rise according to the sway in power of the two kingdoms. The fifteenth and sixteenth centuries were periods of relatively high population in the North Tyne, which is evidenced by the large numbers of fortified Pele towers and Bastles found in the

Catchment was permanently cleared for livestock and cereal production.

Contemporary chroniclers describe a picture of rural depopulation in the 17th and 18th centuries which probably resulted from the deterioration in the climate at this time. The Little Ice Age reduced the settlement pattern in the North Tyne valley to much the same as today, with centres at Bellingham, Tarset, Falstone and Wark. Subsequent increases in population were associated with Coal Mining, Iron ore production and the construction of the Border Counties Railway in 1855. Nevertheless, the North Tyne catchment witnessed nothing like the massive population increases associated with lead and zinc mining in the South Tyne.

The most significant changes in land use have occurred in response to the marginality and low population density of the upper North Tyne. In the 1930's, the Forestry Commission began the development of Kielder Forest. The period of most rapid growth in afforested land occurred between 1946 and 1964, leading to the present day Border Forest/Wark Forest/Kielder Forest amalgamation that dominates the catchment, with some 40% of the total area under forest whilst the catchment of the reservoir is 75% afforested.

The development of Kielder Forest may have had significant affects on the hydrology and sediment productivity of the North Tyne, since the process of afforestation results in an initial increase in drainage density and sediment yields (Newson 1981; Stott 1984). However, as Rumsby (1991) concludes the effects of land use changes are to enhance the signal produced by climatic change. The large flood of 1955 on the North Tyne may well have been enhanced by the drainage associated with forestry.

The next major land use change to dominate the North Tyne valley is associated with the development of Kielder reservoir, which will be detailed in the following chapter.

Chapter 3.0

Hydrological changes resulting from river regulation on the North Tyne.

3.1 Hydrological impacts of river regulation

Before any analysis of the sediment transport within the regulated North Tyne can be undertaken it is necessary to establish the degree to which the discharge has been modified by regulation. Petts (1984) identifies the effect of regulation as a "modification of the distribution of discharge over time", which given the link between the magnitude of flood peak and the transport of sediment, is reason enough to expect a morphological change.

The modification of the discharge regime imposed by the impoundment of a river is related to the physical characteristics of the reservoir itself and the operational procedures that determine the function of the impoundment (Petts and Higgs 1988). The physical characteristics of the reservoir which effect the discharge regime are related to the catchment morphometry through sediment and water yield, the storage capacity of the reservoir, the spillweir characteristics, and the outlet design.

The size of the reservoir in relation to the upstream catchment, determines the degree of flood attenuation, whilst the height of the spillweir above the water level in the reservoir at the time of flood, determines the storage volume. The capacity of the spillweir will determine the discharge passing over the dam once the storage is exceeded. The net effect is an attenuation of inflowing flood peaks reducing the downstream flood magnitude whilst increasing the duration (Petts 1984).

The operational function of the reservoir will affect the magnitude and duration of discharges downstream of the dam, and will exert a control on the degree of flood protection by controlling the water level in the reservoir in relation to inflows. The discharges entering the downstream channel will comprise the compensation flow (a minimum maintained flow whose discharge will be determined by the functional requirement of water users downstream and the age of the reservoir (Gustard et al 1986)), the overflow from the spillweir during floods, and a variable discharge dependant upon reservoir function and outlet design.

The function of reservoirs vary, from conservation storage which traps and stores flood water for use at later periods, through flood storage which traps and stores flood water and therefore requires "empty space" in the reservoir to function, to hydropower regulation, which stores flood and inflow water and releases it as electricity demand dictates, and direct supply regulation, where variable volumes of water are released to the channel depending on the supply requirements of the downstream industry and population. As Petts (1984) indicates these are often conflicting functions, since flood storage requires available volume where as conservation storage requires a volume of water to meet the requirements of the downstream demand. This latter point is perhaps more significant now that the privatised water companies view their resource from an enhanced fiscal position, water released is money spent. The operation of the outlet from a dam is therefore related to the type and magnitude of demand for water downstream.

The specific effects of an impoundment upon the hydrology of the downstream channel will clearly be unique, but broad effects are discernible, and necessary to investigate particularly with respect to the current re-awakening of the water grid proposal for water supply, (The Guardian January 18th 1992).

Petts (1984) and Petts and Higgs (1988) identify the prime effects of regulation as a decrease in the mean annual flood (by 70% on average) and increase in the Q_{95} by 22% as a result of compensation flows and a decrease in flood frequency by as much as 50%. Set against this is the length of channel over which regulated discharges significantly effect the flow regime. Gregory and Park (1974) identified the effects of a water supply reservoir on the discharge regime of a gravel bed channel up to the point when the catchment area of the reservoir was less than 10 % of the total drainage area. For the North Tyne Gustard et al (1986) identify the effects of river regulation from Kielder and Catcleugh reservoirs at the Bywell Gauging station on the Tyne, some 78km downstream of the dam site.

3.2 The Kielder Water Resources Scheme; 1976-1990

The Kielder Water resources scheme was suggested in the late 1960's as part of a nationwide plan to meet the predicted increase in water demand to the year 2000. The Kielder water Resources Scheme was designed to supply water to the conurbations of Tyneside, Wearside and Teeside through a combination of run of river and piped interbasin transfer (Brady 1984). The first enquiry into the Kielder Reservoir proposal was held in February 1972, when figures for the projected increase in population of the conurbations were set at 25% by 2000 AD. This figure was revised down to 5% only 4 months later (Porter 1989). In addition, by the time of the Inquiry in 1973, the indications from the industrial users of the water from Kielder suggested a decline in the rate of increase in water consumption rather than the projected increase. In October 1973 the Kielder Water Resources Scheme was given the go ahead by the secretary of state.

In 1975 against a background of increasing unemployment in the Steel and Chemical industries, and the revised down estimate of population growth, a decision was made to provide an optional hydropower function to the Dam, to be sold to the CEGB for £ 1 million per year. This is set against the cost of the scheme which increased from a proposed £ 50 million at the time of the decision to go ahead, to the approximate actual cost of £ 150 millions (Porter 1989). Construction began in 1976 with dam closure in 1981 and reservoir filling complete by 1982 (Brady 1984). Between 1981 and 1983 two turbines were installed capable of producing 6.0 MW of power. Hydropower regulation began in 1984.

The initial Water supply function of the Reservoir envisaged a run of river release of up to 60 cumecs, discharged from three valves located at the foot of the dam. The decline in water supply demand obviated the need for such releases, and correspondingly the hydropower option was favoured, particularly in light of the escalating costs.

With the closing of the Kielder dam in 1980, the discharge passing down the North Tyne became controlled by the operation policy of the Northumbrian Water Authority and the catchment/reservoir characteristics. The operating policy is governed by a synthesis of legally, functionally and revenue prescribed factors (Johnson and Sanderson 1987):
Legally prescribed

maintenance of compensation flow levels in the North Tyne.

maintenance of minimum prescribed flows in the Tyne, Wear and Tees

support major water abstractions when not to do so would restrict abstraction or violate the minimum prescribed flow levels.

Functional efficiency

to augment local resources where operational maintenance allows

to control Kielder reservoir levels to allow dam maintenance without violating the lower limit on reservoir levels

to support the passage and recruitment of migratory fish

to help manage pollution spillages in the Tyne, Wear and Tees

Revenue

to generate hydro electric power.

The dominant constraints on the release pattern from Kielder reservoir are the compensation flow level and the generation of hydropower, though the reservoir is clearly multifunctional. A further factor dictating the timing of hydropower releases to the North Tyne is the distribution of peak demand times for electricity consumption (and thus revenue). Correspondingly the North Tyne now experiences a tenfold increase in discharge on most bank holidays and major sporting events. During the winter half of the year the generators are run for 16 hours a day for long periods, whereas in the summer the generating hours are reduced and the flow regime is dominated by compensation flows. In practice this operation policy is extremely variable which makes access to the river channel for anglers (and geomorphologists) a stochastic experience.

The compensation flow levels vary during the year from 0.75 cumecs in the winter (8% of the average daily flow) to 1.53 cumecs in the summer months (15% average daily flow, Johnson 1988). The peak operational hydropower discharge is 15.4 cumecs (151% average daily flow) although 16 cumecs is the most frequent release discharge. In an effort to keep the rate of stage change below 12mm per minute the ramp up from compensation flow to peak hydropower discharge is extended over 2.5-3 hours, whilst the ramp down time is approximately 3 hours.

Brierley (1983) reports on a test of the flood wave attenuation effect of Kielder reservoir. Flood waves are attenuated by between 75-80% during passage through the reservoir, which is not made up by the subsequent acceleration in the downstream channel. Attentuation of flood hydrographs has important implications for the dynamics of the riffle-pool sequence in the North Tyne (Chapter 12).

Petts et al (1985) described the downstream progression of a large release from Kielder reservoir, and noted evidence of flood wave steepening and attenuation in the 18km reach between the dam site and Bellingham. This is corroborated by measurements conducted by the NWA which indicated that flood wave steepening occurs between 0 and 10km downstream of the dam site, followed by attenuation between 10-20km downstream, and steepening again as the wave passes through the Countess wood gorge(Johnson 1988). Petts et al (1985) have attributed the steepening of the flood wave to the reduction in channel resistance as flow depths increase, which cause the flood peak to catch up with the wave front. Correspondingly, in the reach downstream of the Tarset/Chirdon burn junctions, flow in the channel is already higher than upstream reaches and the channel bed is composed of finer cobbles which collectively result in a lower initial resistance, therefore the wave front accelerates away from the peak and the flood wave attenuates. This scenario applies to flood waves up to 50 cumecs.

3.3 Calculation of discharge for the study sites

The estimation of discharge in the North Tyne is facilitated by the presence of a suite of gauging stations:

Gauging Station	Distance Downstream of Dam	Flow data
Kielder Burn	(upstream of the reservoir)	1970-
Ugly Dub	0.5 km	1982-
North Tyne (Tarset)	9.3 km	1963-1987
Tarset Burn	10 km	1970-1980
Redebridge (Rede)	21 km	1968-
North Tyne (Barrasford)	36 km	1942-1959
North Tyne (Reaverhill)	34 km	1959-

However the loss of the continuous record from the North Tyne (Tarset) and Tarset Burn gauges reduced the utility of gauged records for downstream of the Tarset/Chirdon Burns. This scenario necessitated the use of discharge estimation based on developing a relationship between discharge in the Tarset Burn and that in the River Rede for the period prior to regulation.

The main consideration in this dissertation is the movement of bedload, correspondingly it was decided to record the possible maximum discharges instead of estimations based on the mean flow. Three years of data, comprising a drought year (1975), a year with high flood frequency (1979) and a "moderate" year (1973) were used to produce the relationship illustrated in Figure 3.1. The regression line yielded an r^2 value of 0.87 which is significant at the 99% confidence level. To check the validity of this relationship, the equation was applied to data for the year 1971 from the Tarset Burn gauging station. The relationship between observed and predicted Tarset Burn discharge is shown in Figure 3.2. The error involved in the estimation averages 19.7% with a tendency towards underestimation of the maximum discharge.

To obtain a value for the discharge from the Chirdon Burn involves calculating the discharge/km^2 for the Tarset Burn, and applying the resultant value to the catchment area

Figure 3.1

Relationship between average discharge at Tarset Burn and Rede gauging stations, for the years 1970, 75, 79.

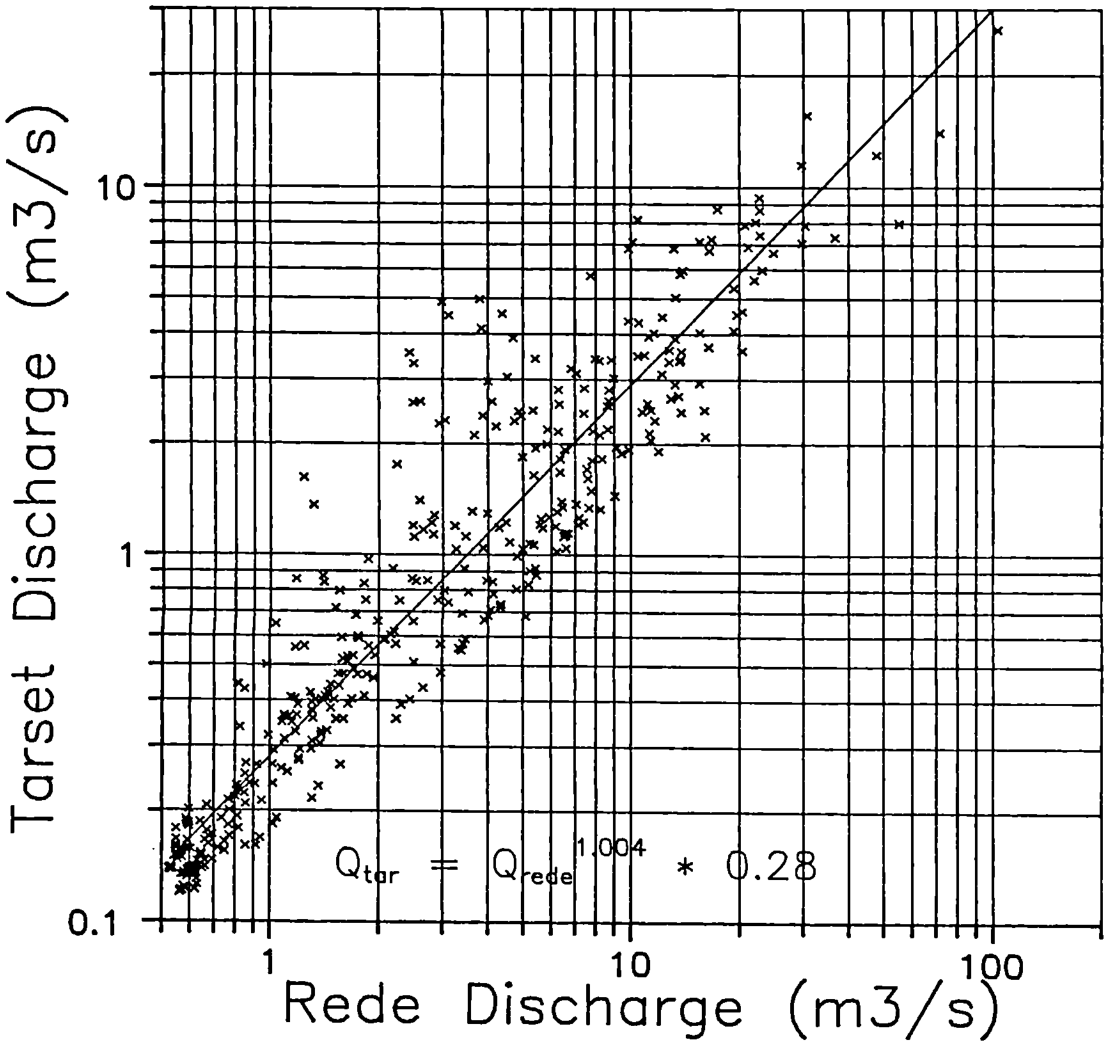
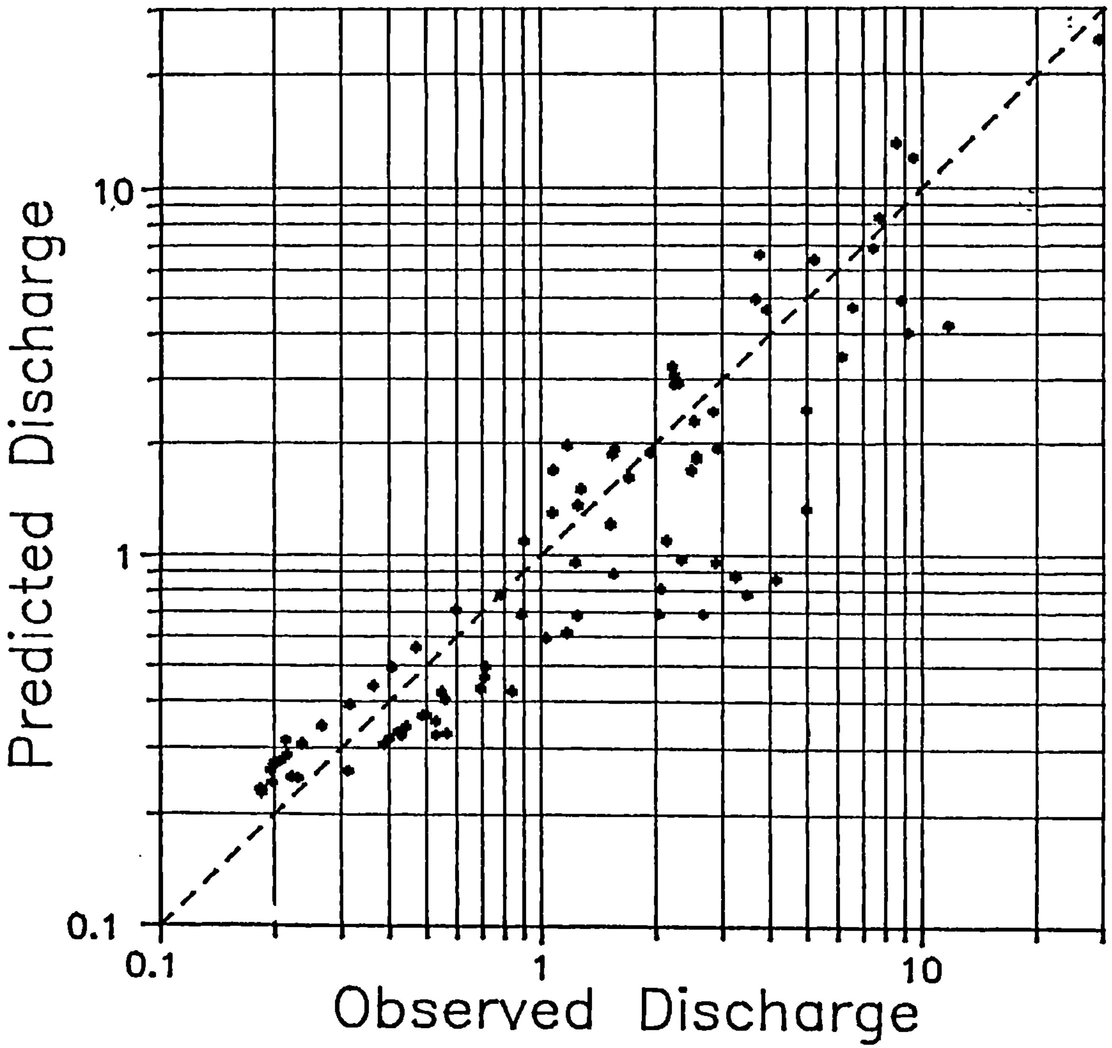


Figure 3.2

Test of the relationship between River Rede and Tarset Burn discharges. Years 1971/74



of the Chirdon Burn. The value for the Tarset and Chirdon Burns are then summed and added to the discharge data for the North Tyne. The discharge within the North Tyne is equivalent to the recorded discharge at the Ugly Dub gauging station, adjusted for flood wave travel time according to formulas developed by the NWA (Archer pers comm).

In addition to these values, stage discharge ratings were developed for the three main monitoring sites. The ratings were developed for the discharge range 0.75-20 cumecs associated with hydropower flow plus some tributary inputs. The ratings for each site are shown in Figures 3.3a-b beneath the hydrographs associated with each of the monitored releases. A comparison between the two methods of calculating discharge was made to assess the validity of the maximum discharge prediction technique, the results are shown in Table 3.1.

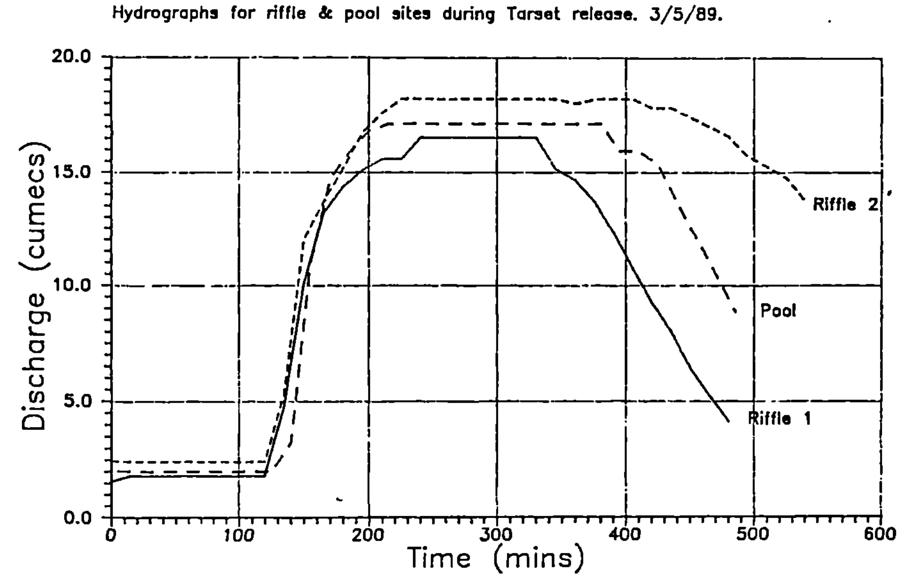
Table 3.1: Comparisons between rated and predicted discharges for the Tarset and Newton sites.

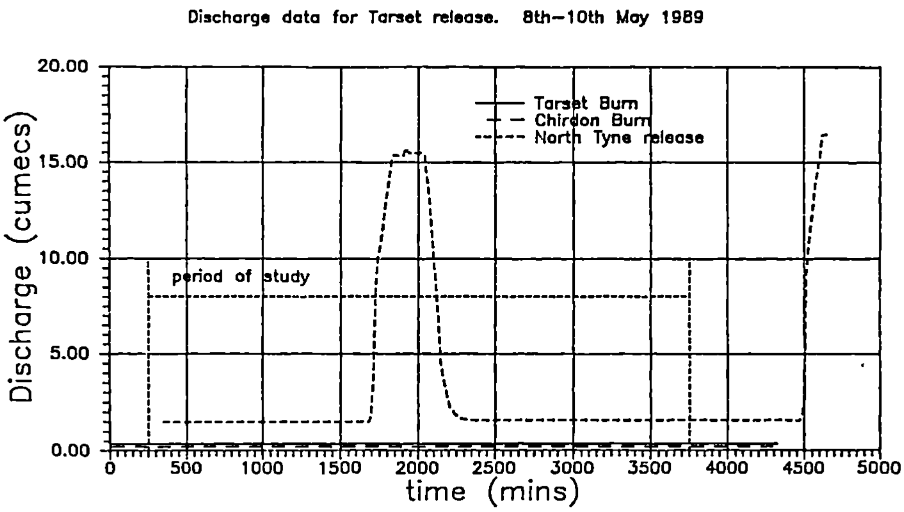
Site	Qmin (Rated)	Qmin (Predicted)	Qmax (Rated)	Qmax (Predicted)
TP2	1.8	1.9	16.1	16.3
TR2	2.0	2.4	16.3	18.7
NR1	6.5	8.2	19.1	20.7

The results from Table 3.1 confirm the validity of the discharge approximation technique for hydropower discharges, whilst indicating that the rating curves for sites downstream of the Tarset/Chirdon Burn junction are within the values expected from the regional regression analysis.

Three release hydrographs are illustrated in Figure 3.3a-c located at the three main study sites used to monitor hydraulic and sediment processes. The structure of each hydrograph preserves the ramp up conditions set by the dam release, with a pronounced flat top to the flood peak resulting from holding the maximum discharge steady for 3-4 hours. The data for each relevant input is also recorded in the hydrograph during the period of study at each site. The contribution from the Tarset and Chirdon Burns is clearly shown in the relative discharge maxima for the Tarset release, Figure 3.3b.

Fig 3.3a: Hydrographs and rating curves associated with the Tarset release.





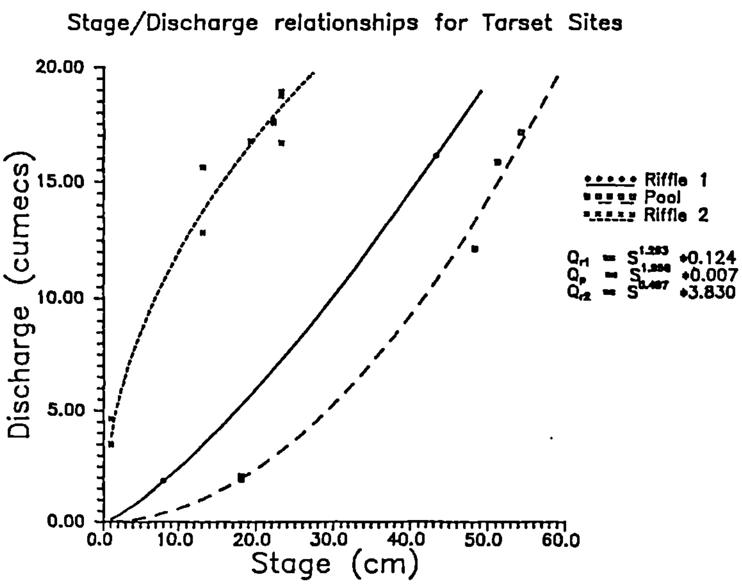
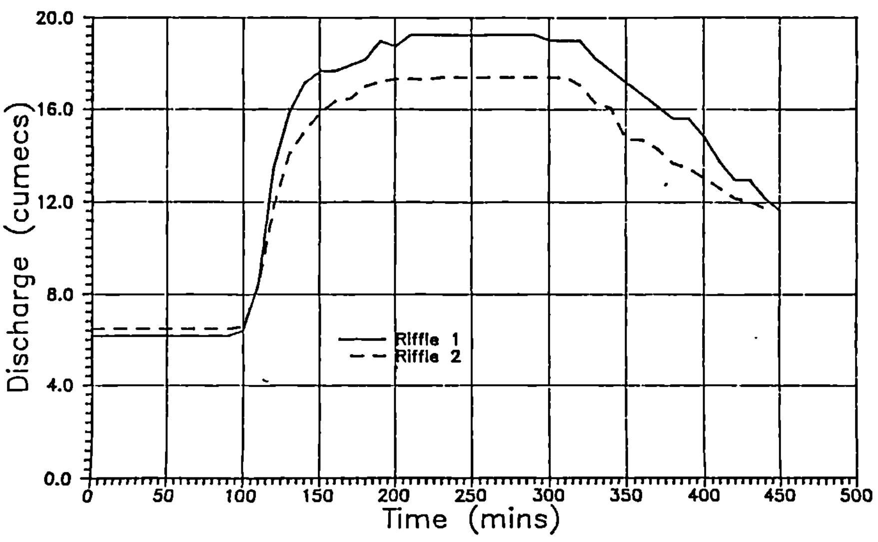
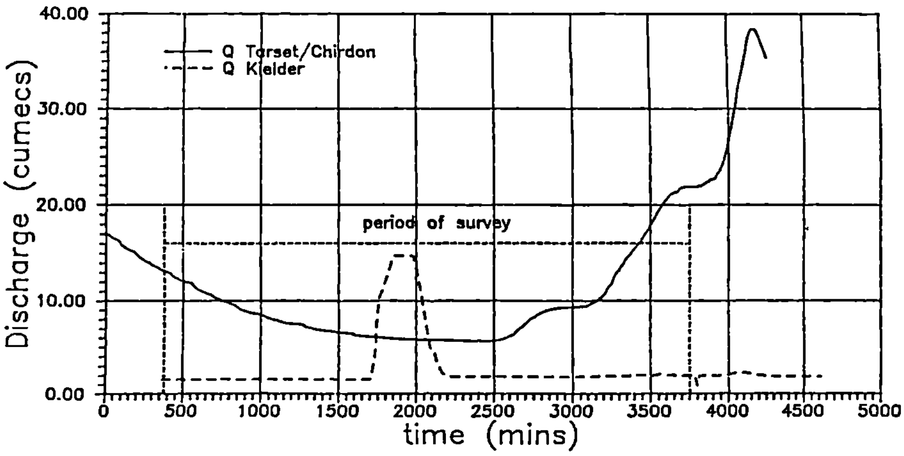


Fig 3.3b: Hydrographs and rating curves associated with the Newton release.

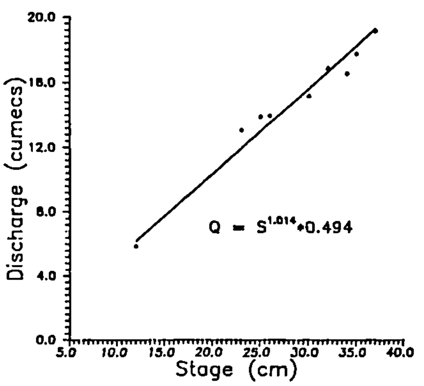
Hydrographs for riffle sites during Newton release. 8/3/89



Combined discharge from Tarset and Chirdon Burns and discharge from Kielder Reservoir. Newton release 7th–9th March 1989.



Stage/Discharge curve for Newton riffle 1



Stage/Discharge for Newton riffle 2

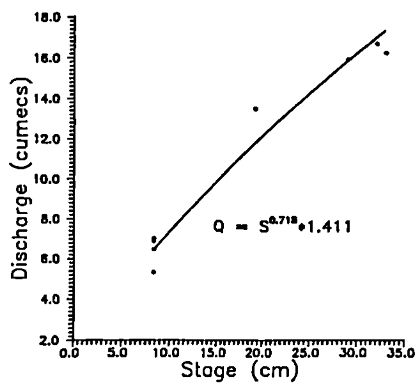
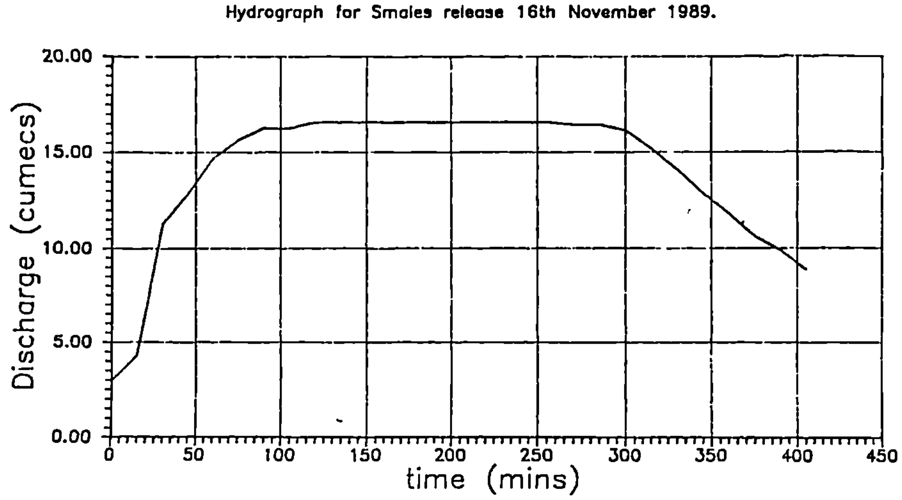
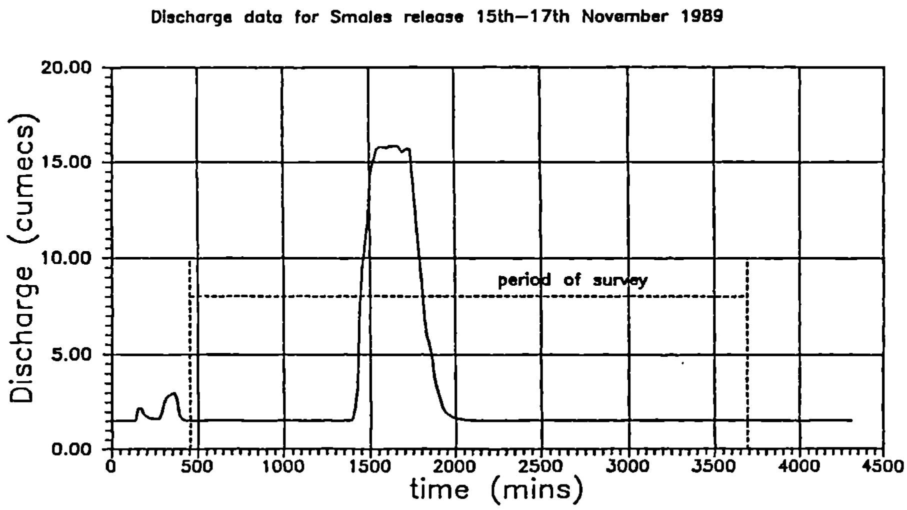
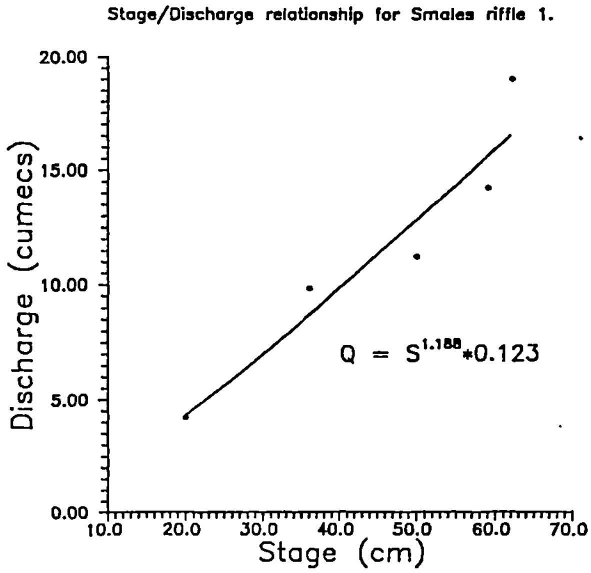


Fig 3.3c: Hydrographs and rating curves associated with the Smales release.







Using the methods of discharge calculation outlined above, it was possible to reconstruct the discharge regime experienced during the period of study (Oct 1987-June 1990). The effect of the river regulation for hydropower generation together with the reduction in flood peaks is clearly shown in Figure 3.4. This records the discharge maxima for each day over the study period 1987-1990 for the reach upstream and downstream of the Tarset/Chirdon burn junctions. During this period the reservoir spilt on four occasions, three of which occurred in February 1990. The wave form of the hydropower releases are clearly seen to dominate the initial 10 km of the North Tyne downstream of the dam. Seasonality in the operating regime is identified by a dominance of compensation flows, or flows of 6-8 cumecs in the summer months, and prolonged periods of continuous hydropower generation during the winter. Downstream of the Tarset/Chirdon burn junction, discharges are modified by unregulated tributary inputs that exceed comparable upstream flows by 300%. The "flashy" runoff response that characterised the North Tyne (Hall 1964) has effectively been muted within the first 10 km downstream of the dam.

To assess the impact of regulation, values for the frequency of bankfull flooding were recorded for the years of flow data at two guages, the North Tyne at Tarset and Reaverhill. Although flow data from North Tyne (Tarset) cease to be recorded officially in 1987, stage charts are available, from which discharge can be calculated, although these are continuously overwritten so only major flood peaks are legible. To supplement this data, values from Ugly Dub can be used to assess the dates and magnitude of dam spill; this data was used to reconstruct the flood hydrographs for the February 1990 event.

Figure 3.5 illustrates the reduction in bankfull flood frequency since river regulation at the Tarset gauge. The Reaverhill gauge still experiences bankfull floods, which are attributable to the input from the river Rede, Tarset and Chirdon Burns and Wark and Houxty Burns. The Tarset gauge has only 15.3% of unregulated catchment contributions compared with 76% for the Reaverhill gauge. Bankfull flood at the Tarset gauge is 140 cumecs, whilst that at the Reaverhill gauge is 247 cumecs. The highest flow recorded at the Tarset gauge since the dam was constructed occurred in February 1990, when the discharge reached 102 cumecs, with 77 cumecs derived from Dam spilling. Prior to the impoundment the average frequency of bankfull flooding for
Reaverhill gauges was 3.9 and 4.6 per year respectively; since regulation this has

3.4 Hydrographs for period of study, 01.01.88 – 31.05.90

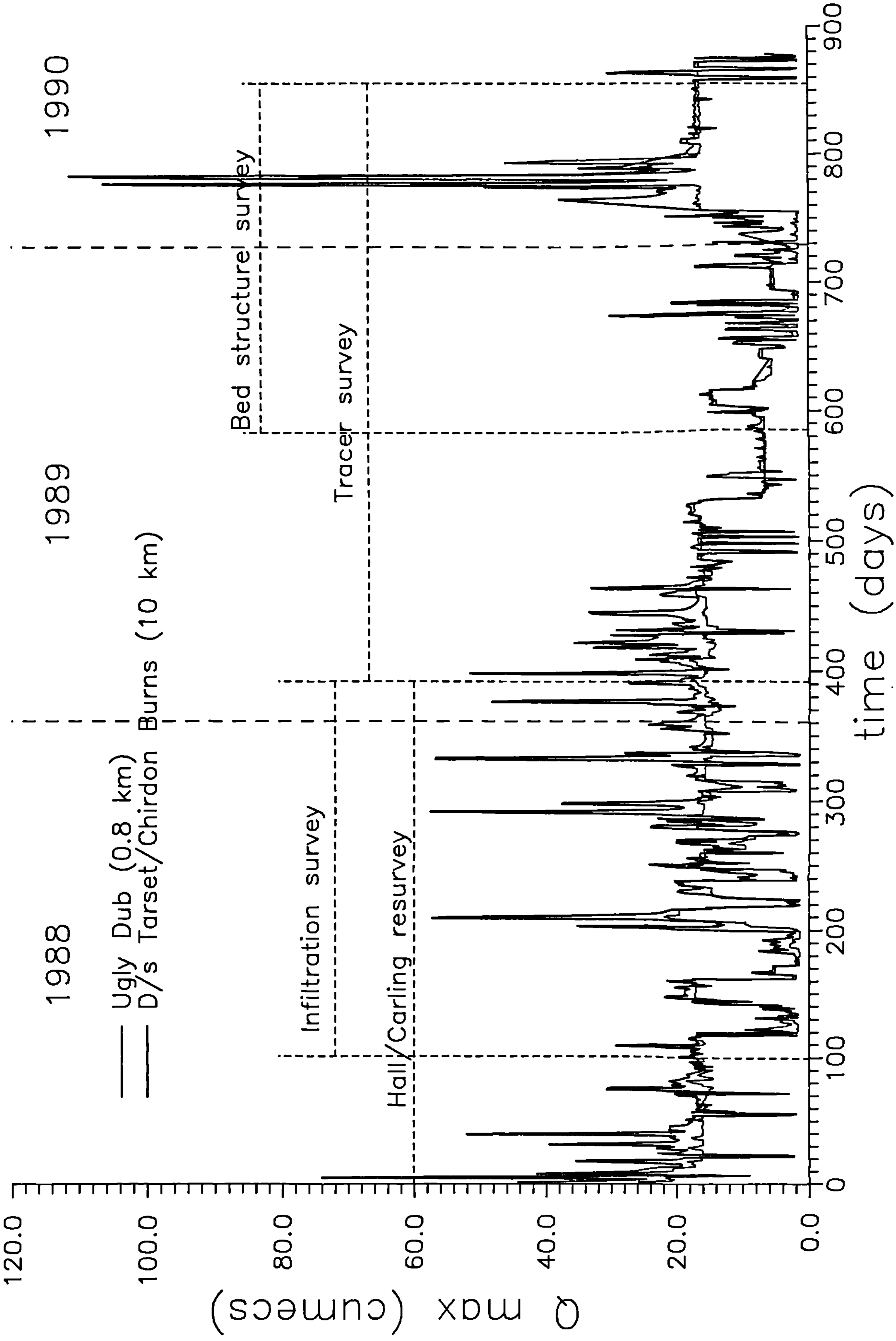
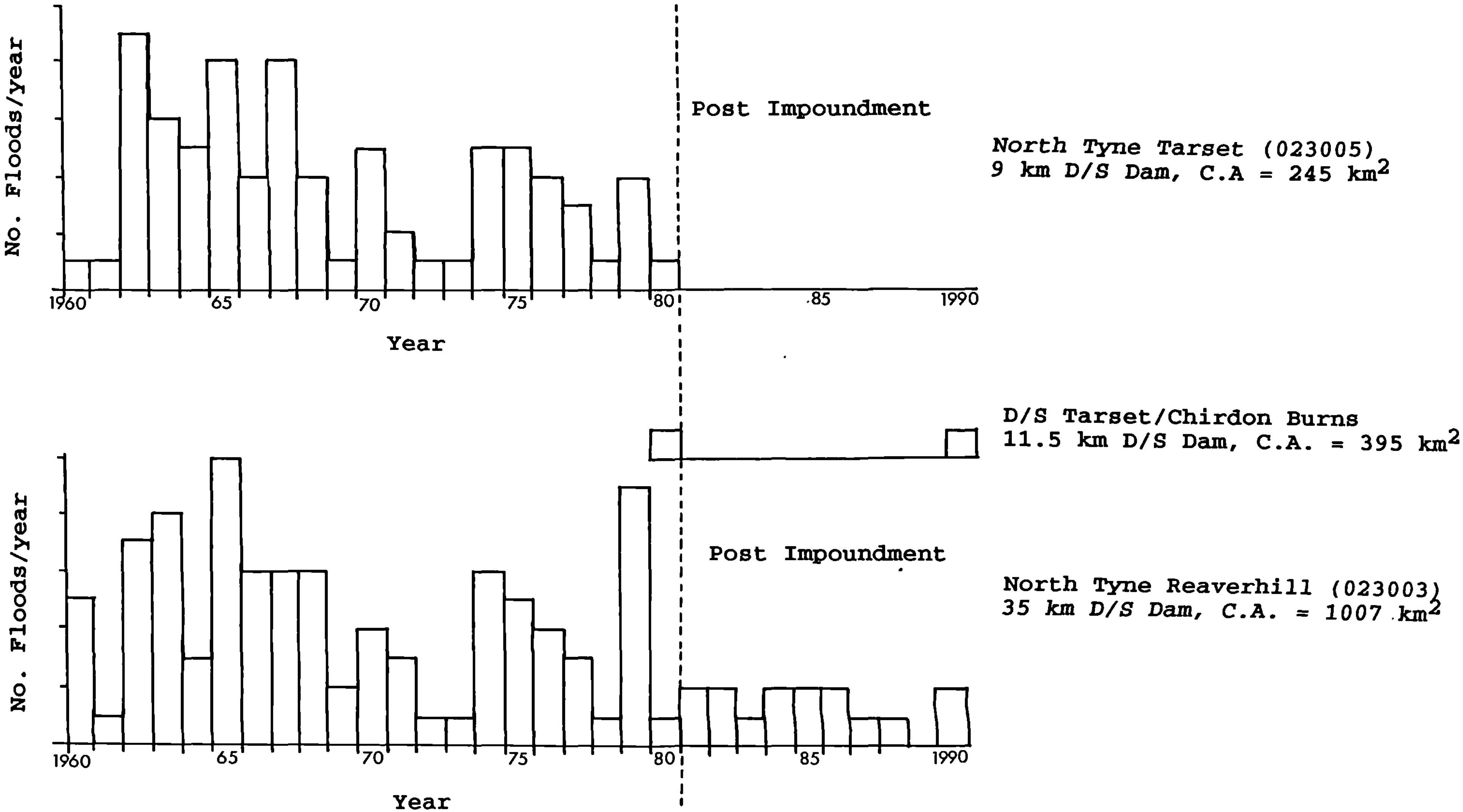


Figure 3.5: Bankfull flood frequency on the North Tyne at two gauging stations, showing the reduction in frequency at the site closest to the dam site following regulation.



dropped to zero and 1.5 per year. These reductions equate to a 100% and 66% reduction in frequency since impoundment.

The eradication of bankfull floods on the upper 10km of the North Tyne has occurred as a result of the regulation for hydropower, and appears to be independent of climatic change, as is evidenced by the continued (though reduced) frequency of bankfull floods at the Reaverhill gauge and the general increase in flooding experienced in the late 1980's and early 1990's (Rumsby 1991).

Figure 3.6a depicts the flow duration curves for the North Tyne at Tarset for the periods 1963-1979 (pre regulation), 1981-1984 (post impoundment but pre hydropower) and 1985-1988 (post hydropower). Clearly the information for post regulation is derived from a reduced database, yet the effects of regulation can clearly be seen. The period post regulation, but pre-hydropower witnessed an increase in the discharge associated with the Q95 flows resulting from compensation flow. The slight increase in the frequency of flows up to 50 cumecs reflects the testing of the three water supply valves, the combined discharge of which is estimated at 60 cumecs. Hydrological records for this period show continuous discharges of over 20 cumecs for up to 18 days at a time on 5 occasions.

Since regulation for hydropower, the frequency of discharges less than 20 cumecs have increased, whilst those greater than 20 cumecs have reduced. This is reflected in the values associated with a range of discharges frequencies (Table 3.2).

Fig 3.6a: Flow duration curves for the North Tyne at Tarset (data from I.O.H.).

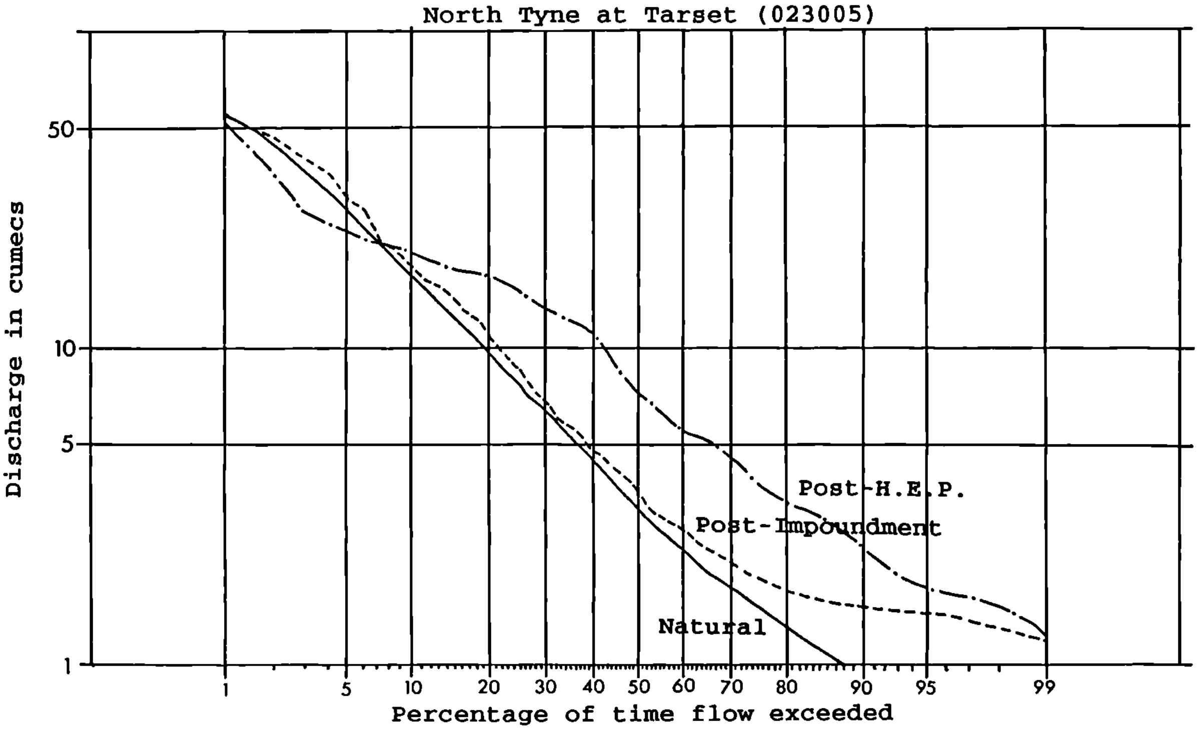
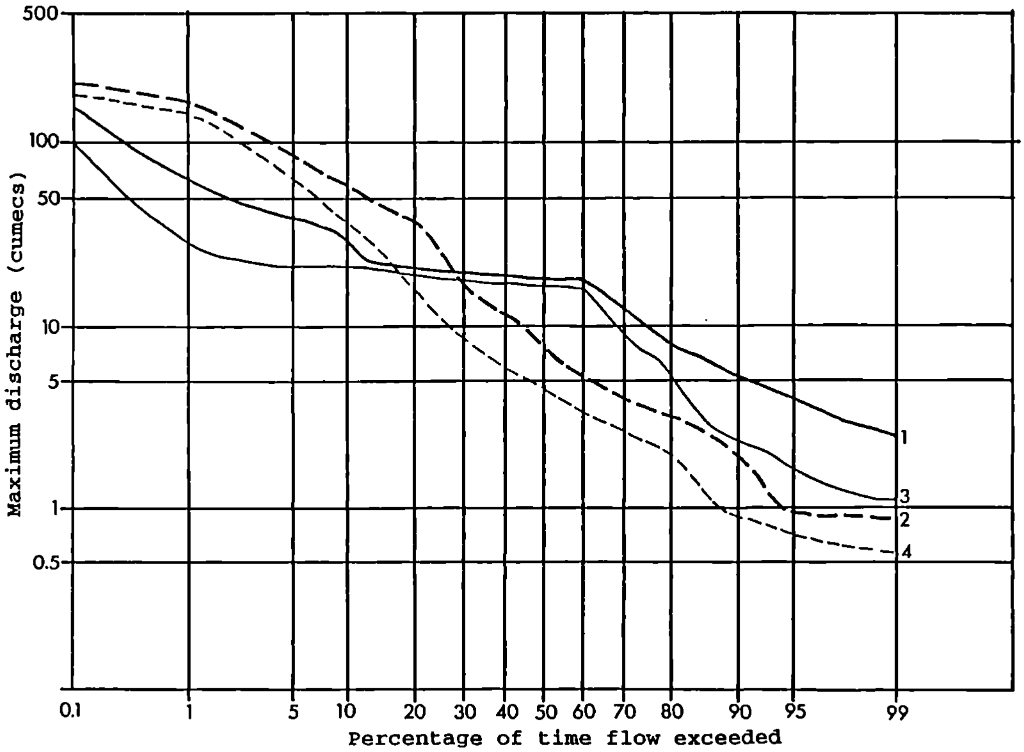


Figure 3.6b Maximum discharge exceedance curves for the North Tyne upstream of Bellingham.



1 Downstream of the Tarset/Chirdon Burns (1988-90)
2 Downstream of the Tarset/Chirdon Burns (1978-80)
3 Dam site - Tarset Burn (1988-90)
4 Dam site - Tarset Burn (1978-80)

Table 3.2 Changes in the discharge value associated with given frequencies as a result of river regulation for hydropower.

Tarset Gauging Station.

Frequency	Discharge (Natural)	Discharge (Hydropower)	% change
Q_5	28.00	23.0	-17.9
Q_{10}	17.00	20.0	+17.6
Q_{50}	3.00	7.0	+133.3
Q_{90}	0.96	2.3	+139.6
Q_{95}	0.91	1.7	+86.8

The highest increase is associated with the peak hydropower flow range of 15.4-16 cumecs, which have increased in the frequency of exceedance from 12% to 26%. The Q_{50} and Q_{90} discharges exhibit the highest percentage increase, again a function of hydropower discharge.

Figure 3.6b depicts the flow duration curve of maximum discharges experienced upstream and downstream of the Tarset/Chirdon Burn junctions. The data for downstream of the Tarset/Chirdon junction was generated using the calculation process explained above for the period 1975-1980 and for 1987-1990.

The same pattern of reduced high magnitude, low frequency events and accentuated low magnitude, high frequency events is found in the Qmax data as for the Qmean data in Figure 3.6a. However, the point of cross over is lower down the frequency scale for both reaches of channel. Figure 3.6 shows that the North Tyne upstream of the Tarset/Chirdon Burn junctions, experiences a much greater reduction in the frequency of high magnitude events than the reach downstream. Correspondingly the first 10 km of channel downstream of the North Tyne is anticipated to show more evidence of the impact of regulation resulting from flood reduction than the reach downstream of the Tarset/Chirdon Burns. The sediment transport implications of this disruption of discharge regime are discussed in Chapter 12.

The regulation of the North Tyne for hydropower has increased the frequency of discharges from 0.75-18 cumecs, whilst reducing the frequencies of higher magnitude events. This imbalance is redressed as the percentage of unregulated catchment area increases, however the effects of regulation are monitorable throughout the 42 km length of the North Tyne. Analysis of the discharge records for two gauging stations show that the frequency of bankfull flooding has been reduced for at least 34 km of the North Tyne, and have, to date, stopped completely in the upper 10 km. The regime within the North Tyne is now largely controlled by the operation policy of the Northumbrian Water Authority, and the public consumption of electricity.

The physical impacts of the change in discharge regime are reported in subsequent sections, however it is important to note that with the emphasis on financial returns now placed on the operation of Kielder Water since privatisation, the present scenario is likely to change.

Chapter 4

The morphology of the North Tyne: temporal and spatial aspects.

4.1 Introduction and rationale

Chapter 2 described the North Tyne catchment in terms of the catchment geomorphology, whilst Chapter 3 detailed the hydrological impact of the Kielder water scheme. This section examines the long term changes in the morphology of the river North Tyne, and uses this to identify post-regulation adjustments.

A number of recent studies have documented the importance of putting contemporary fluvial processes into context by extending the time frame and detailing the long term trends in river behaviour (Newson and Macklin 1989; Macklin and Lewin 1989; Sear and Newson 1991). Often the result of such studies is the realisation that rivers are responding to catchment processes or climatic trends that occurred over 50-100 years ago. Indeed, Newson (1992) has suggested that contemporary channel processes may be responding to the last flood of sufficient geomorphological effectiveness to change the boundary conditions of the channel. In this context, "flood" becomes a generic term for the conjunction of a range of factors including channel dimensions, sediment supply (themselves dependent on the antecedent hydrology), as well as flood magnitude, which mitigate to cause the crossing of a "geomorphological threshold" (Schumm 1977; Newson 1992). The corollary of this model is the need to put present day channel process into a longer term framework of sediment supply, storage and hydrology. In the case of the North Tyne this is also the added justification of wanting to put an anthropogenic effect into a geomorphological (and political) perspective.

4.2 Methodology

The determination of long term temporal behaviour of the North Tyne was achieved by examining a range of historical sources. Information on the river terraces, palaeochannels and the long profile of the North Tyne were available through the work of Miller (1884) and Peel (1941;1949). Ideally, the dates of these surfaces should be established, but this was beyond the scope of this project. Nevertheless it is possible to put a minimum age to the lower terraces and palaeochannels through their position relative to the contemporary channel as depicted on historical maps. For the purposes of this study the terraces and palaeochannels are all pre-1867, the date of the first edition Ordnance Survey 1:10560 maps of the North Tyne.

To determine channel changes and a crude estimate of sediment storage area (gravel area), series Ordnance Survey 1:10560 maps and 1976/1983 1:10000 scale aerial photographs were used. These provided data on the course of the North Tyne, together with the size and distribution of "active gravel" areas (Macklin and Lewin 1989) for the dates 1867, 1898, 1925, 1957, 1976, and 1983. For each date, the channel downstream of the dam site was divided into 500m lengths, and the area of active gravel determined by planimeter. Whilst the dynamic nature of sedimentation zones (see Church 1983) precludes detailed inferences of sediment transport rates, the data recorded on sequential maps can provide evidence of the change in total active gravel area for reaches of a channel, or for the channel as a whole. Furthermore, the division of the channel into 500m lengths provides evidence for the large scale translocation of sediment downstream (Needham and Hey 1992), as well as some indication of the location of sediment storage in the channel.

The loss of sediment to long term storage by incorporation within the floodplain is also distinguishable from erosion to downstream storage at a site. Vegetation rapidly develops on exposed bar surfaces during periods of prolonged low flows, whilst active gravel bars are maintained free of vegetation by frequent surface reworking during floods (Petts 1984; Macklin and Lewin 1989).

The historical map evidence in combination with aerial photographs and contemporary channel surveys were also used to identify the stability of riffle-pool sequences. Riffles are readily identified with the sites of fords, marked on the Ordnance survey maps. These were recorded for the North Tyne between the dam site and the confluence with the River Rede. Subsequent analysis of aerial photos enabled the identification of all the individual riffle-pool sequences for the North Tyne to the River Rede confluence for 1976 and 1983, together with values for riffle spacing.

Aerial photos taken in 1976 and 1983 were available at the 1:3000 and 1:7000 scale for discontinuous reaches of the North Tyne and River Rede. From these it was possible to make accurate measurements of the active channel width, where active width is delimited as the distance between vegetated banks identified as a gravel bed (Harvey 1975). Values from map estimates were matched with field measures of active width and were found to be accurate to within 0.5m where the boundary between vegetation and the channel was clear-cut, and 1.0m for indistinct boundaries. These values were used to supplement the field measures of channel width, and to extend the database for riffle spacing.

Data on the post-regulation channel morphology was collected from the 1983 aerial photos, Northumbrian Water Authority (NWA), surveyed cross sections, Freshwater Biological Association (FBA), surveyed cross sections (Carling 1979), and measures of width, depth and morphology made during the period of this study. This information was used to identify changes in the channel capacity at 40 sites between the dam site and the confluence with the River Rede. In addition, values for riffle spacing, sediment storage, and active width, were collected for the River Rede, Tarset Burn and Chirdon Burn. Further information on the development of a tributary confluence bar at the junction of the North Tyne and Tarset Burn was supplied by Professor Geoff Petts.

Contemporary surveys of channel cross sections were made using two techniques. At riffles, a section was demarcated that was within the middle of the riffle as identified at compensation flow and each end was marked by a yellow wooden peg. The levels across the section, together with the levels of the section relative to other sections within a reach, were surveyed using a Zeiss theodolite and electronic distance meter accurate to 0.5 seconds of arc and 0.5mm respectively.

Surveys within the pools were made with the use of a high resolution Lowrance X-16 Echo sounder, accurate to 0.01m in depths less than 10m. This instrument takes a continuous record of the bed elevation below the level of the transducer. The requirements for an accurate survey over a known distance are a stable platform for the transducer and a constant rate of travel over the section. The transducer was mounted on the transom of a large inflatable Zodiac boat, and the depth below the water surface recorded. The elevation of the water surface was calculated from rating curves developed for gauge boards at each riffle and mid-pool. A rope, marked at 1cm intervals, was stretched taught over the section between fixed posts, and the boat was pulled across at a constant rate of 5cm/second. All measurements were made during hydropower discharges so as to maximise the operating width; the X-16 has a minimum operating depth of 0.3-0.4m. Each section was digitised and transformed to the coordinate dimensions of the real section. These were then overlaid using the Arc Info GIS software package. The results of these surveys are shown in AppendixA, together with the riffle surveys. An example of a raw, echo sounding trace is given in Appendix Aa.

4.3 Historical channel change and sediment storage

A review of the studies of Miller (1884), and Peel (1941, 1949), in conjunction with contemporary catchment "windshield" survey, revealed the existence of extensive terraces and palaeochannels within the floodplain of the North Tyne and tributaries. Miller (1884) identifies a sequence of four terraces at the confluence of the Chirdon Burn and North Tyne (GR NY783852), whilst downstream at Snabdaugh farm (GR NY787847), an extensive, silted ox-bow testifies to the former course of the North Tyne (Passmore on-going). The Geological Survey drift map for the North Tyne reveals paired terraces at discontinuous intervals throughout the course of the valley floor, with particularly prominent examples at Hesleyside (GR NY815844), Bridgeford (GR NY843828) and Chipchase Castle (GR NY873755).

The pre-1867 North Tyne experienced lateral and vertical instability at sites where the valley floor is not confined by rock or glacial drift. The date and cause of the periods of instability are probably associated with a response to forest clearance episodes in the Iron Age and Romano-British period and climatic changes, most recently during the Little Ice Age climatic deterioration, of the 17th and 18th centuries (Rumsby 1991).

The analysis of post-1867 data revealed little evidence of major channel change. The low sinuosity of the North Tyne (1.05) precludes active meander dynamics, but where meandering does occur, no major migration is discernible since 1867. What lateral movement of the channel has occurred since 1867 is associated with discrete zones of in-channel sediment storage. Figures 4.1 - 3 depict the sequence of channel change

Figure 4.1 Historical development of sediment storage and channel course at the Ridley Stokoe/Smales Site: North Tyne

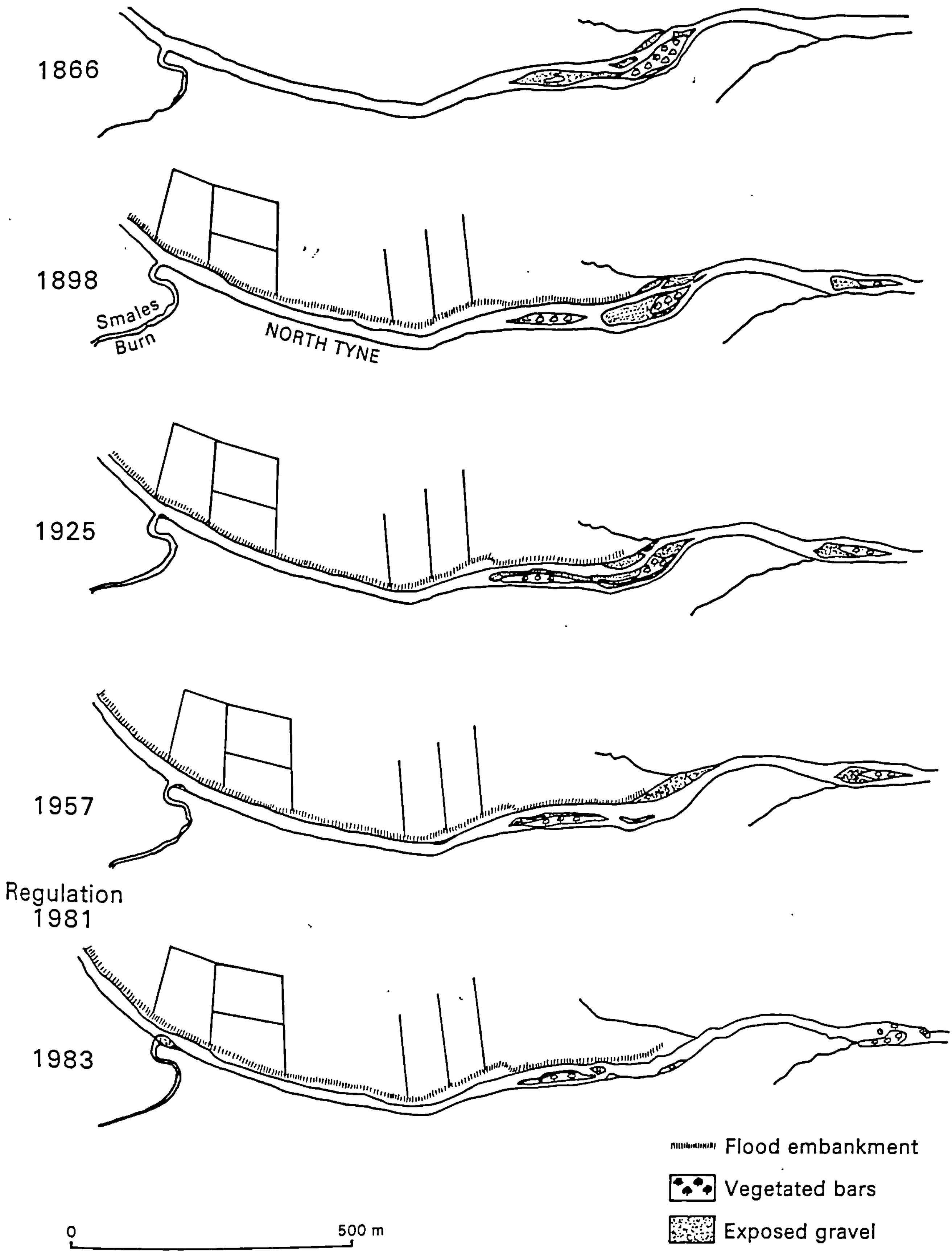


Figure 4.2 Historical development of sediment storage and channel course at the Tarset Site: North Tyne

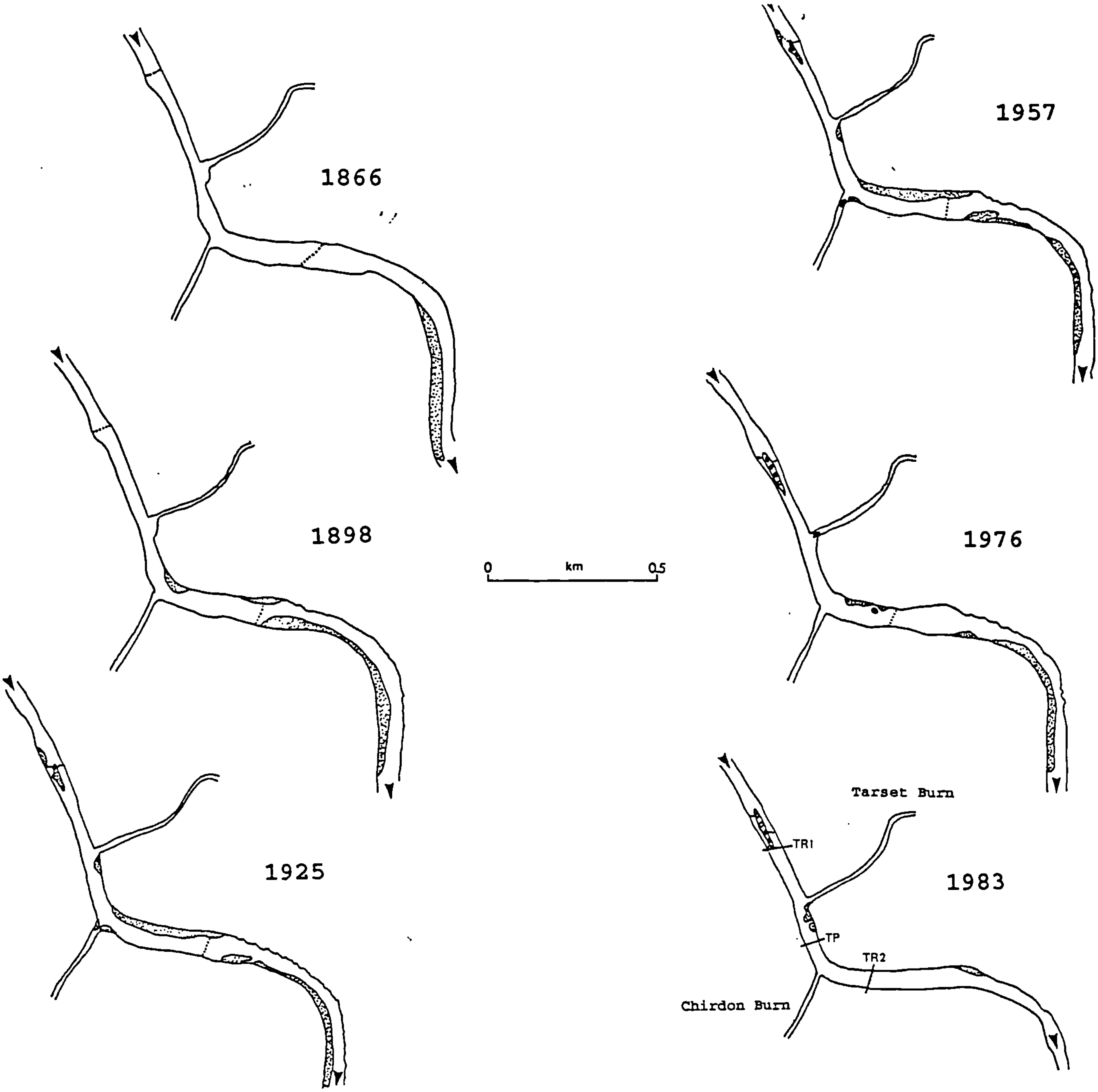
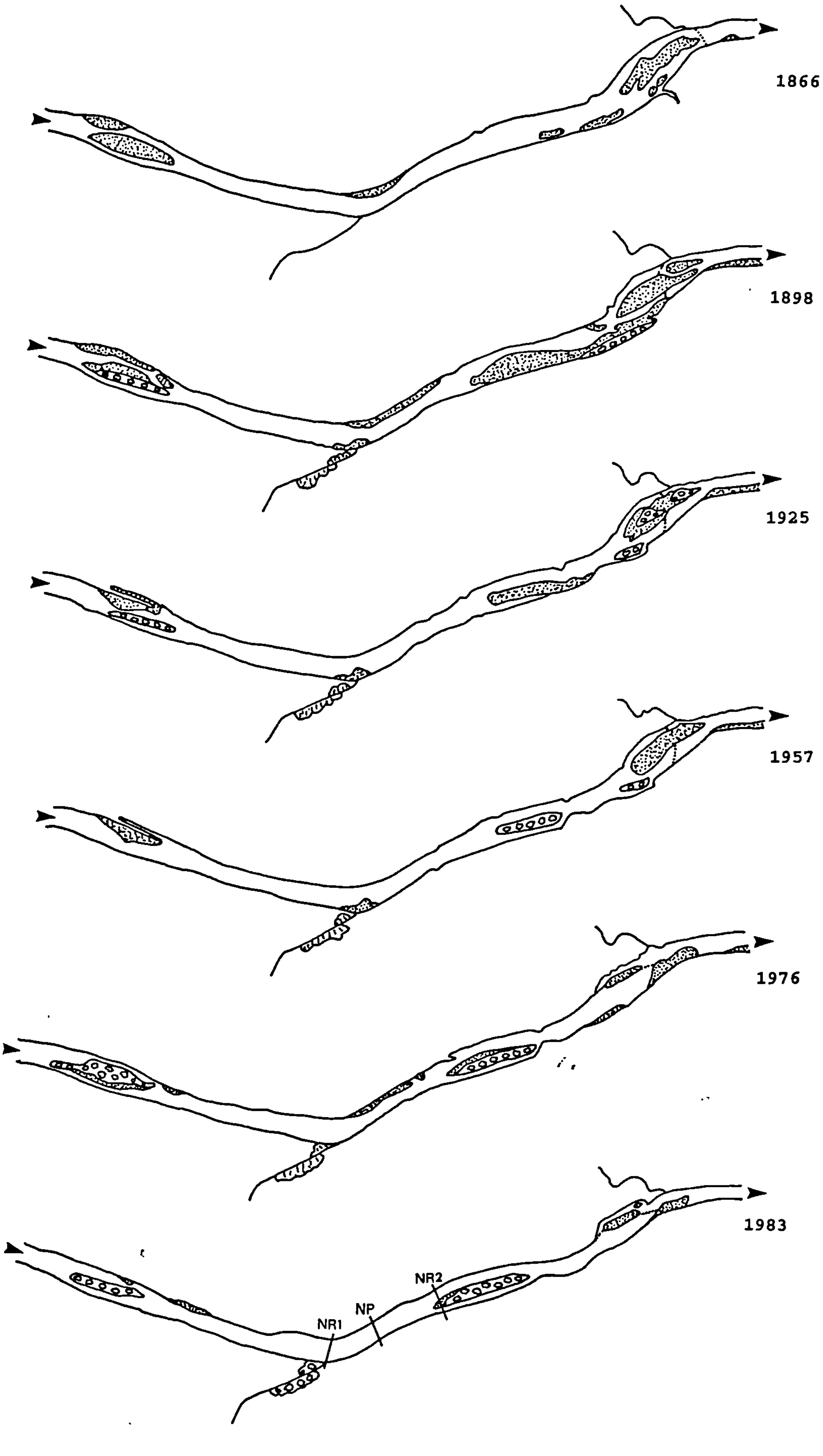


Figure 4.3 Historical development of sediment storage and channel course at the Newton Site: North Tyne



associated with the three main study sites at Smales, Tarset and Newton. The Ridley Stokoe and Newton sites are both examples of discrete sedimentation zones (sensu Church 1983). Channel changes have been associated with the supply and transfer of sediment through the reach, and the stabilisation of bar surfaces by riparian vegetation followed by subsequent incorporation into the floodplain.

Channel change in this context represents within channel switching of course, rather than migration across the floodplain. Consequently it can be concluded that for the past 125 years the course of the North Tyne has remained relatively stable in planform. A similar picture is evident for the River Rede, and for the Tarset and Chirdon Burns in their lower reaches.

Evidence from other local catchments presents conflicting views of temporal stability. The course of the River Coquet has experienced considerable lateral migration within the last 125 years (A. Clarke pers comm), and Macklin and Lewin (1989) describe spatially discontinuous lateral instability on the South Tyne for the same period. In the latter case, however, the lateral instability exists in discrete sedimentation zones, which are similar to those located on the North Tyne. Consideration of the sediment loads of both the North Tyne and South Tyne rivers reveals that the South Tyne, though draining a catchment area 28% smaller than the North Tyne (800 vs 1,118 km^2), stores almost 50% more sediment within the channel than the North Tyne (see below). The sedimentation zones correspondingly receive a greater load, and the lateral migration of the channel is therefore accentuated.

The sediment storage within the North Tyne is expressed in Figure 4.4, in terms of the area of active gravel per 500m stream length for the whole course of the river downstream of the dam site. The locations of major tributaries are indicated, since these are among the primary sources of sediment. Five zones of gravel storage are identified, separated by reaches in which comparatively little sediment is stored. Church and Jones (1982) describe such features as megaforms, associated with local injections of sediment, and powered by climatic or anthropogenic supply episodes (Church 1983). Macklin and Lewin (1989) describe similar, though more extensive, features on the South Tyne, which they attribute to sediment supply from tributary streams. A similar association between tributary junctions and the position of the sedimentation zones is evident on the North

Figure 4.4 Changes in active gravel area (per 500 m) in the North Tyne downstream of the Kielder dam site (Data taken from 1:10560 O.S. maps and 1:10000 Aerial photos (1976/83).

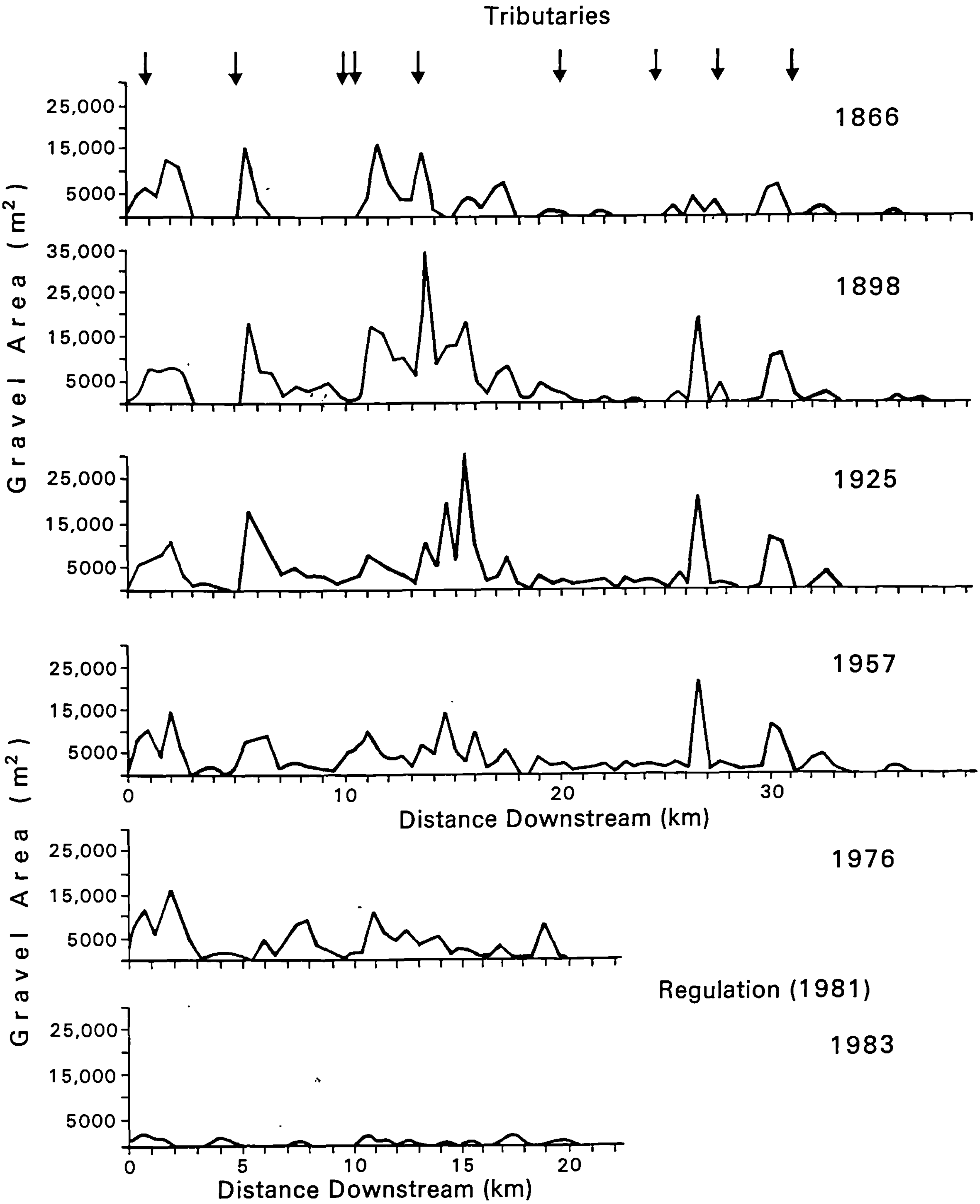


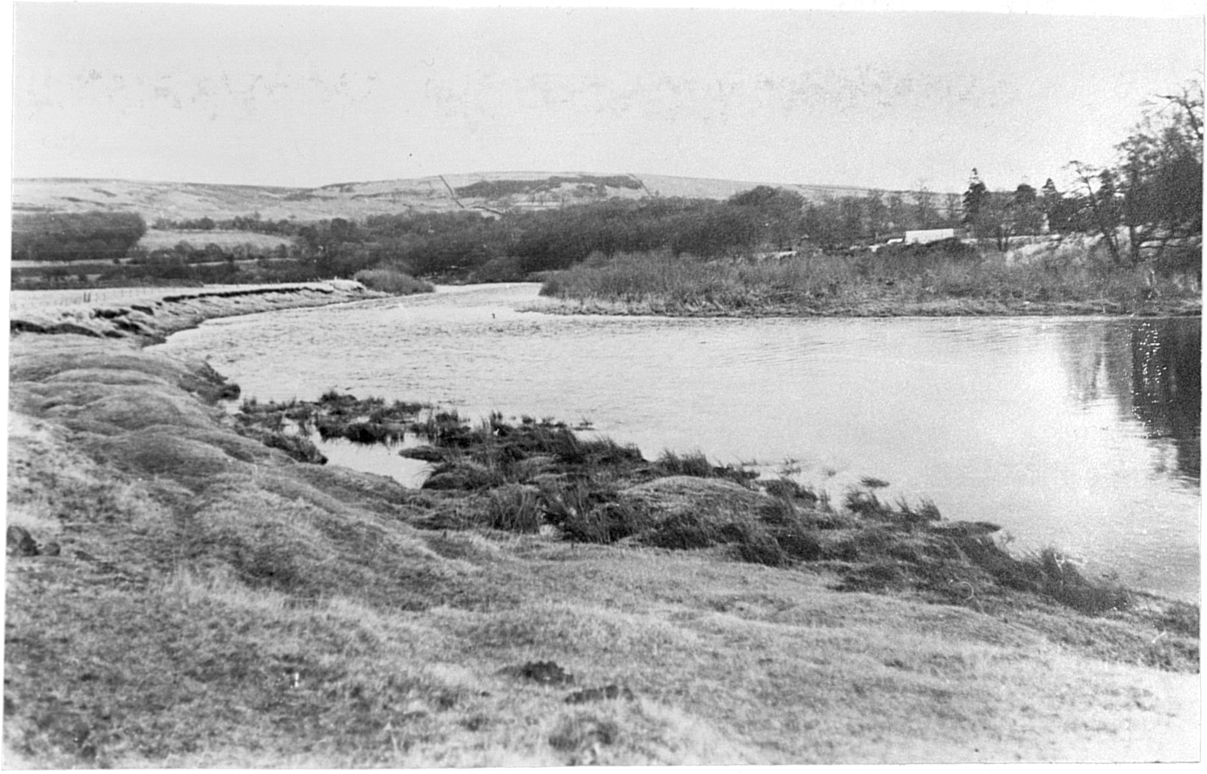
Photo 4A: Comparison between 1978 and 1990 photos of Ridley Stokoe illustrating the growth of vegetation on channel bars (after Carling 1978).

1978

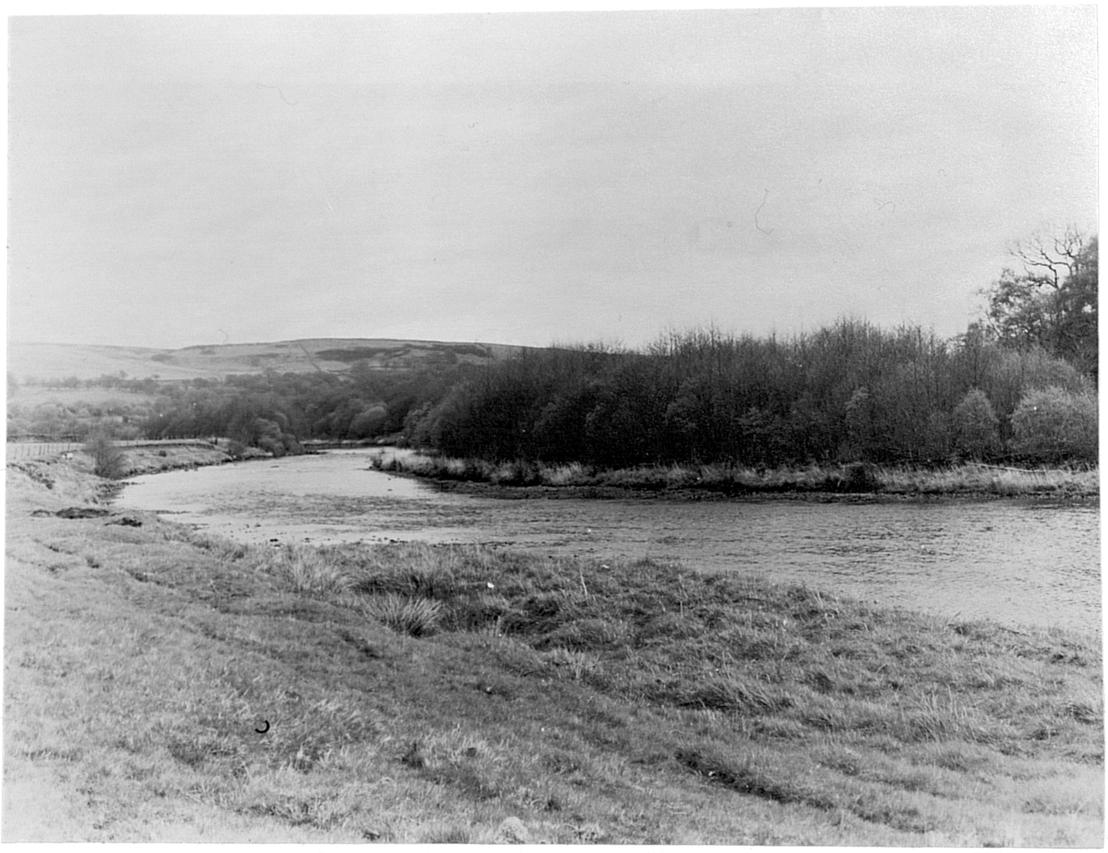
1990

Photo 4B: Comparison between 1978 and 1990 photos of Newton illustrating the growth of vegetation on channel bars (after Carling 1978).

1978



1990



Tyne. Subsequent development of tributary confluence bars within the regulated North Tyne indicates the significance of the tributary supply of coarse sediments (Petts and Thoms 1987). This system of sedimentation is, to a certain extent, self sustaining, since the injection of tributary sediment promotes the lateral erosion of the floodplain gravels and the corresponding development of new sources.

The supply of sediment to the North Tyne increased from 1867 to 1898, for all but the first zone. This is significant since it implies a local (tributary) source of sediment rather than the routing of material from upstream. In addition to the injection of sediments, there is evidence that material was being routed through the stable reaches separating the sedimentation zones. This process is continued for the period 1898 to 1925, particularly for the reach between 15-25 km downstream of the present dam site. A similar scenario is described for the South Tyne system (Macklin and Lewin 1989).

From 1925 to 1957, coarse sediment was distributed throughout the channel, with a corresponding "blurring" of the sedimentation zones. This is again in correspondence with the South Tyne, though in this system Macklin and Lewin (1989) have attributed the reduction in gravel storage at the sedimentation zones to a reduced supply consequent upon the cessation of metalliferous mining. The similarity between the North Tyne, where little significant mining occurred, and the South Tyne, indicates that climatic factors dominate the production and subsequent transfer of material from the tributaries; this has been exemplified by Rumsby (1991).

The period 1957 to 1976 shows a continued reduction in gravel storage within the channel brought about through transfer downstream. Reference to Figures 4.1-3 indicates that colonisation by vegetation was not the main cause of the loss in gravel area, although it does account for some of the loss since 1925.

The most significant reduction in gravel area occurs between 1976 and 1983. During this period, gravel area is reduced and confined to the former sedimentation zones. The reduction in gravel area is largely brought about by vegetation colonisation, which is exemplified in Photos 4A-B. The increase in vegetation can be attributed to two factors; first the prolonged period of low flows from 1970-1978 (Newson 1989; Rumsby 1991), and secondly the artificial extension of this period from 1981 as a result of the regulation of the North Tyne. The period 1978-1981 witnessed a cluster of flood events peaking during the winter of 1978/79, when bankfull events occurred in December, January, February and March. These floods locally reworked the bar surfaces and promoted

of vegetation (NWA reports). The corresponding development of the present situation of densely vegetated bar surfaces is due to the reduction in flows since regulation. As a result, the supply of sediment available from exposed bars has been reduced.

Table 4.1 shows the total annual storage areas of sediment for the period 1967-1983. The reaches are all 20km long, on fifth order streams, located approximately 15km downstream from their respective sources. This data is designed to put the gross changes in sediment storage in the North Tyne into perspective. The total gravel storage in the South Tyne is significantly greater than the North Tyne or Coquet, a reflection of the steep entrenched tributaries and the historical legacy of mining. Of interest is the similar behaviour of the North Tyne, South Tyne, and the Tarset burn for the period 1867-1925. In contrast, the Coquet, which drains the Cheviot Massif, responds in a totally opposite manner, which may reflect the gross channel typology, which is meandering, rather than wandering in nature, and hence does not possess the sedimentation zones found in the Tyne system.

The North Tyne experiences a net reduction in gravel area from 1957-1983, whilst both the Coquet and the South Tyne experience a trend towards increasing sediment storage. This latter point would confirm the effect of regulation on the stabilisation of gravel surfaces by vegetation colonisation (Petts 1984).

The lower 5 km of the Tarset and Chirdon Burns show that, within the same system, trends in the total sediment storage (and subsequent supply to the main North Tyne) can vary. The Tarset Burn mirrors the behaviour of the main North Tyne, whilst the Chirdon Burn experiences a progressive increase in gravel storage from 1867-1925. The reduction in gravel area since regulation is put into context when viewed against a general increase in gravel area on both The South Tyne and Coquet for the same period.

The historical evidence of sediment transfer and storage in the North Tyne reveals a picture of pre-1867 lateral instability, with subsequent incision into the present channel

Table 4.1: Total sediment storage (m^2) shown as bars on 1:10560 OS Maps and aerial photos for 20 km reaches of the Rivers North Tyne, South Tyne and Coquet, and for the Tarset and Chirdon Burns.

River	1863	1898	1925	1957	1976	1983
N. Tyne	130000	240000	180000	228000	210000	30000
S. Tyne	430000	590000	370000	315000	410000	480000
Coquet	270000	180000	200000	80000	25000	80000
Tarset B.	44000	81000	36000	38000	-----	39000
Chirdon B.	45000	60000	68000	65000	-----	60000

course. Following the injection of a large quantity of sediment during the period 1867-1898, the North Tyne system exhibited a process of redistribution from distinct sedimentation zones, through intervening stable, single channel reaches. Complete redistribution was achieved by the 1957 resurvey, with 1867 levels of channel storage attained by 1976. This indicates that the sediment transport system of the North Tyne exhibits a rapid reaction time to change, possibly in the order of 10 years, as indicated by the decadal nature of accentuated flood frequency (Rumsby, 1991), which is suspected as the cause of the late 19th century input. The subsequent relaxation time for the system to adjust and accommodate the change in sediment supply has taken approximately 78 years. This is important for the subsequent interpretation of the impact of river regulation, which can be expected to show a rapid reaction in the sediment system and a protracted period of complex recovery.

The response times inferred from historical evidence are confirmed for regulation impacts by the study of post impoundment changes on the River Rede (Petts 1979; 1984). The Rede was impounded in 1905 for water storage, and inundates only 2.72 % of the catchment; however, Petts (1979) showed, from regional regression analysis, that the channel has reduced in capacity along much of its length to the North Tyne. Increased capacity has resulted immediately below the dam at Catcleugh for a distance of 0.15 km due to clearwater erosion (Petts 1979). The amount of channel change is variable, with accentuated levels of capacity reduction in meandering reaches and downstream of tributary confluences. The former may have been accentuated by 1940's channel dredging that was carried out in the meandering channel, but the rapid response below tributaries is confirmed from other regulated streams. On this basis, the reduced flood flows in the North Tyne can be expected to affect the total channel over a period of 80-100 years. However, the effects will be influenced by the regulation for hydropower.

4.4 Contemporary channel geometry: morphological evidence for the effects of river regulation.

The present course of the North Tyne is characterised by stable, vegetated bars, now functionally islands, a system of well defined riffle and pools, and a suite of tributary confluence bars. The vegetated bars have been discussed above, and form one of the immediate impacts of the reduced flood frequency resulting from regulation. Some gravel bars still exist as exposed surfaces of cobbles, but these are typically defined by the flow level associated with maximum hydropower generation (15.4 cumecs).

The availability of sediment has therefore not only been severed from the head-waters by the dam, but the in-channel stores have been deactivated. In addition, bank erosion, formerly identified as one of the main sources of sediment in the North Tyne (Hall 1964), has been effectively eradicated as a source of coarse material in the first 15 km downstream of the dam. The reduction in bank erosion sources of sediment has been affected by vegetation stabilisation of the banks, reduced flood power as a result of the lower flood peaks which makes effective the bank protection, applied since the dam was closed in 1980 (NWA records).

Active deposition of bedload in the channel upstream of the confluence with the River Rede is now limited to localised reaches of the North Tyne channel associated with regions of accelerated flows, and specifically downstream of tributary junctions. Deposition of tributary sediment has been described in Chapter 1 as a typical reaction response of a stream to a reduction in flood peak in the main channel. A corollary of the reduced base levels in the main stream during floods is the initiation of tributary rejuvenation, and a subsequent increase in sediment yield.

In the North Tyne, tributary deposition of sediments has been an intermittent feature of the pre-regulation channel (Figures 4.1 - 3) in response to increased tributary sediment supply. However, this material was relatively rapidly transmitted downstream. In contrast, the post regulation channel exhibits tributary confluence bars at the mouths of all tributaries, regardless of size, down to the River Rede. Downstream of Rede confluence, the percentage of regulated water supply is decreased considerably during floods, and although present, not all tributaries possess bars.

A feature of most of the post-regulation confluence bars is a vegetated surface, demarcated by the level of maximum hydropower flow (Photo 4c). This effectively stabilises the deposits and limits the sediment available for downstream release during subsequent flood events. In contrast to this, the tributary bar at the Tarset burn confluence is composed of unvegetated gravel, and represents a major injection of

Figure 4.5 Development of the Tarset Burn confluence bar. (Data prior to 1987 courtesy of G.E.Petts).

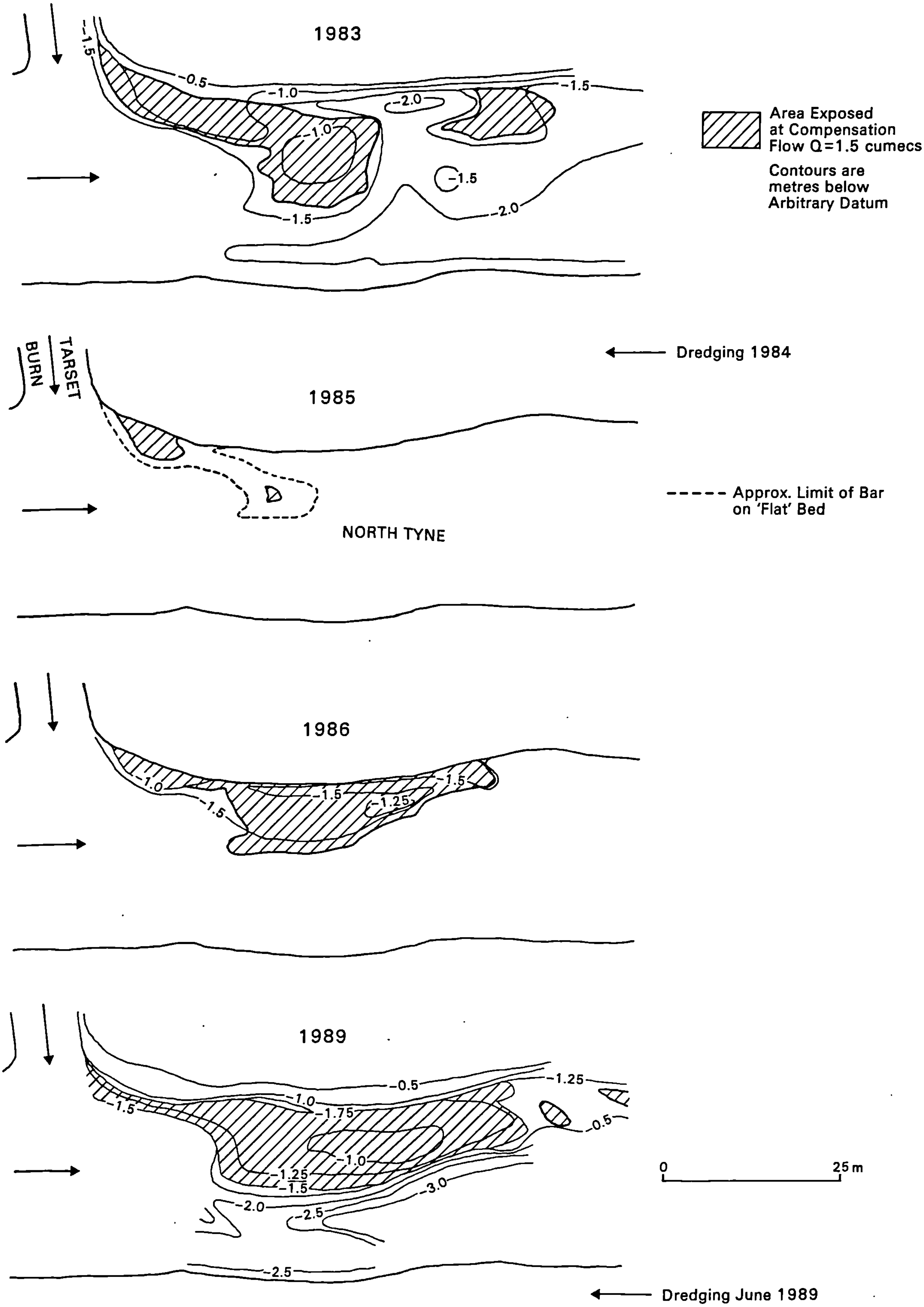


Photo 4C: Smales confluence bar illustrating the encroachment of vegetation up to the limit of maximum hydropower stage.

material. This bar is dredged at intervals of approximately three years, to protect a minor road from erosion as a result of the deflected flows. Nevertheless, the bar redevelops as soon as a flood event of sufficient magnitude occurs on the Tarset burn. Figure 4.5 depicts this bar and the subsequent reformation following dredging.

Petts (1983), and Petts and Thoms (1987), have described a process whereby material from the tributary is routed around the bar, and through time develops into extensive berms. This scenario is evident downstream of the older, unaltered bars on the North Tyne, and provides loci for accentuated reduction in channel capacity and *sediment* storage. To date, a period of accentuated flood frequency has not been experienced on the North Tyne since regulation, but in the light of the historical data on sediment supply, the tributary junctions will clearly be areas of major channel change in the future, particularly if associated with rejuvenation.

4.5 The morphology of the riffle-pool sequence.

Alternating riffles and pools are recognised as fundamental morphological features of alluvial streams of low-moderate slope. An analysis of the substantial literature connected with the objective discrimination of riffles and pools presents the following definitions:

Riffles: are topographically high, transverse, lobate accumulations of coarse sediment, spaced at relatively regular intervals along channels, separated by regions of deeper flow. In section they are relatively symmetrical, with little cross stream variation in flow depth Milne 1982b; Bathurst 1979). once formed, Functionally they are considered to be hydraulic elements, storing little sediment (Church and Jones 1982; Ashmore 1982), and controlling the low-moderate discharge hydraulics of the upstream pool. Riffles are often considered to be spatially stable within a channel over extended time periods (Dury 1970), although very large floods and high sediment loads can destroy them (Lisle 1982; Brookes 1988). The longitudinal oscillation in bed height is often (though not exclusively) matched by an oscillation in bed width, with riffles associated with wider channel sections than pools (Richards 1976b; Clifford 1990).

Pools: are topographic low regions of channel, associated with the deeper flow depths in a channel, narrow bed widths, and highest sectional asymmetry of flow depth (Milne 1982b; Knighton 1984). Functionally, pools are considered to be regions of temporary sediment storage (particularly fine sediments), and morphologically associated with lateral or point bars. Pools can be divided into three distinct regions a pool-head, mid-pool and pool-tail (Ashworth 1987). These regions have been shown to be hydrodynamically distinct, though necessarily transitional in morphology from riffle to pool (Keller 1972b; Ashworth 1987; Petit 1987). The mid-pool is often (though not exclusively) the deepest region of the pool, whilst the pool-tail is generally the shallowest. Pools are often (but not always) much longer than riffles, and occupy a greater area of the total channel.

The discrimination of riffle-pool sequences on the basis of morphology is based on four techniques:

1. discrimination on the basis of low flow water depth;

2. discrimination on the basis of residual analysis of long-profile trends in bed elevation (Richards 1976);

3. the differenced bed elevation series, based on the cumulative trend in differenced bed elevations (O'Neill and Abrahams 1984);

4. autoregressive modelling to identify the presence of well developed riffle-pool sequences though not their position (Clifford 1990).

Clifford (1990) reviews the latter three techniques and concludes that none is satisfactorily objective, since each depends upon subjective decisions of measurement spacing, and selection of a definitive long profile. The first technique is clearly limited to conditions of low flow, but in fact represents the most widely used and arguably most unambiguous method of discrimination, based on morphology alone. The subjectivity associated with this technique involves the differentiation of riffle from run, pool from scour-hole, and the choice of flow level at which to identify a particular bedform. Whilst the latter problem is not of concern in techniques 2 and 3, the former problem of bedform discrimination is also inherent in the more complex techniques described below.

The regression technique of Richards (1976) and Milne (1982a), has been widely used to discriminate riffles from pools on the basis of positive (riffle) or negative (pool) residuals from the regression trend in bed elevations. The technique's efficiency to identify riffles from pools is governed by the distance over which the survey is conducted, and the spacing of measurements (O'Neill and Abrahams 1984). As with all regression techniques, the presence of particularly large residuals towards the ends of the distribution affects the gradient of the curve and therefore the discrimination of riffle and pool. Furthermore, the scale of the sampling distance affects the slope of the regression curve, so that on long reaches, fewer and larger riffles will be discriminated than over a shorter sequence, particularly where the amplitude of successive riffle-pools is low (Clifford 1990).

The bed differencing technique is considered by its originators to be simpler and yet more objective than the regression approach to riffle-pool discrimination. This is based largely on the ability of the technique to resolve more "realistic" riffle-pool sequences. In fact the technique is inherently subjective, since the differencing relies on a "suitable" choice of value for the minimum value of "tolerance" level (a multiple of the standard deviation of the absolute differences in bed elevation) required to discriminate riffles from pools.

A problem relevant to both the "objective" methods of determining riffle-pool sequences, is the choice of longitudinal profile. This point is made by Clifford (1990), who illustrates that considerable variance is encountered in the discrimination of riffles from pools, depending on whether the long profile is taken in the centre, margins, deepest or average flow depth regions of the channel. Intuitively, the deeper thalweg will increase the amplitude of pools, but decrease that of the riffle.

The subjective determinations of long profile, and sample spacing is not a problem for the first technique. Instead, this technique relies on the hydraulic discrimination of riffle from pool at low flow, since evidence of flow depth is demarcated by a response in the hydraulic conditions of the flow, which in the light of the results of this study, and that of Clifford (1990), is reasonable; it is this technique that was chosen for the discrimination of riffle and pools in this study.

A further factor influencing the choice of the first technique for discriminating riffles and pools is the presence of a standard low flow level equal to the compensation discharge of between 0.75-1.5 cumecs, which while subject to variation downstream, does provide a benchmark for reasonably objective discrimination. Another consideration was the scale of the riffle-pool sequences in the North Tyne, which make both the techniques that rely on surveying extremely time consuming and, for the reasons discussed above, subjective with respect to the determination of the representative long profile.

Autoregressive studies of riffle-pool sequences represent the final method of objective determination of riffle-pool morphology. The initial premise for the application of this technique is based on the considerable evidence for a "rhythmic" spacing of riffles (or pools), independent of bed material, identified at between 5-7 times channel width at bankfull (Leopold et al 1964; Keller and Melhorn 1978; Thompson 1986). In addition, Richards (1976) has commented on the study of macroturbulence by Yalin (1971), and suggested a physical cause of riffle-pool development which incorporates a cyclic term at 6.3 times channel width.

The autoregression technique is theoretical, and whilst providing evidence of pseudo-cyclic trends in the bed elevation, is again dependent upon the spacing of the elevation measurements used to determine the regression line from which the residuals for the process are developed Clifford (1990). Knighton (1983) comments on the assumptions of the autoregressive model; the influence of variables other than upstream bed elevations are omitted, and the elevations at the time of survey are considered invariate. This latter assumption does not allow for the observed scour-fill sequences of pools and riffles during the very flood events that mobilise the bed sediment (Andrews 1983).

Although Church and Jones (1982) have utilised the technique for long reaches of the Bella Coola and South River, British Columbia, for the reasons of scale, sufficient observations were not made on the North Tyne. Instead, the inter-riffle spacing was determined from 1983 1:3000 scale aerial photographs, made during a period of compensation flow. Active channel width was also determined from these photos, and checked for accuracy against Northumbria Water Authority surveyed sections. These measurements enabled the determination of riffle spacing for the reach from the dam site to the confluence of the River Rede, and include 56 riffles and pools. Richards (1976) has suggested the use of active bed, as this represents the width of channel capable of supplying and transporting bedload. In addition, Harvey (1975) found that riffle spacing was more closely correlated with the channel widths associated with intermediate flows, which in the North Tyne approximate to the active bed width.

Riffles (and therefore pools) are regarded as stable equilibrium bedforms that are capable of withstanding floods of 100 year recurrence interval (Dury 1970). Furthermore, the position of riffles has been established as stable over periods of 100 years (Dury 1970). The stability of riffles is taken to be an indication of equilibrium within a river channel, between the rate of erosion, sediment transport, deposition and dominant flood frequency. Riffle-pool spacing is most frequently described in the context of meandering (Keller 1971; Hooke and Harvey 1983; Thompson 1986). In these instances the width relationship is considered secondary to an increase in path length. Accordingly, extra riffles are developed when the path length around an actively migrating meander bend reaches a critical length of 9-13 times channel width. Changes in channel width are not considered as a first order control on riffle-pool spacing. Instead, both Hooke and Harvey (1983), and Thompson (1986), relate the development of new riffles and pools to the breakdown of secondary flow patterns as path length (pool length in both studies) increases.

An additional factor in determining the position of riffles within a channel was alluded to by Milne (1982), who described the linkage between locally increased sediment supply (river cliffs) and riffles. In this case the position of a riffle is related to a sediment overload.

To summarise, a spatial change in the position of the riffle-pool sequence will be expected as a result of:

1. a change in channel width, whereby an increase in width should increase the inter-riffle spacing, and a decrease in width reduce it;

2. an increase in channel length due to meandering or river capture, which will increase the number of riffles and pools;

3. a locally accentuated input of sediment which will cause the development of a riffle/bar.

4.6 Riffle-pool morphology in the North Tyne

The temporal stability of riffles and pools within the North Tyne can be determined by monitoring the position of fords on the 1:10560 scale Ordnance Survey maps, together with more recent, 1:10000 scale aerial photos. Fords represent riffle or bedrock features in the channel, the former being the most prevalent in the North Tyne.

Figure 4.6 depicts four sites where the movement of fords have been identified over the last 125 years. It is evident that in the post regulation North Tyne, riffle instability was associated with areas of sediment storage, whilst stable reaches of the channel have riffles that have remained in the same position for the past 125 years. Furthermore, the riffle spacing in the stable channel reaches is much greater than those associated with active sedimentation zones, a feature maintained within the contemporary North Tyne (Table 4.2 below).

Riffle spacing at five sedimentation sites varied through time, such that the mean spacing appears to react to the area of sediment stored in a reach Table 4.2.

Table 4.2 Variations in riffle spacing with area of sediment stored at sedimentation zones through time.

Date	x Sediment Storage (m^2)	x Riffle Spacing (m)
1867	15946	275
1898	18223	236
1925	11390	325
1957	12923	347
1976	7973	333
1983	1139	333

1983 x riffle spacing for sediment transfer reaches = 407m

Figure 4.6 Stability and migration of riffles over 126 years recorded from ford sites on 1:10560 Ordnance Survey Maps.

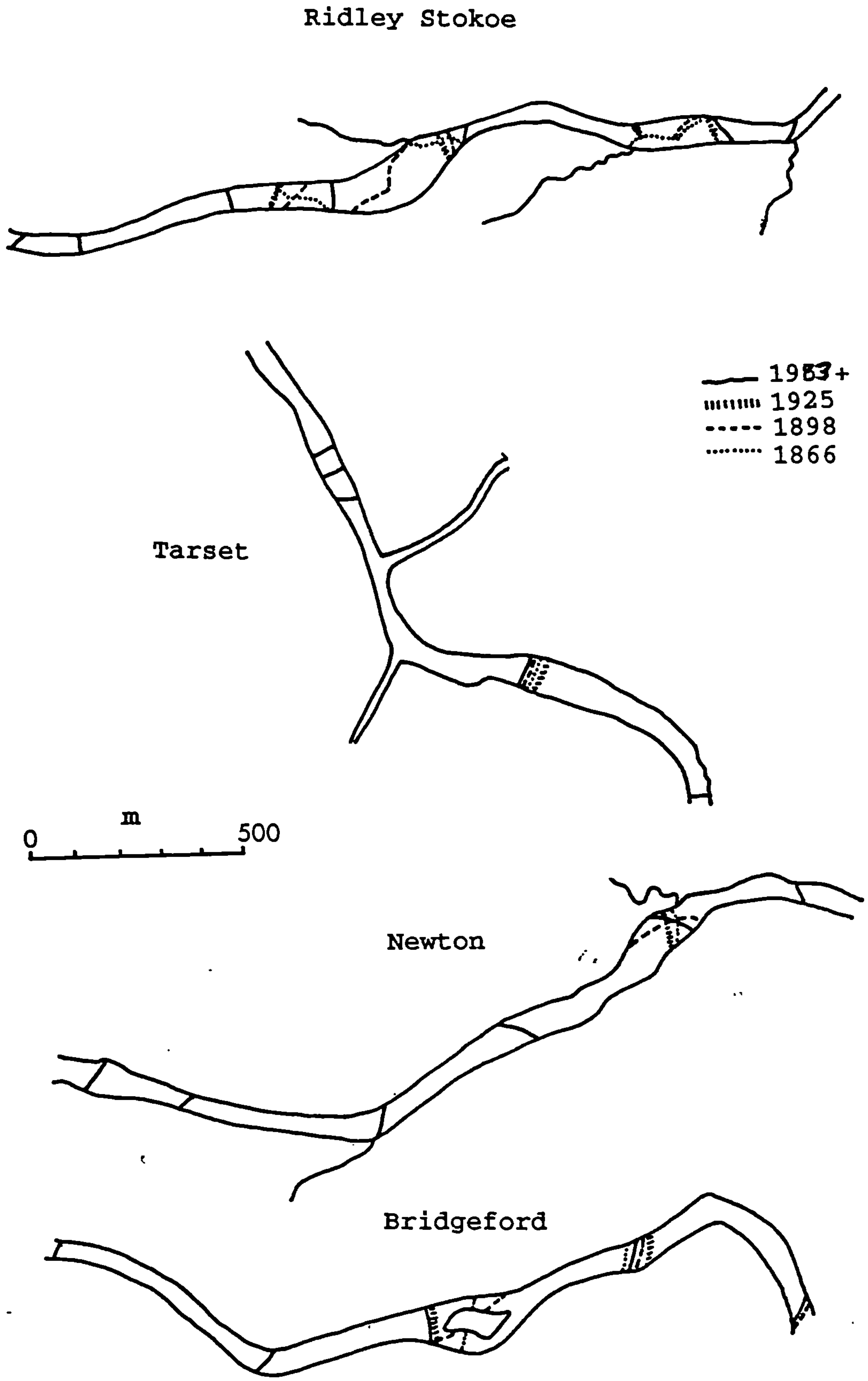
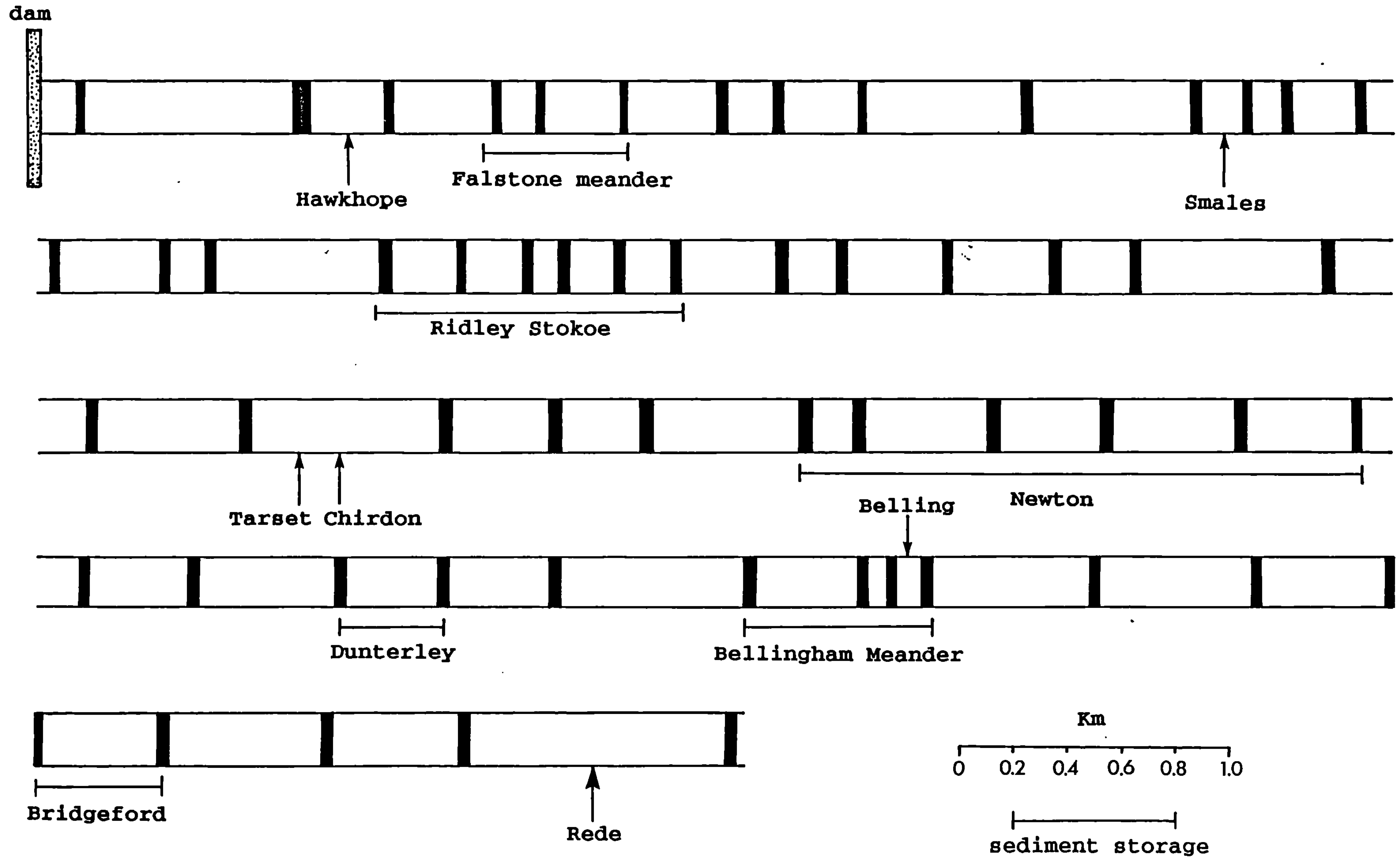


Figure 4.7 Schematic representation of riffle spacing on the North Tyne between the dam site and the River Rede.



The difference in the spacing of riffles associated with sediment storage or sediment transfer reaches is largely independent of width. The bankfull or active channel widths in the sedimentation reaches are on average almost twice as wide as the more stable channel reaches (65m vs 38m) and yet the riffle spacing is much shorter. This is more easily explained today when the mid channel bars are vegetated, since the channel width is much reduced by bifurcation around the islands. However, from the discussion above, this was not the case in the past, and therefore one must conclude either that riffle spacing is unrelated to channel width, or that channel width is merely a surrogate for another factor. Harvey (1975) makes this point, and developed a strong positive correlation between riffle spacing and the width associated with discharges above the mean annual discharge but below bankfull. However, from the evidence of riffle stability in the North Tyne, it appears that it is the availability of sediment at a site that determines the spacing and temporal stability.

To test this hypothesis is difficult, since few riffles are marked on the old maps and much of the exposed gravel areas today are vegetated, and do not reflect the sediment storage that was associated with the contemporary riffle-pool sequence. A test of the statistical significance of the relationship between past sediment areas versus contemporary inter-riffle spacing was conducted, but the results, though consistently recording a negative correlation (xr^2 = -0.003) between sediment area and riffle spacing, were not statistically significant. This may form a useful avenue for future research using dynamic river channels and large scale aerial photographs.

The contemporary riffle spacing in the North Tyne from the dam site to the confluence of the River Rede, a distance of 22km, is illustrated schematically in Figure 4.7. The sedimentation zones are identified along with the major tributary junctions. The total number of pools is 56, whilst the total number of riffles is 57, including the weir at Ugly Dub, at 320m downstream of the dam site. The riffle spacing (pool length) is apparently variable throughout the channel, with little obvious spacing. The relatively short riffle spacing in areas of sedimentation is confirmed, but this is not exclusive. There is also some tendency for riffle spacing to be shorter downstream of tributary inputs, but this is not conclusive.

The riffle spacing results were analysed for evidence of the relationship alleged to exist with channel width. Values were recorded for the North Tyne, Rede, Smales Burn and Tarset Burn. Interestingly, the individual datasets revealed no statistically significant correlation with either bankfull or active width, but the aggregated dataset was significantly correlated with active width. This result throws some doubt on a specific width control on riffle spacing, particularly in the North Tyne. However, a consideration of the average riffle spacing in terms of bankfull channel width, reveals that these fall within the 5-7 times channel width defined as typical for gravel-bed river (Table 4.3), (Petts and Foster 1983; Ferguson 1981; Leopold et al 1964). The modal value for riffle spacing on the North Tyne of four times bankfull width is consistent with the results of a survey of streams within the region (including the Rede) by Milne (1982b).

Table 4.3 Average values for riffle spacing/width

	Active Width			Bankfull Width
North Tyne	$\bar{x}$ = 6.65	sd = 2.85	n = 56	$\bar{x}$ = 4.64 sd = 1.92
River Rede	$\bar{x}$ = 9.91	sd = 0.03	n = 37	
Smales Burn	$\bar{x}$ = 2.94	sd = 1.10	n = 7	
Tarset Burn	$\bar{x}$ = 5.15	sd = 1.11	n = 8	

Range of values for Riffle spacing/active width

North Tyne	5.5 - 32.2	3.6 - 22.1 (Bankfull width)
River Rede	3.6 - 16.3	
Smales Burn	1.5 - 4.3	
Tarset Burn	3.9 - 7.1	

Table 4.3 also contains the range of values for riffle spacing in terms of active width and bankfull width. Thompson (1986), and Hooke and Harvey (1983), identified an apparent threshold value of 9-13 times active width before secondary flow cells broke down (or redeveloped) and formed another riffle. This value was formerly identified as nine times bankfull width by Keller (1972), and was criticised by Richards (1976) on the basis of limited data and little theoretical basis. Nevertheless, the maximum values of 32.2 times active channel width and 22 times bankfull channel width for the North Tyne would appear to be at variance with both these thresholds, indicating that channel width is only part of the control on riffle spacing.

The correlation coefficients for riffle spacing and active channel width, for the watercourses listed in Table 4.3, showed consistent values of between 0.303 - 0.395, which were not significant at the 95% confidence limit for the Smales and Tarset Burns, but were significant for the North Tyne and River Rede. Regression analysis was even less successful, with no linear relationship accounting for more than 15.7 % of the observed variance on any of the watercourses surveyed.

Riffle spacing data for the North Tyne was also investigated for possible association with values for bankfull discharge, discharge at intermediate channel widths, channel slope, and distance downstream from tributary sediment sources. No relationships were significant at the 95% confidence interval. Multiple regression analysis of riffle spacing against bankfull discharge, channel slope and distance from tributary source yielded a relationship that accounted for only 13.7% of the observed variance.

From these results, and in the absence of more detailed data, it is concluded that although riffle spacing in the North Tyne catchment is on average within the theoretical spacing limits of 6.28 times active width dictated by turbulence structure (Yalin 1971; Richards 1976), there is no firm evidence for any consistent trends; rather the riffle spacing in the North Tyne probably reflect conditions at a site and the legacy of historical sediment transport. As Thompson (1986) concludes, the spacing of riffles is linked more to an inherent feature of the sediment transport than to the flow structure itself. Given that the riffle sites in regions of sediment transfer have tended to remain stable over 125 years, it is conceivable that the present scenario is a legacy of past sediment dynamics.

Although no conclusive relationship exists between riffle spacing and channel width, there does exist a distinct pattern within the morphology of the North Tyne riffle-pool-riffle sequence. Table 4.4 lists the average values for active and bankfull channel width, flow depth at bankfull and peak hydropower generation for riffle, pool-head, mid-pool and pool-tail regions of the riffle-pool-riffle sequence. The determination of each region was made by dividing the inter-riffle spacing in half to obtain the mid-pool, and then dividing the two adjacent sections in half again to find the pool-head and pool-tail (Ashworth 1987).

Table 4.4 Morphological features of the riffle-pool-riffle sequence within the North Tyne catchment.

Site	Width (a)	Width (Bf)	Depth (HEP)	Depth (Bf)
Riffle	39.8	47.8	0.51	2.25
Pool-head	34.4	44.0	0.74	2.80
Mid-pool	35.9	46.0	0.83	3.03
Pool-tail	38.9	44.3	0.59	2.76
	Area (Bf)			
Riffle	129.7	n = 37 (NWA Surveys)		
Pool-head	126.1	n = 6		
Mid-pool	141.8	n = 18 (+ NWA Surveys)		
Pool-tail	135.0	n = 7		

It is clear from these results that, although variable, riffles and pool-tail regions are both the widest and shallowest features of the riffle-pool-riffle sequence. The pool-head is generally the narrowest region within the sequence, and the mid-pool the deepest. Significantly, there is no occasion in any of the sites measured where the pool-head is not the narrowest region of the riffle-pool-riffle sequence, although the mid-pool is sometimes of similar width. The pool-tail is always equal to or wider than the mid-pool and pool-head, and the riffle is always wider than all other regions. This latter point is in agreement with the observations of Richards (1976b), who concluded that riffles were on average 12% wider than associated pools, which he attributed to bank erosion caused by diverging flow induced from medial accumulation of sediment at riffles. The value for the difference between riffles and mid-pool regions is 9.7% and 13.6% for pool-heads.

The depth of flow at peak hydropower and bankfull discharges reveals a general picture of increasing flow depth into the mid-pool, and a shallowing downstream to the pool-tail. This model was consistent for all sites measured. Problems with the estimation of bankfull depth (and width) stem from the presence of 19th century flood embankments and stone pitching along much of the North Tyne. The embankments are set close up to the channel in'many instances, which is reflected in the former frequency of flood bank maintenance required on the pre-regulation North Tyne (NWA maintenance records). The embankments effectively increase the bank height, whilst the stone pitching maintains a set channel width. This latter point is probably a compounding factor in the poor relationships between riffle spacing and active/bankfull widths discussed above.

Channel capacity at bankfull (under the imposed dimensions) indicates, on average, that pool tail and mid-pool regions can accommodate the largest flow volume, whilst pool-heads record the smallest. However, this is not exclusive, and pool-heads were found to be of equal capacity to riffles in 32% of cases. Nevertheless, the implications from these measures of cross-sectional form at bankfull discharge are for an increased velocity in pool-head regions, relative to the riffles, and for a lower velocity in mid-pool and pool-tails. This will be discussed further in Chapter 7.

4.7 Changes in Channel Capacity since river regulation

The typical (though not exclusive) reaction of a gravel channel to a reduced discharge regime as a result of impoundment is for a reduction in channel capacity (Petts 1984). The North Tyne was surveyed by the Northumbrian Water Authority (NWA) and the Freshwater Biological Association (FBA) in 1978. The NWA sites were resurveyed in 1987, whilst the FBA sites were resurveyed during the course of this study. The results are discussed fully in Chapter 13, but a consideration of the channel capacity of the total sections is relevant to the discussion of channel morphology.

Table 4.5 lists the percentage change in channel capacity between the two survey dates, together with a classification of the type of change per section. Some 71% of sections surveyed have experienced a reduction in channel capacity since regulation. These are particularly evident at pool-tail sections, and it is these sections that have experienced the most dramatic change in capacity; this will be discussed further in Chapter 13. The causes of the reduction in capacity are attributed to the development of in channel berms, vegetation of in-channel bars, and in one case, bank filling by a local farmer. The development of berms within the channel is a typical response to river regulation, caused by fine sediment deposition at the channel margins during long periods without flood events (Petts 1979; Petts 1984). In time these berms will colonise with emergent aquatic plants, and develop into a low terrace floodplain within the channel (Petts 1979).

An increase in channel capacity is evident at riffles and pool-head regions, and is associated with scour of the bed or banks. The scouring of riffles will be discussed in Chapter 13, with reference to the active bed zone. Scour is particularly evident at the first riffle downstream of the dam, and around the bridge piers at Falstone.

Table 4.5 Changes in channel capacity between 1978-1987 for the first 18 km downstream of Kielder reservoir.

Section	Distance D/s of Dam (km)	% Change	Typology of change
1	0.80	+ 2.0	Bed Scour (R)
2	1.25	- 1.7	Berm (R)
3	1.65	- 3.9	Berm (PT)
4	1.75	- 2.6	Bed Scour (PH)
5	2.23	- 4.9	Bank Fill (R)
6	2.40	+ 2.6	Bridge Pier Scour (R)
7	2.76	+ 4.4	Bed Scour (R)
8	3.18	- 0.6	Bed Scour (R)
9	3.62	+ 0.1	Bed Scour (MP)
10	4.10	+ 0.2	Bed Scour (R)
11	4.78	+ 0.7	Berm (PT)
12	5.33	- 1.7	Aggrading Bars (R)
13	5.88	- 0.3	Bank Scour (R)
14	6.60	- 0.1	Bank Scour (R)
15	7.35	- 1.8	Berm (PT)
16	7.88	- 0.9	Berm (R/B)
17	8.71	- 0.5	Bed Scour (PH)
18	9.26	- 0.6	Berm (MP)
19	9.71	- 1.3	Berm & Bank Fill (PT)
20	10.10	+ 0.8	Bank Scour (R)
21	14.47	- 2.7	Berm (Both Banks) (PT)
24	15.22	- 2.5	Berm (Both Banks) (R/B)
25	16.13	- 5.4	Berm & Bank Scour (MP)
26	18.20	- 2.6	Berm & Bank Scour (MP)

Table 4.6 Channel Morphology at the three main study sites

	YR1	SMR1	SMP	SMR2	TR1	TP1	TP2	TR2	NR1	NPH	NMP	NPT	NR2
Width (Bf)	28	35	35	38	40	48	43	68	76	65	59	65	109
Width (HEP)	25	26	26	23	31	38	36	49	44	35	34	50	32
Depth (Bf)	2.1	2.5	2.9	2.2	3.0	3.2	3.3	2.3	2.2	2.5	2.8	2.5	2.1
Depth (HEP)	0.5	0.8	1.1	0.7	0.6	0.9	1.2	0.7	0.5	0.8	0.9	0.7	0.5
W/D (Bf)	13	14	12	17	14	15	13	29	35	26	21	26	51
W/D (HEP)	69	33	24	32	50	43	31	75	90	47	38	69	68
Area (HEP)	14	19	30	15	26	34	41	32	22	26	30	36	15
Aysymetry *	1.3	1.3	1.1	1.3	1.2	2.1	2.0	1.3	1.3	2.1	1.7	2.1	1.1
Riffle Spacing (m)	315		112			480					340		
Channel Widths)	9.1		3.1			11.0					5.1		

* Asymmetry Index after (Milne 1982b): 1.00 = symmetrical x-sect

The values for the change in channel capacity are well below the values recorded by Petts (1979) for the River Rede. The Rede exhibits an increase in channel capacity immediately below Catcleugh reservoir of 60%, whilst, within the first 4 km downstream of this point, channel capacity has reduced by approximately 50% over a period of 72 years. The average rate of reduction in channel capacity on the River Rede is approximately 0.69% pa for the first four km downstream from the dam site, and 0.34% pa for the remaining 40km downstream. These figures compare to an average rate of reduction in channel capacity of 0.28% pa and 0.19% pa for the equivalent reaches on the North Tyne. The process of capacity reduction is therefore approximately half as rapid as that operating on the Rede, although the percentage of catchment impounded is much greater on the North Tyne. Four factors are likely to be responsible for the apparent lower rate of channel change on the North Tyne: first, the Rede is a smaller channel, conveying a higher fine sediment load than the North Tyne (Hall 1964); second, the Rede was extensively dredged for the War Agricultural Drainage campaign which destabilised the banks; third, the estimation of capacity reduction in the Rede is based on regional regression curves of channel capacity vs catchment area; and fourth, the North Tyne experiences hydropower regulation which clearly limits the colonisation of riparian vegetation, and throughputs fine sediment more efficiently than the Rede. Nevertheless, if the current rate of reduction continues, then the channel capacity of the North Tyne may be reduced by between 19% and 28% in 100 years, assuming a linear model.

The mechanism of channel capacity reduction in the North Tyne is similar to that described for other UK regulated gravel bed rivers, namely by the primary reduction in width due to berm development. However, this scenario is particularly evident in pools on the North Tyne, the riffles generally experiencing a net scour of the bed. This contrasts other UK studies which have tended to concentrate on regression analysis space-for-time-substitution, centred on riffle sites (Petts 1979). Correspondingly, a further divergence from the situation on the River Rede is a general (though not exclusive) increase in capacity due to the degradation of riffle beds. This will be investigated further within this dissertation.

The conclusions from the morphological survey of the North Tyne suggest that since regulation, active gravel bars have been stabilised by riparian vegetation, and berms have developed at points along the channel at least 18 km downstream of the dam, and particularly in pool-tails. Channel capacity has decreased in some reaches at a rate of only half that of a neighbouring regulated river system, whilst riffles and pool-heads have increased in capacity through bed degradation. Tributary confluence bars have decreased channel capacity downstream of all tributary junctions for 20 km downstream of the dam site, and pose an flood defence engineering hazard in one case.

The riffle-pool morphology seems to be unrelated to gross channel geometry, but rather responds to local changes in the sediment transport system through time. Nevertheless, the average spacing of riffles is within typical values expected for gravel bed rivers in the region.

Section 4.8 The morphology of the three main study sites

Having examined the morphology of the North Tyne, it is necessary to define the morphology of the three main process study sites at Smales (SMR/SMP), Tarset (TR1/TP1/TO2/TR2) and Newton (NR1/NPH/NMP/NPT/NR2). The channel morphology of each site is depicted in Figures 4.8a - c and individual cross-sections are given in Appendix A.; the cross-section geometries are given in Table 4.6.

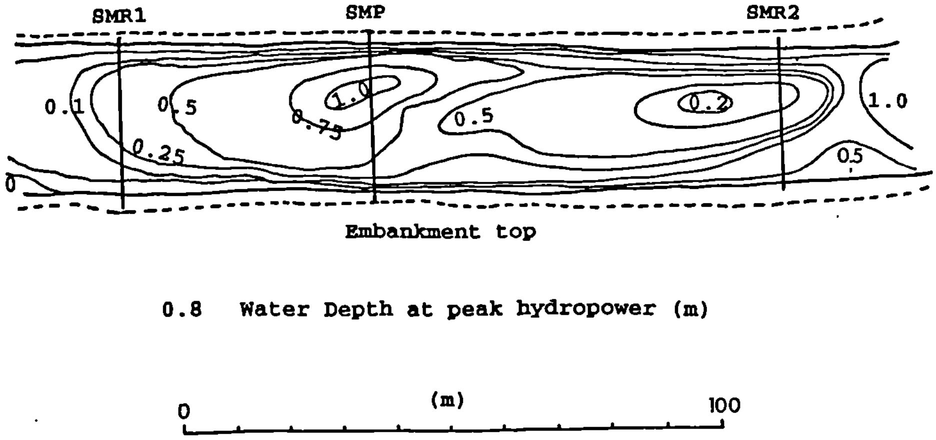
The Smales site is characterised by a relatively short pool, narrow channel, and symmetrical section in both riffle and pool (Appendix A, Photo 4d). This site is upstream of significant tributary inputs and correspondingly has a discharge regime dominated by regulation. Flow in the pool is on average 39% deeper than the upstream riffle at peak hydropower discharge, whilst flow width is equal between riffle and pool. A gravel berm exists within the right hand reach of the mid-pool-pool-tail, which increases in topographic expression downstream. The channel throughout the sequence is embanked up to the bank edge, which locally increases bankfull flow depths (Figure 4.8a, Photo 4d-e).

The Tarset site represents the transition between the dominantly regulated reach of the North Tyne, and the reach downstream of the Tarset and Chirdon Burns, which experience significant unregulated flood events. In addition, this site experiences sediment supply from the two tributaries, which deposit locally as bars (Figure 4.8b,

Figure 4.8 Morphological maps of the three main monitoring sites.

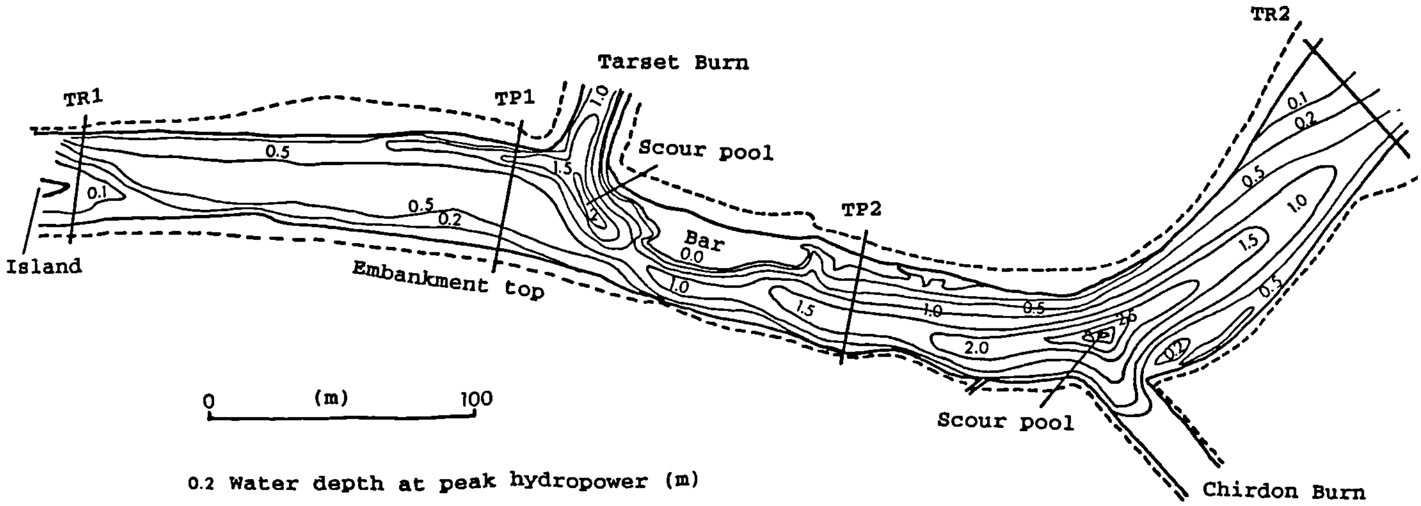
A

The morphology of the Smales riffle-pool-riffle sequence



B

The morphology of the Tarset riffle-pool-riffle sequence



C

The morphology of the Newton riffle-pool-riffle sequence

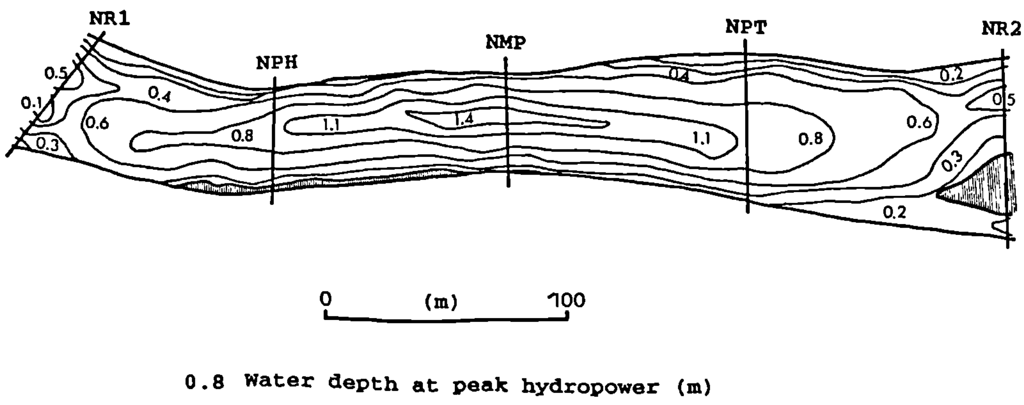


Photo 4D/E: General view of the Smales riffle-pool site and SMR1 cross section.

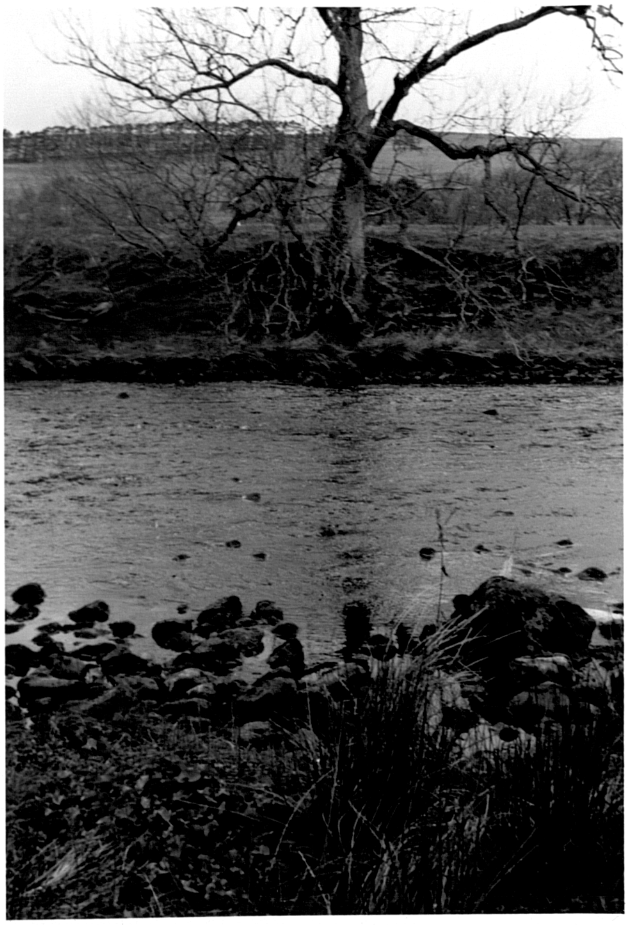
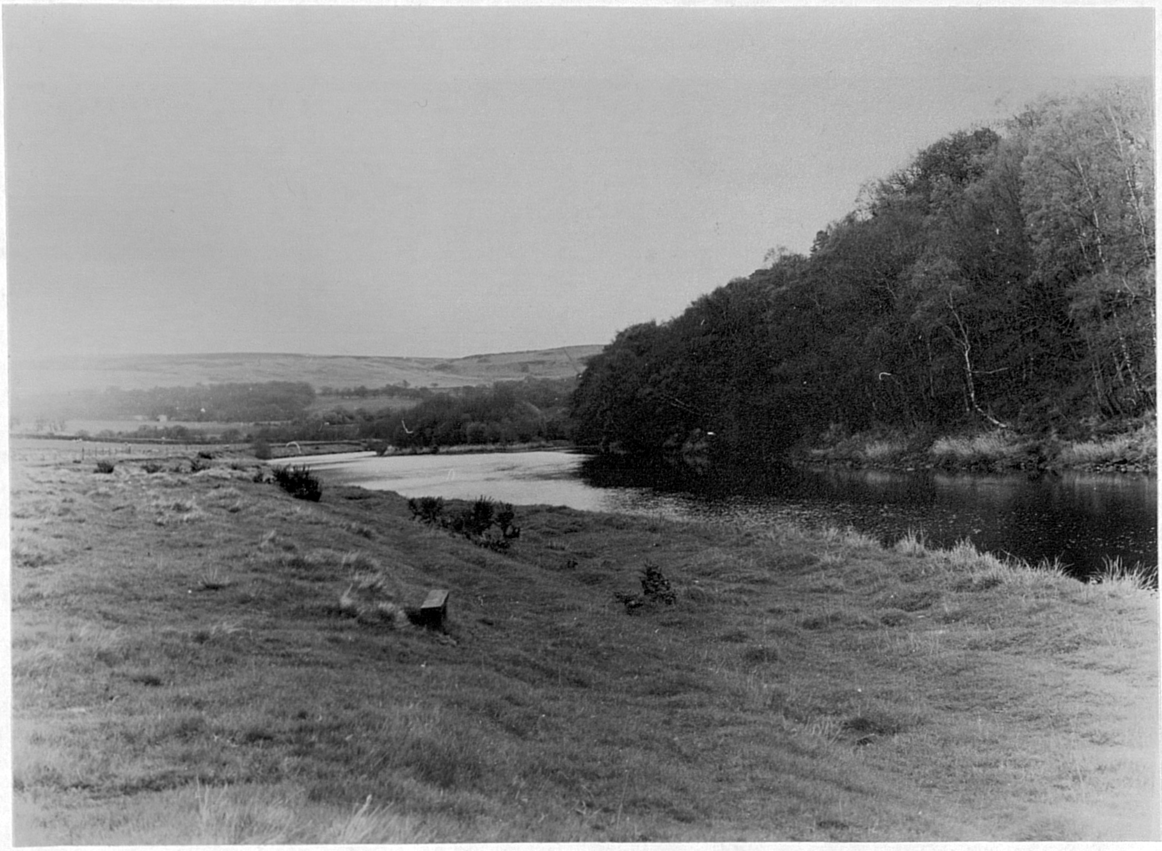


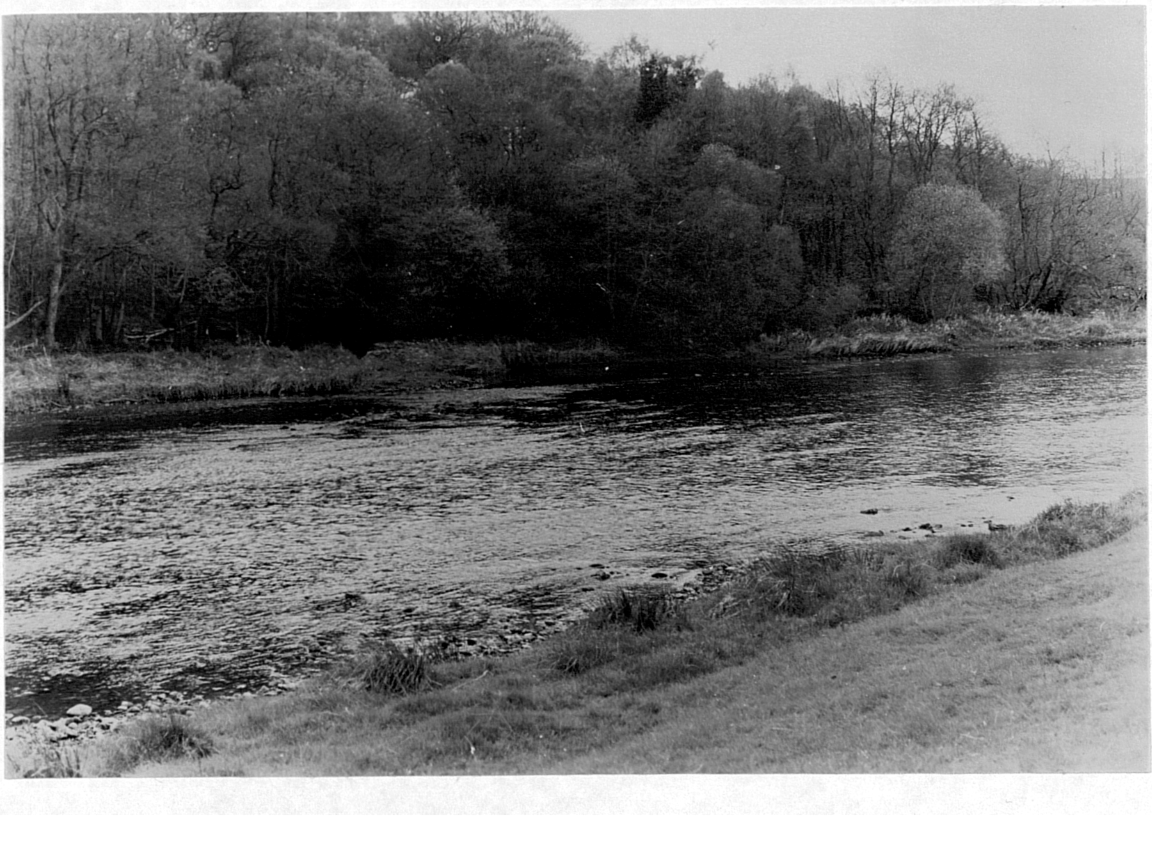
Photo 4f). The morphology of this reach is necessarily complicated, with typical scour holes and separation zone bars associated with the tributary junctions (Best 1986; 1987). An island affects the flow pattern over the upstream riffle (TR1) (Photo 4g), whilst the presence of a large separation bar causes a backwater effect within the upstream pool (TP1). Downstream of the Tarset Burn junction, flow is constricted through a narrow channel, with a corresponding increase in depth within the downstream pool (TP2). Rip-rap on the right bank prevents channel widening to accommodate the increased discharge. Downstream of the rip-rap, the channel widens by 57%. Within this section, the discharge is again increased by the entry of the Chirdon Burn. The scour hole at the mouth of the Chirdon Burn locally reaches 3.6m at compensation flow levels. The sediments from the Chirdon Burn are deposited as an incipient bar immediately downstream against the right bank. Flow patterns are constrained to the left bank by the discharge from the Chirdon Burn, and therefore no point bar develops on the left bank curve. Cross section asymmetry is locally accentuated by the gravel bars and scour pools; however, riffles remain consistently symmetrical (Appendix A). The TP1, upstream of the Tarset Burn junction, exhibits a progressive shallowing towards the right bank; this marks the presence of a shallow gravel bank. Flow within TP2 is 78.5% deeper than over TR2 at peak hydropower, and 43.5% deeper in TP1 than in TR1. During hydropower discharges, flow backs up both tributaries, locally increasing flow depths by 0.2m some 25m upstream. Both sides of the channel have been embanked, locally increasing the bankfull flow depths by approximately 1.0m (Table 4.6).

The Newton site is depicted in Figure 4.8c and Photos 4h - i. This riffle-pool-riffle sequence is confined by a rock bluff on the right bank, but is not embanked along the left bank. The morphology of this riffle-pool-riffle sequence is similar to the general model discussed above, with a narrow pool-head and mid-pool, and wider pool-tail and riffles. The pool (locally named the Tick Tock pool) is asymmetrical, particularly in the pool-head and pool-tail. Symmetry is restored in the mid-pool and riffle sections. The left hand side of the pool is characterised by a gravel bank, which extends throughout the pool-head, dissipating as a feature in the pool-tail. An emergent bar, together with a small tributary confluence bar, channels flow into a deep scour pool downstream of NR1. This initiates the asymmetry in association with deeper flow on the left side of the riffle which directs the current into the deep pool trench. The pool narrows towards the mid-pool and widens by 47% to the pool-tail as the flow depth decreases up to NR2. The

Photo 4F/G: Tarset confluence bar and Tarset riffle 1 with Island.

Photo 4H/I: Newton pool looking downstream to NR2 and upstream to NR1.





right hand side of the channel, although deeper, shallows towards the island (formerly an active bar). The flow bifurcates around the island, with the dominant channel associated with the left bank NR2. The presence of the island funnels 80% of hydropower flows through a channel only 64% as wide as the upstream pool-tail; correspondingly the riffle experiences rapid velocities. Flow depths in the mid-pool at peak hydropower discharge are 45-49% deeper than the associated riffles.

The channel morphology of the three main sites described above will be refered to throughout the following Chapters.

Chapter 5

The sedimentology of riffle-pool sequences and the changes resulting since the construction of Kielder reservoir.

The character of a given grainsize population relates to the source of the sediment, the transport processes, lithology (through rates of attrition and fracturing), position in the river system and sampling technique or error (Ibbeken 1992). The sediments in the bed of a river generate the morphology of the channel through interaction with the flow field, which in turn supplies the material for channel evolution downstream. In gravel-bed rivers, the bed morphology is constructed from the coarser elements of the sediment population that are moved infrequently, and for relatively short distances (Leopold 1992). The total sediment yield (but not the morphology) of gravel-bed rivers is dominated by fine sediment transport, and in particular suspended sediments (Newson 1986; Sear and Newson 1991). Given the interaction between the sediment and discharge regime of a river, it is the sediments that can be anticipated to exhibit a rapid reaction time to an alteration in the extrinsic hydrological conditions. The response of the sediments of some gravel-bed rivers to the imposition of river regulation has already been discussed (Chapter 1).

5.1 The sedimentology of gravel-bed rivers

The grainsize populations of gravel-bed rivers are characteristically heterogeneous, involving sediment size ranges from 0.063 - 1000+ mm particles existing in different proportions, and varying in proportion, laterally, longitudinally, vertically and through time. Sampling procedures adopted for the definition of such sediments further add to the complexity, by favouring the collection of certain sized particles over others, and blurring the population characteristics through adherence to summary statistics (Milne 1982a; Moseley and Tindale 1985; Church et al 1987).

Despite this pessimistic outlook for sedimentary analysis, research has identified certain characteristics of gravel bed river sediments.

5.1.1 Sediment Populations: Modality

Carling and Reader (1982), and Klingeman and Emmett (1982), characterised gravel-bed grainsize populations on the basis of modality, such that some gravel-bed streams (or areas of a stream) exhibit unimodal or bi-modal distributions. Others have referred to a 'saddle' in the grainsize population generated by a paucity of particles within the size range 2-4 mm (Petts 1988a), 2-10mm (Church et al 1987; 1991), or 1-20 mm (Ibbeken 1992).

Carling and Reader (1982), and Church et al (1987), characterise bi-modal sediments in terms of two populations: a coarse framework of gravel and cobbles, and a finer matrix of sands and granules. Gravel beds can thus be defined in terms of the relative proportions of matrix and framework material. According to Pettijohn (1975), the framework gravels form a self supporting structure in which the amount of matrix material is determined by the porosity of the framework. Conversely, where matrix material exists in proportions > 30% by weight, the sediment is considered to be matrix supported, and the coarse framework particles do not touch. Fraser (1935) considers these sediments to be rare, and Carling and Reader (1982) suggest that they are only formed during conditions when the reduction in sediment transport is sudden. Conversely, these sediments can occur during conditions of high fines concentration, such as occur in debris flows or during locally catastrophic landslips directly into the channel (Harvey 1992). More recently Petts (1988), Petts and Thoms (1987), and Carling and Glaister (1988), have described local conditions whereby matrix supported gravels can occur as a result of the interaction of channel morphology, sediment supply and hydraulics. Petts (1988) describes the dominance of matrix fines in pool sediments downstream of tributary confluences in two regulated rivers, whilst Petts and Thoms (1987) record the downstream transition of a tributary confluence bar, from framework supported gravels at the bar head to matrix supported gravels at the bar tail. Ashworth et al (1992) identify a similar transition in medial bars, which they ascribe to the routing of fines around the bar head to be preferentially deposited in the bar tail. Nevertheless, the dominant gravel population of the Northern Pennine streams is characterised by framework supported gravels (Carling and Reader 1982).

The existence of a secondary mode in framework supported gravels has been attributed to the ingress of fines into a static bed (Carling and Reader 1982; Church et al 1987; Diplas and Parker 1992). The process of fines ingress will be described in more detail later in this dissertation, but the process itself is important for determining the texture of a gravel-bed. Church et al (1987) describe two textural states of framework supported gravels: a fines-infilled framework with a censored surface, and a framework of coarse particles with only a matrix-filled surface. The former condition will be examined in more detail below, whilst the latter, "filled gravel", presumably occurs where high fines concentrations coincide with relatively tranquil flow conditions over a static gravel framework.

Ibbeken (1992) has recently described the existence of a secondary fine mode in gravel samples in terms of the mixing of two discrete sediment populations, a coarse gravel population, and a fine sand population. The two populations are derived independently, with the gravel fraction preserving the sample population of the weathered source rock, whilst the sand fraction is derived from the attrition of coarse bed sediment during floods. The paucity of the coarse sand-granules is a function of the efficiency of the attrition process at these sizes. The concept of the existence of two discrete sediment populations is in accord with the observations of bedload transport, which consistently reveal a finer grainsize population than the river bed, whilst the morphology of the river bed is determined by a coarser gravel/cobble population (Leopold 1992).

5.1.2 Vertical stratigraphy: Armouring, Paving or Censoring?

The grainsize population of gravel-bed rivers is often characterised by a vertical textural change, predominantly defined by a coarse surface layer of only one particle thickness overlying a matrix filled framework (Church et al 1987). The nature of the surface sediment is particularly important with respect to sediment transport, since it is the particle size of surface sediments which determines the grain resistance, and thus grain shear stress, and the pivoting angle, and thus the limit of the entrainment threshold.

The nature of coarse surface layers is complex (Gomez 1984), and their definition is again dependent to some extent on the method of sampling (Church et al 1987). Nevertheless, two basic surfaces are documented: armoured (censored) surfaces, and paved surfaces (Bray and Church 1980). Armoured surfaces do not exhibit manganese staining, are still active contributors to the bedload of the channel, and result from the winnowing of finer particles from the surface "during and after periods of motion" (Bray and Church 1980). Paved beds are characteristically immobile for long time periods, are consequently dark stained due to manganese scavenging, have strongly interlocked particles and result from the progressive removal of fines from a static bed during low frequency large floods. Paved beds are also a characteristic of channels degrading into material containing a high proportion of large immobile particles, (Bray and Church 1980). It should be noted that the dark staining of paved beds below dams may be accentuated by the release of relatively anoxic water from the reservoir (Haile et al 1989). The extent to which the two surfaces relate to two different processes has been questioned by Gomez (1984), who prefers to term all segregated surfaces as armours. However, three process-based definitions exist that suggest that the use of a collective term is oversimplified.

Church et al (1987) discriminate on the basis of the literature between winnowed or censored surface layers and surface layers that result from the processes of equilibrium transport (Parker and Klingeman 1982; Andrews and Parker 1987). The censoring of surface layers (Carling and Reader 1982) results from either vertical or downstream winnowing (or both). Gomez (1984) suggests that vertical winnowing can only occur when the gravel surface particles are in motion, whilst downstream winnowing of fines occurs when the larger particles are static. However, research into the process of infiltration suggests that vertical winnowing can equally occur when the bed is static, and particularly in regions of locally high velocity (Frostick et al 1984; Diplas and Parker 1992).

The concept of equilibrium transport is based on the observations from some river systems that particles of varying sizes are equally mobile. Equal Mobility during floods is explained by the concept of a mobile pavement (armour), which preserves the presence of coarse particles in the bedload population, whilst enabling fine subsurface sediment to enter the bedload through a process of vertical exchange. As the shear stress increases during a flood so the presence of coarser particles at the surface is required to maintain equal mobility. The coarse armour is therefore present throughout the history of bedload movement (Andrews and Parker 1987). Quite how this latter process operates has not been conclusively demonstrated (Church 1987).

More recently, armouring has been shown to be variable within a channel, depending either on the sediment supply (armouring occurs in conditions of supply limitation - Deitrich et al 1990), or as a result of the variable spatial pattern of shear stress (armouring is at a maximum, defined by D50surface/D50subsurface, in regions of high shear stress - Lisle and Madej 1992). In the case of a reduction in sediment supply, the channel bed coarsens as particles still competent to be transported are removed from the surface; this situation is the characteristic of armouring below dams (Chapter 1).

The difference between armour or paved layers has been quantified on the basis of sedimentology. Censored armour layers are characterised by possessing the same grainsize composition as the subsurface gravels when truncated of their matrix. Pavements, or armours developed through a process of equilibrium transport (vertical winnowing during bed motion), possess a surface layer which is coarser than the subsurface when truncated of matrix fines (Bray and Church 1980; Church et al 1987).

The effect of the armour layer is to protect subsurface fines from erosion, and to result in near equal mobility of coarse and fine sediments in some rivers (Parker and Klingeman 1982). This latter effect has been questioned recently, and much more work is required to investigate the role of coarse surface layers on sediment transport (Ashworth and Ferguson 1989). The problem remains that observation of the armour layer is made after a flood event, whilst its behaviour during a flood can only be inferred from bedload transport rates.

Bluck (1987) reports on another role of the surface armour, which operates in association with bed morphology. In this mechanism, a coarse surface layer acts as a filter which accepts or rejects under or oversized particles passing over it. This is based on the availability of given pockets within the surface framework. Ashworth et al (1992) describe the role of a coarse bar head in this process, whilst Lisle et al (1991) describe the function of the development of a coarse surface layer at bar heads in terms of the stabilising of alternate bars, and the sorting of bedload through a reach.

5.1.3 The sedimentology of riffle-pool sequences

The discrimination of riffle and pools on the basis of morphology alone is insufficient to fully describe their characteristics. An important component of the riffle-pool sequence (and one that is yet to be satisfactorily confirmed) is the apparent differences in sediment populations between riffles and pools. The discrimination of riffles from pools on the basis of a sedimentological distinction implies a difference in their sediment transport characteristics, and must therefore be of interest to this study. In addition, one of the first order effects of river regulation is a change in the sedimentological character of the stream bed (Petts 1984).

The identification of the sedimentological differences between riffles and pools was first alluded to by Wolman (1955). Wolman distinguished a dominantly coarser sediment population associated with riffles by using the method of numerical sampling of particles from the surface of a stream (as opposed to sampling on the basis of weight - Wolman 1954). However, Hack (1957) using a similar technique, found that bed material was not ordinarily affected by position with respect to riffles and pools, other than for the presence of a sand deposit in the pool-head. The presence of fines in the pool-head region was attributed to the winnowing of sediment from the upstream riffle during low flows (Hack 1957).

Despite the apparently conflicting evidence from grid sampling of surface sediments, the notion that sediments on riffles were coarser than on the pools was incorporated into contemporary models of riffle-pool sequences (Leopold et al 1964).

Confirmation that the observed surface sediment variations between riffles and pools also extended to the subsurface populations came with the investigations of Keller (1971). Keller cut trenches through both a riffle and pool section and sampled the sediments from the surface and subsurface layers. He concluded that the largest material in both surface and subsurface riffle sediments were larger than the largest material in the same regions within pools (Keller 1971; Keller and Melhorn 1978). It is important to note that in a review of 57 references concerning the riffle-pool sequence, 19 refer in some way to the relative bed material size differences between riffles and pools, in which three make the point that the variation is statistically insignificant (Hack 1957; Milne 1982a; 1982b). In addition, only Keller (1971) and Clifford (1990) describe the subsurface characteristics of pool sediments, and yet the tendency for riffle subsurface sediments to be regarded as coarser than pools has been accepted in the scientific literature as a fundamental feature of the riffle-pool sequence (Richards 1976; Lisle 1979; Knighton 1984; Keller and Florsheim in prep). Richards (1976; 1982) raises the question of the significance of the sedimentological variations between pool and riffle, based on surface sampling of sediments alone, and concludes that whilst a statistically significant difference between grainsize populations can be proven, it is not always evident and may in fact be largely due to the presence of surface fines in the pools. This point is expanded by Lisle (1979), who describes the movement of large sand sheets over an otherwise static pool bed.

Detailed investigations of the riffle-pool sedimentology became available through the work on the Cattaragus Creek (Hirsch and Abrahams 1981) and the Kingledores Burn by Ashmore (1977) and Milne (1982a). Using detailed surface grain size sampling designed to maximise the topographical distinction of the riffle-pool sequence, Hirsch and Abrahams (1981) attempted to differentiate riffle and pool sediments on the basis of the mean, sorting, skewness, kurtosis and particle shape. Sediments in riffles consistently exhibited larger means, greater skewness and kurtosis and were better sorted than adjacent pool sediments. In addition, there was evidence to suggest that pools contained more spherical particles than riffles, although the authors discounted this as a function of some shape-dependent sediment sorting process, in favour of natural diminution resulting from higher percentages of smaller particles in the pools.

Using comparative techniques (surface grid sampling) on the same stream, Ashmore (1977) identified statistically significant differences between coarser riffle surface sediments (> D_{50}, better sorting than pools) and finer pools, whilst Milne (1982a) commented on the lack of any statistically significant relationship between bed topography and particle size.

Milne concluded from an analysis of the mean, D_{50}, sorting, skewness and kurtosis of the sediment populations that, although riffles exhibited a tendency to contain coarser surface particles, by far the most apparent discrimination was a lateral fining within pools. Furthermore, Milne stated that all previous surface sampling techniques which did not account for the lateral fining of pools into bars would generate artificial fining characteristics for pools. Pool sediments (at least within the Kingledores Burn) were of similar sediment populations as riffles and in some cases were coarser than riffles due to the presence of large residual particles (Milne 1982a). Subsequently, Milne concluded that channel planform exerted a morphological control on sediment sorting via lateral fining, such that the tighter the bend curvature, the greater the lateral fining within pool-bars, and therefore the greater the longitudinal distinction between riffles and pools (Milne 1982b).

Despite this caution, oft-cited studies have continued to identify sedimentological differences between riffles and pools on the basis of cross-sectional surface sampling, with no regard for lateral differentiation (Estep and Beschta 1985; Campbell and Sidle 1985; Ashworth 1987; Noble 1989).

In the absence of further information on the subsurface sedimentology of pools and riffles, it is not possible to comment objectively on the development of the armour layer. However, recent studies of surface sedimentology in degrading and aggrading reaches of the Redwood Creek suggest that riffles possess higher armour ratios than pools, which are characterised by anti-armour, due to the presence of ephemeral sand sheets (Lisle and Madej 1992). The position of coarser gravels, and higher armour ratios, was related to locally high shear stress. Intuitively, riffles would be expected to exhibit higher armour ratios if the armour was caused by selective winnowing. Conversely, evidence of sand deposition in pools, and the preferentially high infiltration of fines into pool bed sediments (Diplas and Parker 1992), would suggest that finer subsurface sediments could increase armour ratios in pools. This is discussed further in this section.

The objective discrimination of sedimentological differences between riffles and pools should incorporate some reference to the shape of the particles present in both grainsize populations. However, the utility of shape depend, first on there being a sufficient differentiation of shape within a given sediment to facilitate identification of a trend, and secondly confidence that the variation in particle shape is not due to size variation or an inherent fracturing property of the sediment lithology (Hirsch and Abrahams 1981). In two studies that specifically investigate shape variation between riffle and pool sediment populations, neither could identify a statistically significant trend, although both showed some evidence for fewer spherical particles to be found on riffles (Hirsch and Abrahams

1981; Clifford 1990). Hirsch and Abrahams found, through multiple regression analysis on particle shape in relation to particle size and location (riffle or pool), that particle shape was more related to particle size, and not at all related to location. Clifford (1990) describes an intuitive reason for particle sorting by shape in riffle-pool sequences on the basis of differential bed structuring, (see Chapter 6). However, despite analysis of nine paired riffle-pool sequences, no significant relationship existed, and Clifford was forced to suggest that the process was complex and locally site dependent. Clifford (1990; in press) cautioned the use of the available shape indices, suggesting that failure to define a difference between riffles and pools in terms of particle shape may be a function of the indices used to define shape to characterise some fundamental of particle form.

Recalling the debate in Chapter 4 regarding the morphological structure of the riffle-pool sequence, Richards (1982) identifies riffles as the lowest point of the leading edge of a single bar form. Riffles are therefore "plinths" of coarser sediment in a "morphologically constant unit" comprising a pool-bar-riffle (Richards 1982). Conceptually this builds on the study of channel adjustment from the River Ystwyth identified by Lewin (1976).

Thompson (1986) also considers riffles and pools to be part of one sedimentary unit, in which the riffle is analogous to a bar-head, and pools represent the bar-tail. Exposed sedimentary units, particularly point bars, have a coarse bar-head attached to a coarse riffle (part of the same bar-head), whereas the finer bar-tail is part of the pool[bar-tail]. Correspondingly, pools would be expected to exhibit finer, poorly-sorted sediments than riffles. However, as Milne (1982a) discusses, pools often contain large residual particles and a grainsize population similar to riffles, whereas bars contain much finer sediment populations, and are the most distinctive sedimentary units in a riffle-bar-pool sequence.

Whilst morphologically it is futile to separate the individual elements of a riffle-bar-pool sequence, except at low flows when hydraulically they are distinct, sedimentologically they can be separated at least into bars and riffle-pools. The problem is one of a synergistic system (Haken and Weimer 1988) whereby interaction of a number of subsytems complicates the overall picture. Clearly, development of the riffle-bar-pool morphology generates an environment for creating a distinctive sedimentology which, like much of the riffle-pool system, is most obviously expressed at low discharges. Further research in detail is required to characterise the sedimentology of the riffle-pool sequence, particularly regarding the subsurface variations. As Church et al (1987) lament, the need for a sampler capable of operating in deep water, whilst preserving fines, is a necessary prerequisite for the successful discrimination of pool sedimentology.

5.2 Methodology

The methodology by which sediments in the North Tyne were sampled was largely conditioned by previous sediment surveys (Hall 1964; Carling 1979), but also by the difficulties in obtaining reliable samples from deep, extensive pools. The initial strategy was based on the re-survey of previous sedimentological databases to reveal the impacts of river regulation (if any). Subsequently, a further, more detailed survey of riffle and pool surface and subsurface sediments was conducted to reveal the sedimentological differences between these morphologies in the hope of elucidating characteristic trends in sediment sorting, which could be used to infer sediment transport. In addition, the choice of sampling sites was designed to reveal any progressive changes downstream of the reservoir, which could be attributed to regulation. Thus sites were sampled close to the dam site and below the junction of the Tarset and Chirdon Burns, where sediment transport was still influenced by unregulated floods. Further sediment sampling was conducted in unregulated tributaries as a control against which the sediment characteristics of the regulated North Tyne could be assessed.

A discussion of the sampling methodology naturally falls into three groupings:

1. Surface grid sampling of gravel bar sediments: Hall (1964) Re-survey.

2. Bulk sediment sampling of selected salmonid spawning riffles: Carling (1979) Re-survey.

3. Surface and Subsurface sediment sampling of riffles and pools.

5.2.1 The re-survey of Bar surface sediments after D.G.Hall (1964).

In the late 1950's, a survey of bar surface sediments was conducted as part of a PhD in the Department of Civil Engineering by the late David Hall. The object at that time was to characterise the sediment load of the Tyne Basin, in terms of gross annual yield, for which a measure of bank erosion rates, average particle volume and the rate of downstream diminution of particles was investigated (Hall 1964). Hall conducted a survey for particle volume and roundness at a total of 47 individual bar sites within the Tyne catchment, concentrating on the North Tyne, South Tyne, Derwent and Allen river systems. Bars were selected at sites that were spaced reasonably equally along the course of each river channel, and which were composed of regularly mobilised sediment. This latter criterion was realised by the colour of the sediments, and was hoped to therefore represent the bed load of the stream.

The technique employed was an areal sample of the surface sediments as delineated by the random casting of a 2ft by 2ft grid (actually only two sides of the grid) onto the requisite bar. All the surface stones within this grid were collected and their A-B-C axis noted. Sample sizes ranged from 60 - 100 stones (Hall 1964). Particle volume and roundness were estimated from the A-B-C axis and reference to the chart of Powers (1953). The values were then plotted against distance downstream, and a regression curve derived for volume and roundness versus distance downstream (Hall 1964).

A resurvey of Hall's sites was conducted in 1988 for sites on the North and South Tyne. Information for the latter was collected as part of a carefully supervised undergraduate research training course within the department of Geography at Newcastle University. This information consisted of the extrapolated B-axis data for 11 of Hall's sites, and was included as a guide to the general pattern within the Tyne catchment against which significant changes on the North Tyne could be judged.

The technique adopted was to randomly sample 100 stones according to the technique outlined by Wolman (1954), and tested for sampling accuracy by Hey and Thorne (1983), and Church et al (1987). Whilst this technique differs from Hall's sampling methodology in terms of the spatial extent of the areal sample, it was considered to be superior as a technique for quantifying the bar sedimentology, and more likely to include the region of bar sampled by Hall. By contrast, the use of a discrete sample area would be more likely to incorporate sampling errors with respect to Hall as a result of the grainsize variation between different facies present on exposed bar surfaces (Church et al 1987).

The identification of individual bar units from 1958 was facilitated by the use of an Ordnance Survey Map, 1:10560 resurveyed in 1956. By following the development of the individual bars through subsequent aerial photographs from 1978-1983, it was possible to pin-point the exact bar sampled by Hall. Several sites upstream of the present dam site are now submerged by Kielder Water; all the sites are illustrated in Figure 5.1.

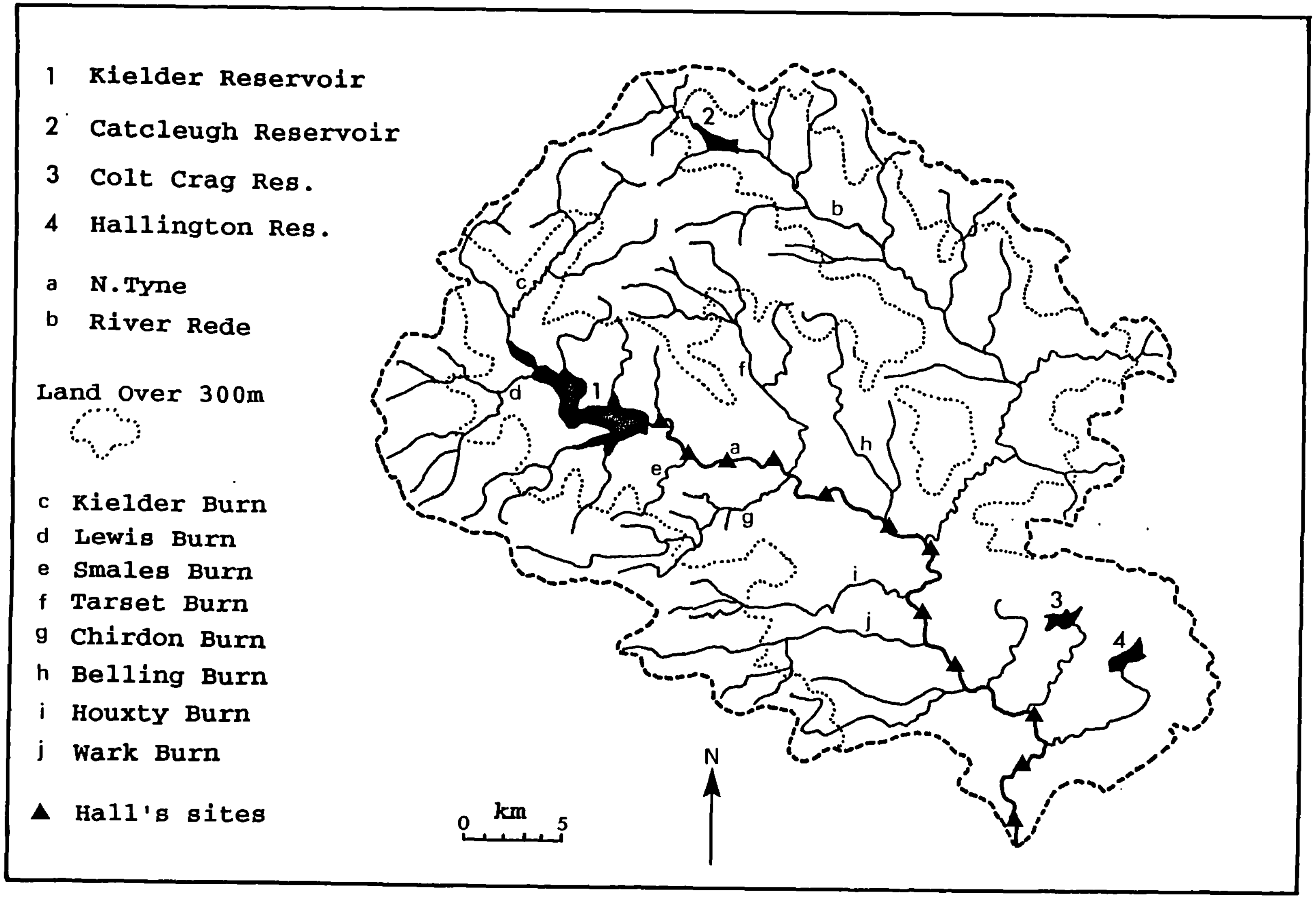
Particle volume was calculated from the A-B-C axis, and roundness estimated according to Powers (1953). In addition Krumbeim's sphericity and Zingg particle shape was also calculated for the North Tyne sites.

In addition to particle volume, an indication of the particle B-axis was determined, in order to assess the size change from 1958-1988. This was achieved by creating a least squares regression curve for contemporary sites between particle volume (cm^2) and B-axis (mm). The resulting relationships yielded r^2 values in the range 0.62-0.75 with a mean of 0.71; all were significant at the 99.9% confidence interval. The error within the sampling procedure was estimated for each Bar according to the method of Hey and Thorne (1983) where the standard error of the mean d (in log units) is defined by:

$$d = ts/ n \quad \text{Equation 5.1}$$

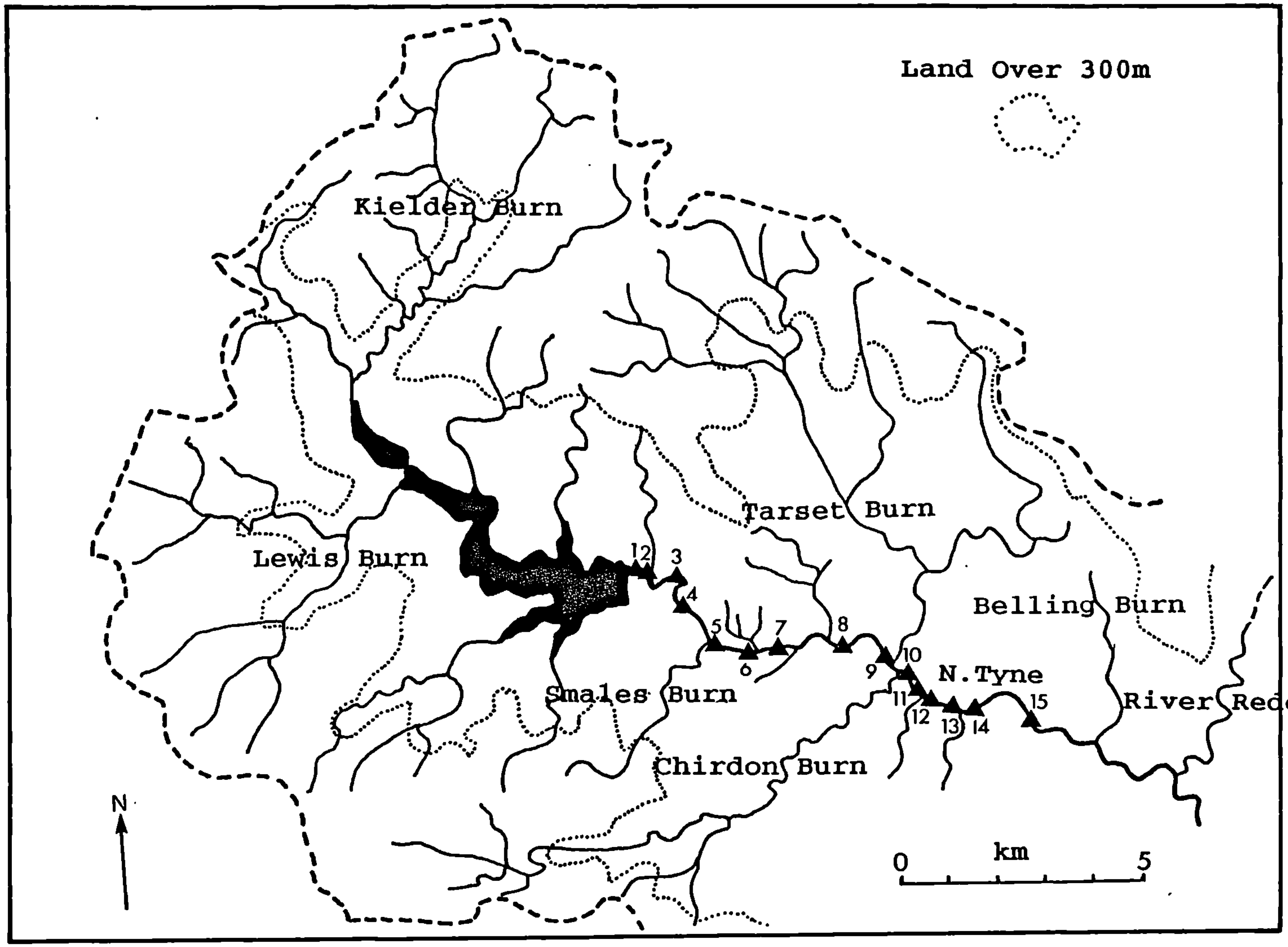
where n is the number of stones sampled, t is the value of student t for n-1 degrees of freedom at the chosen confidence interval (95% in this study, and most others) and s is the standard deviation of the population in log units. The error values for the bar sediments ranged from 17.1-22%, with a mean of 18.6%. Correspondingly, for an average D_{50} of 43mm the expected error will be +/- 7.9mm or a range of 35-50.9mm. Most fluvial gravels have a standard deviation between 0.1-0.45; therefore, by rearranging equation 5.1 in terms of n, for a 1% error and a standard deviation of 0.356 (the average for the North Tyne surface sediments), the number of stones required to be sampled would equal 1,467. This is prohibitively time-consuming over 20 sites and was

5.1a Sampling sites for bar surface sediments (after Hall 1964)



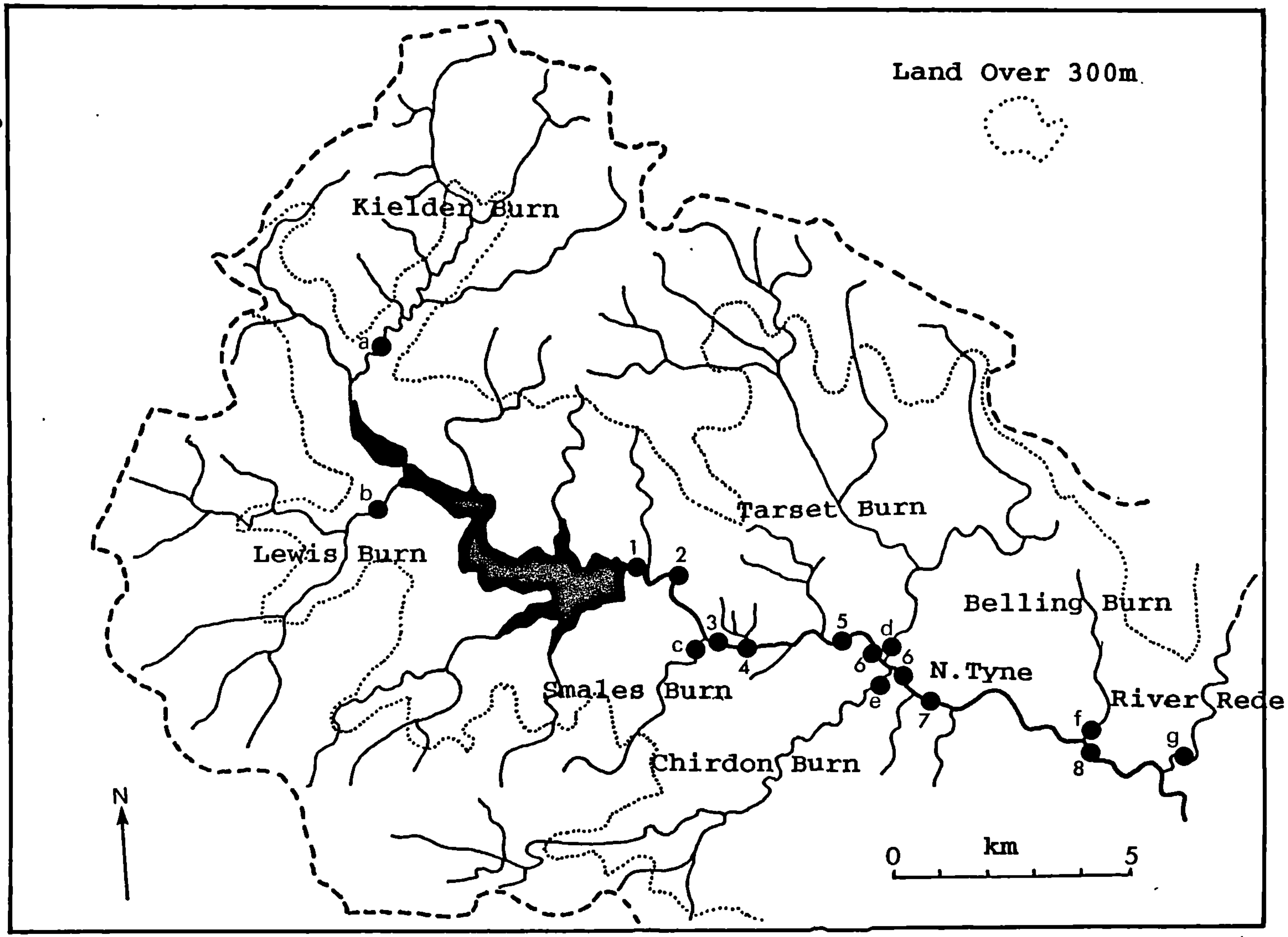
5.1b Sampling sites for riffle bulk sediments (after Carling 1979).

1 YM1
2 YM2
3 FM
4 FB
5 SM
6 RS
7 LL
8 TFB
9 TB
10 SND
11 HCAR
12 NEWT
13 CHAR
14 HM
15 DUNT



5.1c Sampling sites for riffle and pool surface and sub-surface sediments in the North Tyne catchment.

1 Yarrow R/P
2 Falstone R/P
3 Smales R–P–R
4 Ridley Stokoe R/P
5 Hott Farm R/P
6 Tarset R–P–P–R
7 Newton R–P–R
8 Bellingham R/P



not carried out. Subsequent interpretation of the grainsize changes were viewed in the light of the expected error.

5.2.2 The resurvey of Bulk riffle sediments after Carling, (1979).

Prior to dam closure in 1980, but whilst construction was still in progress, the Freshwater Biological Association (FBA) conducted a sedimentological, bathymetric and hydraulic assessment of the North Tyne salmonid spawning grounds for up to 15km downstream of the dam site (Carling 1979). The results of the bathymetric survey are discussed in Chapters 4 and 13.

Bulk sediment samples were collected using a cut down Oil drum, 0.43m high by 0.56m diameter. The principle of such a sampler is analogous to the "cookie cutter" technique described by Klingeman and Emmett (1982), and enables the sampling of bulk sediments in flowing water. Although fines are lost, the amount of loss is considered negligible. The sampling strategy involved the collection of a single bulk sample from each of 15 spawning riffles, chosen according to spawning suitability and proximity to the dam site (Carling 1979). In addition, larger multiple bulk samples were taken from four of the riffles (Falstone meander, Ridley Stokoe, Newton, Charlton). Figure 5.1b depicts the FBA sediment sampling sites.

The original sedimentological data (kindly supplied by Dr Paul Carling) was used to calculate grainsize populations on a frequency by weight basis. The mean sample weight ranged from 9,895-34,377g, with a mean of 15,939g. Church et al (1987) provide a calibration curve for determining the sample weight required for a given grainsize, based on the largest particle occupying no more than 5% of the total sample weight. By reversing this process, and applying it to the FBA samples, it provides an estimate of the largest reliably sampled particle (Church et al 1987; Moseley and Tindale 1985). On this basis, the average sample size yields a maximum reliably sampled particle size of 84mm at 5% of sample weight. Therefore, for meaningful statistical analysis, the samples should be truncated at 84mm. Particles were allocated to phi classes, as these approximate to the BS sizes. Accordingly, an 84mm particle size falls into the 64mm class when sieved at 1/2 phi intervals.

Of the four multiple sampled sites, only the Ridley Stokoe riffle possessed information on the exact siting of the samples;. the three other sites had only the siting of single samples. Consideration of the area of the spawning riffles and the vegetation growth over many of the bars resulted in a decision to use only the positively identified single samples, rather than attempt to multiple sample incorrectly. In addition, the FBA "Newton" riffle had since been extensively modified by engineering dredging (for bank protection), and was not sampled for gravel (NWA pers comm).

The 1988 resurvey of the FBA sites used the same technique together with original field notes (where possible), to locate gravel sampling sites to within 4-10 m^2 of the original. The sample weights ranged from 16,341-49,223g with a mean of 23,111g which yields an average value for the maximum reliably sampled particle of 95mm. Despite this, for the comparison between 1978 and 1988 samples, these were also truncated at 64mm.

In addition to the bulk samples, a value for the armour layer of the Falstone Meander riffle (FBA Riffle 1 in Carling 1979), was available for comparison. The armour layer grainsize population was determined by removal of surface particles from within the area of the oil drum. This was replicated at the positively identified site.

5.2.3 Characterising riffle and pool surface and sub-surface sedimentology.

In order to characterise the sediment grainsize population in riffles and pools, nine riffles and seven pools were sampled in the North Tyne, together with five riffles and five pools from the lower reaches of five tributaries, (see Figure 5.1c). The latter were sampled close to their junction with the North Tyne, so as to compare with the regulated riffle-pool sedimentology.

Surface sampling was conducted according to the grid-by-number technique of Wolman (1954), which approximates to a sample by weight (Church et al 1987). This enabled the comparison of surface and subsurface sediment populations, which in turn can be used to elucidate the mode of armouring (see above).

Surface sampling of pools proved to be problematic on account of their depth and scale. To overcome the scale factor, surface sampling was conducted at a section located in the middle of the requisite pool. In addition, at five sites, surface samples of 50 stones were collected at the pool-head, mid-pool and pool-tail, and at the Tarset and Newton sites sections were sampled every 25m from riffle to riffle, in order to investigate intra-pool sedimentology. The collection of stones for sampling was facilitated by submergence "pearl fisher style" to a point on the bed demarcated by the position along a stretched tape measure (rope).

Equation 5.1 was applied to each sample, to estimate the percentage error expected for the determination of the sample mean. For the total samples, pools and riffles, the error ranged from 14.6-32.4 %, with a mean of 22.7 %. This equates to a variance about the mean of +/- 11mm for the average value of 48.7mm, based on the total samples. The variance for samples of 100 stones were examined for the bar sediments and for three riffle sediments, the calculated error about the mean was 18.7% and 20.5% respectively, which would equate to a variance of +/- 9.1-10.2mm for an average particle size of 48.7mm. The improvement of only 2-0.9mm was considered sufficiently insignificant to continue to sample for 50 stones.

Problems were experienced in obtaining reliable subsurface samples from the pools, primarily as a function of their depth, which mitigated against the efficient use of the "cookie cutter" technique of sampling whilst retaining fines. Instead, a modified surber sampler was constructed, which could be placed on the bed, and the sediment, plus fines, trapped within a mesh bag. The mesh bag was constructed of 0.063 mm nylon meshing, which retained all but the silt/clay fraction. Whilst this technique improved the efficiency of submerged sampling, it did not allay the problem of operating at depths of 1.0 + metres. At the time of sampling, the use of a freeze corer was investigated, but was vetoed on the grounds of finance. This technique is suitable for operation in conditions of submergence, but no information is available on the maximum depth to which it can be used (Carling and Reader 1982; Carling 1981; Petts 1988b). Nevertheless, the sampling process would have been considerably aided by this technique, had a freeze corer been available.

Bulk subsurface samples were made up from at least three smaller subsamples, located along the sections from which surface samples had been made. In this way, it was hoped to achieve a representative sample of the pool sediment population at that section which would incorporate transverse sediment sorting. Ideally, sampling for transverse sorting should be carried out, but the considerable problems associated with the data collection procedure mitigated against this option. Milne (1982) comments on the importance of lateral sorting within pool sediments (see above discussion), and distinguishes between bars and pools on the basis of sedimentology. Correspondingly, pool sediments collected in this study refer to samples collected from the river bed located in regions of the pool that are submerged at compensation flow and deemed to be pools.

Exposed surfaces at compensation flows were deemed to be bars, and were sampled separately from pools and riffles; however, the lack of any substantial exposed bar surfaces corresponding with pools sampled in this study precluded this caution. Information on bar sediments were collected from the resurvey of Hall's sites, and the sampling of three prominent tributary confluence bars at the junctions of the Smales Burn, Tarset Burn and River Rede.

A review of the literature during the course of the study initially indicated that particle shape had little effect on the transport distance of sediment (Melhand and Normann 1969; Carling 1987), and was secondary to particle size in discriminating between morphological elements within river channels, but rather exerted some influence on the initiation of motion, through its effect on pivoting angle (Li and Komar 1986). Furthermore, with the exception of Briggs (1984), the recent works on coarse gravel sampling have omitted references to particle shape (Moseley and Tindale 1985; Church et al 1987). With hindsight, this omission is largely a reflection of the state of the art knowledge with respect to bedload transport calculation, which is dominated by particle size related relationships (Church and Gomez 1989).

Correspondingly, particle shape was not examined in the detail which recent studies indicate it should be afforded (Clifford 1990). Nevertheless, the data collected for the Hall re-survey included values for A-B-C axis for nine bars, and further tests were conducted at six riffle-pool locations within the North Tyne. The data was converted into values of Krumbein sphericity, Cailleaux flatness, and the percentage of spheres, rods, blades and discs according to the classification of Zingg (Briggs 1984).

5.3 Results: Re-survey of bar sediments after D.G.Hall (1964).

The re-survey of bar sediments identified as equivalent to Hall's 1958 sites failed to identify any evidence of active reworking at sites upstream of the confluence with the River Rede. The bar sediments at sites between the dam site and the River Rede showed established vegetation, and a uniform dark manganese staining on the surface (and often underneath) of the particles which is indicative of static immobile sediments. In contrast, at sites below the River Rede, notably at Gold Island (GR861778), large areas of the gravel bars were the characteristic yellow-orange colour of freshly exposed *Fell* Sandstones. This was taken to indicate recent movement of the surface sediments. The contrast between the manganese and iron-oxide staining is notable in October in the freshly cut stream gravels associated with salmon redds, as well as after bed mobilising floods.

The re-survey was conducted in March 1988, which was characterised by a warm winter with little snow. The floods during the winter peaked between the 5th and 8th of January, with maximum discharges of 32.2 cumecs upstream of the Tarset/Chirdon Burn junctions, 74.1 cumecs downstream of the junction, and a maximum of 192 cumecs downstream of the confluence with the River Rede. The latter figure is approaching the bankfull discharge for the North Tyne downstream of the Rede. It is apparent from the

Table 5.1 Comparative datasets for bar surface sediments collected in 1958 (Hall 1964) and 1988.

North Tyne

Distance from Dam (km)	x̄ particle Vol (cm3)		x̄ particle B-axis (mm)		x̄ Powers Roundness	
	1958	1988	1958	1988	1958	1988
0.7	211	287	47.6	49.3	5.30	5.50
3.8	182	292	53.7	59.8	5.19	4.12
5.5	263	255	60.1	59.4	5.17	4.26
8.6	263	95	68.0	42.8	5.22	5.74
13.4	146	118	49.0	45.6	5.76	5.32
17.0	212	---	47.6	----	5.68	----
19.9	174	127	55.9	50.2	6.23	5.78
26.3	292	194	67.2	58.1	6.36	5.71
29.6	141	126	52.9	50.2	6.26	5.42
33.7	163	141	54.6	52.8	6.58	5.34
39.4	86	144	45.1	53.7	6.59	5.21
43.6	163	128	54.6	51.2	6.46	5.59

South Tyne

Distance Downstream (km)	x̄ particle B-Axis (mm)	
	1958	1988
5.4	75.2	95.3
8.1	79.0	64.0
11.6	78.1	105.3
16.8	93.4	100.0
20.8	82.0	125.0
24.8	74.8	130.0
31.2	73.7	75.7
37.0	73.0	56.7
43.4	72.0	87.7
49.0	71.5	125.0
55.1	68.0	90.0

differences between surface particle colouring that little bed mobilisation took place on the bars upstream of the Tarset/Chirdon junction with the North Tyne, and is a direct result of the flood retention capacity of the Kielder Reservoir.

Table 5.1 lists the data from the Hall re-survey for particle volume, extrapolated B-axis, and particle roundness for the North Tyne, together with values of extrapolated B-axis for the South Tyne re-survey conducted as part of an undergraduate research training project (Macklin pers comm). At site six on the North Tyne, a point bar opposite the town of Bellingham, no exposed gravel was evident, but instead, a vestige of point bar existed, which was covered in vegetated alluvium. Correspondingly, no gravel was sampled, and the site was considered to have undergone fining.

Two statistical tests were applied to the data contained in Table 5.1 - a Mann-Whitney U-test for determining the statistical significance of the magnitude of change between (in this case) two populations (1958 and 1988 values of particle volume, particle B-axis and particle roundness), and the Sign test, which indicates the statistical significance of the direction of change between two populations (Siegel 1956; Briggs 1984; Ebdon 1985). Each test was conducted by using the available Minitab statistical software. Both tests are non-parametric and therefore make no assumptions about population normality.

Table 5.2: Statistical significance tests for magnitude and direction of changes between bar surface sediments in the North Tyne and South Tyne.

North Tyne Results

Volume Changes 1958-1988

Mann-Whitney U-test:	NS at 95%
Sign Test :	NS at 95%

B-Axis Changes 1958-1988

Mann-Whitney U-test:	NS at 95%
Sign Test :	Sig. smaller at 97%

Changes in Powers Roundness 1958-88

Mann-Whitney U-test:	NS at 95%
Sign Test :	Sig less rounded at 97%

South Tyne Results

B-Axis Changes 1958-1988

Mann-Whitney U-test:	NS at 95%
Sign Test :	Significant at 96.7%

The results contained in Table 5.2 imply that although the magnitude of the changes between average particle characteristics from 1958-1988 are within the range expected on the basis of chance alone, the direction of change in particle B-axis and Powers roundness are not. Clearly changes in components of the sediment population have occurred, but these are subtle and are not well reflected by consideration of average values alone. However, on the basis of these results it is possible to conclude that fining of bar surface sediments has occurred simultaneously with a slight reduction in particle roundness.

In contrast, the South Tyne re-survey, for which data was available for only the estimated B-axis (1988 undergraduate research training project), indicates a statistically significant increase in extrapolated particle B-axis, but a lack of significance in the magnitude of change (Table 5.2) - the reason for which is possibly linked to large scale, commercial gravel extraction from the bed of the South Tyne in the 1930's to 1960's. Observations from gravel extraction sites in England, Wales and from other countries, indicate a general fining of the bed sediments during the operation, as a result of fines released to the channel, and the subsequent coarsening of downstream sediments by clear water erosion, or the upstream migration of a knickpoint generated by the extraction (Lagasse and Simons 1976; Lagasse et al 1980; Sear and Newson 1991).

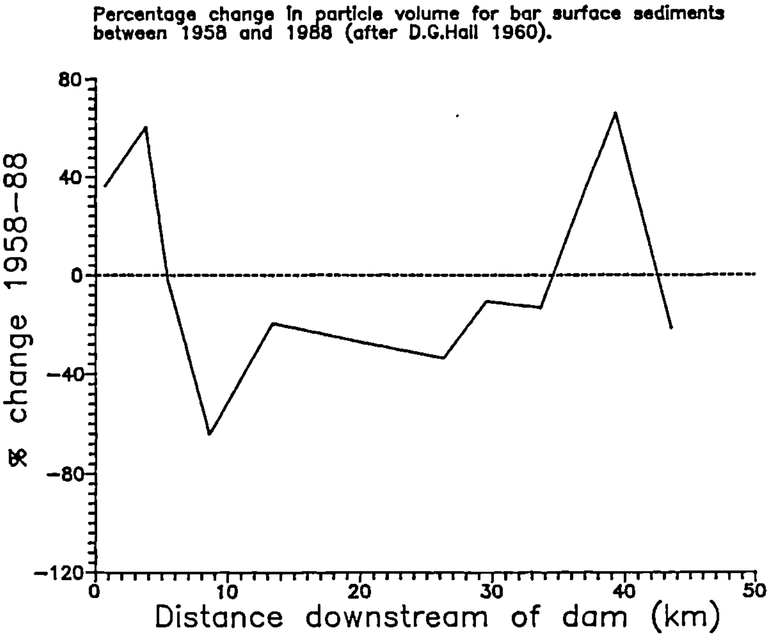
Although Hall (1964) indicates gravel extraction on the North Tyne, the quantities involved were relatively small in comparison with the commercial extractions on the South Tyne. However, the fact that it existed does suggest that some other factor is involved in the overall fining of bar surfaces.

The previous Chapter described a marked reduction in exposed gravel area, and the development of channel side berms within the North Tyne. This was directly linked to the period subsequent to impoundment. In the absence of further information, it is possible that the fining of bar sediments on the North Tyne reflects the transport regime since river regulation, in which reduced flood magnitudes leads to a reduction in competence and the general fining of sediments that are deposited (during floods) on the bar surfaces.

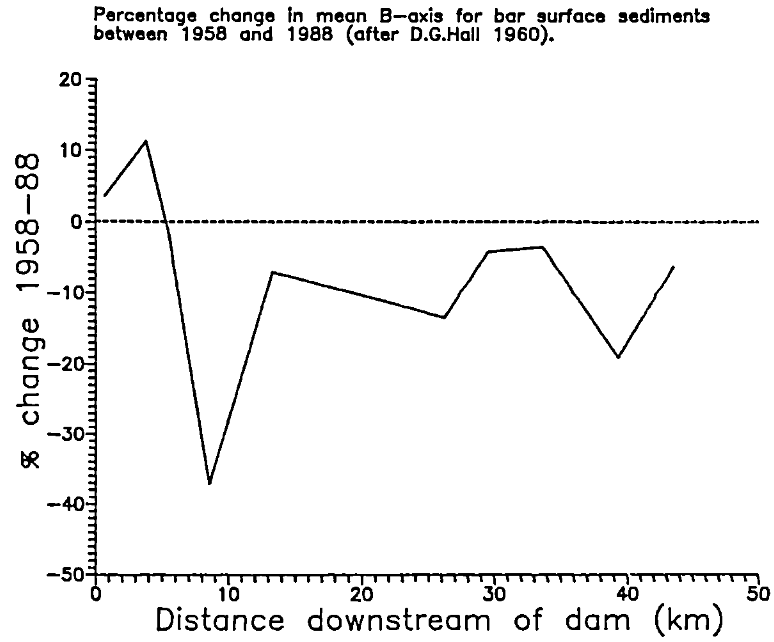
Figure 5.2a-c depicts the percentage change in average particle volume and B-axis, together with actual values for Powers roundness as a function of the distance downstream from Kielder Reservoir. Significantly, the region of increased particle volume and B-axis is located within the first 5km downstream from the dam site. In addition, particle roundness has increased at the site closest to the dam site, and at a site 10 km downstream. Three conclusions can be drawn from these observations: first, that bar sediments up to 5.5.km from the dam site have experienced a preferential increase in particle volume, B-axis and roundness; secondly that the following 30km are characterised by a general fining, and decrease in roundness; and thirdly, that each site responds by a different amount, although the direction of change may be similar. The degree of river regulation clearly affects the deposition processes on bar surfaces close to the dam site.

Figure 5.2 Changes in particle characteristics downstream of Kielder reservoir between 1958-1988.

A



B



C

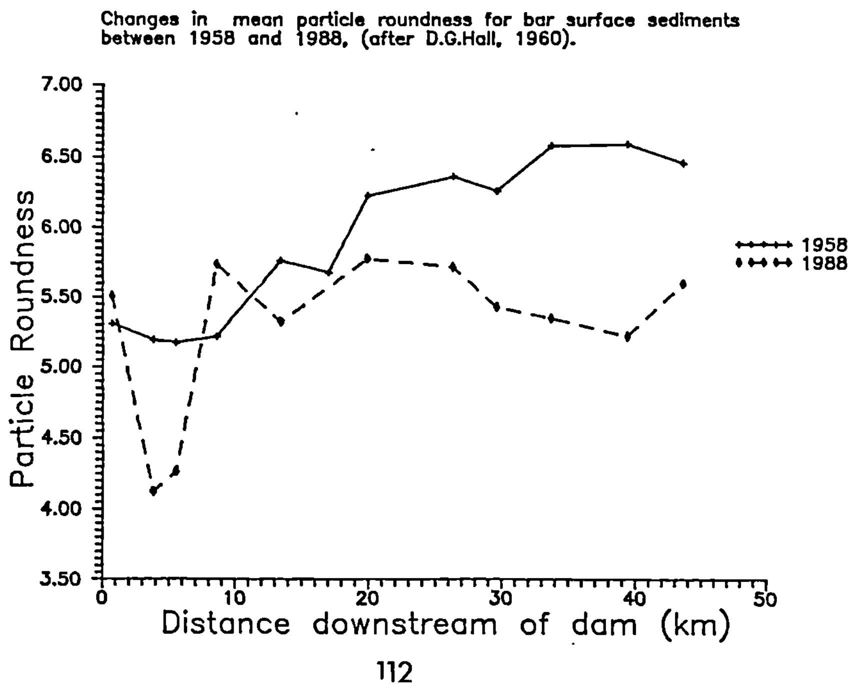


Table 5.3 Comparative datasets for bulk sampled riffle sediments made in 1978, (Carling 1979), and 1988

NOT TRUNCATED

Site	YM1	YM2	FM	FB	SM	RS	LL	TFB	TB	SD	HC	NEWT	HM	DUNT
Distance d/s of dam (km)	0.7	1.0	1.5	2.5	3.8	5.5	6.5	8.6	9.8	11.0	11.5	13.0	14.0	15.5
D_{16} (1978)	2.5	9.5	21	44	66	39	17	76	56	7	20	32	32	20
D_{16} (1988)	0.6	3.5	39	49	26	30	21	50	18	26	21	29	52	34
D_{50} (1978)	28	56	79	91	119	104	50	108	100	94	71	71	66	60
D_{50} (1988)	38	42	79	94	71	74	64	91	64	91	60	71	69	100
D_{84} (1978)	69	119	115	137	147	147	104	132	175	147	66	169	104	124
D_{84} (1988)	84	74	137	169	137	147	104	152	158	180	128	175	133	147
Sorting (78)	2.4	1.8	1.2	0.8	0.6	1.9	1.3	0.4	0.8	2.2	0.9	1.2	0.9	1.3
Sorting (88)	3.6	2.2	0.9	0.9	1.2	2.3	1.2	0.8	1.6	1.4	1.5	1.3	0.7	1.1
Skewness(78)	-0.5	-0.5	-0.6	-0.3	-0.5	-0.6	-0.2	-0.4	-0.1	-0.8	-0.6	-0.1	-0.3	-0.2
Skewness(88)	-0.6	-0.7	-0.2	-0.3	-0.3	-0.2	-0.4	-0.1	-0.4	-0.4	-0.2	-0.1	0.2	-0.4
Kurtosis(78)	0.98	1.53	1.35	1.34	1.67	1.53	1.32	2.24	1.23	1.16	1.34	1.08	1.27	1.26
Kurtosis(88)	0.76	1.76	1.17	1.58	1.05	0.96	1.54	1.42	1.20	1.75	1.05	1.18	1.39	1.35
% < 22mm (78)	52	29	21	12	8	15	26	4	7	29	21	15	15	16
% < 22mm (88)	45	35	22	15	20	20	22	16	29	20	24	13	15	9
% < 2mm (78)	15	10	4.0	2.6	0.6	0.9	2.6	0.2	0.1	7.4	1.4	0.3	0.3	0.8
% < 2mm (88)	24	14	2.0	0.7	1.4	1.5	3.0	1.7	3.3	2.5	2.8	3.0	1.4	2.6

TRUNCATED AT 64 mm

Site	YM1	YM2	FM	FB	SM	RS	LL	TFB	TB	SD	HC	NEWT	HM	DUNT
Distance d/s of dam (km)	0.7	1.0	1.5	2.5	3.8	5.5	6.5	8.6	9.8	11.0	11.5	13.0	14.0	15.5
D_{16} (1978)	1.1	2.1	4.6	8.3	6.3	5.3	7.0	3.2	14.4	1.0	11.1	13.4	13.5	7.2
D_{16} (1988)	0.06	0.8	7.0	9.2	8.0	7.5	11.3	7.5	4.9	7.5	7.5	39.4	22.0	18.4
D_{50} (1978)	15	34	39	41	37	33	31	33	44	9	47	41	41	34
D_{50} (1988)	31	25	29	49	30	21	42	37	27	16	30	50	37	42
D_{84} (1978)	45	50	55	55	52	49	48	47	56	41	54	52	52	47
D_{84} (1988)	49	45	47	58	46	47	54	50	49	54	47	58	52	54
% < 22mm (78)	54	39	34	23	32	39	33	22	18	61	25	26	21	31
% < 22mm (88)	52	44	41	30	37	54	25	30	42	38	37	18	21	21
% < 2mm (78)	21	20	9.1	6.9	4.4	5.1	4.7	8.0	0.7	23	2.5	6.1	1.1	2.4
% < 2mm (88)	29	19	3.4	4.0	4.1	2.5	5.1	6.7	7.6	5.5	5.8	0.4	0.8	3.8

5.4 Results: Re-survey of Bulk riffle sediments after Carling (1979).

The data from the FBA survey of riffle sediments was converted into cumulative frequency graphs and values for the D_{84}, D_{50}, D_{16}, sorting, % < 22mm and % < 2mm noted. These values are recorded for both the total and truncated data in Table 5.3. Values for phi skewness and kurtosis are included for the total dataset.

The data from Table 5.3 was analysed in the same manner as the data for the bar surface sediments. The results for the Mann-Whitney U-test, and the Sign test are presented in Table 5.4.

The statistical analysis presents a picture of subtle changes in the grainsize populations of riffle sediments, which are largely indistinguishable from the results predicted by chance. Furthermore, it is clear that truncating the dataset has an effect on the statistical significance of grainsize changes observed between the total populations.

According to the truncated dataset, there has been only one statistically significant change in the grainsize population of riffle sediments since river regulation - an increase in the D_{16} particle size - although the magnitude of the change is not significant at the 95% confidence interval. This is not reflected in the total grainsize datasets, where 50% of riffles have experienced an increase in D_{16}, and 50% a decrease. In contrast, the total grainsize datasets exhibit a statistically significant increase in the % < 2mm, affecting some 79% of riffles surveyed, whilst the truncated data indicates no such trend.

When viewed on the basis of proximity to the dam site, the pattern of changes within sediments are inconclusive. The site nearest the dam does show an increase in both D_{50} and D_{84} for both truncated and total datasets, but the opposite is found only 300m downstream. However, the YM2 site is derived from lateral bar sediments and may be considered anomalous. Given the distinction, this implies, on the basis of total sediment samples, that riffles up to 2.5km from the dam site are experiencing coarsening of the D_{84} particles.

Consideration of the truncated data would appear to refute this, but this may be more a result of the omission of the armour layer (see below). The preferential coarsening of the

Table 5.4 : Statistical analysis resluts for the FBA gravel sample re-survey.

	D16	D50	D84	Sort	% < 22mm	% < 2mm	Skewness	Kurtosis
Non-Truncated dataset (1978-1988)								
Mann Whitney	NS	NS	NS	NS	NS	NS	NS	NS
Sign Test	NS	NS	+0.07	NS	NS	+0.03	NS	NS
Truncated dataset (1978-1988)								
Mann Whitney	NS	NS	NS	NS	NS	NS	--	--
Sign Test	+0.03	NS	NS	NS	NS	NS	--	--

D_{84} at riffles nearest the dam site supports the observations of bar surface sediments from the Hall (1964) re-survey, but reduces by half the distance affected.

The analysis of the data for phi sorting, skewness and kurtosis indicate, that no statistical differences exist between 1978 or 1988 riffle data for either the Sign test or the Mann-Whitney U-test. The bulk riffle sediments can be described as poorly sorted, negatively skewed, leptokurtic distributions of predominantly cobble sized particles (mean D_{50} = 78mm (1978) and 72mm (1988)). No significant bi-modality is present, except at the YM1 and YM2 sites for 1978 and 1988, where Boulder Clay underlies the gravels and causes a secondary mode in the silt/clay size range.

During the sampling procedure, it was noted that few particles of > 64mm size interval, were collected from the subsurface sediments at any of the riffles. This was subsequently confirmed by the surber sampler surveys of riffle and pool subsurface sediments. It is unclear, owing to the size of samples collected - all below the 50kg sample weight required for 5% rule (Church et al 1987) - whether this represents a sampling inefficiency or a tendency for the spatial concentration of coarser clasts at the surface. The evidence of surface concentration of coarser particles, together with the clear inability of the oil drum technique to sample particles coarser than 64mm from the subsurface layer, leads to the conclusion that particles of 64mm + are derived from the armour surface. Given this hypothesis, it is suggested that the examination of the D_{84} of total grainsize populations reflects the changes in the surface concentration of coarser particles.

Following the assertions above, the results of Table 5.3 indicate that 64% of riffles surveyed have experienced an increase in surface particle size, which is statistically significant according to the Sign test at the 93% confidence interval.

Evidence to support an increase in surface armour grainsize population comes from a comparison between the armour layer data for Falstone Meander riffle (Carling 1979, Fig 2b). The data is depicted in Table 5.5 below.

Table 5.5: Summary grainsize statistics for Falstone Meander riffle armour, 1978-1988.		
D_{16} (1978) = 28mm	D_{50} (1978) = 46mm	D_{84} (1978) = 62mm
D_{16} (1988) = 30mm	D_{50} (1988) = 69mm	D_{84} (1988) = 125mm
Sorting (1978) = 0.56	% < 22mm (1978) = 5%	
Sorting (1988) = 1.05	% < 22mm (1988) = 10%	

A clear increase in the grainsize of the surface armour has occurred since 1978 at this site, located only 1.5 km downstream of the dam site. Reference to Figure A in Appendix shows this site to have experienced degradation of the riffle bed since 1978. An increase in surface armour is associated with degrading river channels (Hey 1982) and is a feature of regulated rivers (Chapter 1).

The data for the multiple sample was collected from the riffle at Ridley Stokoe, a site of historical sedimentation, and one which has experienced aggradation since 1978 (Figure B, Appendix A). The grainsize data available from Carling (pers comm) was divided into size categories based on Fraser's (1975) classification of salmonid spawning gravel suitability. Each sample was collected using the oil drum technique from sites identified from the original field notes (Carling pers comm).

Table 5.6 details the variations in the % frequency of size classes used by Carling (1979). Sites 3.10 and 3.11 could not be sampled due to a thick growth of vegetation, such as is common on the post regulation bar surfaces within the North Tyne. Statistical analysis indicated no significance in either the magnitude or direction of changes at the 90-95% confidence interval. From this it is deduced that although aggradation has taken place since river regulation, the gravel grainsize population has shown no changes that can be attributed to anything other than chance.

The results of the single grainsize population for Ridley Stokoe listed in Table 5.3 shows that some fining has occurred of the D_{16} and D_{50} particle sizes in the total sample. Comparison with Table 5.6, shows that, although statistically insignificant, 54% of samples show an increase in < 1mm material, 69% an increase in particles < 25mm > 1mm, and 69% a reduction in the percentage of particles > 25mm < 150mm. On this

Table 5.6 Changes in bulk gravel samples from the Ridley Stokoe spawning riffle. 1978-1989.(All weights in Kg).

Sample	>150mm		>25mm		>1mm		<1mm	
3.1	---	---	17.4	19.6	2.0	2.8	0.09	0.14
3.2	---	---	18.1	17.6	3.4	3.0	0.18	0.03
3.3	---	---	14.5	15.9	1.4	5.0	0.01	0.17
3.4	---	---	16.8	13.9	3.5	3.7	0.09	0.05
3.5	---	---	17.7	18.1	2.7	3.7	0.16	0.09
3.6	---	---	12.5	22.7	1.8	4.7	0.02	0.09
3.7	3.6	---	10.0	16.6	1.8	3.2	0.05	0.28
3.8	---	4.5	8.8	13.2	2.0	2.9	0.17	0.16
3.9	---	---	12.9	9.2	4.3	3.6	0.24	0.44
3.10	3.2	---	13.2	----	2.5	---	0.12	----
3.11	---	---	13.2	----	3.7	---	0.29	----
3.12	---	---	15.7	10.9	4.4	0.7	0.35	0.00
3.13	---	---	8.6	22.4	1.6	7.4	0.05	0.64
3.14	---	---	9.8	3.8	1.0	4.0	0.02	0.28
3.15	---	---	8.4	16.8	2.3	3.3	0.15	0.05
x	---	---	13.2	15.5	2.6	3.7	0.13	0.16
sd	---	---	3.5	5.3	1.1	2.3	0.10	0.13
%	3.0	1.8	81.0	60.5	16	19	0.80	0.81

basis, it appears that the levels of fines has increased, which would be expected in aggrading areas channel (Lisle and Madej 1992).

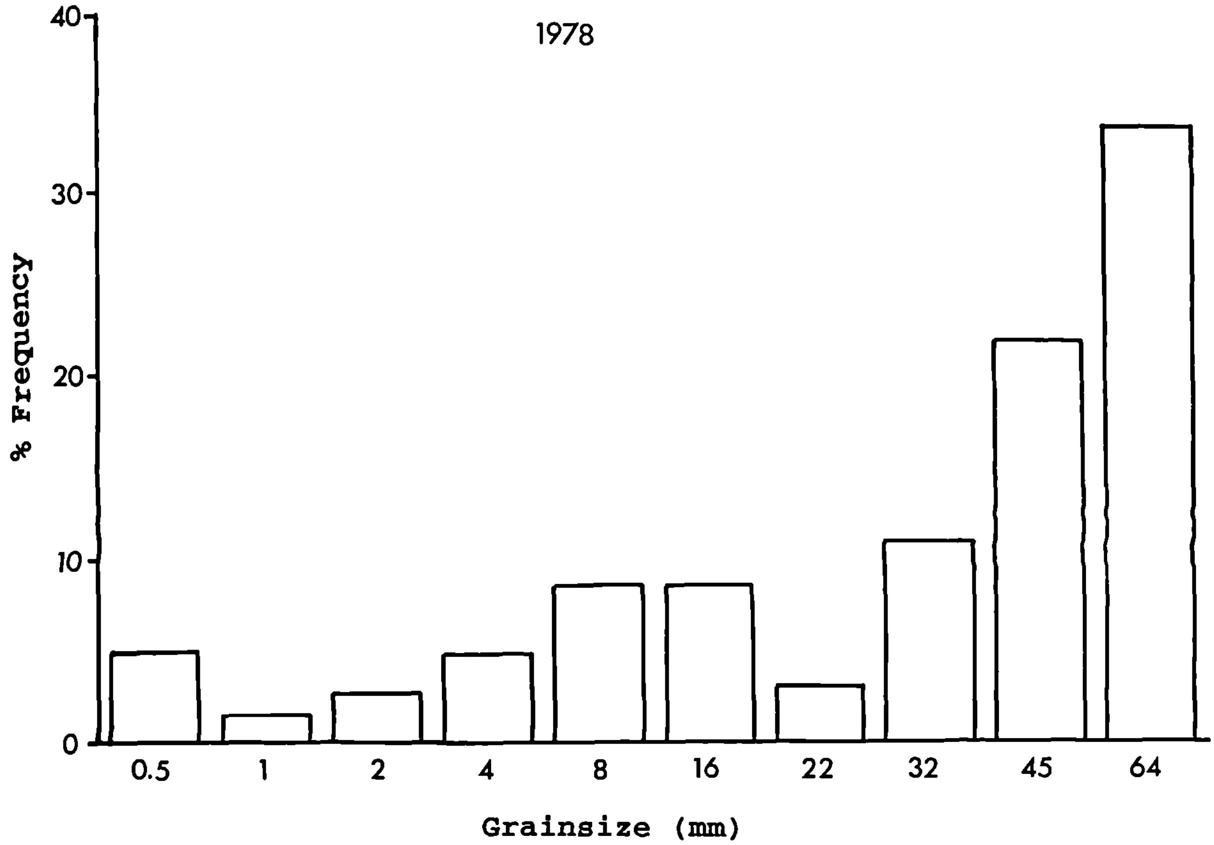
To put the temporal change in grainsize populations into perspective with the inter-site changes, the data for 1978 and 1988 was subjected to a two-way analysis of variance. This indicated that the variance between sites (Mean sum of squares = 730) was greater than the variation at sites over time (MSS = 300). In addition, the mean sum of squares values indicated that the changes recorded for both temporal and spatial scales were greater than the error term (MSS = 250). The F statistic values of 2.92 (spatial), and 1.19 (temporal), for n-1 degrees of freedom (13), indicate that what variation exists is only that which would be expected to occur by chance, given a dataset with a MSS error of 250. Clearly, the changes occurring to the sediment population as a result of river regulation are as yet subtle, and dependant upon the inherent inter-site variations brought about by local boundary conditions.

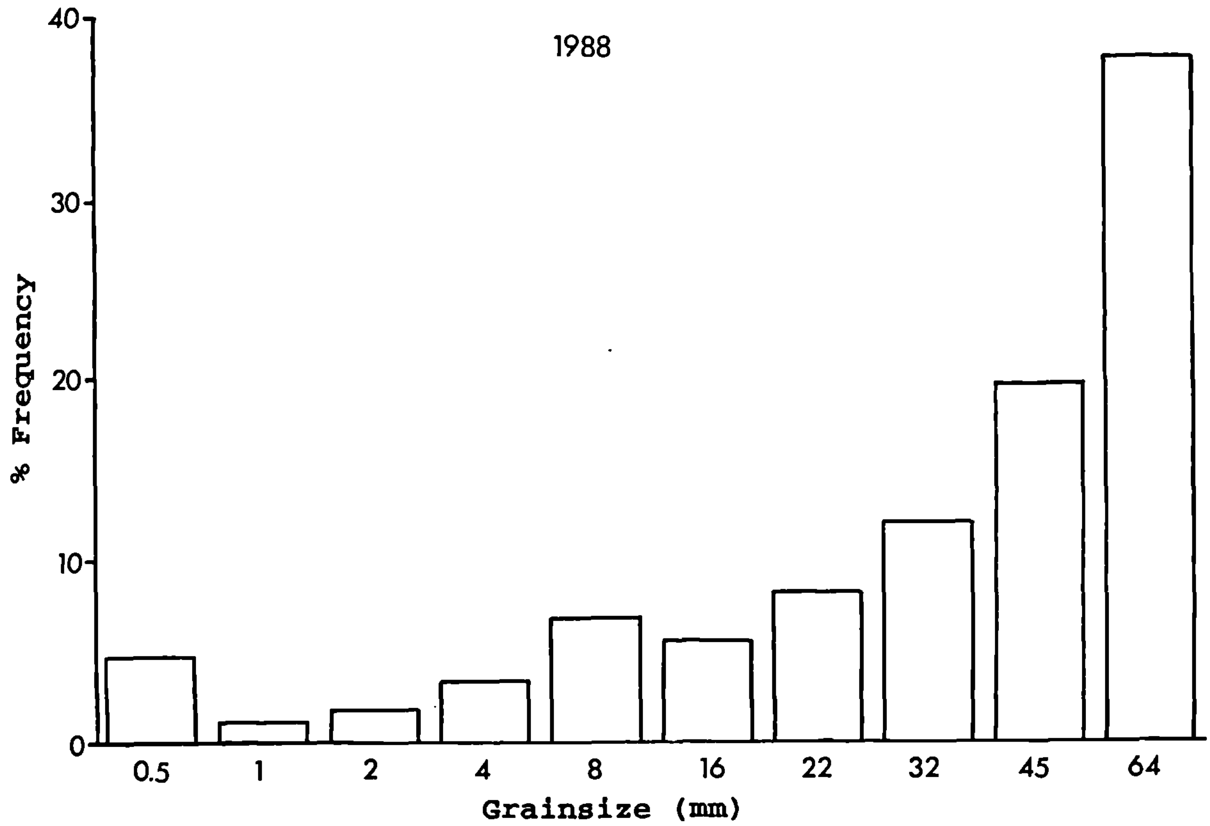
The results of the Hall (1964) and Carling (1978) sediment re-surveys indicate that some coarsening of bar and riffle armour has occurred at riffles closest to the dam site in particular, but also at individual riffles up to 15.5 km downstream. This is viewed against a general pattern of bar surface fining since 1958.

The specific changes in the grainsize population are subtle and site specific, and depend upon the sampling strategy (either truncated or not). For the purposes of this study, the truncated datasets should be used to infer changes in the subsurface sediment population, and the total dataset, the changes in surface armour. Armouring has occurred at 64% of riffles surveyed, together with an increase in the size of the D16 particle size at 79% of riffles surveyed. The levels of fines < 2mm have generally reduced, whilst the proportion of sediments < 22mm have increased since 1978.

The aggregated datasets for the FBA re-survey are shown in truncated form in Figure 5.3. A reduction in the proportion of sediments in the 1-16mm size range is evident, which confirms the reduction in the D_{16} particle size. An increase in the proportion of 64mm particles is also confirmed. The 22mm size class has increased in proportion as a result of the reduction in 1-16mm material, whilst the 64mm size class has increased in proportion as a result of a decrease in 45mm material.

Figure 5.3 Aggregated bulk grainsize populations for salmonid spawning riffles in the North Tyne.





5.5 Results: The sedimentology of riffles and pools.

Table 5.7 contains the summary grainsize statistics for riffles and pools and bars sampled in the North Tyne, and in tributaries. The tributary data was collected for comparison with the North Tyne data in the hope of elucidating any features that were peculiar to the regulated channel. In total, 14 riffles and 13 pools were sampled for surface and subsurface, sediments with five riffle-pools in unregulated tributaries. The same statistical tests were applied to the summary statistics in Table 5.7 as had been applied for the previous datasets of Hall and Carling; the results are contained in *Table 5.8*.

In terms of magnitude, the surface layers of particles in riffles are not significantly coarser than pool surface sediments. However, there is a significant trend ($p = 0.05$) for riffle D_{16}, D_{50} and D_{84} to be coarser than equivalent pool sediments. The exception is the Newton site, where pool sediments are coarser as a result of the presence of coarse slope material derived from a relict river cliff.

An analysis of the statistical moments of the surface sediments revealed no significant differences in either magnitude or trend. Riffles and pools can be characterised as possessing poorly sorted, negatively skewed, mesokurtic surface grainsize populations of coarse gravel/cobbles. Riffle surface sediments are typically, unimodal whilst pool surface sediments possess a weak secondary mode in the <4mm size categories. This latter phenomenon represents splays of fine gravels and sands that were observed overlying gravels in most pools in both the tributaries and the regulated North Tyne.

There is no significant difference between the %<2mm in riffles or pools, which is most likely a reflection of the inadequacies of the surface grid sampling technique rather than a phenomenon in itself (Wolman 1954; Hey and Thorne 1983).

Analysis of the subsurface dataset indicates that the D_{84} of riffles is consistently coarser than in pools, although the magnitude of the variation is insignificant. The values of riffle D_{16} and D_{50} are not significantly different from those in pools. However, the magnitude and trend analysis indicates that riffle subsurface sediments are more poorly sorted than in pools, but there is no significant difference for skewness or kurtosis.

Table 5.7: Summary grainsize data for surface and subsurface sediment samples from riffles, pools and bars in the North Tyne catchment.

	Surface Sediments						Subsurface Sediments						
Site	**D16**	**D50**	**D84**	**Sort**	**Skew**	**Kurt**	**% < 2mm**	**D16**	**D50**	**D84**	**Sort**	**Skew**	**Kurt**	**% < 2mm**
YR1	39	64	119	0.80	0.06	0.96	0.0	.06	8	69	5.55	-0.48	0.85	37.0
YP	22	32	84	0.95	-0.43	1.03	2.0	5	18	69	1.90	-0.07	0.95	6.0
FR	30	69	125	1.05	-0.21	1.07	2.0	6	30	52	1.60	-0.51	1.21	9.1
FP	29	45	90	0.85	-0.02	0.85	2.0	7	22	39	1.20	-0.38	0.96	3.0
SMR	32	56	125	1.00	0.11	1.07	0.0	7	24	39	1.30	-0.46	0.91	2.5
SMP	22	42	97	1.05	0.10	0.93	4.0	10	28	39	1.05	-0.58	0.90	3.6
RSR	20	38	74	0.95	0.11	1.07	2.0	5	28	64	1.56	-0.39	1.32	3.2
RSP	18	30	49	0.70	0.06	0.77	0.0	10	22	60	1.22	0.01	1.12	7.0
TR1	22	42	64	0.75	-0.19	0.81	2.1	4	15	37	1.65	-0.29	1.44	12.5
TP1	26	39	74	0.75	0.05	1.11	1.8	11	18	37	0.90	0.12	1.39	5.4
TP2	18	42	84	1.10	-0.25	1.39	6.5	7	15	29	1.05	-0.17	1.34	7.0
TR2	32	60	137	1.05	0.05	0.95	2.7	9	22	38	1.08	-0.29	1.23	3.8
NR1	24	37	64	0.70	-0.49	1.07	0.0	5	14	30	1.35	-0.20	1.14	8.2
NP	34	49	69	0.50	-0.16	0.72	0.0	5	9	18	1.00	-0.11	1.01	5.0
NR2	32	45	69	0.55	0.43	1.64	0.0	9	26	49	1.20	-0.29	0.88	2.4
BR	34	79	125	0.95	-0.32	0.83	2.0	3	13	39	1.90	-0.21	0.99	12.4
BP	26	49	90	0.90	0.21	0.90	0.0	8	21	32	1.05	-0.39	1.17	3.0
SMBR	30	52	84	0.75	0.03	1.21	1.2	6	45	66	1.73	0.16	1.17	10.9
SMBP	11	32	74	1.40	-0.20	1.23	6.4	2	13	45	2.20	-0.37	1.13	12.6
TBR	30	64	111	0.95	-0.19	1.14	1.9	5	49	84	2.05	-0.64	1.05	9.6
TBP	22	42	90	1.00	0.14	1.39	0.0	1	11	32	2.50	-0.42	0.94	25.3
CHBR	33	60	84	0.75	-0.25	1.45	1.0	1	18	64	2.80	-0.40	0.83	22.6
CHBP	6	24	64	1.70	-0.16	1.10	7.1	1	18	45	2.50	-0.51	0.90	21.7
BBR	22	45	79	0.90	-0.02	1.00	0.0	3	24	52	2.15	-0.53	1.00	11.8
BBP	9	30	90	1.70	-0.33	1.17	5.4	2	16	34	2.10	-0.49	1.23	12.3
RRR	24	49	111	0.95	0.24	0.93	0.0	4	30	66	2.03	-0.46	0.98	12.8
RRP	4	32	69	2.00	-0.54	5.59	0.0	3	34	104	2.50	-0.44	1.08	14.2
Bar1	17	28	45	0.70	-0.01	1.21		1	18	42	3.20	-0.63	1.47	
Bar2	23	42	94	1.03	0.14	1.19		1	22	45	1.20	-0.48	1.01	
Bar3	23	45	104	1.08	0.12	0.98		4	20	40	1.08	-0.20	0.98	
Bar4	21	30	42	0.50	0.02	0.88								
Bar5	20	32	45	0.60	-0.15	0.94								
Bar7	25	34	47	0.45	0.02	1.10								
Bar8	23	34	47	0.50	-0.09	0.98								
Bar9	23	33	50	0.58	-0.01	0.87								

NB: The suffix R = riffle & P = Pool

Table 5.8 Statistical analysis results for riffle, pool and bar datasets.

Surface sediments: **(Riffle vs Pool)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney	NS	NS	NS	NS	NS	NS	NS
Sign Test	+0.05	+0.01	+0.05	NS	NS	NS	NS

Subsurface sediments: **(Riffle vs Pool)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney	NS	NS	NS	-0.02	NS	NS	NS
Sign Test	NS	NS	+0.05	-0.05	NS	NS	NS

Surface sediments: **(Regulated riffles vs unregulated riffles)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney	NS	NS	NS	NS	-0.02	-0.05	NS

Subsurface sed: **(Regulated riffles vs unregulated riffles)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney	NS	NS	-0.03	-0.03	NS	NS	NS

Surface sediments: **(Regulated pools vs unregulated pools)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney	+0.02	+0.04	NS	-0.01	NS	NS	NS

Subsurface sed: **(Regulated pools vs unregulated pools)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney	+0.02	NS	NS	-0.02	+0.02	NS	NS

Surface Sediments: **(Riffles and pools vs bars)**

	D16	D50	D84	Sort	Skew	Kurt	% < 2mm
Mann Whitney(R)	+0.01	+0.01	+0.04	-0.01	+0.01	NS	--
Mann Whitney(P)	NS	NS	NS	NS	+0.01	NS	--

NB: the prefix +/- refers to the direction of the significance with respect to the first morphological group in the title.

There is no significant difference between the %<2mm in riffle subsurface sediments and in pools.

The subsurface sediments of riffles are characterised as poorly sorted, unimodal, symmetrical, leptokurtic grainsize populations of predominantly coarse gravel size. Pool subsurface sediments are poorly sorted, unimodal, negatively skewed, leptokurtic grainsize populations of predominantly coarse gravel. Although unimodal, both riffle and pool subsurface sediments exhibit a weak secondary mode in the 0.5-1mm size ranges. In general, the sediments are dominated by framework gravels of 4-64mm.

The Mann Whitney U-test was also applied to the data from the North Tyne and the unregulated tributaries. Five is the minimum statistically acceptable number of observations for the Mann-Whitney U-test; the Sign could not be applied, as the sample numbers differ. The results indicated that there was no significant difference between the surface sediments of riffles (Table 5.8) in the unregulated tributaries (nearest their confluence with the North Tyne), except for a tendency for North Tyne riffles to be more negatively skewed and leptokurtic. In contrast, unregulated pool surface sediments displayed significantly finer D_{16} and D_{50} particles and were less well sorted than the North Tyne pools; the D_{84} particles, skewness and kurtosis were not significantly different.

The subsurface sediments in unregulated tributary riffles are less well sorted than in the North Tyne; furthermore, the North Tyne riffles possess significantly coarser D_{84} particles. This latter point supports the observations above regarding surface coarsening since river regulation. Values for skewness and kurtosis are not significantly different.

The unregulated pools possess finer D_{16} particles but equivalent D_{50} and D_{84} particles, although they are more poorly sorted than pools within the North Tyne. The North Tyne pool subsurface sediments are significantly more positively skewed than the unregulated pools, which reflects the higher fines content; kurtosis values are not significantly different.

Milne (1982a) concluded that channel bars were "overall the most distinctive bed forms" as characterised by surface sediment populations. To test this hypothesis, and to provide evidence of the sediment type stored on bars within the North Tyne, the surface grainsize sediments collected for the Hall (1964) re-survey were analysed in the same way as the riffle and pool data. The summary statistics are given in Table 5.7 with the results of statistical comparisons between riffle and pool surface sediments with the bar data contained in Table 5.8.

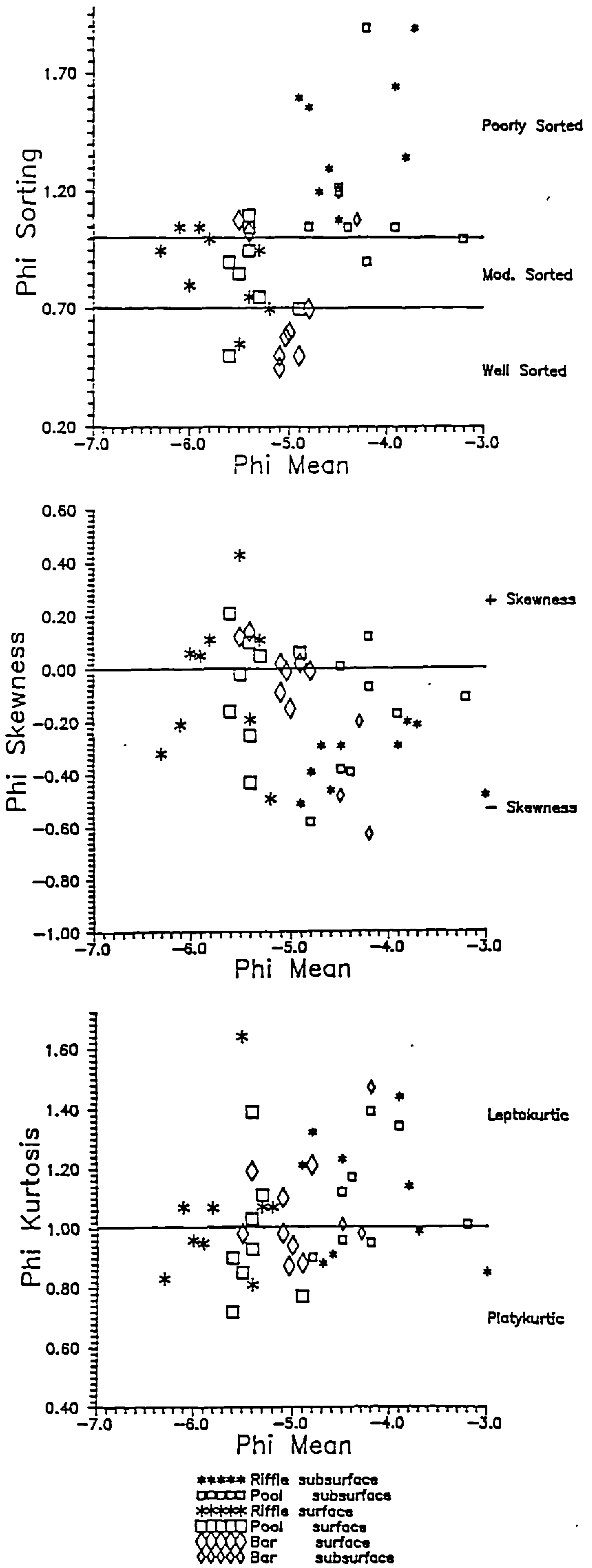
The results show that bar surface sediments are generally significantly finer than riffles surface sediments, but not significantly different from pool surface sediments. However, although the magnitude of the difference between pool and bar surface sediments is not significant at the 95% level, the Sign test reveals a significant tendency for pool sediments to be coarser for any combination of pools versus the bar data.

Milne (1982) provides a useful method of differentiating between grainsize populations which are not statistically different. The technique involves the plotting of bivariate scattergrams of mean grainsize versus phi sorting, skewness and kurtosis. Figure 5.4 depicts the bivariate scattergrams for both surface and subsurface components of riffles, pools and bars. Phi sorting and skewness are apparently the best discriminators between surface and subsurface components of the overall grainsize population, whilst in general it is the mean size of the sediments which differentiates best between bedforms.

Milne (1982a) comments on the discriminative capacity of the mean grainsize, describing a tendency for the bedform sequence to run from the coarser riffle surface to the finer bar surface. This distinction is not evident within the subsurface components, which are best discriminated into individual bedforms on the basis of sorting. The tendency for subsurface riffle sediments to be more poorly sorted than pool or bar sediments is unexpected, given the proposed winnowing of fines from these features during low flows (Hack 1957; Ashmore 1979). A possible cause of the poorer sorted subsurface sediments in riffles may be a result of infiltration deep into the framework gravels as a result of the locally high velocities (Dilplas and Parker 1992; Frostick et al 1984). This phenomenon will be investigated in Chapter 9.

What is apparent from this analysis is that there is no conclusive evidence to support Keller's (1971), observation of coarser subsurface sediments in riffles as well as in pools. The conclusion instead becomes one in which riffle surface sediments express a

Fig 5.4: Scatterplot differentiation of riffle, pool and bar sediments on the basis of four statistical moments.



difference in grainsize from pools and bars, and that the finer elements from the surface are apparently concentrated in the subsurface layers to produce the poorer sorting. Similarly, the data presented here supports Milnes (1982a) observations that lateral sorting of sediments on a size basis are as strong or stronger than the longitudinal differentiation between riffle and pool. The results also suggest that sampling of sediments should take regard of the morphology of the reach, and in particular the storage of fine sediments on bars.

5.5.1 Sediment variation within the riffle-pool sequence

Ashworth (1987) and Petit (1987) have described the variation of surface sediment sizes within a riffle-pool-riffle sequence. Ashworth identifies finer pool-head sediments and a corresponding increase in coarser sediments in the pool-tail, whilst Petit identifies the pool-tail with homogenous deposits of pebbles. Ashworth further states that little within pool sorting of sediment is to be expected, since there is very little difference between shear stress magnitudes at bedload moving flows, between the riffle/pool-head/mid-pool/pool-tail regions.

To investigate the possible surface sedimentological differences within the riffle-pool-riffle sequence, five sites were sampled, with 50 stones taken from each of the riffle, pool-head, mid-pool and pool-tail. Four sites were within the North Tyne, at Smales, Ridley Stokoe, Tarset and Newton, while a fifth site was located on the unregulated Tarset Burn.

The summary grainsize data is provided in Table 5.9. Sorting only was used to discriminate between sediment populations, following the observations described above. In addition, the percentages of sediment < 22mm and < 2mm are shown for each region, in order to investigate the possible downstream sorting of fine sediments.

The general observations indicate the following conclusions:

D_{16}: generally fines through the riffle-pool sequence, with the pool-tail finest in 4/5 cases, (all in the North Tyne), and significantly finer than pool-head sediments at the 95% confidence interval.

Table 5.9 Summary grainsize data for surface sediments from intra-pool regions, Riffle, Pool-head, Mid-pool & Pool-tail (all sizes are in mm).

Site	D16	D50	D84	Sort	% < 22mm	% < 2mm
SMR1	32	56	125	1.00	14	0
SMPH	32	66	137	1.05	12	4
SMMP	22	42	97	1.05	14	6
SMPT	19	40	97	1.18	18	9
RSR	20	38	74	0.95	18	2
RSPH	15	26	49	0.83	38	2
RSMP	18	30	48	0.70	55	5
RSPT	9	16	28	0.80	74	10
TR1	22	42	64	0.75	15	2
TPH	30	42	69	0.70	9	0
TMP	26	39	69	0.70	8	5
TPT	23	37	60	0.70	16	3
NR1	24	37	64	0.70	13	0
NPH	28	45	137	1.15	9	0
NMP	18	51	115	1.35	18	8
NPT	17	32	64	0.95	24	8
NR2	32	45	69	0.55	2	0
TBR	16	45	104	1.35	20	2
TBPH	6	41	111	2.15	39	11
TBMP	2	18	58	2.43	54	19
TBPT	4	24	82	2.18	48	7
TBR2	11	47	119	1.73	24	7

D_{50}: is finest in the pool-tail in 4/5 cases (all in the North Tyne), although the sequence of downstream fining is interrupted by coarser D_{50} in the mid-pool region. The magnitude of change is not significant at the 95% confidence interval for any sub-region of the riffle-pool-riffle sequence.

D_{84}: is finest in the pool-tail and mid-pool regions, and fines from the coarser pool-head. The pool-head is coarser than the upstream riffle in 4/5 cases, including the unregulated tributary.

Sorting: no obvious pattern of sorting exists, although there is a tendency for riffle surface sediments to be better sorted.

% < 22mm: generally increases through the pool to the pool-tail (4/5 cases, all in the North Tyne). The pool-head is often deficient in fines with respect to the upstream riffle.

% < 2mm: is difficult to sample by the Wolman (1954) technique, but in general there is a trend towards an increase in fines in the mid-pool and pool-tail.

The anomaly in the tributary may be the result of sampling soon after a small flood, which supplied fine sediment to the mid-pool region, but was not of sufficient duration to transport the fines into the pool-tail region.

In addition to the grid sampling of stones at individual regions of the pool-riffle sequence, a survey was conducted of the facies within the three main sampling sites: the Smales, Tarset and Newton sites. The survey was conducted by traversing the river bed at 2m intervals, and noting major changes in the sediment size of the bed. In addition, a sample of 30-50 stones was collected from transects located at 20m intervals, and the site of each stone was recorded across the transect. The stone sizes were used to confirm the visual identification of facies, and to assign a size range to each facies.

The object of this investigation was to characterise any lateral or longitudinal variations in sediments, and to identify areas of preferential storage of given sediment sizes. In addition, the results were used to provide data on the sediment size of the bed at the point of tracer and hydraulic measurements for use in later investigations (Chapters 7 and 12).

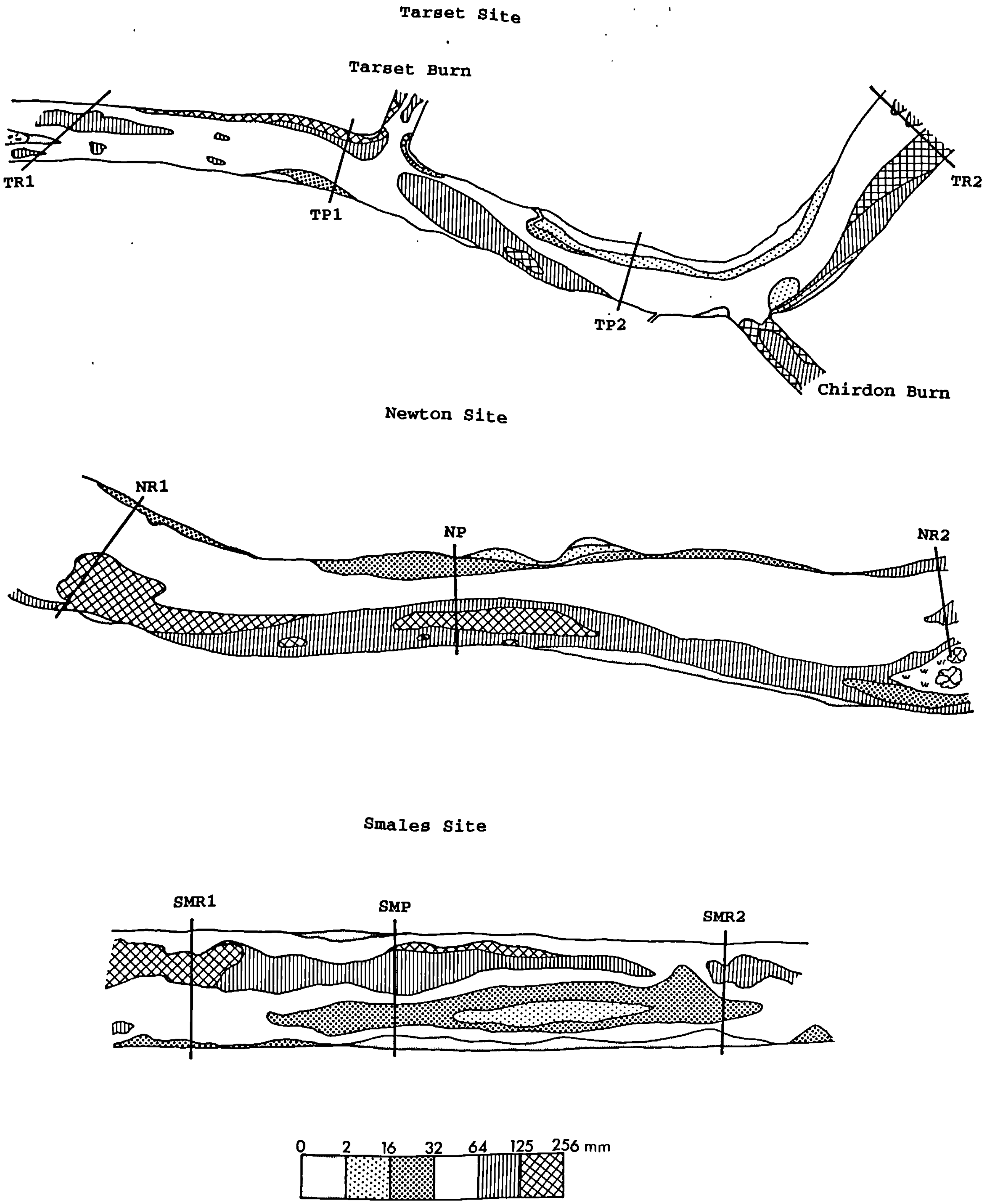
The results of this survey were input into a Unimap 2000 mapping package, and interpolated to produce a map of the river bed sediment surface. Figure 5.5, depicts the resultant facies maps for the three sites. The morphology of the Tarset site has clearly influenced the sedimentology of the reach immediately downstream of the Tarset Burn confluence. Similarly, the presence of large boulders along the right bank of the Newton pool reflects the input of colluvial material from a currently inactive river cliff.

The Tarset site illustrates the localised nature of tributary sediment input storage within the regulated North Tyne. The coarse lag of large cobbles downstream of the Tarset Burn confluence is associated with the confluence bar head, and the narrow channel adjacent to the bar. Downstream of the tributary bar, fine sediments are stored in a berm, equivalent in position to a point bar, but clearly fed from the tributary source upstream. A similar deposit of tributary derived sediments is indicated downstream of the Chirdon Burn. At the time of the survey (October 1988), no bar was evident at the surface at compensation flows; however, following the bankfull flood of February 1990, a small confluence bar had broken the low flow surface. The coarse sediment downstream of the fines at this bar is associated with a local attempt to protect the bank from erosion.

Upstream of the Tarset Burn confluence, the bed of the North Tyne is characterised by a dominant facies of small cobbles, with a coarse lag along the left bank and a localised fine deposit on the right bank of the pool. The coarse lag is derived from stone pitching at the toe of the river bank, whilst the fines are the result of lateral deposition from the pool.

Both riffles have local regions of coarse sediments, which extend into the pool-head. These coarse lags at both riffles are not associated with stone pitching and must therefore result from local processes which are peculiar to riffles. It was noticeable that the coarse lag areas of the riffles were associated with regions of accentuated low flow velocity and deeper flow depths. This suggests that the surface sedimentology reflects the local low flow hydraulics, which is an important consideration in a regulated stream with a profoundly altered low flow hydrology.

Fig 5.5 Grainsize of surface sediments within the three main monitoring sites.



Tarset riffle 1 lies downstream of a small island created when the railway bridge over the North Tyne was constructed in 1858. The effect on the sedimentology of the riffle is to encourage the deposition of sand over the surface gravels, and to locally increase the fine sediment composition of the bed. A subsequent study of fine sediment infiltration confirmed the accentuation of sand deposition in this area of bed (Chapter 9).

The scour pools at the junction of the Tarset and Chirdon burns were too deep to sample; however, echo soundings revealed that the bed was free of large boulders. Best (1987) and Ashmore (1982) have independently confirmed that the sediment transport paths associated with tributary scour pools tend to route around the region of greatest flow depth, thereby keeping them free from infilling. The coarse sediments are evidently routed around or out of the scour pools, and stored as bar head material in the separation region immediately downstream of the Tarset Bar.

The sedimentology of the Newton site is influenced by the presence of colluvium derived from a currently inactive river cliff (Figure 5.5b). The result is the development of a distinct asymmetry in sediment size within the pool, with the right half of the pool dominated by cobbles and boulders up to 1.25m diameter, fining up a gravel bank on the left side of the pool, to sand and silts. Large wake deposits are formed in the lee of the large roughness elements in the pool; however, much of the fine sediment is stored in the gravel bank. Thick splays of sand and silt are developed along the right and left bank margins, in the regions of the bed which are exposed first on the flood recession. The deeper regions of the pool are associated with the boundary between the large-cobble facies and small-cobble facies, whilst the shallower pool-tail is dominated by small cobbles and coarse gravels.

The lateral sorting of sediments within the pool, although clearly influenced by the right bank coarse sediment source, nevertheless suggests that fine sediments are routed towards and along the left bank. This in turn suggests the presence of up-bank secondary flows, which would impart a left bank vector to sediments passing through the pool in the same way as Deitrich (1987) and Markham and Thorne (1992) have described for meander bends. Sediment travelling through the right bank region of the pool is evidently trapped in the lee of the larger roughness elements.

The riffle sediments are characterised by small and coarse cobble facies. The coarse cobble facies at Newton riffle 1 is associated with an emergent bar, and a region of accelerated flow caused by the constriction between a small tributary bar and the bar itself. This is similar to the constricted flow region between the Tarset bar and the bank, and clearly links the high velocity of this region with a surface sedimentological expression. The coarse cobble facies associated with Newton riffle 2 corresponds with the deeper, high velocity region of the riffle, in a similar manner to the Tarset riffles, suggesting that surface sedimentology at riffles is dominated by the low-flow hydraulics.

The pool-head region is dominated by a small cobble facies, which extends in a tongue throughout the pool to the pool-tail. In detail, the mid-pool region exhibits the most complex facies arrangement, on account of the lateral sorting of fines. The reason for the fine sediment deposition at this point along the pool is not clear, but may be associated with the left bank irregularities, which create localised reverse-flow currents or slackwater zones.

The pool-tail marks a transition region, with a coarse gravel facies merging into the cobble facies of the downstream riffle as flow accelerates with the decreasing depth. However, the preferential deposition of fines in the pool-tail is confirmed by the facies survey.

Figure 5.5c depicts the facies map for the Smales site. The width at this site remains approximately constant throughout the riffle-pool-riffle sequence. This is important, since the Tarset site sedimentology is clearly affected by tributary confluence morphology, whilst the Newton site has a progressively increasing downstream width that would affect the gross hydraulics of the reach and hence the sedimentology. In addition, the site is upstream of significant tributary inputs and is consequently subjected to a higher degree of flow regulation.

Despite the relative homogeneity of the reach dimensions, the sediments are arranged into a right bank fining gravel bank within the pool, and coarse cobble facies in the regions of deeper flow. Both riffles are dominated by coarse cobble facies, with small boulders present in the regions of fastest and deepest flow. The coarse riffle sediments extend through the pool-head and along the deep left bank of the pool. The pool-tail is again characterised by finer sediments, with a facies of coarse gravel and small cobbles coarsening up to the downstream riffle in a similar manner to the Newton site.

The centreline of the pool is dominated by a coarse gravel bank that fines to a margin of fine sand and silt at the right bank. Topographically, this bank resembles a medial bar, and is not attached to the right bank, but rather represents an independent storage for finer sediments within the pool. Given the coarse nature of the left side pool deeps, it is again evident that lateral movement of fine sediments may operate at times of bed mobility. This is investigated in more detail in Chapters 7 and 12.

The progressive downstream fining through the Smales and Newton pools confirms the observations based on sediment sampling, and is adopted as a model of the sedimentology of the North Tyne riffle-pool sequence throughout this study. Hydraulic and sediment transport evidence for the observed downstream changes are investigated later, in Chapters 7, 10 and 12.

5.6 Evidence for the magnitude and type of channel armouring within the North Tyne catchment

Section 5.4, above, indicated that surface armouring existed within the North Tyne riffle sediments on the basis of the frequency of particles > 64mm. A useful expression of the degree of armouring is given by the armour ratio (Klingeman and Emmett 1982; Lisle and Madej 1992), which is defined as the ratio between the surface and subsurface D_{50} particle size. Church et al (1987) comment on the armour ratio as a method of determining the process(es) of armouring responsible for the observed surface coarsening, whereby a winnowed armour will possess an armour ratio of approximately 1 when truncated of the finer matrix particles, whilst an armour produced by the preferential concentration of coarse particles due to equilibrium transport will have an armour ratio much greater than 1.

This technique fails to account for the difference between vertical or horizontal winnowing, and is also subject to the problems associated with sampling coarse river gravels, not least the difference between sampling the surface and subsurface layers; as Church et al conclude, "these problems remain largely unresolved". Nevertheless, truncation of the samples can improve the accuracy of the sample estimates of D_{50} to within 10-20% (see above), and the technique does provide a useful guide to the between-site variability of armouring (Leeks and Newson 1988).

The armour ratio was calculated for nine riffles and eight pools in the regulated North Tyne, and five riffles and five pools from unregulated tributaries. The values for armour ratio are presented in Table 5.10, together with the average values for each morphology. The two values from each site refer to the total sample population, and the same sample truncated at 11.2mm and 64mm. The lower limit effectively removes the matrix, and enables a comparison between surface and subsurface D_{50} to be made for assessing the process of armouring, whilst the upper limit reflects the limitations on sample accuracy alluded to in Chapter 9. The regulated riffle and pool sites are listed according to increasing distance from the Kielder Dam site.

The effect of sample truncation is to reduce the values of armour ratio and to reduce the variance between sites; this latter point is notable at the YR1 site. Total sample values

Table 5.10: Armour ratios at riffle and pool sites for total and (truncated) grainsize data.

Site	Armour ratio		Site	Armour ratio	
YR1	8.00	(1.19)	YP	2.30	(1.38)
FR1	2.30	(0.87)	FP	2.10	(1.11)
SMR	2.30	(1.15)	SMP	1.50	(0.93)
RSR	1.40	(1.32)	RSP	1.40	(0.84)
TR1	2.80	(1.47)	TP1	2.10	(1.73)
TR2	2.70	(1.28)	TP2	2.80	(1.41)
NR1	2.60	(1.67)	NP	5.40	(2.21)
NR2	1.70	(1.55)			
BR	6.10	(1.32)	BP	2.30	(1.32)
SMBR	1.20	(1.10)	SMBP	2.50	(1.18)
TBR	1.30	(1.20)	TBP	3.80	(1.44)
CHBR	3.30	(1.03)	CHBP	1.30	(1.32)
BBR	1.90	(1.17)	BBP	1.80	(1.40)
RRR	1.60	(1.24)	RRP	0.90	(1.72)

Regulated riffle: x = 2.74* (1.31)
Regulated pools: x = 2.49 (1.37)
Unregulated riffles: x = 1.86 (1.15)
Unregulated pools: x = 2.06 (1.41)

Statistical Significance of morphological variations

<u>Regulated riffles vs Regulated pools</u>

Mann Whitney: +0.05 (NS)
Sign test: NS (NS)

<u>Unregulated riffles vs Unregulated pools</u>

Mann Whitney: NS (-0.05)
Sign test: NS (-0.05)

<u>Regulated riffles vs Unregulated riffles</u>

Mann Whitney: +0.05 (+0.05)

<u>Regulated pools vs Unregulated pools</u>

Mann Whitney: -0.05 (NS)

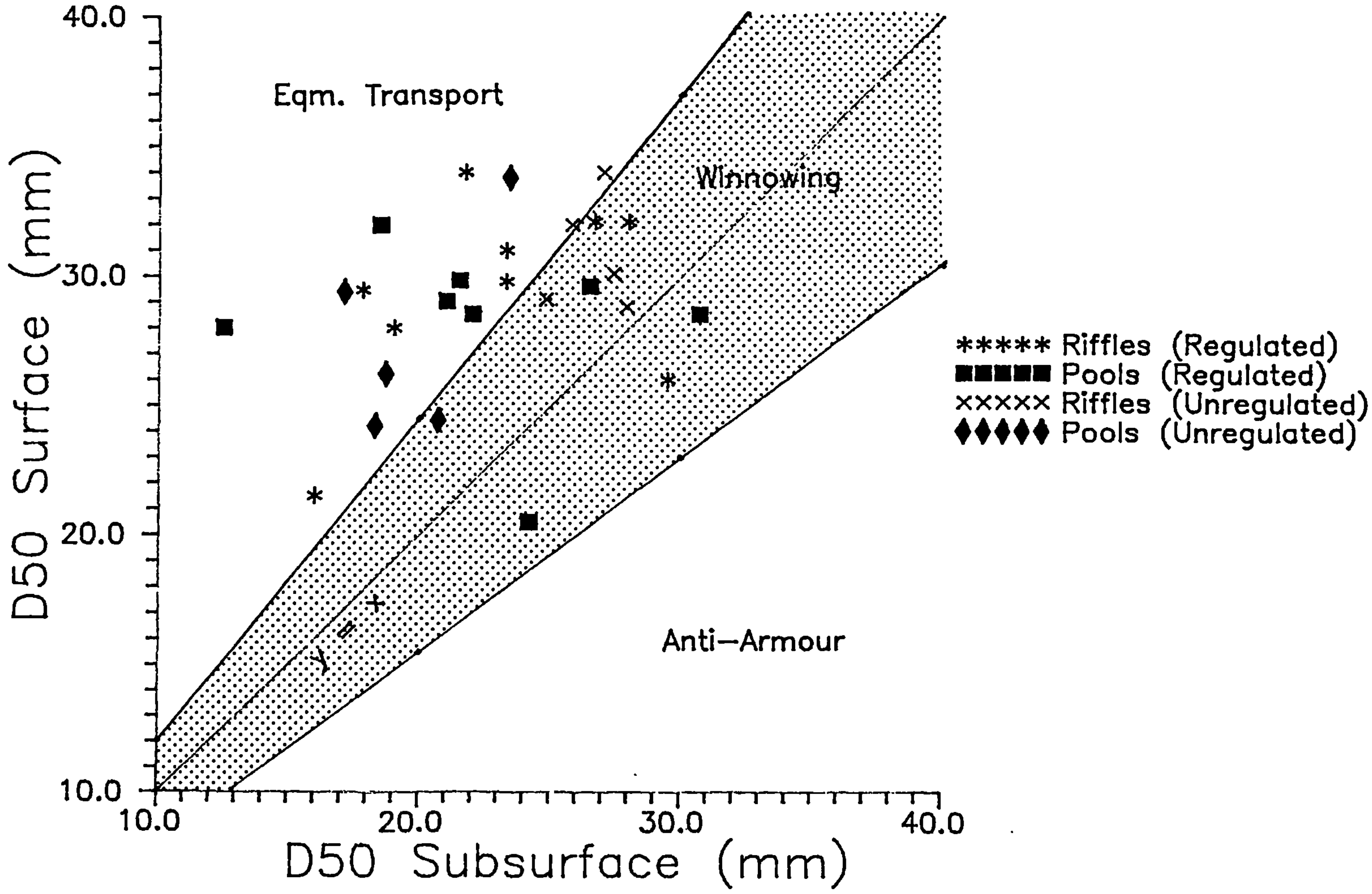
average 2.40 (se = 1.24) for riffles and 2.32 (se = 1.14) for pools within the North Tyne catchment. These values suggest strongly developed armour, on the basis of Lisle and Madej (1992), who report average values of > 2.00 for other rivers, and 1.57 and 1.23 for their aggraded and degraded channel reaches, which they classify as weakly armoured. Truncated values average 1.25 (se = 0.201) for riffles and 1.38 (se = 0.345) for pools within the North Tyne catchment. For comparison, Church et al (1987) record armour ratios for a bar surface over a range 0.8-1.81 ($\bar{x}$ = 1.16, se = 0.248).

The example used by Church et al (1987) was collected for the purpose of investigating the discriminative function of the armour ratio for determining the modus operandi of the causative process. However, there is no reference given to the range outside which the armour ratio discriminates between winnowing or over-representation. To assume a value of 1 for the limiting value is too naive, given the sampling errors inherent in coarse gravel sampling; the unstated value used by Church et al (1987) is > 1.20 for equilibrium transport, but no rationale is given for this cut-off. For the purposes of this study, a cut-off based on a 20% margin of error (the expected error for a sample of 50 stones - see above), about the average calculated truncated armour ratio (1.38), was used to discriminate between the over representation of coarse particles at the surface, and that resulting from the winnowing of finer particles on the recession limb of floods; this gives a range of between 0.72-1.28 for winnowing to be the dominant process.

Figure 5.6 illustrates the scattergram of D_{50} surface vs. D_{50} subsurface sediments for truncated pool-riffle sediments. Both equilibrium transport and winnowing are operating within the North Tyne riffle sediments, whereas winnowing is the only process operating to produce the armouring on unregulated riffles. Analysis of the grainsize distributions indicates that the accentuated levels of coarse surface sediments result more from the lack of 16-22mm sizes than from an increase in 45mm particles. This is supported by the evidence from the re-survey of FBA gravel sampling described above. This suggests that winnowing dominates the development of riffle armour, and furthermore, that the regulated riffles are experiencing enhanced winnowing of large particles over and above that present on the unregulated riffles.

The position of pool sediments indicates a dominance of over-representation of coarse sediments at the surface, suggesting conditions equating to a mobile pavement.

5.6 Armour ratios for riffle and pool sediments truncated at 11mm and 64mm for regulated and unregulated sites.



Winnowing is suggested as the main armouring process operating within 31% of the pools surveyed, although in two of these pools, the surface coarsening is reduced by a surface of fines overlaying much of the surface gravels.

The implication is that two different transport systems are operating in pools and riffles; on the riffles, armouring is largely effected through winnowing of fines from essentially the same coarse grainsize population as the subsurface, whilst in the pools, there is a general over-representation of coarse particles indicative of a mobile pavement.

Returning to Table 5.10, it can be seen that the values for armour ratio of the regulated riffles are on average greater than those of unregulated riffles for both truncated and total samples. In contrast, the unregulated pools exhibit an average armour ratio in excess of the regulated pools for truncated samples, but this position is reversed when the total samples are used. Clearly the regulated riffles are experiencing winnowing which is significantly affecting the grainsize populations of the surface layers, whilst the pool sediments are responding in no obvious manner to the imposition of regulated flows.

The armour ratio values for the total samples indicate that riffles possess a greater degree of armouring than pool sediments; however, upon truncation this position is reversed. The reversal is due mainly to the reduction of surface coarsening in the riffle surface sediments as a result of truncation at 45mm.

An application of the Sign test reveals that for total sample armour ratios, the only statistically significant variation between riffles and pools is an accentuated value for unregulated pools over unregulated riffles. The Mann-Whitney U-test showed that the armour ratio of regulated riffles derived from the total sample was significantly higher than for regulated pools at the 95% ci, and that unregulated pools exhibited a significantly higher armour ratio than unregulated riffles for truncated sample data.

In a comparison between regulated and unregulated riffles using the Mann-Whitney U-Test, both the total and truncated samples showed statistically significant lower armour ratios on unregulated riffles, indicating that the observations are not the result of random variation. A similar test applied to regulated and unregulated pools indicated that only total samples revealed a significant difference between populations, with unregulated pools exhibiting higher values of armour ratio.

5.7 Particle Shape of surface sediments in riffles, pools and bars.

The data collected for particle shape gave the following average values for the three dominant morphologies within the North Tyne:

Table 5.11 Average values for particle shape indices for riffles, pools and bars within the North Tyne.

Morphology	Flatness	Sphericity	%Sphere	%Disc	%Blade	%Rod
Riffle	229	0.673	28	37	17	18
Pool	207	0.687	20	53	12	15
Bar	213	0.670	19	45	18	18

Riffle n = 6; Pool n = 6; Bar n = 9.

On average, the values indicate that riffles possess flatter, less spherical particles than either pools or bars. Contrasting evidence is derived from the Zingg classification of particle shape, which indicates that riffles possess more spheres and fewer discs than either pools or bars, whilst blades and rods are inconclusive as morphological discriminators.

Statistical analysis indicates no significant difference between values of flatness or sphericity for riffles, pools or bars in terms of magnitude. However the Sign test indicates that pools possess a significant incidence of higher sphericity values than riffles at the 95% level.

The results of the Zingg particle shape analysis reveals that, in terms of magnitude of difference, pools possess a significantly higher number of Disc shaped particles, all other shape classes exhibiting insignificant variations between morphologies. The application of the Sign test does show that pools have fewer spheres and greater numbers of discs than riffles, all other variations being statistically insignificant.

These results appear to confirm that sediment sorting on the basis of particle shape is present within riffles and pools, but is not significant in terms of the magnitude of variation. It is also clear that the choice of shape index will determine the nature of the variation between riffle, pool and bar morphologies. The use of the Zingg classification of particle shape suggests that riffles possess accentuated levels of spheres and fewer disc particles than pools, whilst the opposite is suggested sphericity and flatness indices. This latter point confuses the arguments for a shape-based discrimination of riffles and pools, and supports Clifford's (1990) arguments for more research into both particle shape in terms of its actual characterisation, and the variation within gravel-bed channels.

5.8 Conclusions: the effects of river regulation on riffle and bar sediments and the variations between grainsize populations of riffles and pools.

The results of the sedimentological analysis confirm that subtle sedimentological differences have occurred since river regulation, dominant of which is the armouring of the salmonid spawning riffles against a basin-wide trend of bar fining. Armouring of riffles and bar sediments is particularly evident at sites within 5 km of the dam site, although other sites further downstream are similarly affected. This is supported by the results of a contemporary survey of riffle sediments from unregulated tributary streams, which indicate that the armour ratio within the regulated North Tyne is accentuated above unregulated levels. Furthermore, the results indicate that the process of riffles armouring is largely through the winnowing of fines from the surface layer of particles.

The discrimination of riffle and pool sediments is not clear cut, and although there is a significant trend towards finer pool surface sediments, the magnitude of the variation is not significant. In contrast, bar surface sediments are clearly differentiated from riffle sediments both in terms of surface and subsurface sediment size. The subsurface sediments of pools and riffles are not significantly different, except for a tendency for riffle D_{84} particles to be coarser than pools. The sedimentological variation between riffles and pools is therefore subtle, and most obviously expressed in the surface sediments.

In contrast, the intra-pool sediment sorting produces significantly different grainsize populations, characterised by a downstream fining from pool-head to pool-tail. Consequently, the coarse surface riffle sediments are adjacent to the finer upstream pool-tail sediments. The pool-head and pool-tail regions therefore represent transition regions between mid-pool and riffle. This is reflected in the morphology of the riffle-pool sequence, whereby pool-heads are often narrower, deep regions of pools, whilst pool-tails are wider shallower regions (Chapter 4).

The armouring process of riffles varies from that in pools, with winnowing dominating the development of armour on riffles, and equilibrium transport dominating that in pools. Importantly, this suggests that the armour layer on riffles is developed whilst the coarse particles are static, whilst pool armour is developed during floods when the bed is mobile.

Though inconclusive, there is evidence to confirm the observations of Clifford (1990), that riffle sediments contain flatter particles than pools, although the method of shape characterisation governs the evidence for this observation.

Armouring, and sediment size and shape considerations, provide only part of the analysis of sedimentology within gravel-bed rivers. The following section will examine the variation in bed structure and the strength of the river-bed at riffles and pools.

Chapter 6.0

Bed structure and bed strength in riffles and pools

6.1 Introduction

The previous section described the variability between sediment sample populations on the basis of particle sizes and shape. Discussion of the armouring process, and the protection afforded by this state to subsurface sediment, introduces the effect of particle interaction (Clifford 1990; Richards and Clifford 1991). The armouring or paving condition alone does not define the complexity of a gravel bed.

A review of the recent literature on gravel bed river sedimentology reveals a picture of increasing complexity of particle arrangement (Brayshaw 1984; Naden and Brayshaw 1987; Billi 1988; Wolcott 1989; Hassan and Reid 1990; Clifford 1990; Clifford and Richards 1991). Furthermore, a sequence of papers has highlighted the importance of bed structure in delaying the initiation of sediment transport, and in conditioning the transport length of a given particle (Reid and Frostick 1986; Reid and Hassan 1990; Reid et al 1992; Clifford in press).

In a flume study of bed sedimentology and its effect on sediment transport, Wolcott (1989) defined "bed structure" as comprising "textural structure" including armouring and particle interlock, and "geometric structure" involving pebble clusters and imbrication. Wolcott further differentiated between particle sorting in terms of vertical segregation (armour or paving), horizontal segregation (pebble clusters), and particle alignment (imbrication).

The importance of bed structure to sediment transport is put succinctly by Wolcott, who states: "The ability of the bed material to resist transport is much more a function of the architecture of the surface material than it is of the grainsize" (Wolcott 1989).

6.2 The structure of river beds

Forms of bed structure within gravel-bed rivers have been identified since Johnson (1922) discussed imbrication. Subsequently, numerous authors have added to an increasing typology of structural elements, ranging in size from microscale features of two or more particles (pebble clusters, Dal Cin 1968) to mesoscale features discernible across a channel width (transverse ribs, Kosta 1978).

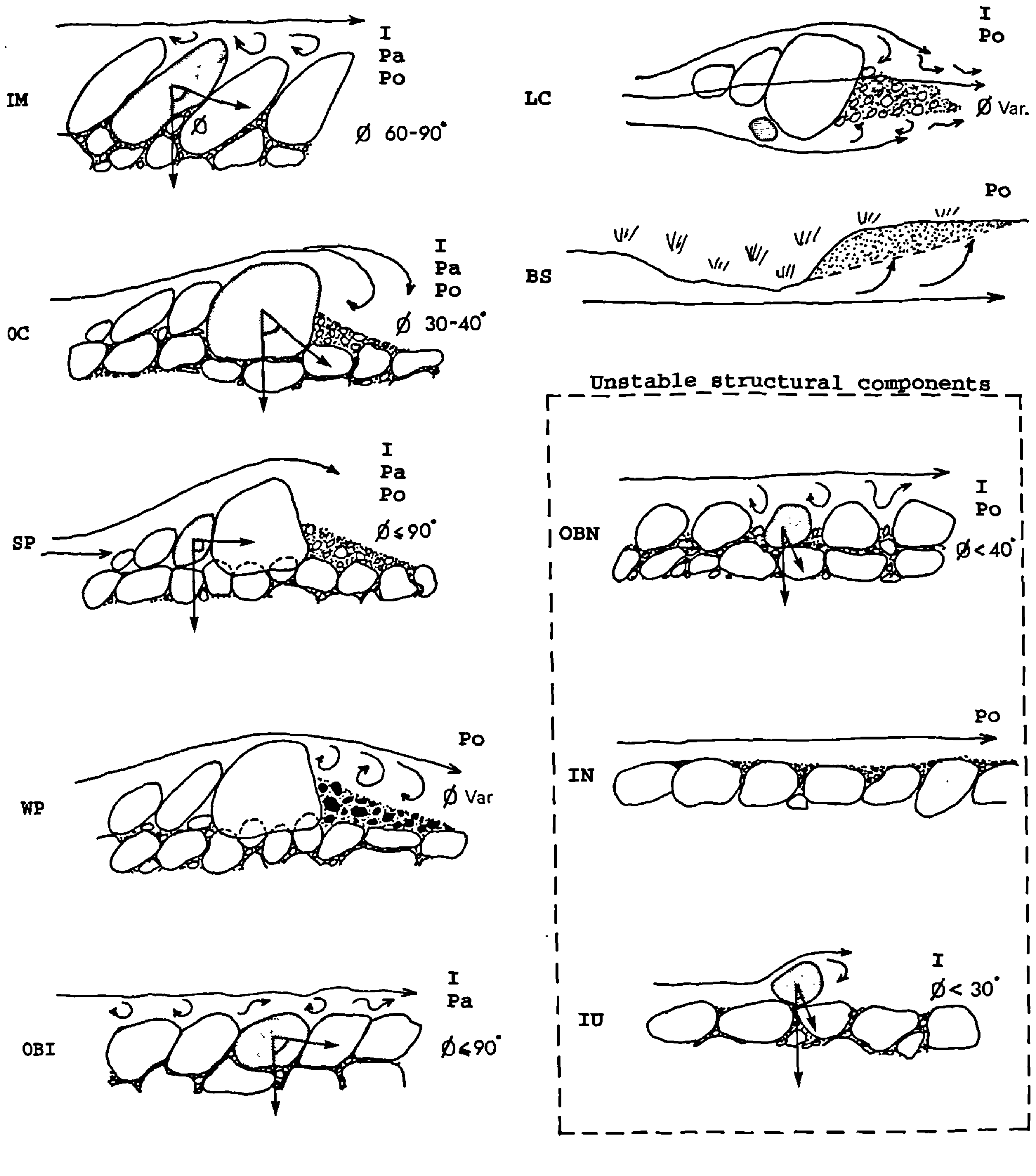
Several authors have attempted to distinguish between bed structures on the basis of size (Naden and Brayshaw 1987); alignment, parallel to flow or transverse (Richards and Clifford 1991); in terms of particle arrangement, interacting or open (Clifford 1990); morphologically clustered (Brayshaw 1984;1985); degree of dip (Rust 1972); and degree of packing (Larrone and Carson 1976; Billi 1987).

Brayshaw (1983) identifies cluster bed forms as the most prevalent feature of bed structure within gravel-bed channels, covering up to 15% of the stream-bed. Dal Cin (1964) was amongst the first to describe these features, although the comprehensive description of cluster morphology is attributable to Brayshaw (1983;1984;1985). Clusters are built of three essential components (Figure 6.1): an obstacle clast, frequently the largest of the component particles; a variable number of stoss particles; and a tail or shadow of wake particles. The forms of pebble clusters themselves have been subclassified on the basis of the presence or absence of stoss or wake particles (Billi 1987). Size sorting occurs within a cluster, although not necessarily consistently, as Figure 6.1 depicts. Obstacle clasts are often (but not exclusively) the largest particle (>D_{95}), followed by stoss particles. Wake particles are consistently of fine calibre (D_{46} max) and are considered to represent the temporary storage sinks for under-capacity bedload (Carling and Reader 1982).

The formation of pebble clusters is attributed to the pressure field developed around an isolated large particle (Brayshaw et al 1983). The separation wake downstream of an isolated particle produces conditions that reduce a particle's exposure to lift and drag. Conversely, the stoss side position is exposed to strong downward flow that scours out small particles. The depostion of larger particles results from their collision with the obstacle clast under conditions of decreasing discharge (Brayshaw et al 1983; Brayshaw 1984).

Loosely clustered particles are considered by Brayshaw et al (1992) to be intermediate in stability between pebble cluster components and open-bed clasts. Loosely clustered particles are those that, whilst not a functionary element of a cluster, are nevertheless stable relative to open-bed particles by virtue of the distortion of the flow field generated by proximity between clasts. Leopold et al (1964), and Langbein and Leopold (1968), isolated this phenomenon in the field by examining the entrainment, transport length and velocity of particles in positions of decreasing proximity. Efficiency of entrainment decreased as particle spacing

Figure 6.1: Definition sketches of structural components and their associated stability factors and hypothetical pivoting angles.



Stability Factors: I = Inertia, Pa = Packing, Po = Position

Ø = Approximate Pivoting Angle

decreased (Brayshaw et al (1992), and particle velocity declined with particle proximity (Langbein and Leopold 1968).

Imbrication refers to the alignment of particles with the major (A) axis transverse to flow direction, and dipping upstream (Figure 6.1). Rust (1972) identifies a relationship between particle A-axis and the angle of imbrication. This has important implications for particle entrainment, as Li and Komar (1989) have shown that increasing the pivoting angle (essentially the angle a particle must turn through in order to exit the stream bed) decreases the ease of particle entrainment. In fact Li and Komar (1989) found that imbrication increased the pivoting angle by a factor of two, making imbricated particles amongst the most stable positions on the stream-bed. An analysis of particle pivoting angle provides a useful aid to the development of a stability hierarchy of structural components (imbrication, obstacle clasts etc; see below).

Carling et al (1992) found that particle shape and amplitude of bed roughness (effectively the depth of cols between clasts) were important determinants of particle imbrication. Disc and ellipsoidal particles tended to imbricate on the roughest beds more readily than spherical or rod shaped particles (flume experiment).

Bluck (1987) has identified spatial variation in the degree of imbricated particles on a stream-bed; bar heads possessing higher numbers of particles in imbricated positions than associated bar-tails. Consequently, Bluck (1987) identifies bar heads as more stable areas of the stream-bed; fulfilling a role as "turbulence templates" (sensu Richards and Clifford 1991).

The establishment of bed structure is also conditioned by the lithology and particle shape, although the relationship is inevitably site specific (Clifford 1990; Billi 1987). Intuitively, the lithology of the stream load will influence the prevelance of different structural components; for example, the spherical flint gravels of the Turkey Brook mitigate against the development of imbrication, whilst the platy shales of mid-Wales favour imbrication. Billi (1987), although failing to link particle shape to cluster density in two Welsh mountain streams, does note the prevalence of imbrication over clusters in the stream with the highest percent frequency of disc shaped particles. Hassan and Reid (1990) suggest that particle shape may affect the streamwise spacing of clusters and therefore the density of clusters on a streambed. Clifford (1990) notes that the degree of structuring in pools was affected by the dominance of a given particle shape; less structure when particle shape is dominated by spheres and greater structure when discs dominate. However, this relationship is not consistent and other factors are important for determining the spatial structuring observed in rivers. The evidence for the effect of particle shape suggests that it is not important for determining total transport lengths (Carling 1987), but plays an indirect role in influencing initial motion through its effect on pivoting angle and bed structure (Komar and Li 1986). Melhand and Norman (1969) found that shape influenced the velocity of particles, with spherical particles travelling faster than other categories of shape. However, this was considered of secondary importance to particle weight and size.

Reid et al (1984) refer to the effect of fine sediment infiltration into porous gravel-beds in terms of bed consolidation. In conjunction with measurements of bedload, Reid and Frostick (1986) identified a two-fold increase in the entrainment threshold for the initiation of bedload motion as a result of consolidation. Furthermore, the authors showed that the amount of infiltration was increased during extended periods of low flow; in relation to the annual hydrology experienced in Britain, this equates to a more consolidated bed at the end of the low summer flows. The infiltration of fine sediment into the pores within the gravel-bed of the North Tyne was discussed in the previous chapter, and identified a relationship between discharge and the amount of infiltration. However, an important observation noted in this investigation and in the flume experiments of Diplas (1992) is the censoring of the surface layers. Under these conditions the bed surface will not be consolidated as a result of infiltration, but rather the subsurface. Consolidation of riffle surface sediments where local hydraulics and sediment supply will determine fines infiltration, are compacted by the continuous "rattling down" of bed particles as described by Dietrich et al (1990).

At this time no rigorous hierarchy of structural stability exists within the literature, but rather confusion as to the relative roles of structural assemblages in the sediment transport process. From the discussion above, it is clear that three forms of particle stability exist:

* stability by virtue of position (clustering distorts the flow field, creating loci for preferential clast deposition);

* stability by virtue of inertia (mass of particle);

* stability by virtue of packing (tightness of packing/interlock).

Clearly, in order to quantify the stability of the stream-bed, a measure of all three parameters is required. This is discussed further on in this chapter (Figure 1).

6.3 The effects of structure on sediment transport.

The documented effects of bed structure on the entrainment and transport of sediment are summarised in Table 6.1. Contained within this Table are references to different types of bed stability, including structure and consolidation. The summary of Table 6.1 suggests that bed structure (including consolidation) affects sediment transport through:

1. increasing the force required to move a given particle;

2. interacting with the flow to produce boundary layer separation, whereupon the force acting on the constituent bed surface particles is reduced;

3. providing a rougher surface which traps particles overpassing and reduces the sediment transport rate.

The evolution of structure theory can be summarised by a sequence of diagrams lifted from several complementary studies (Figure 6.2). Although of different dates, these arrange logically into a picture of structural restraint on sediment entrainment. Clustering is shown to delay entrainment of particles by increasing the shear stress required for motion through structure/flow interaction. This is illutrated in Figure 6.2a from a flume study utilising glass spheres (James 1991). The effect of structure (in general) is indicated in Figure 6.2b. Wolcott (1989) isolated the effect of structure on entrainment through the comparison of Shields stress values for particles in motion and the theortical value based on particle diameter. Figure 6.2b extends the observations of James (1991) to a live-bed flume model.

Confirmation from field conditions are shown in Figure 6.2c. Brayshaw et al (1992) present a similar analysis to Wolcott's, but based on the difference in entrainment threshold shear stress of non-structured (exposed) particles and different components of pebble clusters. Thus in Figure 6.2 there is evidence for a transport limiting effect of bed structure from controlled flume to unsteady field conditions.

Table 6.1 : Documented effects of bed structure/compaction on entrainment thresholds in gravel-bed rivers.

Frostick et al, (1984)	**Bed Consolidation**	5x increase in Stream Power required for entrainment.
Brayshaw, (1985)	**Bed Structure**	> % of open-bed particles entrained per flood than clustered particles.
Komar & Li, (1986)	**Imbrication**	The threshold Shields stress for imbricated particles is 5-6x > than for spherical particles, and 2-3x > than for elipses.
Naden & Brayshaw, (1987)	**Bed Structure**	Critical shear stress for open bed particles is, on average,10 % lower than for clustered.
Robert, (1988)	**Pebble clusters**	Cluster microforms increase the roughness of the stream bed and impart an additional component of shear stress. Density of microforms reduces grain resistance.
Ferguson et al, (1989)	**Bed roughness**	To entrain 8-64mm particles requires a shear stress of 40-50 N/m2 on gravel beds, and 8-16 N/m2 on sand beds.
Wolcott, (1989)	**Bed Structure**	Increases the Shields stress required for entrainment. Structure also reduces sediment transport rate. Structure is destroyed above a Shields stress of 0.12. Bed structure takes 1 month to develop under uniform flows.
Petit, (1990)	**Imbrication**	Imbrication increases the shear stress required to entrain 8mm gravel on riffles
Hassan & Reid, (1990)	**Pebble clusters**	Increasing density of pebble clusters reduces the sediment transport rate.
Carling et al (1992)	**Bed roughness**	Increasing roughness increases the value of the Shields entrainment parameter for a given grainsize and shape.
Reid et al, (1992)	**Bed Structure**	Shields stress for clustered particles is on average, 1.2x that required for plane-bed particles, although the range of values are similar. Travel distance of particles is affected by structural position: WP travel 35% distance of plane bed, SP 54%, LC 81%.

Fig 6.2 Documented effects of bed structure on the dimensionless shear stress at entrainment. After (James 1991; Wolcott 1989; Brayshaw et al 1992).

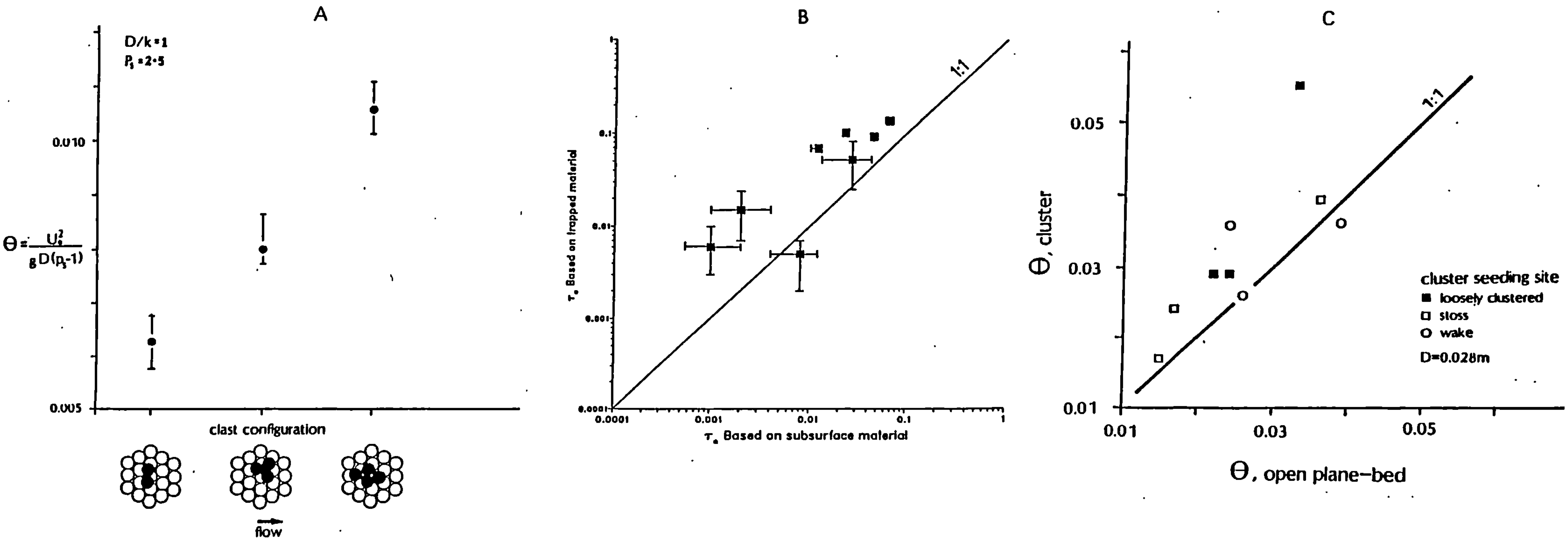


Figure 6.2c also suggests that there exists a stability hierarchy within bed structure. Quantitative approaches to the effect of bed structure on sediment transport have been conducted in field conditions by Brayshaw (1984;1985,) Reid and Frostick (1984), and Reid et al (1992). Using a combination of electromagnetic bed load sensors and painted tracer particles, the authors developed a hierarchy for the entrainment thresholds and transport distance between pebble cluster components (stoss,obstacle and wake particles), loosely clustered and open-bed micromorphology. They found that open-bed particles moved first and further than loosely clustered, stoss, wake and finally obstacle clasts. Field measurements by Billi (1988) have subsequently challenged the stability hierarchy between stoss and wake clasts. Both Billi (1988) and Clifford (1990) attribute the uncertainty in stability hierarchy to the effect of secondary current activity and turbulence, claiming that the presence of both phenomena will cause cluster decomposition by lateral dispersion. Considerable scatter was found both in the transport length data and the entrainment thresholds.

Petit (1990) has shown from field and flume experiments that "geometric structure" can have significant effects on the force required to entrain a particle. Documented values show that imbricated particles require up to three times the force needed to entrain a comparable exposed particle.

Larrone and Carson (1976) concluded qualitatively that "form structure" and bedload movement were "closely interrelated" and that flood severity greatly increased "bed structure" (a fact observed earlier by Scott and Gravlee 1968), and as a result the river bed would react to flooding by stabilising. However, as Gomez (1983) and Wolcott (1989) have shown, the time after flooding that an observation is made will determine the degree of structural development. Wolcott (1989) identified limiting conditions to structure development, including a lack of structure development at Shields stress values greater than 0.12, and at a density of structural elements greater than 10-15% of the bed surface. Billi (1988), however, observes that the processes of structural assemblage and decomposition are complex, being dependent upon the position in the channel, the flood intensity and antecedent flood history. Wolcott (1989) suggests a time for maximum bed structure development of 1 month under conditions of steady flow below the critical threshold for structural decomposition, whilst Gomez (1983) records 1-3 months under unsteady flow for redevelopment of the armour layer.

The Turkey Brook experiments conducted by Reid et al (1992), Reid and Frostick (1986), illustrated that an important effect of bed structure was in delaying the entrainment of particles during a flood event. In conjunction with flume experiments (Brayshaw 1985), the data on the role of flooding in structural development was determined to be one of destruction of structure (clusters) on the rising/peak of an event, and the reformation during the recession. De Jong (1990) describes a process of cluster dispersion (and reformation) during floods which supports Billi's (1988) contention that clusters represented active elements of the bed, based around a stable obstacle clast. It is important to note that in all flood surveys, concentration on the dispersal of tagged clusters leads to ignoral of other cluster development. The observations of Billi and de Jong strongly suggest that clusters are dispersed <u>and</u> developed during flood events.

Bed structure, in conditioning the entrainment of particles, is also likely to affect the local patterns of sediment transport. Two flume studies by Wolcott (1989) and Hassan and Reid (1990) have shown that sediment transport rate is inversely related to the flow resistance generated by increasing density of bed structure on the flume bed. Both experiments were conducted under steady *flow conditions* where resistance reduction during rising stage will be absent (Bathurst 1982). Furthermore, recent findings by Nouh (1990) suggest that the form of the flood hydrograph will condition the subsequent bed surface. As ever, care must be exercised with the extrapolation of flume results to field conditions; however, both independent studies confirm a reduced sediment transport rate as structure develops.

Two theories are developed by these flume studies which account for the reduction in sediment transport in two different (but interrelated) manners:

1. The reduction in sediment transport is due to an increasing percentage of particles becoming incorporated into stable structural positions (Wolcott 1989); this is the scenario applicable to stuctural development from an "overloose" bed (Church 1972).

2. Once formed, increasing structural density (pebble clusters in this experiment) initially increases the flow resistance, which decreases the energy available for entrainment until "skimming flow" (sensu Nowell and Church 1979) occurs, at which point bedload transport is further reduced, since the mainstream flow is lifted clear of the bed by a "quasistable vortex" generated by high cluster densities (Hassan and Reid 1990). This is the scenario applicable to the condition where structure already exists.

Recent studies of bed morphology in gravel-bed rivers have shown bed structure to be spatially varied (Billi 1987; Clifford 1990; Lisle and Madej 1990). Lisle and Madej (1990), investigating degrading and aggrading sections of the Redwood Creek, described a morphological linkage between riffles and pools and the degree of armouring. Armouring (defined as the ratio D_{50}surface/D_{50}subsurface) was found to be well developed on riffles, whilst in pools the armour was poorly developed and in many cases cloaked by sand. Billi (1987), in his analysis of the bed fabric of two small mountain streams, noted a propensity for riffles to exhibit higher frequencies of pebble clusters than pools. Independent confirmation by Clifford (1990), from granite streams in Exmoor, suggests a linkage between riffle-pool morphology and the extent of bed structure. Although the techniques vary, both writers show that riffles exhibit up to 80 % more bed structure than associated pools. Hassan and Reid (1990) describe the spatial distribution of clusters on the stream bed of Turkey Brook, and identify bar surfaces with regions of high cluster density. Hassan and Reid (1990) also suggest, from both flume and field experiment, that the spacing of clusters represents an equilibrium response to sediment transport control, whereby the spacing of pebble clusters responds to maintain a balance in sediment throughput, similar to a ripple/dune system. Naden and Brayshaw (1987) expand this point on theoretical grounds, and suggest that pebble clusters function as micro-kinematic waves; as such they can operate as potential entrapment sites for particles, even though they are themselves in motion during floods.

6.4 Methodology

With the importance of bed structure and interlock established, it was considered necessary to investigate the effect that the regulation of the North Tyne had produced. This is particularly pertinent when considering the degree of armouring within the channel as a result of regulation (Chapters 1 and 5) and due to the prolonged periods of constant low-to-moderate discharge. The latter point is important when one considers the conditions required for maximum structural development identified by Harrison (1951), Wolcott (1989) and Gomez (1983).

6.4.1 Location

The hypothesis that a morphological link existed between channel morphology (riffles and pools) and the degree of structural development was first developed whilst on an

Figure 6.3: Location of sites used in the structural and strength assessments of gravel beds (Site list is contained in Appendix B).

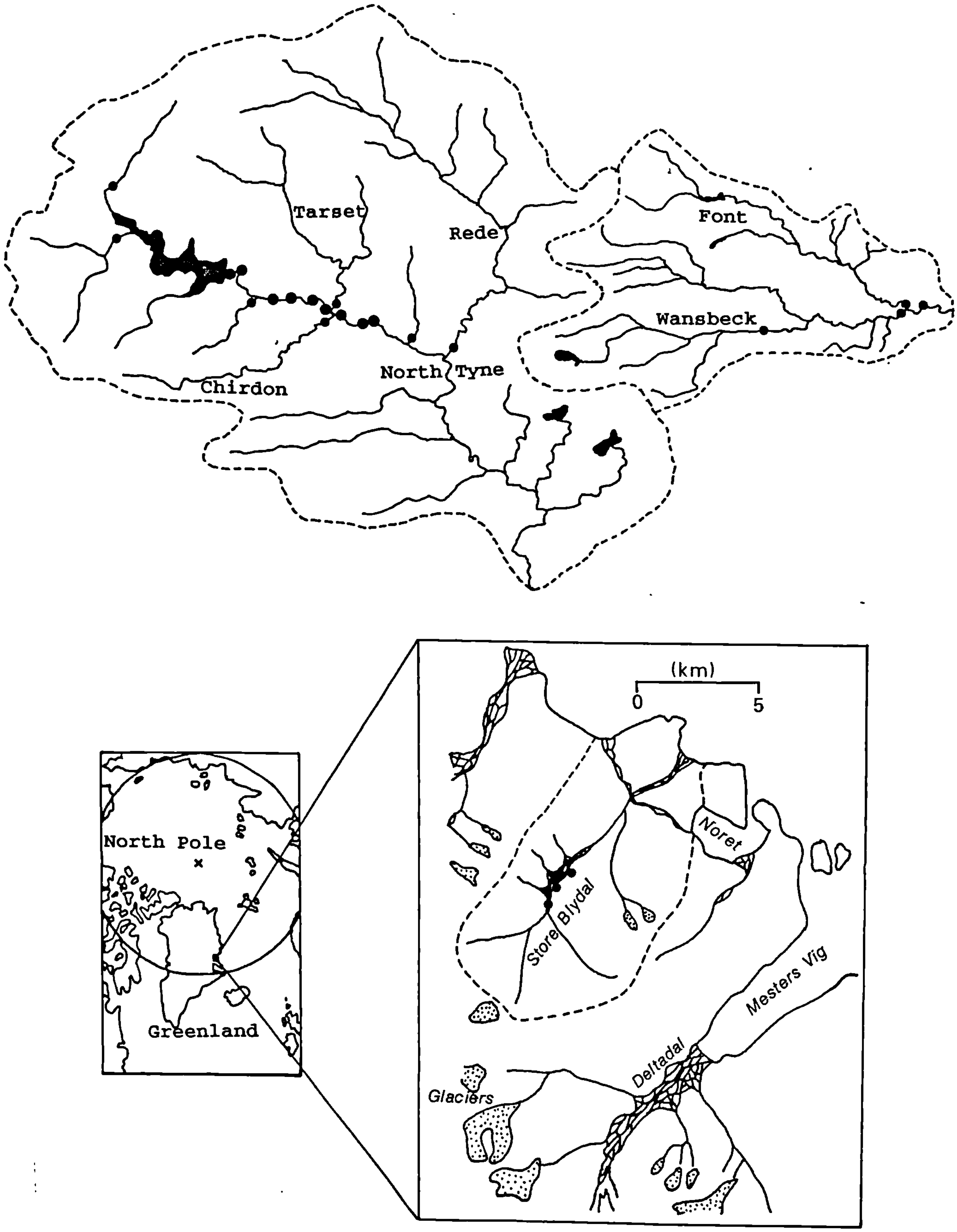


Table 6.2 Catchment details for the three rivers from which data for bed strength and bed structure were derived.

Stream	Store Blydal	North Tyne	Wansbeck
Catchment Area	115 km^2	1118 km^2	315 km^2
Geology	Tertiary Shales & Sandstones	Carboniferous Limestones & Sandstones	Carboniferous Limestones & Sandstones/Grit
Landuse	Arctic Tundra Mining (Pb/Zn)	Forestry Pasture Hydropower Moorland	Forestry Urban Arable Pasture
Slope	0.010	0.0018	0.0010
Planform	Braided	Meandering	Meandering
Width (m)	250	35	23
D_{50} (mm)	37	54	36

expedition to Arctic Greenland (Carver et al 1989; Carver et al in prep). Subsequently, upon return to the U.K., the concept was explored within the North Tyne catchment.

The data presented in this Chapter was collected from three different locations (Figure 6.3):

1. the Store Blydal River, Mesters Vig, North East Greenland;

2. the regulated River North Tyne and associated tributaries, Northumberland, U.K.;

3. the River Wansbeck catchment.

Comparative catchment data is depicted in Table 6.2, which illustrates the differing nature of the fluvial environments examined.

The Store Blydal River was investigated as part of Newcastle University's East Greenland Expedition (Carver et al 1989). The channel is a braided meltwater system, fed by neoglacial snowfields. Extensive injection of fine sediments from a lead/zinc mine in the 1950's has locally increased the fine sediment content; however, the dominant substrate is gravel.

The River Wansbeck data was collected as part of a National Rivers Authority (NRA) research project (C5.02/2). The geology and particle size are both similar to the North Tyne system.

Catchment data for the regulated North Tyne and associated tributaries is discussed in detail in the preceding chapters.

6.4.2 Methods of structural definition

Two separate techniques were developed to quantify the bed structure of the river bed: by counting the number of pebble clusters per square metre, and by establishing the percentage of particles within different morphological components.

Results from the Store Blydal river were collected whilst on an expedition to North East Greenland; correspondingly, the techniques were necessarily simple. A major braid channel was traversed and, at every 2m intervals, a transect of two, 1 metre square grids was laid. The number of pebble clusters in each grid was recorded, and the size of each obstacle clast measured. Mean water depth was also recorded and the section assigned to a morphological class, depending on whether it was at a riffle, pool-head, pool-mid or pool-tail, after Ashworth (1987). The results were then converted into a mean value for each cross section.

The preliminary results from the Store Blydal confirmed the existence of a morphological link with bed structure. In addition, it was recognised that a simple account of pebble clusters was unsatisfactory for the categorisation of structural development at a site. A technique was developed that was based on a modified "Wolman 100" grid sample of surface particles, that also accounted for morphological position (Wolman 1954). The morphological classes were drawn from a review of existing literature on bed micromorphology (see preceding discussion above), and revised according to field observations in the North Tyne. Meso-scale structures, such as transverse clast dams (Koster 1978; Bluck 1987), were omitted from the classification, since individual clasts within these features could be accounted for under the structural component classification. Figure 6.1 summarises the structural components, and Table 6.1 documents the information listed in the literature that suggested the stability hierarchy used in the classification.

Stable positions account for classes: Imbricated (IM), Obstacle clast (OC) to Open bed interlocked (OBI); and unstable position classes: Open bed no interlock (OBNI) to isolated unprotected (IU). Particle stability broadly decreases from IM to OBI. However, this is yet to be confirmed for all structural components and would provide a useful avenue for further research. The basic division into particles occupying relatively stable or unstable sites is confirmed from the literature, as well as considerations of pivoting angles, relative exposure and stability by virtue of position.

Given the recent work of Robert (1990), it would be appropriate (for future consideration) to account for the effect of different structural components upon the flow field. A higher percentage of turbulence-generating components (eg obstacle clasts) may lead to the delayed stability of the stream bed due to the development of skimming flow (Hassan and Reid 1990). In this way, structural components could be assessed in terms of delayed entrainment, degree of flow interaction and sediment transport.

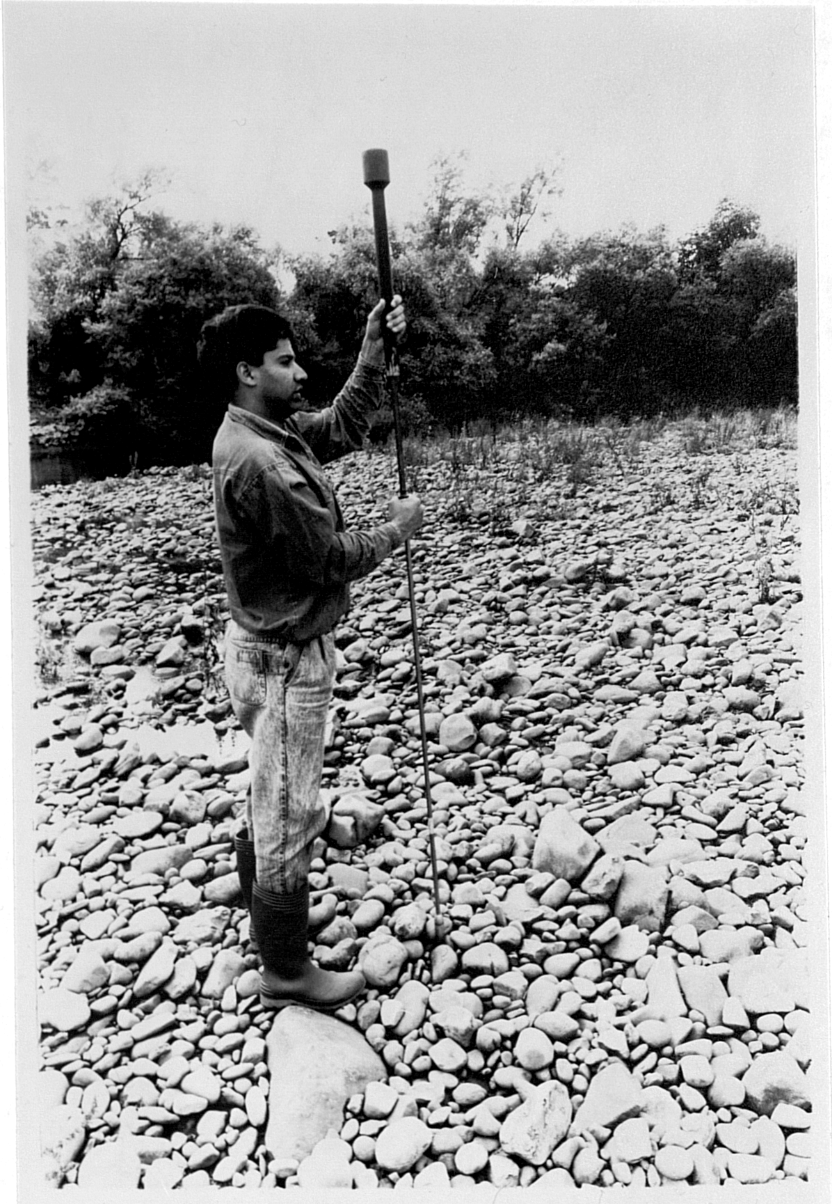
At a given morphological site (riffle or pool component), sufficient cross-sections are traversed until (ideally) 100 particles are selected (after Wolman 1954). In practice, the operational difficulties experienced in sampling large particles in deep pools limited the data collection to 50 stones. This was taken to be adequate for the determination of bed structure and particle size at a site, for the same reasons applied to "Wolman sampling" by Hey and Thorne (1983).

Each stone is allotted to a structural component and the B-axis recorded. A form developed for the collection of this data is depicted in Figure 6a (Appendix B), which includes a key to the structural components to facilitate identification. Analysis of the data included the allotment of a single value for the percentage of particles sampled occupying stable structural sites. This is achieved by summing the individual percentages for the stable structural components.

6.4.3 Determination of bed strength

The effect of geometric and textural structure is to produce a bed surface of varying strength, formerly described qualitatively by terms such as "overloose" or "compacted" (Church 1972). To index these often considerable differences in bed strength, a technique was developed based on a dynamic penetrometer. The Mackintosh probe is a robust, hand held, boring and prospecting tool used for geotechnical determination of soil strength. The principle behind the penetrometer is based on the proportional relationship between the force applied in penetrating a sediment and the force resisting penetration. In alluvium or gravels, the resisting force (expressed as the number of blows required to penetrate a given distance) is proportional to the density of the sediment and the confining pressure (Narahari et al 1967; Burland and Burbridge 1985). The confining pressure is a function of the resistance of particles to lateral displacement which involves sediment density, packing, and the degree of interlock of individual particles which will include pivoting angle resistance (Narahari et al 1967; Sanglerat 1979). There is, to date, a controversy over the interpretation of dynamic penetrometer readings, but most studies agree that, with surface values (the initial penetration from ground (or in this case river bed) level), the readings obtained can only be regarded as an index (Meigh and Nixon 1961; Sanglerat 1979; Burland and Burbridge 1985). Nevertheless, the use of dynamic penetrometering is used world wide for the qualitative determination of the compaction of sediments, and as an index of sediment stability (Narahari et al 1967).

Fig 6.4: The penetrometer used in the determination of bed strength.



The technique adopted for determining the strength of the river bed surface involves the application of a known force (10kgs falling 0.5m) through a steel cone of a given dimension to the surface river gravels. The value for penetration resistance increases with increasing surface area of the cone, which must therefore be specified in order to compare with other studies (Narahari et al 1967). A minimum amount of penetration of the cone is required for the full development of penetration resistance (Narahari et al 1967). The probe head is placed on the interstices of the gravel, and the number of blows required to penetrate 5 cm into the bed is recorded (Figure 6.4). The reference penetration depth is determined by the median diameter of bed material, and placement on interstices ensures the measurement of lateral resistance to penetration. A single reading was made at each point at two metre intervals along the same cross sections used for the structural analysis. Multiple readings per site were initially tested, but the impact of penetration tended to disrupt the surface gravels for up to 0.6m from the penetration point, producing spurious values for subsequent tests. The mean value at each section was taken as the representative value for bed strength for the particular morphology. Refusal to penetrate was taken at values of +50 Blows/5cm after Sanglerat (1979), although in some cases penetration was still evident and a reading was continued. An upper limit for practical penetration is quoted at 200 Blows/2cm (Sanglerat 1979). A major problem with the technique is in interpreting whether the resistance to penetration is due to confining pressure or the presence of a large stone beneath the surface gravels. This is largely avoided by the choice of a reference depth based on D_{50}, but in cases where finer particles occur, then some subsurface resistance is encountered. However, with practice, it is evident from vibration and sound during penetrometering whether a large stone is impeding penetration.

Narahari et al (1967) and Sanglerat (1979) provide useful qualitative scales of sediment compaction. These are summarised in Table 6.3 below.

Table 6.3: Documented values of penetration (N) adjusted to Blows per 5cm, for gravels up to 50mm (after Narahari et al (1967) and Sanglerat (1979)).	
Qualitative Description	**N value (Blows/5cm)**
Clean gravels some fines	6 - 15
Dense sand and compact gravel	15 - 30
Very loose	0 - 4
Loose	5 - 10
Medium	11 - 30
Dense/Hard	31 - 50
Very Dense/Hard	50+

Bed strength and bed structure readings were made simultaneously at a site, in order to quantify the bed stability status; this was necessary because the penetrometer readings do not take account of the hiding factor within bed structure. For example, a wake deposit will have a low penetrometer reading, although the stability of wake particles will be relatively high due to protection. High values of bed structure and bed strength are taken to indicate a higher resistance to particle entrainment at that morphology/site. This is confirmed by the literature for bed structure, and by the interdependence of bed strength on structural and inertial restraint to lateral motion.

Bed structure and bed strength were determined at 42 and 57 sites respectively. The individual sites and their associated structural and strength readings are given in Tables 6a and 6b in Appendix B. From these tables, it can be seen that repeat surveys account for nine structural surveys and 15 strength tests.

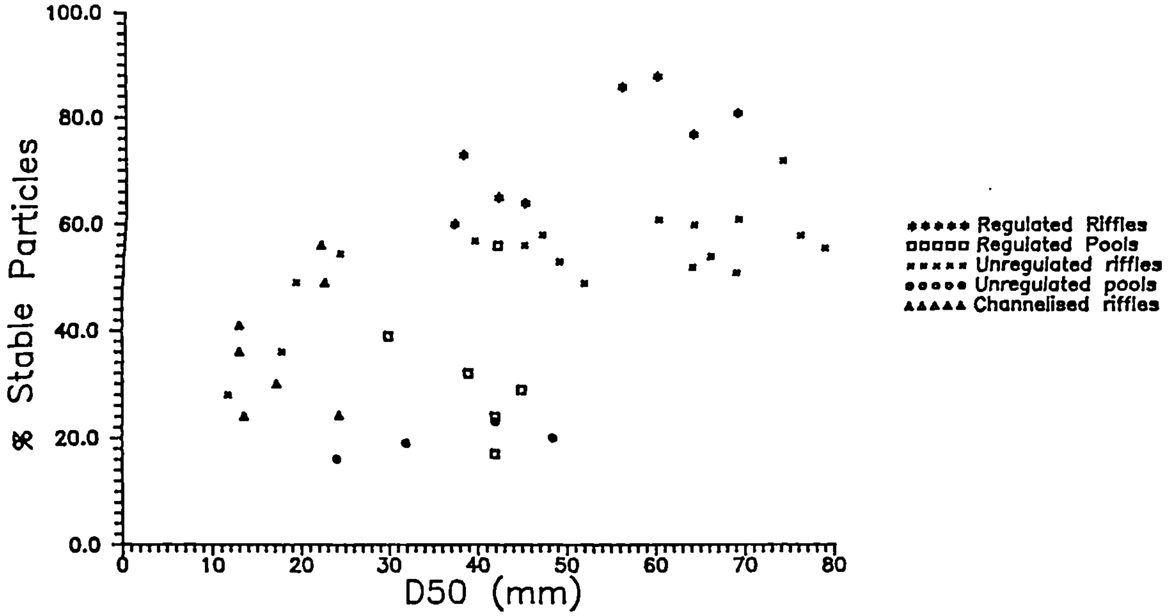
6.5 Intrinsic controls on bed structure and bed strength.

Before further discussion of the results of the bed stability analysis (bed stability refers to structural and strength tests), it is necessary to identify the interrelationships between bed structure, bed strength and a range of sediment characteristics.

Figures 6.5a-c depict scattergrams of the mean values for bed strength, bed structure and D_{50} of the surface bed material. From the discussions above, it is to be expected that both structure and strength readings will increase with increasing sediment size. Figure 6.5a appears to support the observations of Harrison (1951), that surface structure increased with particle size. However, there are clearly other contributory factors involved which cause scatter in the relationship. Within the broad pattern of

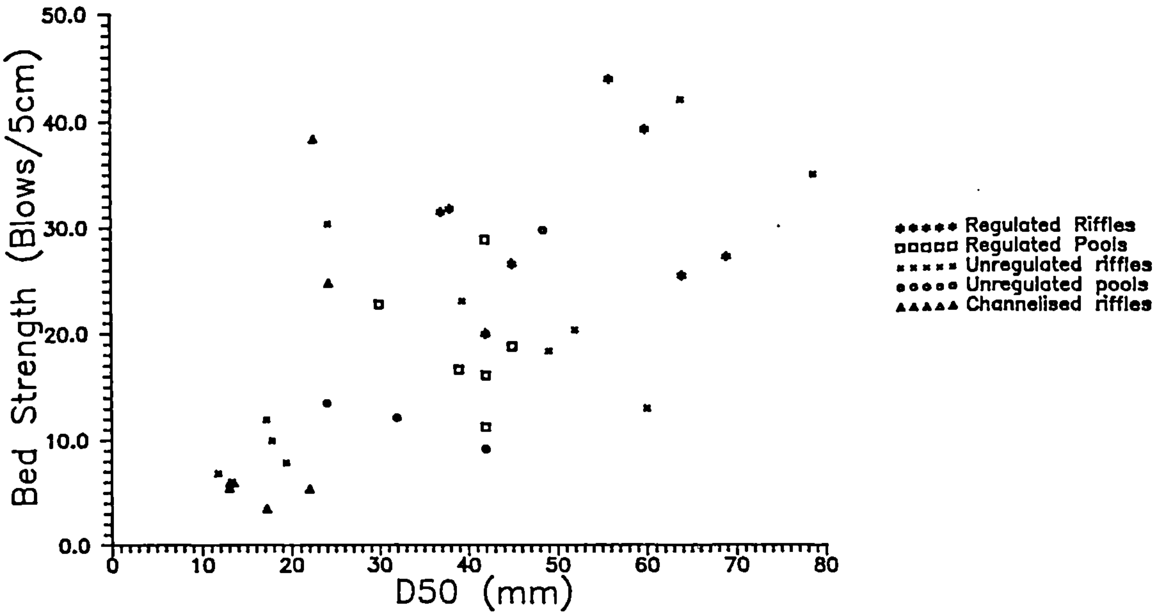
6.5 Scattergram of the Percentage of stable particles versus the D50 of the bed surface sediments. Note regulated riffles exhibit consistently enhanced values of bed structure independent of sediment size.

A



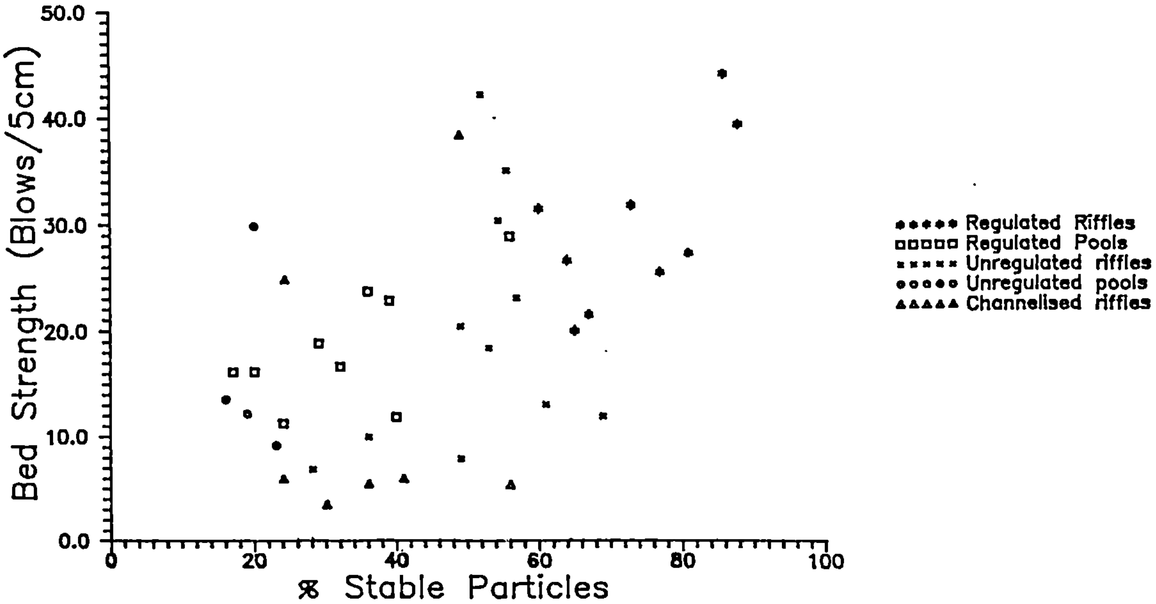
Scattergram of the average values for bed strength (determined by dynamic penetrometer) versus surface sediment D50.

B



Scattergram of the average values for bed strength (determined by dynamic penetrometer) versus the degree of bed structure as represented by the percentage of particles occupying stable positions on the stream bed.

C



increasing structural development with increasing particle size are sub-patterns that counter the observations of Harrison (1951). This is particularly evident within pools, where regulated pools show a decrease in bed structure development as particle size increases, whilst the converse pertains for unregulated pools. Similarly, the rate of increase in bed structure development with particle size appears to vary between unregulated riffles, regulated riffles (> rate of increase) and riffles in channelised rivers (>> rate of increase). More research is required to elucidate this pattern, but it appears that disturbance to the sediment transport system is reflected in the structural development of (riffle) bed surfaces. Clearly there is more to structural development than particle size alone.

Of particular note in Figure 6.5a are the consistently lower structural values (independent of sediment size) for riffles and pools, and the consistently higher values for structural development on regulated riffles than unregulated riffles. This will be discussed in detail later on in this chapter.

Figure 6.5b depicts the scattergram of mean bed strength readings against surface sediment D_{50}. There is evidence of a proportional relationship between the two variables which indicates that bed strength tends to increase with particle size. Since particle diameter is often used as a surrogate for particle weight, it is not suprising that bed strength should increase with size, since the particle mass will also increase. Nevertheless, as with bed structure, there is sufficient scatter in the relationship (particularly within morphological catagerories) to suggest the operation of additional factors in determination of bed strength.

Figure 6.5c indicates that there is also some degree of interdependence of bed strength and bed structural development. As the percentage of particles occupying structurally stable sites increases, so the strength of the stream bed increases. However, since not all structurally stable sites involve strong inter-particle contact (eg Wake particles), there is considerable scatter in this trend.

Statistical analysis between variables was conducted using the raw data for the number of particles in a 50 particle sample in structurally stable sites. This makes the assumption that although the sample size was finite, the numbers of particles in the bed are infinite, thereby satisfying the requirement for statistical analysis using regression or correlation (Ebdon 1985). Similar analysis was conducted for the average bed strength readings.

Table 6.4: Statistical analysis between bed strength and bed structure development and a range of sediment characteristics.

Variables	Rs	% variance explained	p	n
		Unregulated Riffles		
D_{50}/Structure	0.624	36	NS	11
Sort/Structure	-0.140	2	NS	11
Armour/Structure	0.000	0	NS	11
Strength/Structure	0.299	2	NS	11
D_{50}/Strength	0.471	18	NS	11
Sort/Strength	0.351	7	NS	11
Armour/Strength	0.514	0	NS	11
		Regulated Riffles		
D_{50}/Structure	0.765	52	0.03	12
Sort/Structure	0.865	71	0.001	12
Armour/Structure	-0.788	56	-0.02	12
Strength/Structure	0.665	36	0.05	12
D_{50}/Strength	0.164	0	NS	16
Sort/Strength	0.558	20	NS	16
Armour/Strength	-0.194	0	NS	16
		Regulated Pools		
D_{50}/Structure	-0.233	0	NS	6
Sort/Structure	0.000	0	NS	6
Armour/Structure	-0.585	18	NS	6
Strength/Structure	0.893	75	0.02	6
D_{50}/Strength	-0.232	0	NS	11
Sort/Strength	-0.120	0	NS	11
Armour/Strength	-0.726	41	0.05	11

Insufficient data for unregulated pool analysis.

Table 6.4 above indicates that the relationship between bed structure and bed strength is variable between bed morphology. Regulated riffles exhibit a higher degree of correlation between structural development, bed strength and surface sediment characteristics than any of the other morphologies, including unregulated riffles. Only in regulated pools was there any statistically significant relationship between bed strength and sediment characteristics, and this is an inverse relationship with armour ratio. With the exception of unregulated riffles, bed strength decreases with increasing armour ratio. In contrast, with the exception of regulated pools, bed strength increases with increasing sorting coefficient. The implications (although tenuous and requiring further research) are that poorly sorted sediments on riffles increase bed strength whilst increasing armour ratio decreases bed strength. This is intuitively correct, since an increase in armour ratio is likely to result in a decrease in sorting (Chapter 5). Clearly a widely graded sediment is required for a greater magnitude of bed strength. The lack of a relationship between sediment sorting and bed strength, in pools where surface sediments are generally more poorly sorted than riffles, suggests that another factor is involved which interacts with the poorly sorted riffle sediments to produce an increased bed strength.

Although not always statistically significant, D_{50} is always positively correlated with the number of particles in stable structural sites. However, as with all the relationships given in Table 6.4, between 30 and 100% of the variance in bed structure and bed strength is not explained by these sediment characteristics.

Particle shape has been shown to be important for the development of bed structure, both from flume studies (Li and Komar 1986; Carling et al 1992) and through the field observations of Clifford (1990). As explained in Chapter 5, particle shape was not accounted for in the same detail as other sediment parameters; however, where available, these are shown in relation to the associated average bed structure and bed strength values in Table 6.5.

Table 6.5: Bed structure and bed strength in relation to particle shape in riffles and pools. * (after Clifford 1990)						
Site	% Disc	% Sphere	Flat	Sphere	% Structure	Strength
SMR	33	27	249	0.655	86	44.1
SMP	55	12	209	0.682	56	28.9
NR1	28	37	204	0.683	60	31.5
NPH	39	29	216	0.714	40	16.1
NMP	39	29	185	0.713	36	23.7
NPT	59	14	216	0.688	20	11.8
NR2	51	20	204	0.694	64	26.6
TBR1	32	28	223	0.685	56	42.2
TBPH	56	28	223	0.669	43	----
TBMP	56	16	274	0.650	39	9.1
TBPT	40	32	200	0.692	35	----
* Quarme R	--	--	66	0.500	70	----
* Quarme P	--	--	62	0.520	42	----
* Exe R	--	--	103	0.610	71	----
* Exe P	--	--	83	0.630	48	----
* Avill R	--	--	87	0.540	62	----
* Avill P	--	--	90	0.510	29	----

The higher the flatness index, the flatter the particles and the higher the sphericity index, the more spherical the particles. The results in Table 6.5 are inconclusive, but yield some evidence to suggest that pools possess more spherical particles than riffles. Importantly, it is also evident that sorting by particle shape is of similar magnitude between components of pools as it is between riffles and (mid) pools. Both the Newton and Tarset Burn riffle-pool-riffle sequences indicate a decline in the percentage of particles in stable structural components downstream from riffle to pool-tail. However, no particle shape trend accounts for this pattern. As mentioned in Chapter 5, there is a conflict between the flatness and sphericity indices and the percentage of spheres and discs recorded in pools and riffles. Consequently, pools are shown to possess higher percentages of discs and fewer spheres than riffles, whilst in 70% of pool components a greater sphericity value is recorded than on associated riffles. This is also contrasted by flatness values that only subceed riffle values in 50% of cases cited.

Statistical analysis yielded no significant correlations between bed strength and structure and values for particle shape. Correspondingly, it can only be concluded that particle shape probably affects bed structure (particularly imbrication), but it is one of several variables. This study has failed to identify this connection with any clarity and it must therefore be put on the agenda for future research.

6.6 Results: Store Blydal

The survey results conducted in the Store Blydal river are summarised in Table 6.6. A clear morphological distinction is apparent in the mean density of pebble clusters (No./m^2). Riffles, on average, exhibit 50 % more pebble clusters than mid-pool regions. Within the pool, a distinct gradation in pebble cluster density occurs, with maximum values in pool-head regions declining through the mid-pool before rising again through the pool-tail, towards the downstream riffle.

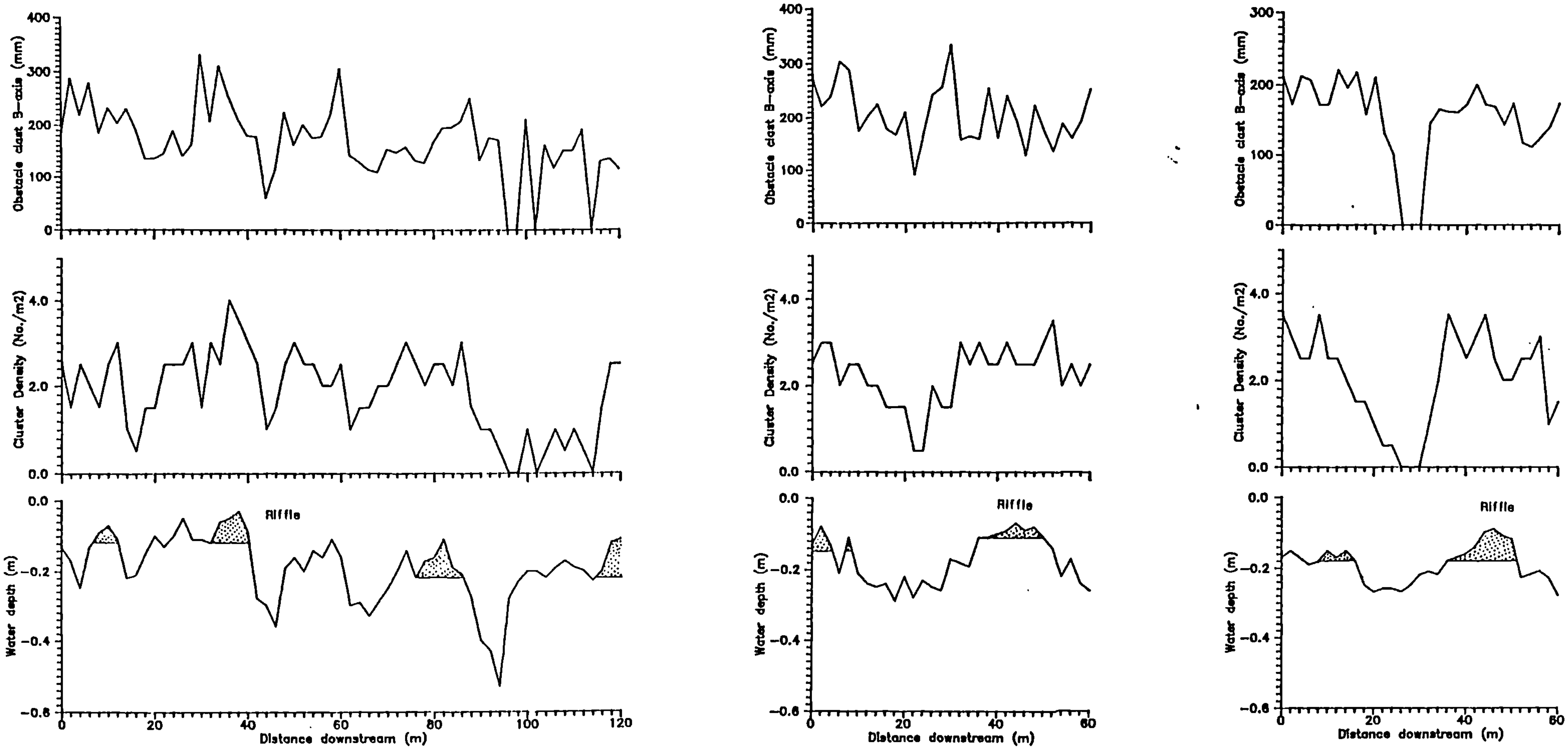
Table 6.6: Variation in the pebble cluster density and B-axis of obstacle clasts within riffle-pool sequences in the Store Blydal river.

	$\bar{x}$ Pebble cluster density (No./m2)							
Morphology	1	2	3	4	5	6	7	8
Riffle	2.3	2.9	2.6	2.7	2.9	2.3	2.3	1.6
Pool-head	0.8	1.8	2.0	2.5	1.5	2.0	2.8	---
Mid-pool	1.5	2.4	1.2	1.5	0.2	1.5	0.5	---
Pool-tail	2.1	2.5	2.3	2.3	2.4	2.5	0.6	---
	$\bar{x}$ Obstacle clast B-axis (mm)							
Morphology	1	2	3	4	5	6	7	8
Riffle	206	230	265	186	195	162	170	95
Pool-head	210	113	195	185	195	137	196	--
Mid-pool	134	174	176	172	115	122	185	--
Pool-tail	241	156	219	221	161	145	153	--

There are, of course, variations to this pattern, with some pools exhibiting enhanced cluster densities in the mid-pool relative to the pool-head.

A similar pattern exists for mean obstacle clast size, with riffles generally exhibiting the largest obstacle clasts. The sequence broadly matches the pattern of pebble cluster density, with maximum sizes on riffles fining into mid-pool regions and coarsening through pool-tails up to the following riffle. Obstacle clasts generally represented the largest bed material particles (based on a visual assessment). Although eroding banks supplied material into riffles and pools, the calibre of particles was identical to the bed material. The sequence of obstacle clast fining in riffle-pools was therefore considered to be entirely the result of downstream fining

Fig 6.6 Downstream variation in the density and B-axis of pebble cluster obstacle clasts, Store Blydal, N.E. Greenland.



caused by reach scale hydraulic and sediment transport properties, rather than sediment supply from eroding banks.

Figure 6.6 depicts the downstream trend in water depth and pebble cluster density for the channels surveyed in the Store Blydal. Each reach includes riffle-pool-riffle sequences that were delineated according to the method outlined in Chapter 4. A clear downstream variation in pebble cluster density is evident which effectively mimics the undulating bed morphology. Cross-section pebble cluster densities (calculated by multiplying the mean values by 2) ranged from 0 to 8 per square metre which compares well with the values obtained by Hassan and Reid (1990) from the single-channel Turkey Brook. The distinct spatial variation in relation to reach morphology within the Store Blydal is more pronounced than the patterns observed by Hassan and Reid, although the authors do refer to accentuated densities on bars. This distinction is predominantly a function of the well developed riffle-pool morphology that is clearly exhibiting some control on the formation (and preservation) of clusters. This supports the observations of Clifford (1990) for an enhanced bed structure on riffles in relation to pools.

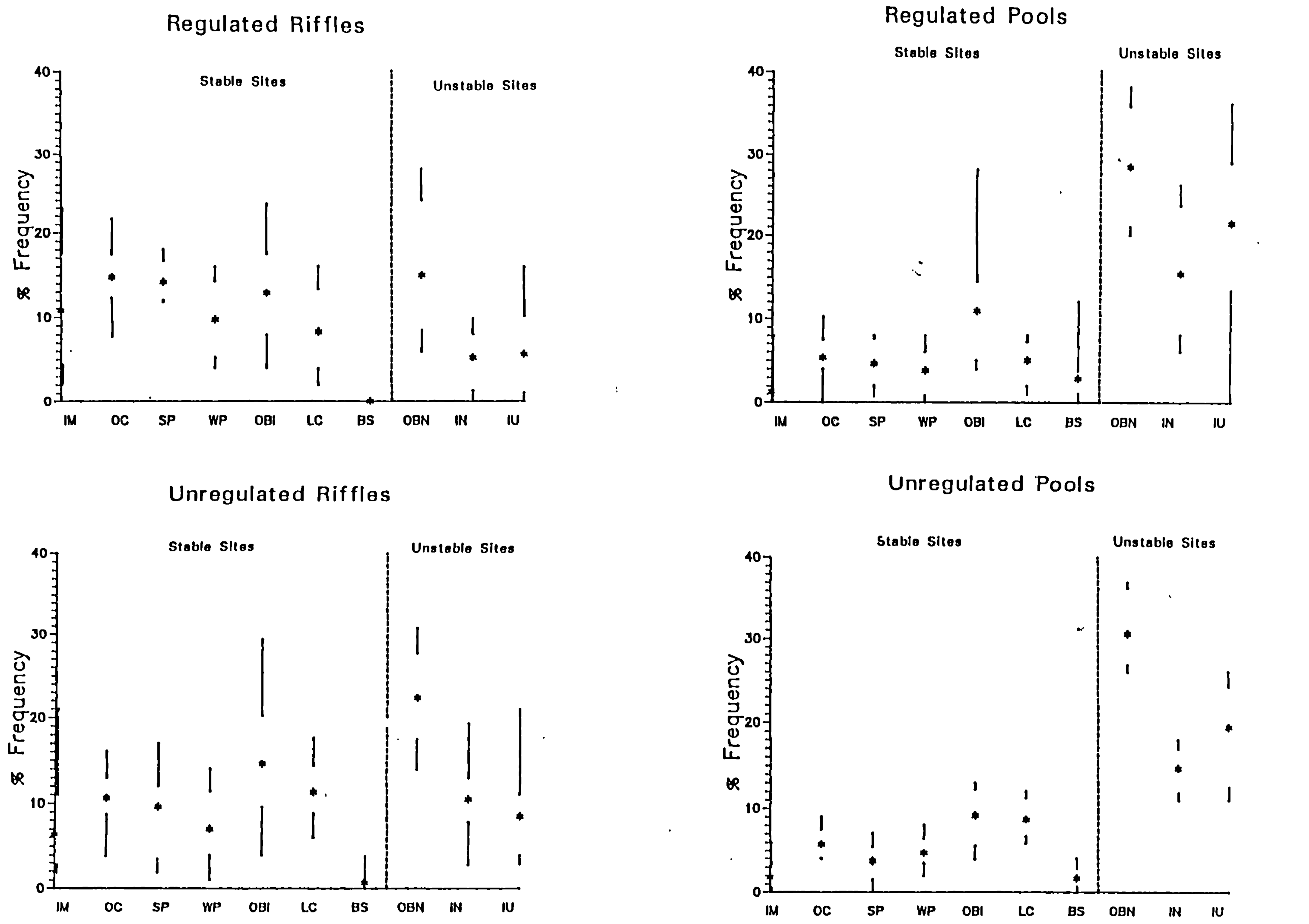
Figure 6.6a clearly shows a downstream fining in obstacle clast size, which supports the observations of Bluck (1987). Bluck suggested that sequences of bars and pools progressively rejected over and under-sized particles, which led to a downstream fining of bar-head sediments as the largest particles were trapped in the pools.

The results of the Store Blydal survey confirmed that a morphological link existed between riffles and pools and the density of pebble clusters. Furthermore, there appears to be a sorting process operating for at least the largest particles, whereby obstacle clasts decrease in size through pools, and with increasing distance downstream. The hydraulic and sediment transport implications of this are discussed later in this chapter.

6.7: Results: North Tyne

Following the results obtained from the Store Blydal, an investigation of bed structure was implemented on the North Tyne and, for comparison, on unregulated tributaries. Table 6a (Appendix B) contains the raw data which is summarised in Table 6.7 and Figure 6.7, and which illustrates the values of bed structure obtained for different morphological elements of the riffle-pool sequence. The data was collected using the

Fig 6.7 Variation in the frequency of bed structure components in regulated and unregulated riffles and pools.



modified "Wolman 50" sample.

Table 6.7: Average values of the percentage of particles occupying stable structural sites within riffle-pool-riffle sequences.

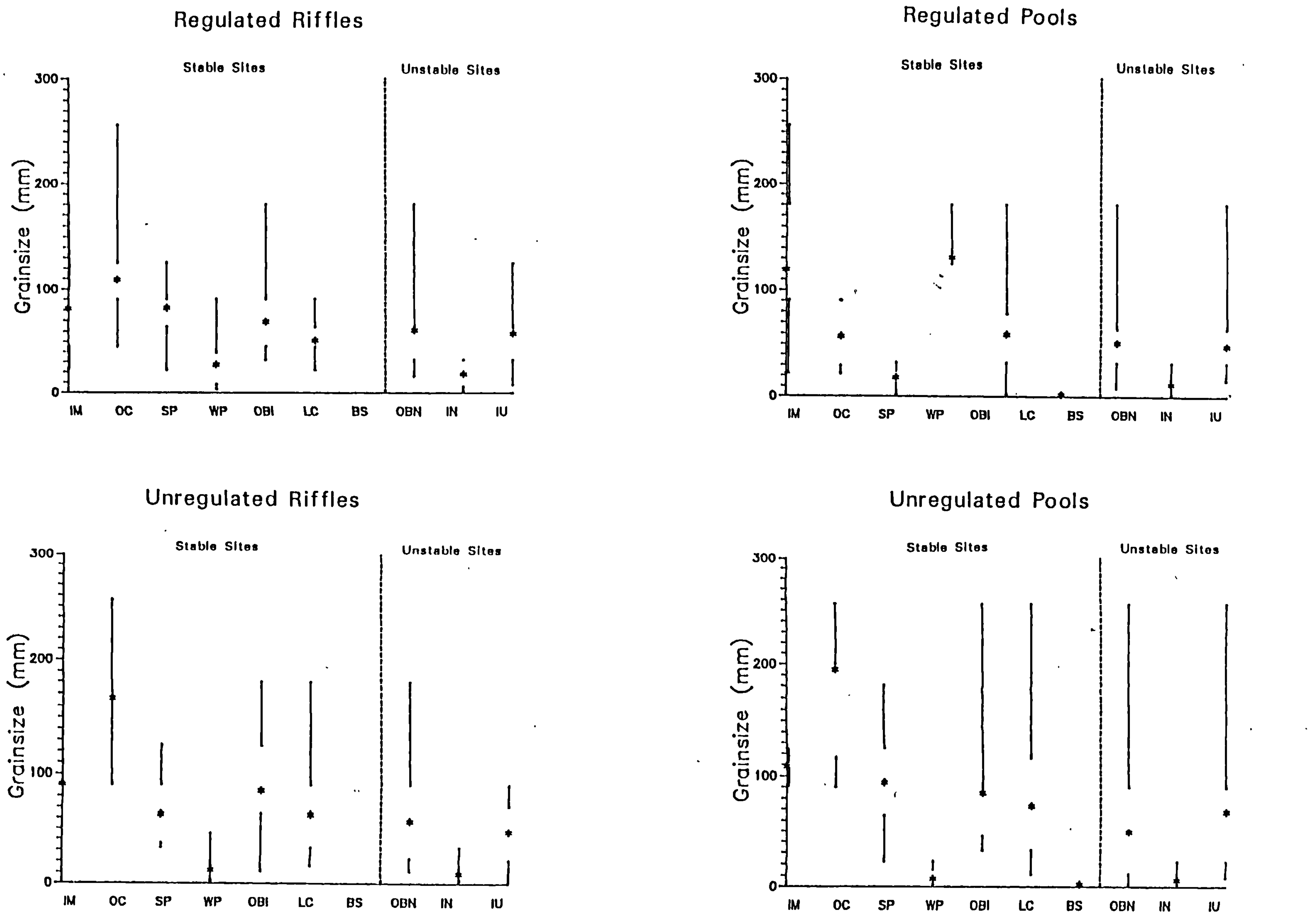
	$\bar{x}$ % Structure					
Stream	Riffle	Pool-head	Mid-pool	Pool-tail	Riffle	n
North Tyne	76.0	40.0	36.0	20.0	64.0	2
Tarset Burn	56.0	43.0	39.0	35.0	58.0	1
Chirdon Burn	60.0	----	35.0	----	----	1
Belling Burn	61.1	----	---	----	----	1
Smales Burn	73.0	----	40.0	----	----	1
Lewis Burn	72.6	----	----	----	----	1
Kielder Burn	53.8	----	----	----	----	1
River Wansbeck	57.8	----	20.0	----	----	3
River Font	54.4	----	----	----	----	1
Mimmshall Br.	50.0	----	----	----	----	3
River Avill*	72.0	----	42.0	----	----	3
River Exe*	60.0	----	28.0	----	-----	3
River Quarme*	72.0	----	46.0	----	----	3

* after Clifford (1990)

The data from Table 6a was aggregated to provide the data for Figure 6.7. A clear distinction is evident between riffles and pools. Riffles consistently exhibit higher percentages of stable surface particles than pools. This is in close agreement with the observations made by Clifford (1990) for streams on Exmoor (Table 6.7). The regulated North Tyne riffles possess the highest percentages of stable particles so far documented (88% maximum).

Clifford's (1990) technique differs from that employed on the North Tyne, in that each stone across a single section was allotted to one of three classes, according to whether a particle was "loose", "interacting" or "tight". Whilst the technique is

Fig 6.8 Variation in the grainsize of structural components in regulated and unregulated riffles and pools.



admirably simple, the adherence to a single cross-section at each riffle or pool is limiting, particularly in the light of the inter-pool variations shown in Table 6a (Appendix B). The similarity between contrasts in riffle-pool surface particle stability for all the streams studied is particularly remarkable, given the contrasting lithologies of the Exmoor streams (granite/metamorphics), North Tyne/Wansbeck catchments (sandstone/limestone), and Mimmshall Brook (Flint and Reading Beds) respectively. Clifford (1990) notes that the incidence of discoid particles is reflected in the development of imbrication in the Exmoor streams. This contrasts with the North Tyne sediments, where particle shape is dominated by discoidal particles, but imbrication is poorly developed. The Mimmshall Brook sediments are ovate (Sphericity 0.785), with few discoidal particles. Imbrication is poorly represented, with most of the surface structure generated by OBI components. The similarity between values of bed structure in riffles and pools under such contrasting conditions suggests that an independent process is operating to produce the structural variability. Clifford (1990) identifies structural development with the high frequency, high magnitude shear stress fluctuation on riffles experienced during low-moderate flows (up to half bankfull in Clifford's experiments). This is independently confirmed in this dissertation (see Chapter 7).

Figure 6.7 depicts the relative frequency (and range) of the structural components used to determine bed structure, whilst Figure 6.8 reproduces the grainsize ranges for particles within those groups. The contrast between riffles and pools is characterised by the abundance of OBN, IN and IU structural components in pools over riffles. This pertains for regulated and unregulated systems. A further structural distinction is evident in the abundance and greater range of IM, OC, SP, WP and LC structural components on riffles relative to pools. The range of frequencies associated with structural components on riffles is considerably greater than within the pools for both regulated and unregulated systems. This represents the generally low frequency of structurally stable components in pools, in contrast to the comparatively even distribution of structual components in riffles. This is supported by the wide range of frequencies associated with the high frequency unstable structural components in pools.

The modal grouping for particles in both riffles and pools is in the structurally unstable OBN components. The occurrence of these particles (together with IN and IU particles) on riffles helps explain why sediment transport is monitored at low-moderate discharges at riffles for comparatively large grainsizes (Beschta et al 1981;

Sidle 1985; Chapter 11 this study).

Table 6.8 depicts the statistical analysis of the observed structural varaitions between riffles and pools.

Table 6.8: Statistical significance of the magnitude of variations between structural components from riffles and pools in regulated & unregulated systems (Mann-Whitney U-Test). (+ = larger on 1st group - = larger on 2nd group).

Bed structure

Regulated Riffles vs Regulated Pools

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
+0.01	+0.01	+0.01	+0.04	NS	NS	--	-0.01	-0.01	0.01

Unregulated Riffles vs Unregulated Pools

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	+0.02	+0.05	+0.05	NS	NS	--	-0.03	NS	0.01

Regulated riffles vs Unregulated riffles

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	+0.04	+0.03	NS	NS	NS	NS	-0.05	-0.03	NS

Regulated Pools vs Unregulated Pools

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Grainsize

Regulated Riffles vs Regulated Pools

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	NS	+0.03	+0.02	+0.02	NS	--	NS	+0.04	NS

Unregulated Riffles vs Unregulated Pools

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	NS	NS	+0.02	NS	NS	--	NS	NS	NS

Regulated riffles vs Unregulated riffles

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	-0.01	NS	NS	NS	-0.04	--	NS	NS	NS

Regulated Pools vs Unregulated Pools

IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NS	-0.03	NS	NS	NS	NS	--	NS	NS	NS

Table 6.8 indicates that riffles generally contain significantly more OC,SP and WP (ie clusters)

clusters) structural components than pools and fewer OBN and IU components. In addition, reference to Figure 6.8 and Table 6.8 above indicate that in general, riffles possess larger WP particles than pools. This confirms the observations from the Store Blydal that riffles contain higher frequencies (densities) of pebble clusters than associated pools.

The differentiation between riffles and pools on this basis is clearly accentuated in the regulated North Tyne. Regulated riffles contain significantly more and larger SP and WP structural components than associated pools, and more IM and OC particles. In addition, regulated riffles possess significantly fewer OBN, IN and IU unstable structural components relative to pools. IN particles on regulated riffles are significantly coarser than in pools. These observations indicate that the interaction between local hydraulics and sediment transport under the hydropower regime is selectively removing the unstable particles from riffles, whilst preferentially encouraging cluster development and imbrication. The structural distinction between riffles and pools is therefore becoming accentuated.

The comparison between regulated riffles and unregulated riffles confirms the significant increase in OC and SP structural components on regulated riffles. Furthermore, there is a significant lack of OBN and IN particles on regulated riffles relative to unregulated. No significant differences exist between regulated and unregulated pools, which suggests that the processes responsible for the observed differences between riffles are a function of low-moderate flow conditions, when pool sediments are largely immobile.

Grainsize differences between regulated and unregulated riffles and pools reflect the presence of large boulders in some of the tributary streams, relative to the main channel. This is particularly expressed in the significantly larger OC particles in unregulated riffles.

6.8 Results: Intra-pool variation in structural development

Table 6a(Appendix B) shows that there are clear intra-pool differences in structural development. These were alluded to in the discussion of pebble cluster density in the Store Blydal river.

Table 6.9: Changes in the frequency of structural components through two riffle-pool-riffle sequences. The change is expressed in +/- or = according to the direction of change between upstream and downstream morphology.

Site	IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
NR1	0	0	0	0	0	0	0	0	0	0
NPH	-	-	-	-	+	=	=	-	=	+
NMP	=	-	-	=	-	=	+	+	=	-
NPT	=	-	=	=	-	=	-	-	+	+
NR2	+	+	+	+	+	-	-	-	-	-
TBR1	0	0	0	0	0	0	0	0	0	0
TBPH	-	-	-	=	=	+	+	+	+	+
TBMP	-	+	-	+	-	-	-	+	-	+
TBPT	=	-	+	-	+	+	-	-	+	+
TBR2	+	+	+	+	+	-	+	-	-	-

Table 6.9 above shows that (within the limits of a two sample database) the development of bed structure within pools is complex. Clear changes in structural components occur from riffle to pool-head, and from pool-tail to riffle. These are characterised by a decrease in IM,OC and SP stable components, and an increase in IU unstable components from riffle to pool-head. The change from pool-tail to riffle involves an increase in IM,OC,SP,WP,OBI and a decrease in LC stable structural components. This transition is also typified by a decrease in OBN,IN and IU unstable particles.

In the Newton riffle-pool-riffle sequence there is clear evidence for a downstream reduction in OC components to the pool-tail. In contrast, in the Tarset Burn, the pool-tail exhibits an increase in OC particles. The development of obstacle particles through the riffle-pool sequence will be influenced by bank material, which in the Newton pool decreases downstream to the pool-tail. This is also expressed in the grainsize, which shows a decrease in OC size from pool-head to pool-tail. Bank material supply was also evident in the pool-head and mid-pool in the Tarset Burn.

Table 6.a (AppendixB) shows some evidence of downstream fining within the OC,SP and OBI structural components, but there is nothing conclusive. Fining occurs from pool-head to mid-pool in some categories of structure in one riffle-pool sequence and not in others. The evidence from Chapter 5 suggests that downstream fining to the pool-tail is a feature of the riffle-pool sequence, particularly in the regulated North Tyne. The evidence from the Store Blydal suggests that for the largest components of

the bed material, fining occurs from riffle to mid-pool. Further elucidation must await future research.

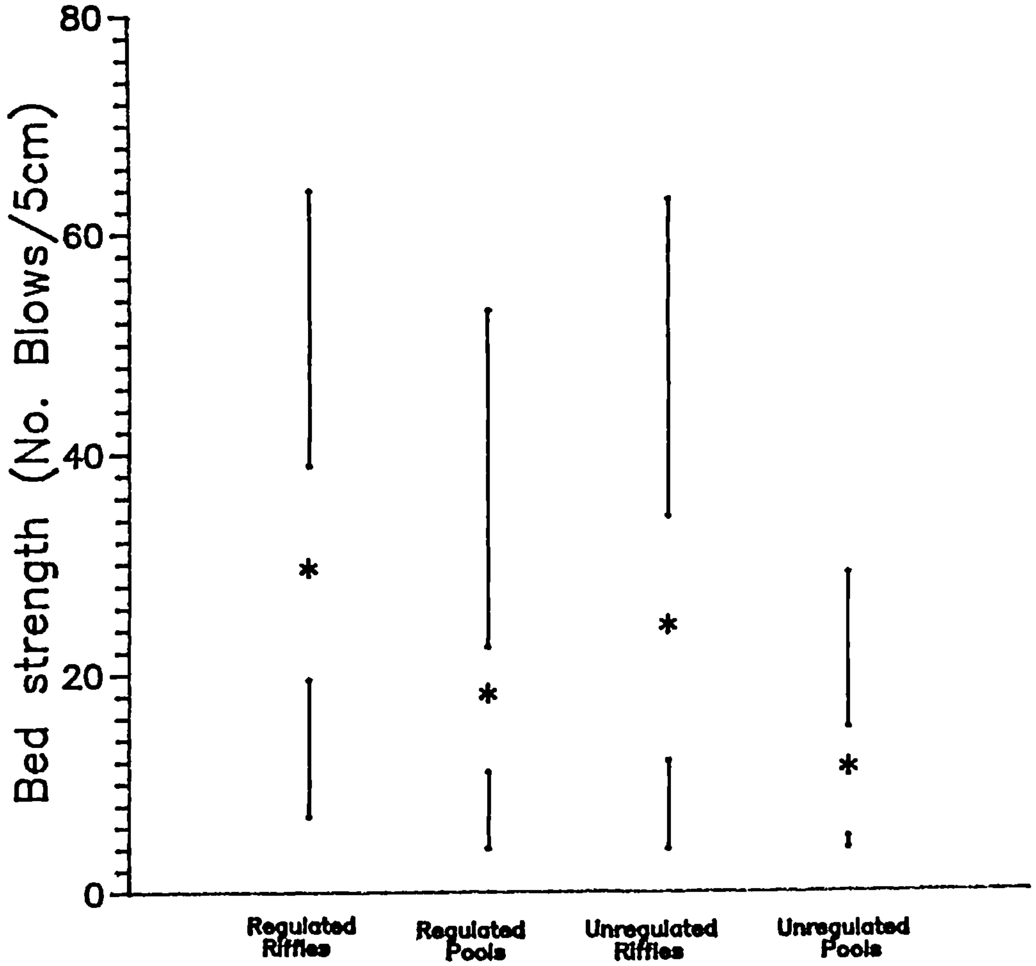
6.9 Results: Bed Strength

The values recorded for bed strength have implications for sediment transport, since the force resisting lateral motion of bed surface particles will reflect the force required to laterally displace them. However, this neglects the lift force operating on the particle during high discharges, and therefore the results can only be an index of particle resistance to entrainment. More research is required to isolate the relationship between bed penetrometer readings and the entrainment of sediment. Of direct relevance to the North Tyne is the degree of spawning ground compaction, which is of importance for the successful spawning of salmonids (Kondolf 1992). Clearly, since salmonid spawning requires the excavation of a redd through the bed surface, a measure of the compaction of that bed will provide a useful assessment of the spawning suitability. More research is required to determine the exact link between spawning ground compaction and the selection by salmonids. However, the readings made during this survey in relation to unregulated systems will provide an indication of the direction of spawning ground compaction under the regulated discharge regime.

Figure 6.9 presents the mean, quartiles and range of aggregated bed strength readings for regulated and unregulated riffles and pools. The total numbers of readings per morphological group were 109, 121, 53 and 36 respectively.

Riffles possess significantly ($p = 0.001$) stronger surface sediments than associated pools, with a broader range of values. In addition, regulated riffles are significantly stronger than unregulated riffles from the same/similar catchments ($p = 0.02$). Regulated pools are also significantly stronger than unregulated pools ($p = 0.001$), which reflects the presence of large boulders in the deeper regions of the Newton Pool and Smales Pool (Chapters 4 and 5). The differences in bed strength readings between regulated and unregulated systems are shown in Figure 6.10. Regulated riffles clearly possess a higher frequency of bed strength readings in the 25 - 55 B/5cm range than unregulated riffles. Unregulated riffles, in contrast, exhibit a much higher frequency of bed strength readings in the 0 - 15 Blows/5cm range. Reference to Figure 6.5b indicates that bed strength on regulated riffles is generally greater than unregulated tributaries of the same D_{50} grainsize. Clearly some process (independent

Fig 6.9 Mean and range of bed strength readings for aggregated data from regulated and unregulated riffles and pools.



of grainsize characteristics) is causing accentuated levels of bed strength on regulated riffles.

The variation between regulated and unregulated pools is largely explained by the presence of large residual elements in the bottom of some of the North Tyne pools. Nevertheless, bed strength readings in unregulated pools are clearly dominated by the 0-5 B/5cm range, in contrast to the regulated pools. The bed strength surveys were conducted during a relatively dry period (summer of 1989) and therefore the observed differences were not considered to result from flooding.

Whilst levels of bed structure can be easily determined for individual morphology (eg riffle, pool, bar etc) or cross-sections as a whole, considerable logistical problems are faced in trying to extend the resolution to include inter-section variability in a river the size of the North Tyne. The determination of bed strength by dynamic penetrometer provides a rapid assessment of cross-sectional and reach scale diversity of sediment compaction. Figure 6.11 depicts the variation in bed strength within the Newton riffle-pool-riffle sequence, described in terms of bed structure above. Bed strength is clearly variable throughout the sequence, with particularly accentuated values associated with riffles. A distinct asymmetry of bed strength characterises the pool-head and mid-pool region,s with this pattern diffusing through the pool-tail. Cross-sectional variation in bed strength reflects the topography and particle size of the reach. The bed strength readings within the pool also reflect the supply of coarse slope material that resides in the channel in the form of a lag of large boulders (Figure 6.11). It is the prevalence of these boulders that account for the marked asymmetry of cross-sectional bed strength in the mid-pool region. Riffles exhibit a more complicated sectional distribution of bed strength than pools, with areas of enhanced bed structure (the surface of the incipient bar on NR1 is significantly more imbricated than other parts of the riffle) recording high values of penetration. Bed strength generally declines towards the channel margins, particularly within the pool. Hassan and Reid (1990) describe a similar lateral decrease in pebble cluster density towards the channel margins, which they attribute to the reduction in shear stress at channel boundaries.

The pool-tail region experiences the weakest bed surface, with values rarely exceeding 20 blows/5cm depth penetration. This is supported by the bed structure values, which show a decrease in stable clasts within the pool-tail. This conflicts with the data from the Store Blydal, which consistently identified the pool-tail as a

Fig 6.10 The percentage frequency of bed strength readings on regulated and unregulated riffles and pools.

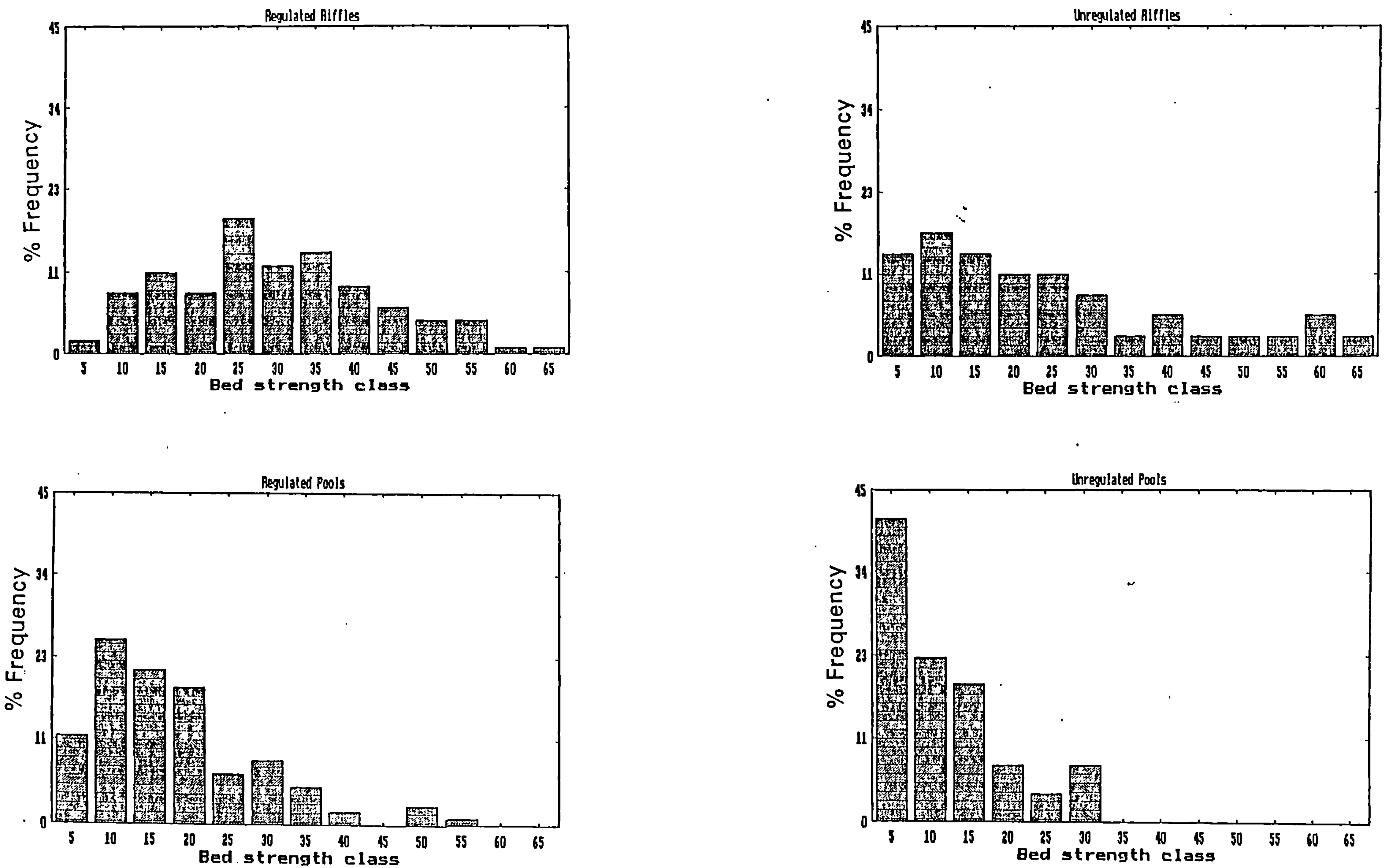
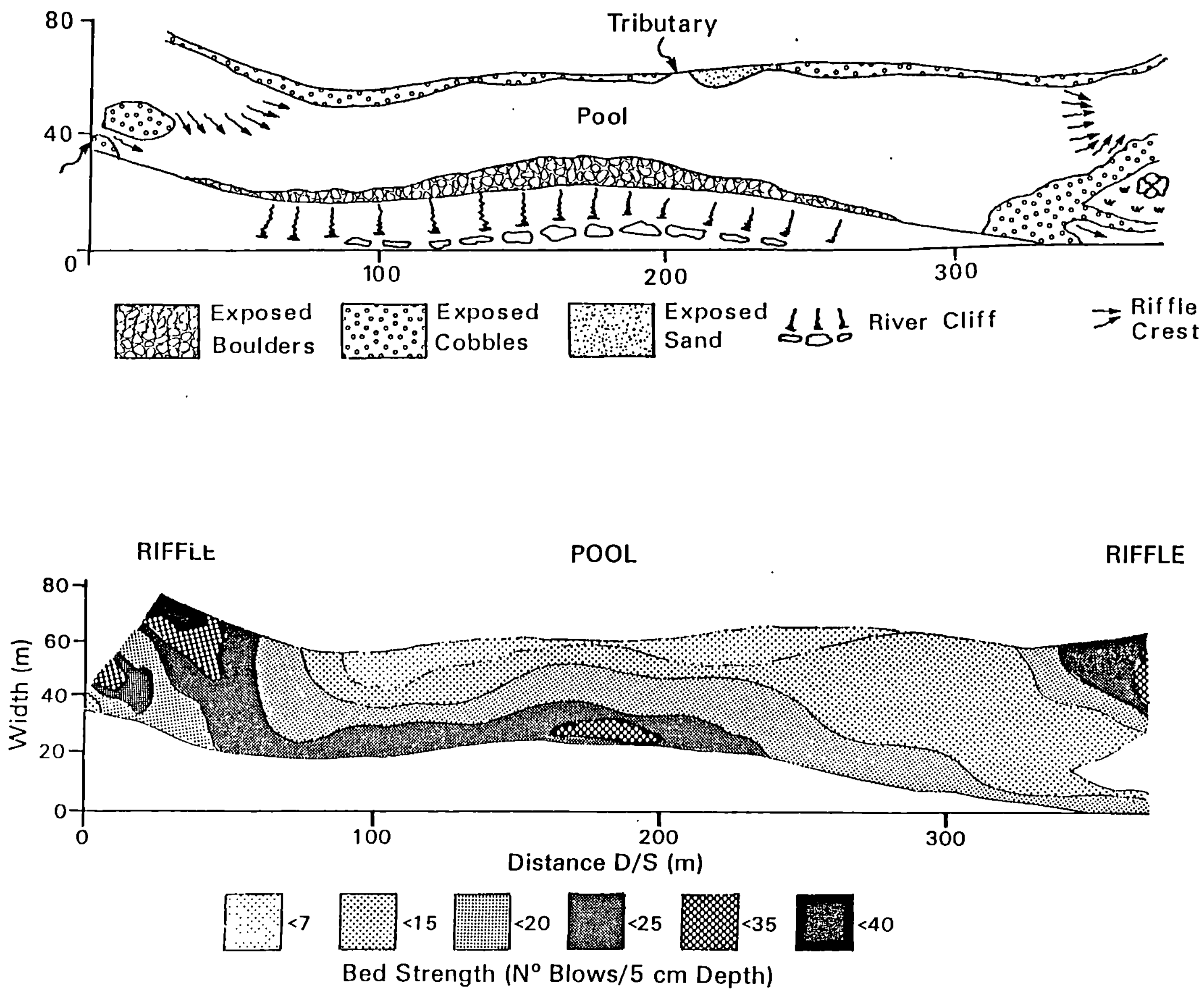


Fig 6.11: The spatial variation of bed strength within the Newton riffle-pool-riffle sequence.



region of increasing pebble cluster density (although with lower densities than associated riffles). The suggestion from this conflict is that longer pools accentuate the downstream fining process and mitigate to reduce bed structure development. A further consideration is the relatively simple technique used in the Store Blydal, which did not account for all the structural components present. It is conceivable that the pool-tails in the Store Blydal exhibited lower structural development, but a preferential pebble cluster development.

The results described above, collected from three contrasting environments, suggest the following characteristic bed stability status for different river morphologies :

i. Riffles possess stronger, more structured bed sediments than pools, with a higher density of pebble clusters. Lateral distribution of bed strength is complex, but broadly reflects the distribution of structured sediments. The sediment size of pebble cluster elements is generally larger than those in pools. Regulated riffles show enhanced bed structure and bed strength readings in comparison to unregulated riffles, particularly in the OC and SP structural components. In contrast, unregulated riffles possess higher frequencies of OBN and IN unstable structural components.

ii. Pool sediments vary both laterally and downstream, according to cross-sectional form and particle size. Pools experience low strength, low bed structure and low cluster densities. Within the pools there is a complex pattern of size and structure sorting. However, in general, bed strength readings decrease downstream from pool-head to pool-tail.

iii. Pool head surface sediments vary downstream, from structured, strongly packed sediments proximal to the upstream riffle, to weaker (though still structured) sediments towards the mid-pool. Particle size is variable, but is generally coarser than mid-pool and pool-tail regions. Pool-head cluster density varies between pools, but in general exhibits enhanced values over the mid-pool (in the absence of colluvial input).

iv. Mid-pool regions are areas of pronounced bed strength asymmetry associated with lateral sediment sorting. Cluster density and bed strength are dependent upon sediment supply, and are influenced by the presence or not of residual boulders. In the absence of colluvial inputs, mid-pool regions exhibit the lowest cluster densities and obstacle clast size of any pool component.

v. Pool-tail regions experience transitional effects from mid-pool to riffle. This is reflected in the variability of results for bed structure. In general, pool-tails become more structured toward the downstream riffle, and bed strength is generally lower over a greater proportion of the bed than in mid-pool or pool-head regions. Cluster densities are comparable to pool-head regions (in the absence of colluvial inputs).

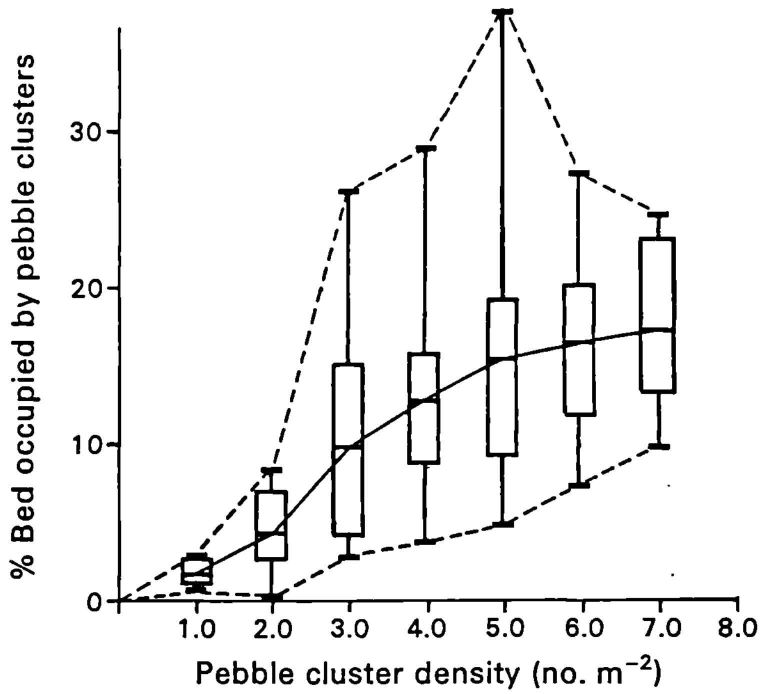
6.10 Hydraulic controls on bed stability

Hassan and Reid (1990) related decreasing cluster densities to low shear stress at channel margins, and high cluster densities on bars to shallow water depths and high sediment transport rates. Wolcott (1989) contends that "any correlation between surface structure and flow conditions will be complex and must include the effects of the previous events". This supports similar conclusions of Billi (1988,) who described the dispersal of clusters along the margins of a point bar as dependent upon local flow conditions and preceding event history. De Jong (1990) also remarks upon cluster dispersal in terms of the importance of the local turbulence structure that is generated by the cluster distribution itself. This latter point has recently been expanded by Clifford (1990), based on the work of Roberts (1988) (see above).

For the Store Blydal data, in the absence of more specific information on pebble cluster area, an approximate, conservative value based on the B-axis of obstacle clasts was used after Naden and Brayshaw (1987). The results suggest that areas as high as 46% of the stream bed can be occupied by pebble clusters at riffles (Figure 6.12). This is in marked contrast to previous values reported in the literature of between 10%-20% for unspecified bed morphologies in other gravel rivers (Reid et al 1992), and the 10%-15% recorded for flume experiments (Wolcott 1989). Billi (1987) reports that up to 50% of the bed in mountain streams may be occupied by imbricated clusters, the value of 46% is then within this range, although the channel morphology of the Store Blydal is markedly different to the mid-Wales channels. The mean values for the percentage of stream bed occupied by pebble clusters in the Store Blydal rises to 16%, which is similar to other documented values.

The data from the North Tyne indicates that pebble cluster components add up to 32-47% of particles sampled from regulated riffles, and 16-36% from unregulated riffles. Pools span a range of 4-23% of particles in pebble cluster components. The values for riffles are comparable to those recorded from the Store Blydal, and confirm that

Fig 6.12: The relationship between the percentage of bed occupied by pebble clusters and the density of pebble clusters, Store Blydal, Greenland.



regulated riffles possess accentuated cluster development.

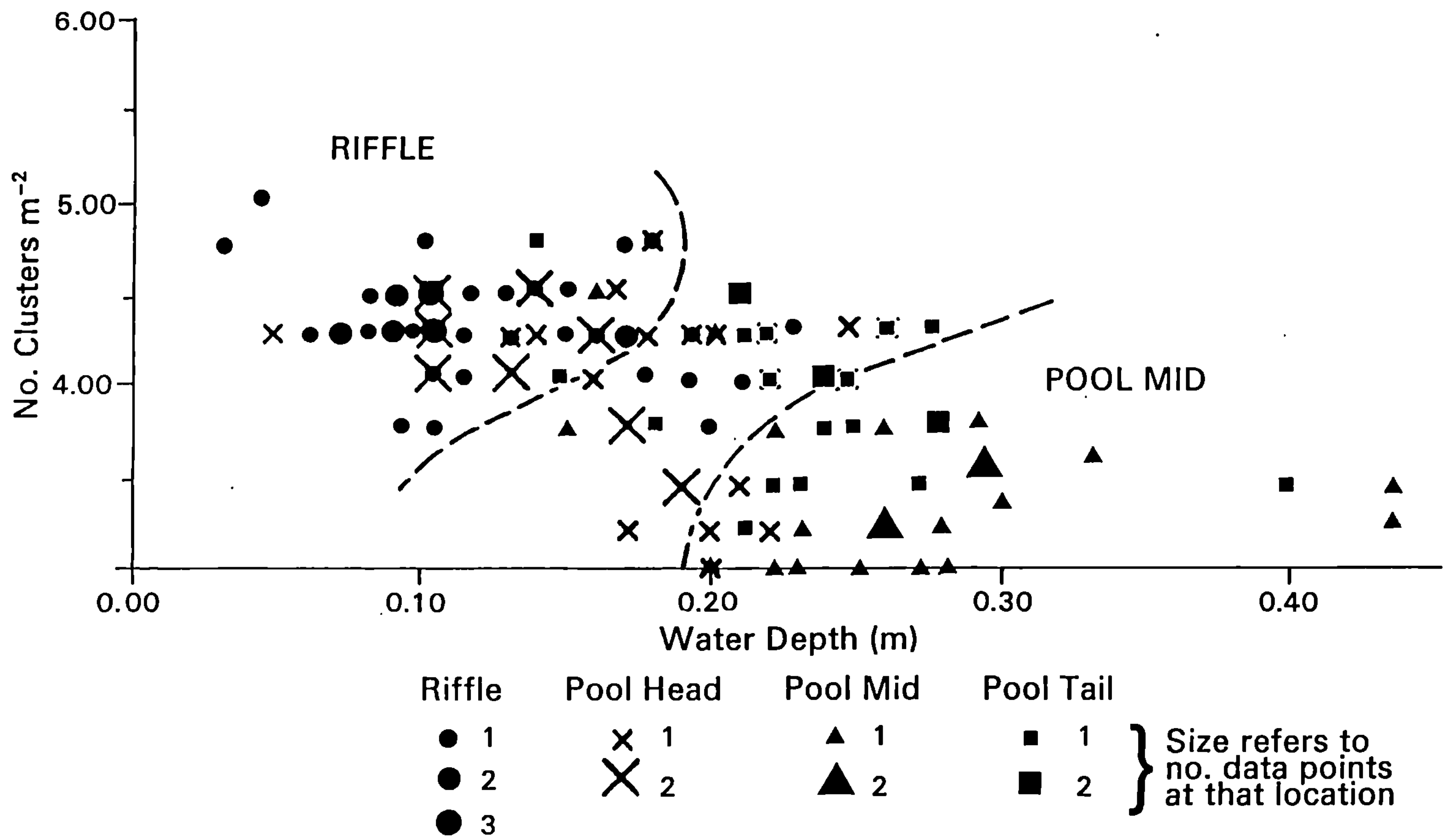
From the discussions in Section 6.3 above, it is clear that increasing structural development will lead to decreased sediment transport, either through delayed entrainment, or as a result of reduced (or deflected) energy at the bed (Hassan and Reid 1990; Robert 1990). The implications from the spatial patterns of bed structure developed in the discussion above, are that riffle sediments will require higher entrainment thresholds than pools (and particularly mid-pool and pool-tails), and that sediment transport rate will be lower over riffles as a result of turbulent energy loss and flow skimming.

Hassan and Reid (1990) record a theoretical limit to the continual development of bed structure at the point where free flow skims over the turbulent wakes developed around high cluster densities. This corroborates the earlier work of Nowell and Church (1979). The corollary of this is the measured decline in sediment transport. Consequently, as sediment transport declines, the motion of individual particles is reduced and no further structure is developed. However, as Carling et al (1990) note, individual particles can still move into more stable positions without entrainment. Hassan and Reid (1990) record that cluster spacing (and therefore density) is conditioned by the resistance generated by the spatial arrangement of clusters. This point of resistance reduction is related to the ratio of cluster spacing to obstacle clast C-axis. Consequently, the larger surface grainsize and larger obstacle clasts on riffles will be a further factor contributing to a reduced sediment transport on riffles.

Clifford (1990) has recently suggested that bed structure is developed (preferentially) in regions of accentuated turbulence. Short term, high magnitude shear stress fluctuations on riffles lead to intermittent motion of surface particles and rotation of particles into structurally stable positions. This is confirmed to some extent by the observations of Carling et al (1992), who observed individual clasts rotating into more stable positions prior to entrainment as the shear stress increased. A hydraulic differentiation between riffles and pools during hydropower regulation will be discussed in Chapter 7.

Figure 6.13 illustrates the variation of pebble cluster density with mean water depth for each metre quadrat. Riffle and mid-pool regions are successfully discriminated by cluster density; pool-head and pool-tail locations are transitional between the two. An inverse relationship exists between water depth and cluster density, which, despite the

Fig 6.13: The variation of pebble cluster density with water depth, showing the delineation of riffles and pools, Store Blydal, Greenland.



scatter (largely resulting from the transitional environments in the pool-head and pool-tail), suggests a hydraulic linkage to cluster development driven by the low flow environment, as opposed to a development under flood conditions when the hydraulics are considered to reverse or equalise between riffles and pools (Keller 1970; Lisle 1979; Carling 1990; Clifford and Richards in press). In the absence of additional hydraulic data, it is a reasonable first approximation to infer that the spatial patterns of cluster development in the riffle pool sequences in the Store Blydal are largely the result of differential velocity or turbulence environments present at low flows. The low flow pattern of high shear stress (and highly turbulent flow) is experienced for greater periods of time at riffles, with pools only experiencing comparable conditions during floods.

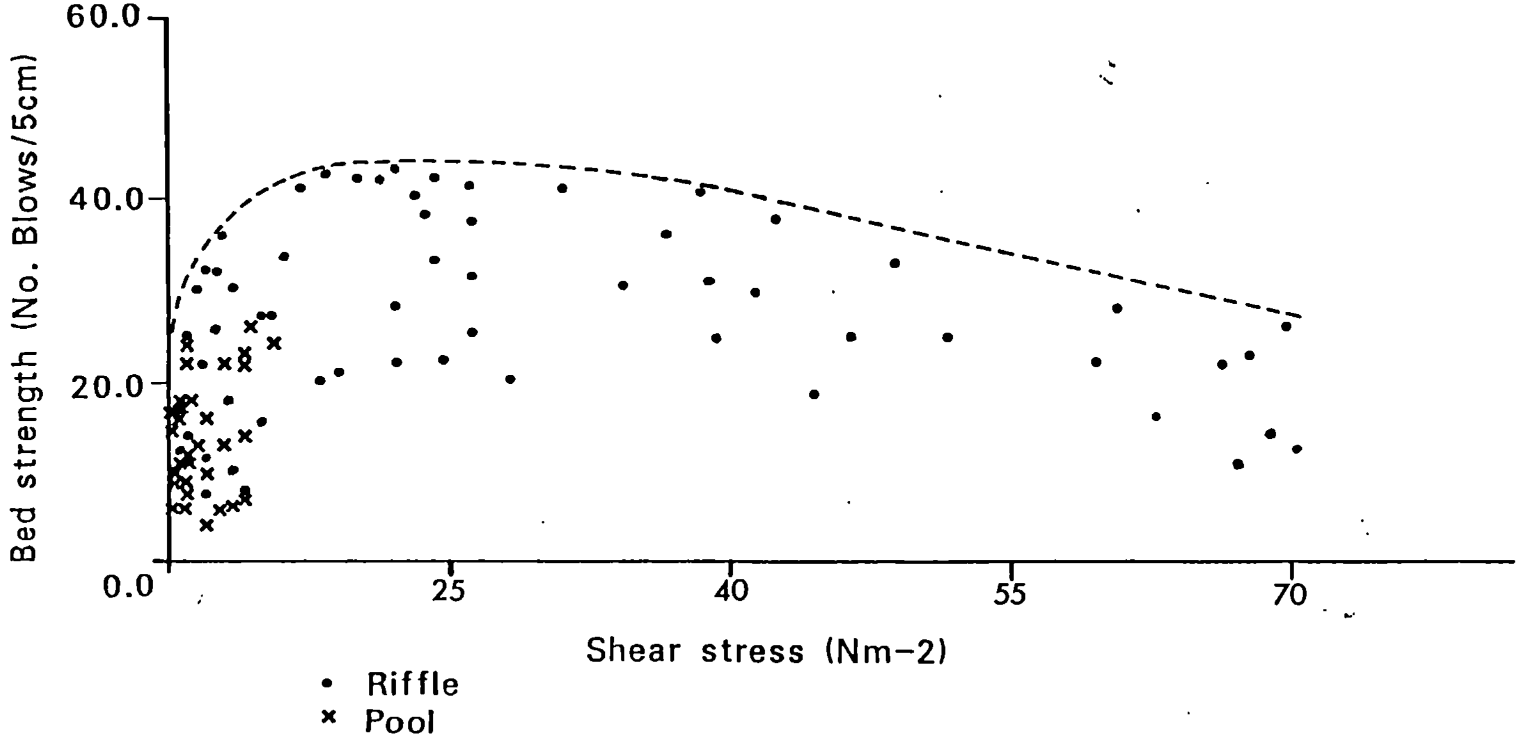
Confirmation of a low flow link between bed structure and hydraulics is evident in the accentuated values of structure (and particularly pebble cluster) developed on regulated riffles. Hydropower generation is expressed hydraulically by an increase in flow velocities over the riffles and pools, and a reduced frequency of high magnitude floods. If one accepts the observations from other workers for a high dishcharge requirement for pool bed mobilisation, then it is reasonable to assume that the accentuated differences between bed structure in riffles is a result of enhanced low-moderate flows. This will be expanded in Chapter 7.

To investigate the hypothesis that bed strength is in some way related to the low flow forces exerted on the bed, a series of penetrometer readings were made in association with time-averaged point shear stress within pool and riffle sections.. Figure 6.14 shows the relationship between point shear stress at compensation flow (Q=1.5 cumecs) and the corresponding value for bed strength at that point. A limit to bed strength readings occurs at 50 Blows/5cm which marks the point above which no further penetration is considered practical. Scatter in the relationship is produced by the effect of large boulders and the transverse reduction in shear stress at riffle margins. This latter point suggests that the development of bed strength at riffle margins is associated with hydraulic conditions during discharges greater than hydropower flows. Two significant points are evident from Figure 6.14:

1. values of bed strength increase with shear stress up to a maximum at 15 Nm^{-2};

2. with a further increase in shear stress to 70 Nm^{-2}, bed strength decreases to values of approximately half the maximum.

Figure 6.14 Envelope curve illustrating the decrease in bed strength associated with shear stress values in excess of 20 N/m^2.



The results of Figure 6.14 were collected from the Newton pool and riffle locations. Figure 6.14 indicates that although many of the low bed strength readings are associated with the pool, the relationship is not purely an artifact of the riffle pool morphology. Low bed strength readings on riffles are associated with low shear stresses.

The lack of a relationship between the force acting on the pool bed and the strength of pool sediments is in keeping with the hypothesis of low flow development of spatial patterns in bed structure and strength. The pool sediments are not structured, due to the low shear stresses experienced for most of the time; consequently particle size effects in the absence of bed structure (cf discussion of boulders above) and antecedent flood control on bed strength will dominate the low flow patterns.

The limit to bed strength imposed by high shear stresses is consistent with the research findings in flume experiments (Wolcott 1989; Harrison 1950). The trend exhibited in Figure 6.14 implies a reduction in bed strength to zero as shear stress increases. This is intuitively correct, and marks the point when the bed becomes fluidised. It is hypothesised that structure and bed strength in regions of high shear stress are consistently broken up by relatively frequent sediment mobility.

To further investigate this hypothesis requires the determination of bed structure and strength following a mobilising flood. Clearly, if high shear stresses are responsible for the destruction of bed strength and structure, then lower values will be recorded subsequent to a bed mobilising event. This is discussed in the next section.

6.11 Bed structure response to flood events

Wilcock and Southard (1989), and Wolcott (1989), have shown that the D_{50} of surface sediments increase very little after initial surface coarsening has occurred. Wolcott observes, however, that the sediment transport rate (in supply limited conditions) continues to decline. Wolcott attributes this to the alignment of particles into structures that resist entrainment. The investigations by Wolcott and Wilcock and Southard, were conducted under steady flow conditions. Nouh (1990) has shown that, as the duration of the flood hydrograph increases and the amplitude decreases, so the size distribution of the armour layer becomes coarser. Furthermore, the degree of armouring is greater after an unsteady flow event than a steady flow event of comparable discharge and slope. Nouh's results have important implications for the development of armouring within regulated channels. Chapter 3 described the changes in flood hydrograph resulting from flood attenuation through the Kielder reservoir. Flood peaks are reduced and flood duration increased. These conditions are exactly those that Nouh describes as promoting armour development. This is supported by the armour ratio values described in Chapter 5.

Wolcott (1989) asserts that bed structure (including armouring) is not only created by flowing water, but that its development is limited; at high shear stresses bed structure is destroyed.

There is some controversy over the role of floods in the development of bed structure. Field evidence is used to investigate cluster dispersal, and Billi (1988) suggests that it is during floods that the role of clusters change, from one of sediment trapping (and delayed entrainment) to one of dynamic sediment exchange. De Jong (1990) describes the dispersal (and destruction) of clusters over two flood events. No evidence of low flow reformation is given, which would at least support Billi's (1988) observation of general cluster dispersal following floods.

The flume study of Wolcott (1989) suggests that structure is destroyed at dimensionless shear stresses of > 0.12. What occurs as the flood wanes is not clear in the field, although Billi does mention replacement of "lost" structural components. Existing data suggest that clusters are dispersed, but similarly new clusters are formed (Billi 1988). A general dispersal by floods suggests that cluster development must occur during waning flows. However, the influence of sediment supply is not known; the post flood dispersals recorded in the field to date may have resulted in an absence of suitable sediments to replace the removed stoss and wake clasts. The development of other structural components is unknown (empirically), but the observations of accentuated structural development on riffles suggests that unsteady, turbulent flows are required that generate sporadic bedload motion.

Brayshaw (1984) reports on the development of clusters during "floods" in a series of flume experiments. Importantly, the final development of clusters was not related to the boundary shear stress at flood peak (4 different shear stresses were generated). Rather, the development of clusters occurred as the "flood" receded. Obstacle clasts dropped out first, whereupon the wake separation trapped fine sediments in transit, to produce the cluster wake. Stoss particles were not entrapped until the discharge dropped below the level required to transport the median size of sediment. This further strengthens the arguments for the low flow accentuation of bed structure; however, the role of large obstacle clasts in transit is yet to be established.

A bankfull flood of 151 cumecs peak discharge occurred in the North Tyne on February 28th 1990. A distinct downstream variation in peak discharge was experienced as a result of the flood storage capacity of the Kielder reservoir. Maximum discharge at the dam site was recorded at 77 cumecs, whilst peak discharge at the North Tyne at Tarset gauging station was recorded at 105 cumecs. Downstream of the Tarset and Chirdon Burns, the peak discharge was estimated at 151 cumecs. Tracer movement and scour and fill measurements establised that significant bedload transport had occurred at the sites downstream of the Tarset and Chirdon Burns. Upstream, sediment transport had occurred, but was characterised by high competence, short distance transport (see Chapters 12 and 13). Discharge conditions following the flood event(s) were characterised by an almost continous daily release of 16 - 20 cumecs for 76 days. Consequently, access to the channel for post-flood monitoring was only possible on two occasions, at +6 and +76 days post flood (recession not peak); the +6 days was achieved only after negotiation with the Water Authorities.

Post-flood structural assessment was made at nine sites, at +6 days, when discharges of 16 cumecs had been continuous since flood recession. Bed strength tests were made simultaneously, and again at +76 days.

Table 6.10 presents the net structural changes per site as indicated by the pre- and post-flood values for the frequency of stable structural components.

Table 6.10: Net changes in the frequency of stable structural components, D_{50} and Sorting of surface sediments following a bankfull flood event.

	Pre-Flood			Post-Flood		
Site	% Structure	D_{50}	Sort	%Structure	D_{50}	Sort
SMR	86	56	1.00	60	42	2.00
SMP	56	42	1.05	54	51	1.60
TR1	65	42	1.18	44	45	1.18
TR2	88	60	1.05	38	42	1.00
NR1	60	40	0.90	48	42	1.15
NPH	40	45	2.25	33	45	1.29
NMP	36	51	1.35	43	45	2.35
NPT	20	32	0.95	30	40	1.56
NR2	64	45	0.55	30	42	0.65

A clear decrease in the frequency of structural components is evident at all riffles, which is statistically significant (Mann Whitney test and Sign test) at p = 0.001. The highest percentage reductions in bed structure on riffles are recorded downstream of the Tarset and Chirdon Burns, where the highest discharge and bed mobility were experienced. Nevetheless, the structural definition between riffles and pools is broadly preserved post flood.

Pools exhibit a variable response to the flood, largely in response to the degree of bed mobility (although the sample is somewhat limited). The Smales pool records only a 4% loss in bed structure, whilst the magnitude of change in the Newton pool is consistently over 15%. Within the Newton pool, a pattern of increasing downstream structural development is evident, with pool-head sediments losing bed structure, whilst mid-pool and pool-tail increase structure. Nevertheless, the pool-tail remains the region of this riffle-pool sequence with the lowest stable structural development.

The median grainsize of the riffles consistently show a decrease post flood, associated with an increase in fine sands and gravels, trapped as infill or wakes, and a general exchange of coarse for finer particles in structural components.

Pools exhibit a general increase in particle size, although this pattern is neither systematic or conclusive, with only two samples. Sediments in the pool-head and pool-tail become coarser whilst the mid-pool sediments become finer. Sediments in both pools and riffles show a genéral tendency for poorer sorting, although this is again variable per site. Sediments become more poorly sorted in the mid-pool and pool-tail post flood.

Table 6.11 illustrates the statistical significance of the post-flood change in the frequency and size of riffle structural components.

Table 6.11: Statistical significance of the post-flood changes in the frequency and grainsize of structural components on riffles.

Frequency of structural components

Test	IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
MW	NS	NS	-0.01	-0.05	NS	NS	NS	+0.05	+0.05	NS
ST	NS	NS	-0.05	NS	NS	NS	NS	NS	NS	+0.05
% Sites	-60	-80	-100	-80	-60	-60	+40	+80	+80	+100

x Grainsize of structural components

Test	IM	OC	SP	WP	OBI	LC	BS	OBN	IN	IU
MW	-0.02	NS	NS	NS	NS	NS	NS	NS	NS	NS
ST	-0.05	+0.05	NS	-0.05	NS	NS	NS	NS	NS	+0.05
% Sites	-100	+100	-50	-100	-60	-60	--	-60	+60	+100

No such analysis could be performed on the pool sediments due to the low sample numbers. The analysis indicates that SP and WP particles are significantly reduced in frequency on riffles, whilst OBN and IN are significantly increased. The Sign test values indicate that although the magnitude of reduction in WP particle frequency is significant, the trend is not consistent throughout all riffles. Interestingly, although the magnitude of the increase in IU structural components is not significant, the trend is significant. The percentages of sites sampled reveal that a reduction in all structurally stable components has occurred at over 50% of riffles sampled, whilst at over 50% of sites the frequency of unstable structural components has increased.

The magnitude of change in the grainsize of structural components on riffles exhibits little significant varation. Only IM particles record a significant decrease in the magnitude of particle size. However, the Sign Test results indicate that IM and WP particles show a significant decrease in size, whilst OC and IU particles are significantly larger post flood. The percentages of sites exhibiting change indicate that at 60%+ of riffles, OBN and IN particles experience a decrease in particle size post flood, whilst for a similar percentage of sites, OBI and LC are finer.

These results establish that pre-flood bed structure on riffles is destroyed by large floods and is replaced (initially) by finer structural elements, and a higher frequency of unstable structural components. Interestingly, OC particles are significantly coarser post-flood at all the riffles sampled, although in a reduced frequency. This implies a selective deposition process which favours the larger obstacle clasts. This supports the flume experiment observations of Brayshaw (1985) for the size selective development of clusters on the recession limb of flood events. However, it remains to be established how many coarse OC particles remain in situ during the flood events. Tracer studies indicated that particles up to 157mm were moved during this flood event, which would include many OC particles and correspondingly suggest general OC dispersal (sensu de Jong 1990; Billi 1988).

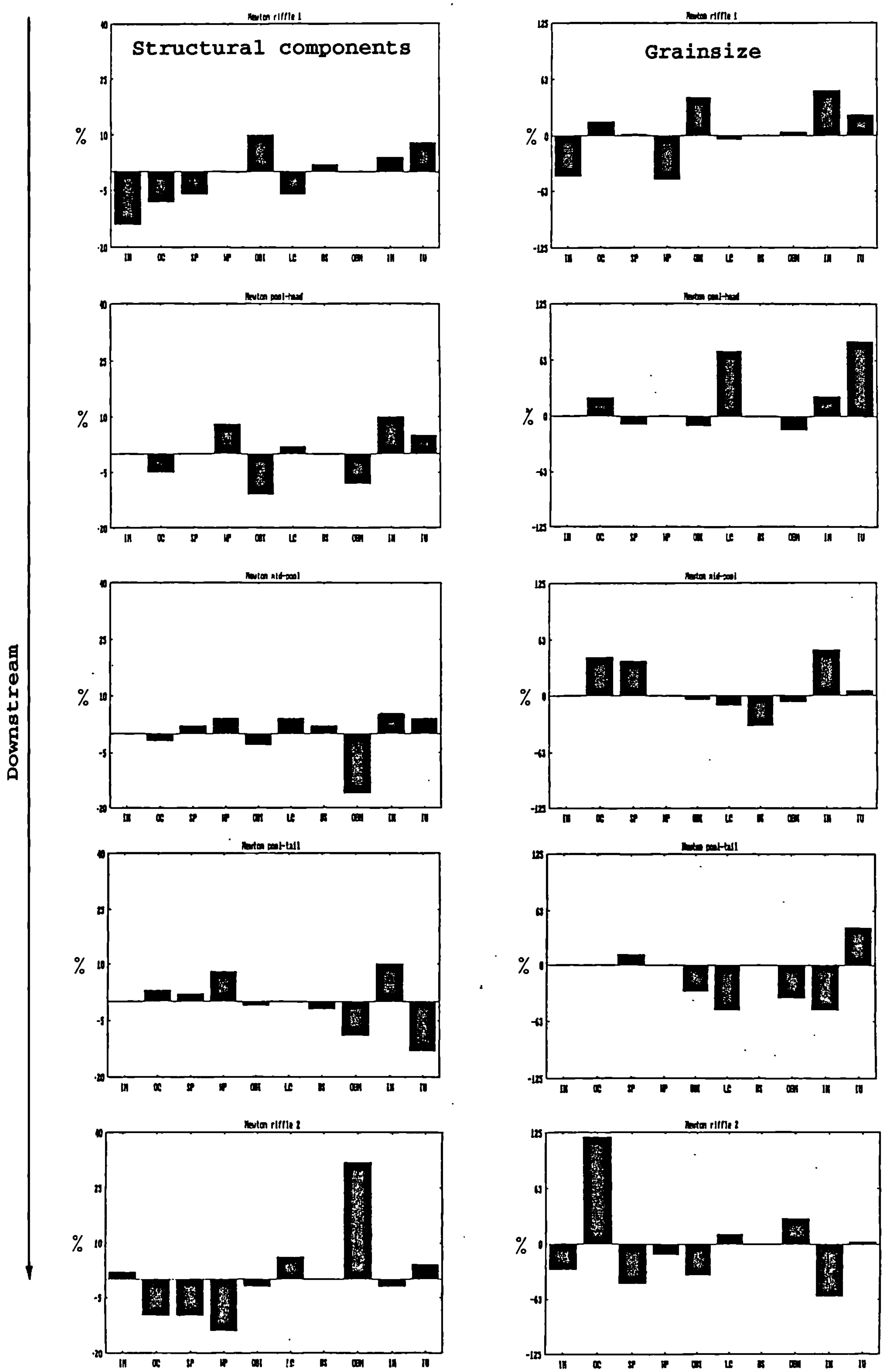
Figure 6.15 depicts the post-flood percentage change in the frequency and grainsize of structural components within the Newton riffle-pool-riffle sequence. Tracer studies indicated that the pool sediments were mobilised during the flood, although the presence of large boulders in the pool has a significant effect on sediment transport and structural definition.

The pattern of downstream structural change through this riffle-pool-riffle sequence is complex. Broadly, the magnitude of change in the frequency of structural components is lower in the pools, despite clear evidence for major sediment transport (see Chapter 12). This is particularly evident for the stable structural components. The changes in specific structural components vary between the two riffles, with a decrease in IM and LC particles on NR1, whilst these components increase in frequency on NR2. OC and SP decrease on both riffles. Both riffles experience a net increase in the frequency of unstable structural components, but again the distribution is variable.

Within the pool, the effect of the flood event was to increase the frequency of stable structural components, particularly in the mid-pool and pool-tail regions. The frequency of WP increased throughout the pool, whilst SP particles increased in the mid-pool and pool-tail only. OC particle frequency decreased in the pool-head and mid-pool, but increased in the pool-tail. OBI particles decreased in frequency throughout the pool, although the magnitude of the change declines downstream.

The frequency of unstable structural components in the pool shows a consistent loss of OBN particles and an increase in IN particles, the latter, represented as drapes of

Figure 6.15 Changes in the frequency and grainsize of structural components within a riffle-pool-riffle sequence following a bankfull flood.



fine gravels and sands, clearly representing deposition over a static bed. IU particles increase in frequency between pool-head and mid-pool, but decrease in frequency on the pool-tail. The increase in pebble cluster components on the pool-tail are consistent with the observations of accentuated cluster densities in the Store Blydal. This implies that it is during bed mobilising floods that pool-tail structure develops. The frequency of pool scouring discharges in the Store Blydal is much higher than in the North Tyne as a result of seasonal snowmelt runoff. It is suggested that this would account for the disparity betwen pebble cluster densities recorded in the Store Blydal and North Tyne.

The grainsize changes are equally complex through the riffle-pool-riffle sequence. However, with the exception of the pool-tail, OC particles have become coarser. This results either from selective deposition (coarse particles first) or selective entrainment (coarse particles last). As discussed above, the tracer results indicate that particles in the size category of OC were entrained. However, if the effect of structural protection is to "increase" the apparent size of particles, then larger OC particles may have been undercompetent. IM and WP are finer on the riffles, post-flood, suggesting their replacement with finer sediment from upstream. A contrast is again evident between riffles, with NR1 experienecing an increase in the size of IU and IN particles, whilst the converse occurs at NR2. IN particles are coarser post-flood in pool-head and mid-pool regions, and finer on the pool-tail and NR2. This suggests that fine sediments were routed through the pool after the bed became stable, and were preferentially deposited on the pool-tail (see Chapters 7 and 12).

Within the pool, IU particles increased in size throughout, whilst OBN particles decreased in size. SP also increased in size at pool-tail and mid-pool regions, but decreased in size in the pool-head. Reference to Table 6a (Appendix) indicates that in terms of absolute sizes, the downstream fining within the pool is maintained for many of the structural components. IU particles are actually larger in the pool post flood than on the riffles. A similar particle size "reversal" is evident for SP particles. OC particle size in the pools remains larger than the riffles due to the presence of colluvium.

In general, the post flood sedimentology of the riffle-pool-riffle sequence maintains the pre-flood patterns, but with the difference reduced. Finer and more unstable particles are present on riffles, whilst larger and increased frequencies of unstable IU particles are found in the pools. These will be among the first particles to be entrained in the following floods events, whilst the riffles clearly develop enhanced bed structure during low-moderate discharges. Whilst these observations indicate that bed structure on riffles is destroyed by large floods, there is clear evidence to indicate that it is also developed during floods. This would appear to confirm Billi's (1988) observation of a dynamic role for pebble clusters in sediment transport.

6.12 Bed strength response to flood events

Table 6.12 shows the change in bed strength readings before the February flood event and at +6 and +76 days after at the Newton site. Bed strength values are generally lower on riffles following the flood event, which supports the observations of reduced bed structure. With the exception of the Newton pool-head, pools sediments experience a net increase in bed structure following the flood, and particularly in the Newton pool-tail. Values for the percentage change in post flood bed strength readings increase downstream, with the maximum changes occurring where the discharge was 151 cumecs. This again confirms a link between the degree of sediment mobility and the magnitude of bed *destabilisation.*

Table 6.12: Post-flood changes in the mean values for bed strength. (Figures in brackets are the standard deviation of readings per site).

Site	pre-flood	+6 days	%	+76 days	%
SMR	44.1 (9.2)	33.0 (16.7)	-25	--------	---
SMP	28.9 (6.7)	29.5 (12.1)	+2	--------	---
TR1	20.0 (10.9)	17.5 (13.6)	-13	--------	---
TR2	39.4 (14.4)	20.2 (12.3)	-49	--------	---
NR1	31.5 (8.2)	27.5 (13.0)	-13	29.3 (10)	+6.6
NX3	20.5 (13.0)	21.3 (13.0)	+4	--------	---
NPH	16.1 (7.2)	15.9 (8.0)	-1	16.2 (9.8)	+1
NMP	23.7 (17.3)	31.9 (13.9)	+35	24.3 (11.4)	-24
NPT	11.8 (7.4)	18.9 (6.4)	+60	14.6 (6.3)	-23
NR2	15.3 (6.7)	26.6 (8.0)	+74	26.1 (8.1)	-2

The pre-flood distinction between riffles and pools is maintained post-flood, but like bed structure, the magnitude of the distinction is reduced. In fact, in the mid-pool region of the Newton pool, there is a strength "reversal". However, this result is more a reflection of the large boulders present at this site.

The standard deviation of bed strength readings per site generally increases post flood, indicating a more variable bed strength reading across the channel. This, together with the net reduction in the strength of riffle sediments, has important implications for salmonid recruitment. Atlantic Salmon (Salmo salar) "run" up river to their spawning grounds during floods. Clearly, from these results it is evident that the spawning grounds, post flood, will possess a less compacted and structured surface into which the fish can cut their redds.

Returning to Table 6.12 reveals the state of the bed strength after 76 days of almost continuous 16 cumec discharges. Values show that the development of a compacted, structured surface varies bewteen NR1 and NR2. At NR1, bed strength readings show a 6.6% increase, whilst NR2 exhibits a decrease of 1.8%. Shear stress over NR2 is much higher than at NR1, which, from the discussions above, may impede the development of a structured and compacted bed. NR2 is also recognised as the second most successfull spawning ground on the basis of redd counts (Carling 1979).

A much greater change in bed strength is evident in the pool, with the mid-pool and pool-tail recording decreased bed strengths of 23.8 and 22.8 respectively. This is not unexpected, since the results of magnetic tracing experiments (discussed in Chapter 10) indicate a net transport of fine sediments from the pool-head to the mid-pool and pool-tail. Such an increase, expressed as fine sediment drapes, over the gravel bed, would decrease the bed strength readings. Alternatively, the bed, tightened by movement during the flood, "relaxes" during the post flood conditions of tranquil flow. Clearly more research is required to elucidate this process still further.

Wolcott (1989) suggests from flume experiments that a period of up to 1 month of steady flow would be required to fully redevelop structure in gravel bed channels; however, Wolcott cautions that it is unlikely that such a period of steady flow will be experienced. In regulated rivers such as the North Tyne, periods of steady flow at compensation discharges are often extended above natural channels. On the North Tyne, periods of up to 56 days of compensation flows have been recorded, whilst 76 days of peak hydropower generating flow were experienced post flood. Under these conditions the spatial differentiation of bed structure between riffles and pools should become more fully developed. The evidence above suggests that, although bed strength increased by 6.6% on one riffle in 76 days, the distinction between riffles and pools results more from a decrease in pool bed strength due to sediment redistribution and relaxation. Although no structural surveys were made (due to time constraints largely imposed by the regulated flow regime), the bed strength tests from a limited sample suggest that periods longer than 2 months are required to re-establish pre-flood levels of bed strength. This is most likely to occur over summer periods with few flood events. Bed consolidation would then be at a maximum for the first winter floods, as observed by Reid et al (1986).

It is clear that a more detailed study of the mechanics of structural development should be placed on the research agenda, in conjunction with a comprehensive analysis of the causes and development of bed strength. An important omission from this study is the role of particle burial on the preservation or destruction of structure. Hassan and Schick (1989), and Drew (pers comm), stress the importance of clast burial in determining the transport of sediment. Analysis of the cross-section data described in Chapter 13 shows the characteristic "filling" of riffles and the "scouring" of pool sediments. Conceivably the bed structure and strength readings made 6 days after the flood result, in part, from burial of the bed surface on the riffles: this is discussed further in Chapter 14.

The work conducted by Harrison (1950) identified a link between sediment size and structural development. Conceptually, this link should be expressed on a river bed experiencing accentuated armour development, or a reduction in sediment supply (Dietrich et al, 1990). These three pieces of information leads to the suggestion that one of the effects of a river regulation scheme should be the maximisation of bed stability at riffles. However, the effects of hydro-power should also be to reduce bed strength on riffles through the mobilisation of surface sediments. Both these processes are evident. In addition, it is clear that bed structural contrasts are fully established during periods of major hydraulic differentiation between riffles and pools which occurs (in the North Tyne) at discharges below 50 cumecs (see Chapter 7).

Chapter 7.0

Hydraulic chracteristics of the riffle-pool sequence

7.1 Flow characteristics that influence sediment transport

The shearing force acting on a river bed is that which initiates and sustains the motion of particles along the channel. In order to understand the transport of sediment, it is essential to identify the spatial and temporal distributions of shear stress (or some analogous measure of bed force) within the channel, and to quantify the factors influencing these patterns (Bathurst 1979).

For engineering purposes, it is convenient to assume that flow in gravel-bed rivers is uniform and two-dimensional. This assumption is largely a reflection of the experimental conditions under which many of the sediment transport formulae were developed. For conditions of flow uniformity, mean bed shear stress can be calculated from the product of unit weight of fluid (y), flow depth (d) and the slope of the energy grade line (S), which is approximated by the water surface slope (Andrews 1983; Carling 1983; Bathurst 1979; Petit 1986; Lisle 1979). This DuBoys method of determining fluid shear stress underpins a range of important concepts in geomorphology. Initiation of particle motion is largely related to a critical shear stress determined from the Shields equation and sediment transport rates are often calculated on the basis of the shear force in excess of the critical shear stress calculated from the depth/slope product (Meigh 1987; Church and Gomez 1989; Robert 1990). Of importance to this study, models of sediment routing through riffle-pool sequences are also based on the hydraulic parameters determined using the DuBoys formula (Lisle 1979; Petit 1986; Komar 1987; Carling 1990) and in situations without contemporary flow data; paleaohydraulics are inferred on the same assumption of flow uniformity (Komar 1988; Baker and Ritter 1975; Williams and Costa 1988).

Temporal and spatial steadiness of flow in natural gravel-bed rivers is disrupted by a combination of grain and form roughness, turbulent bursting and secondary flow development. The uniformity of flow is disrupted by changes in channel geometry or planform which generates nonuniform shear stress distribution. The result is a non-uniform distribution of shear stress within the channel and through time, which means that gross channel characteristics are unlikely to describe effectively the forces operating on the bed (Bathurst 1979; Bathurst et al 1979; Meigh 1987; Clifford 1990; Robert 1990).

Flow non-uniformity is compounded by the sedimentological and morphological variations within channels. Meandering profile asymmetry, and the downstream oscillations in bed slope, characterising the riffle-pool sequence, effect a positive feedback mechanism that tends to enhance flow non-uniformity, thereby complicating the shear field and sediment transport patterns (Hey 1982; 1988). In addition, grainsize variations within the channel (themselves a reflection of the variable shear field) further complicate the distribution of shear stress through differential grain roughness, whilst Robert (1991) identifies a second form of grain roughness associated with bed micromorphology. Ferguson et al (1989), and Petit (1987; 1990) have shown how variable bed roughness produces a corresponding variation in the shear field and sediment transport rates.

7.2 Shear Stress and flow resistance

Carling (1983), and Petit (1990) identified two components that characterise mean bed shear stress (τ_o); grain shear stress (τ') and form shear stress (τ'') including internal friction. For sediment transport, grain shear stress is the most important, since it represents the energy lost in overcoming frictional resistance due to individual particles. For wide gravel-bed rivers (W/d > 11), Hey (1979) considered form resistance to be negligible. However this assumption is complicated first by the riffle-pool topography of alternating deeps and shallows, and secondly by variations in resistance during rising discharge (Carling 1990; Petts et al 1985) and particularly during floodplain spilling (Lewin and Manton 1978; Knight and Shiono 1991). Carling (1983) concluded that with rising discharge, grain resistance proportionally increases as form resistance is drowned out. This was later confirmed by the same author during measurements of bankfull flow over riffle-pool sequences (Carling 1990). Bathurst (pers comm) describes data from riffle-pool sequences on the River Swale, supported by flume data, which indicates that as discharge rises, the form roughness of the riffle-pool sequence becomes drowned out to produce values of flow resistance similar to plane bed conditions.

Differences between channel morphology expressed as width/depth (w/d) ratio impart additional variations in flow resistance. Broader channels experience less energy loss due to form resistance than narrow channels. Correspondingly, a lower mean shear stress was required to initiate sediment transport in broad channels than narrow (Carling 1983). The effects of bank resistance described by Carling (1983) on the initiation of motion of sediments require further confirmation, particularly since the slopes in each channel were significantly different.

Petit (1990) in an analysis of grain shear stress required to initiate sediment motion, concluded that grain resistance varied with sediment size, and between riffles and pools, itself a function of variation in form resistance (> losses in pools with lower W/d ratio and well developed secondary flows). Petit (1990) found that grain shear stress accounted for 30% of the total stress at riffles and only 15% at pools. However, Petit concluded that the variations in grain resistance could not explain the observed patterns of sediment transport. Instead shear stress calculated from the friction velocity provided the best predictor of sediment transport. Robert (1990) has shown that the proportion of grain resistance to total resistance also varies with time under fluctuating discharges which he attributes to changes in the bed roughness height associated with the onset of bedload transport.

The latter point is important to sediment transport in riffle-pool sequences since the ratio of τ_p/τ_0 will vary between riffles and pools and between areas of differing grainsize. Failure to account for this when applying mean shear stress relationships between riffles and pools may obscure the reality of the situation (Clifford 1990).

Robert (1990) has described a third contribution to total flow resistance which although incorporated in velocity profile estimates of grain resistance is nevertheless a distinct component of bed roughness. Robert (1990), by using fine detailed measures of bed rugosity and applying fractal analysis to the bed profiles, identified a component of flow resistance that was associated with microform roughness elements. The conclusion was that careful interpretation of the near-bed velocity profile was required in order to obtain the grain shear stress from that associated with wake shedding and reattachment from microforms, and that only the lower 7 cm of a velocity profile would equate with grain shear stress (Robert 1990).

7.3 Turbulence and flow structure

Water flowing over a surface exhibits viscous properties and responds to the application of gravitational force by movement. In laminar flow resistance to movement will be greatest nearest the bed and declines exponentially with decreasing depth. Motion of water layers is parallel. With an increase in velocity, depth , the water layers become distorted and the flow becomes turbulent. In uniform flow, the pattern of velocity in the vertical profile remains similar to the laminar flow but turbulent structure will generate fluctuations in the shear field at a point with time. Once turbulent flow is established, the influence of boundary roughness will accentuate the development of turbulence by generating areas of flow separation and eddying. Separation effects are found in natural channels over a range of scales from the individual separation wakes downstream of individual particles (Brayshaw and Reid 1983) through to large scale separation forms affecting 100m + of channel (Best 1986; Carling 1989).

Fluctuations in the shear force due to turbulence are known to exhibit a degree of structure known as turbulent bursting (Jackson 1976). Turbulent bursting describes a deterministic cycle of events that, though apparently random in space and time, nevertheless reflects a degree of process continuity (Laufer 1975). The burst cycle, as observed under experimental conditions, consists of a localised detachment of the boundary layer that generates a vortex which controls the upward migration of the low speed boundary layer flow until, with subsequent interaction with downstream boundary separations, the low speed separation flow breaks up or bursts. Surface manifestations of bursting are described by Jackson (1976) as "boils"; "locally elevated sections of water displaying flow divergence from a central point". Although Lawfer (1975) describes the phenomena as being random in space and time, distinct bed conditions appear to favour bursting. Jackson reviews observations of "boils" in alluvial rivers and concludes that increased bed roughness and flow depth, develop larger and more frequent boils. He supports this observation with evidence of boiling downstream of a bar crest (Jackson 1976). More recently Clifford (1990) has reported a significantly higher frequency of "event structures", analogous to turbulent bursting, at riffle crests than in corresponding pools. Clifford has linked this phenomenon to the accentuated development of sediment structure largely on the basis of the inferred roughness contribution from pebble clusters (Robert 1990) (see Chapter 6).

Turbulent bursting is suggested by Jackson as an important mechanism for entraining sediment of all sizes through the localised increase in shear stress operating on the bed (Jackson 1976). This hypothesis is supported by Clifford's observations of more frequent, higher shear stress events at riffles corresponding to a sedimentological difference, which at least implies a local redistribution of sediments coarser than sand size (Clifford 1990).

7.4 Secondary flows - macro scale flow structure.

Turbulent bursting and its role in sediment transport is poorly understood, and requires greater research input. In contrast, macro-scale flow structure has achieved attention principally through its role in meander development, (Yalin 1972; Hey and Thorne 1975; Clifford 1976; Bathurst 1979; Markham and Thorne 1991). Church (1982) distinguishes between turbulence and secondary flows on the basis of persistence; secondary flows being persistent (and hence monitorable) expressions of skew-induced or stress-induced transverse velocity transfer. Bathurst et al (1979) distinguish secondary "currents" as "currents which occur in the plane normal to the local axis of the primary flow". Two types of secondary flows exist; stress-induced (which only form under conditions of anisotropic turbulence and non-uniform shear stress distribution), and skew-induced which is possible whenever cross-stream vorticity is present in the flow (Bathurst et al 1979). Stress induced secondary currents have been observed in flume studies, where regions of differential roughness impart anistrophy to the lateral shear stress (flow) distribution (Muller 1979; Tsujimoto 1989; Houjou et al 1990). Indeed, a positive feedback mechan ism can be developed in these circumstances whereby lateral variations in bed roughness generate secondary flow cells which contribute to further lateral sorting of sediments (Tsujimoto 1989). Stress induced secondary flows have been observed in natural channels by Deitrich and Smith (1983), but the field based literature is dominated by skew induced secondary flows. Skew-induced secondary flows are generated and controlled by profile asymmetry in meander bends, and stress-induced secondary flows are found mainly in straight channels.

Secondary flows are typically an order of magnitude lower in velocity than primary flows, are produced almost instantaneously, and decay over distances controlled by local

bedform spacing and flow conditions (Bradshaw 1971). Secondary flows are typically 1-2% of the magnitude of primary flow velocities (Studerus 1982), although this varies with discharge with maximum strength associated with moderate - bankfull discharges (Bathurst 1979, Clifford 1990; Markham and Thorne 1992). Bathurst (1979), suggests that the strength of secondary flows in bends is greatest at moderate flows, however, the observations of Markham and Thorne (1992) indicate that this is an oversimplification, and that secondary flow strength can be strongest at bankfull discharge. Flow straightening and the drowning-out of bed irregularities will affect the shear stress distribution as the discharge rises, but inevitably local channel morphology, and bed roughnesses will impart some measure of non-uniformity in the flow field.
It is suggested that the strength of secondary flows is weakest at low and high discharges, a function of generally low velocity at low discharges, and an increasing uniformity of transverse shear stress distribution at high discharge as profile asymmetry and bedform roughness is drowned out (Bathurst 1979). The distribution of secondary flows is complex, particularly in channels with high W/d ratios. Laboratory measurements suggest that a total circulation diameter is limited to flow depth, and therefore secondary flow cells exist as numerous rollers disposed across a section. However, field measurements by several authors have shown single flow cells, of complex shape, extending over most of the cross section, (Markham and Thorne 1992; Bathurst et al 1979; Bhowmik 1982).

The importance of secondary flows to sediment transport stems from their effect on the magnitude and distribution of shear stress across the bed. Bathurst (1979) inferred multipeak shear fields observed in pools, with downwelling of flow associated with adjacent, counter-rotating secondary cells. By the same argument, Bathurst suggested upwelling regions of flow with zones of low shear stress. The pattern of shear stress across the bed was observed to change with rising discharge as a result of the weakening and translocation of the secondary flow cells. This phenomenon has subsequently been confirmed by laboratory flume measurements (Studeras 1982; Knight and Shiono 1990).

Associations between secondary flow and sediment transport are largely iterative, with observed sediment transport attributed to inferred flow structure. An exception is the study by Thorne (1978) who observed maximum bed scour and particle transport within a region known to experience secondary flow downwelling and a corresponding shear stress maxima. An important link has been established between longstream patterns of shear stress, effected by the decay of secondary flow cells, and patterns of scour and fill. Scour is effected by longstream increases in bed shear stress and fill by a corresponding longstream decrease (Bathurst et al 1979; Thorne and Lewin 1979). Clearly bed topography that undulates in the longstream dimension will, at low flows, control the evolution of the secondary flow structure and hence shear stress distribution. At higher discharges when the riffle-pool topography is drowned out, the effect on flow structure may not be so pronounced. A clear need for more high flow measurements of related hydraulic and sediment transport parameters is required.

7.5 Hydraulic discrimination of the riffle-pool sequence

Hydraulic discrimination of riffles and pools was suggested as early as 1894 by de Leliavsky, who concluded that riffles were associated with surface flow divergence and pools with surface flow convergence. Riffles were also associated with higher velocity flow. Although qualitative, these observations have formed the basis of subsequent hydraulic models of the riffle-pool sequence (Keller 1971; Hey and Thorne 1975). The contrast in velocity between riffles and pools and the apparent paradox of low velocity and yet bed scour in pools, was investigated by Gilbert in 1914. Gilbert concluded that a velocity reversal occurred at flood flows such that pools experienced higher velocities than riffles, and scoured. This hypothesis has been subsequently developed by Keller (1970;1971) and underpins most sediment routing models in riffle-pool streams (Ashworth 1987; Carling 1990).

Definition of riffles and pools on the basis of a flow criterion was mooted by both Wolman (1955) and Doling (1968). Discrimination of riffles and pools was determined by the difference in the ratio of v/d where v = mean velocity and d = mean flow depth. Richards (1976) criticises this method of discrimination in view of velocity reversal, since an increase in discharge will reduce the variation between v/d values. Yang (1971) attempts to discriminate between riffles and pools by using the energy grade line, simplified to water surface slope. However, in the same way that velocity is a poor discriminator, water surface slope is known to vary with rising discharge (Lisle 1979; Bathurst 1982) therefore presenting the same inadequacies.

Quantitative hydraulic discrimination between riffles and pools has been achieved through the development of hydraulic geometry (Leopold and Maddock 1953). This technique seeks to define channel form and flow as a series of exponents related to discharge. Empirical data are fitted as a power function of discharge on a logarithmic scale. The function is fitted by a simple linear regression and exponents are determined that define width (Q^b), depth (Q^f), velocity (Q^m), Slope (Q^z), and resistance (Q^{ff}). Variations in these exponents are then used to distinguish between cross sectional response to a change in discharge. Riffles (r) and pools (p) are therefore discriminated according to the magnitude of the exponents:

Depth $Q^{fr} > Q^{fp}$

Velocity $Q^{mr} < Q^{mp}$

Slope $Q^{zr} < Q^{zp}$

Morphological pattern has been shown to be an important control on riffle-pool hydraulic response. Richards (1976) observed higher exponent values for curved riffle-pool sequences over straight sequences. Keller (pers comm) in a re-appraisal of his Dry Creek data has observed a similar change in the hydraulic behaviour of riffle-pool sequences located at meander bends.

Recently this technique has been criticised, primarily for oversimplification and the assumption of linearity in the relationship between morphometric variables and discharge (Knighton 1984). Richards (1973) advocates a reappraisal of the linearity of the variable/discharge response and suggests that more complex quadratic models should be tried. Knighton goes further and concludes that "there is now doubt as to the validity of a mean hydraulic geometry, and that the time is right not only for a reappraisal of existing techniques (sensu Richards), but also of the basis of the approach itself", (Knighton 1984). Carling (1990), concludes that the adherence to hydraulic geometry as a means of discriminating between riffles and pools, has obscured the underlying complexity of the flow mechanisms. This has recently been supported by Clifford (1990) and Petit (1986;1987) who concluded that mean hydraulic values for cross sections do not account for the patterns of sediment transport or the complexity of flow within riffles and pools.

As Carling (1990) implies, the reversal hypothesis is a function of hydraulic geometry rather than a process in itself. Carling's (1990) observations at flows up to overbank flow, show equalisation of section shear velocity and velocity between riffles and pools. Clifford and Richards (in press) describe a more complex picture of localised velocity reversal within sections of the pool but no evidence of a gross sectional velocity reversal.

Discrimination between riffles and pools in terms of flow structure have already been alluded to with respect to the observations of De Leliavsky (1894). The presence of differential patterns of surface flow convergence and divergence have been widely used to discriminate between riffles and pools and have been developed into models of secondary flow and sediment transport (Keller and Melhorn 1978; Hooke and Harvey 1983; Petit 1986; Thompson 1986; Clifford 1990). Keller and Melhorn's (1978) extensive review of riffle-pool research concludes that the divergent/convergent flow association with riffle-pool topography is an important factor in explaining the maintenance of the sequence but not its evolution. However the observations by Bathurst et al (1979) cast some doubt on the viability of the single or double flow cell model of riffle-pool flow structure. Observations of shear stress peaks in straight riffles and pools suggests a more complex, multicellular arrangement of secondary flow. The streams in which observations of simple two-cell structure have been made are consistently small, and of relatively low w/d ratio (Hooke and Harvey 1983; Thompson 1986; Petit 1986). The observations made by Bathurst et al (1979) were conducted in a gravel-bed channel of much greater w/d ratio.

Clifford (1990) also dealing with relatively small Exmoor streams, concludes that flow structure in riffle-pool sequences is much more complex than previously considered, and is shown to exhibit cycles of varying periodicity. The variation in velocity fluctuations are attributable to local skin friction affects, secondary circulation arising from the riffle-pool topography and possibly an inherent periodicity in macroturbulence as reported by Yalin (1972) and Richards (1976).

Further complexity of flow structure within the riffle-pool sequence is discussed by Bathurst (1979) and Beschta (1982) in terms of high velocity "jetting" off the upstream riffle. A jet, by hydrodynamic definition, is a discrete body of water, possessing accentuated velocity, entering a body of slower moving water through an orifice

(Raudkivi and Callander 1975). Jetting is discussed by Bathurst (1979) and Beschta (1982) as a possible cause of the accentuated near bed velocities observed in pools.

The preceding discussions have developed the notion of the complexity of flow within gravel-bed rivers experiencing a riffle-pool topography. The result of this has been to cast doubt on the validity of using cross-section averaged hydraulic parameters for discriminating between behaviour of the riffle and pool sections of a channel in response to a rise in discharge. Furthermore doubt in the ability of mean hydraulic parameters to account for the observed (or inferred) patterns of sediment transport is also established. To attempt to predict the effects that a variable discharge will have upon the morphology, sediments and sediment transport within riffle-pool sequences as a result of hydropower generation, it is clear that some measure of the local hydraulic parameters must be made at least to cross reference with gross parameters.

7.6 Methodology

Following from the preceding discussion, it was considered necessary to establish the complexity (or otherwise) of flow in the riffle-pool sequences within the North Tyne and how the patterns of flow and the magnitude of fluid forces varied under hydropower conditions. In particular, the pattern of flow divergence and convergence at the bed was considered important to discern for interpreting the pattern of sediment transport and predicting the likely direction of sediment movement under hydropower conditions.

7.6.1 Determination of flow structure

The determination of flow structure in cobble-bed channels on the scale of the North Tyne is complicated by logistical problems of scale and equipment. To overcome the problems of scale, representative sections of the riffle-pool sequence can be chosen from which to determine the variation of flow structure and hydraulic parameters throughout the sequence. This approach was adopted by Ashworth (1987) who divided his study sites into riffle, pool-head, pool-mid and pool-tail. Clifford (1990) developed this methodology to include riffle-crest sites as well. Thorne (1980) and Bathurst (1979) both divided their study sections into representative cross-sections from which reach-scale patterns of secondary flow and bed shear stress were deduced.

The measurement of secondary flows and flow turbulence is difficult not least because of argument over the interpretation of the data derived from the electromagnetic flowmeters (EMF) used for data collection (Clifford et al 1991). Thorne (1980) used EMF readings extensively in the gravel-bed River Severn, and developed a technique for interpreting the output. Clifford (1990) used EMF readings to quantify the distribution of turbulence and turbulent stress within a small gravel-bed pool-riffle sequence. However, although representing the "state of the art" field measure of flow structure, the equipment was not available for this study.

An alternative to the determination of flow structure by EMF is discussed by Bhowmik (1982) and relies upon the distortion of isovels to predict secondary current direction. There is some controversy over the validity of this technique in straight channels, but the results of flume studies of secondary flows in relation to the isovel distribution suggests that this technique provides a resonable approximation (Muller 1979; Tsujimoto et al 1990). This technique requires the measurement of velocity profiles at regular intervals across the representative sections, and the construction of an isovel field. The nature of the research programme mitigated against a detailed velocity profiling for all three sites and therefore a compromise solution was developed to investigate the presence of flow structure within the riffle-pool sequence. The Newton site was monitored for flow structure by detailed velocity profiling at five sections, riffle 1, pool-head, pool-mid, pool-tail and riffle 2. Measurements were made with an Ott-C320 current meter at 1cm intervals up to 10cm from the bed (cf shear stress determination section below) at the surface, and at 0.6 times flow depth. In the pool sections, an additional reading was made at 0.8 times flow depth. In addition, the direction of flow was determined by noting the angle from the cross-section line, that coloured string adopted at the flow surface, mid-depth and at the bed. This technique was used by Thompson (1986) to determine the flow structure in a riffle-pool sequence at low and high discharges. The success of the technique stems from its rapidity, enabling large numbers of measurements to be made. However there is a limit to the depth at which the string can be seen, particularly in the peat stained waters of the North Tyne pools. Despite this drawback, the flow visualisation technique was used at the Smales and Tarset sites.

7.6.2 Determination of shear stress

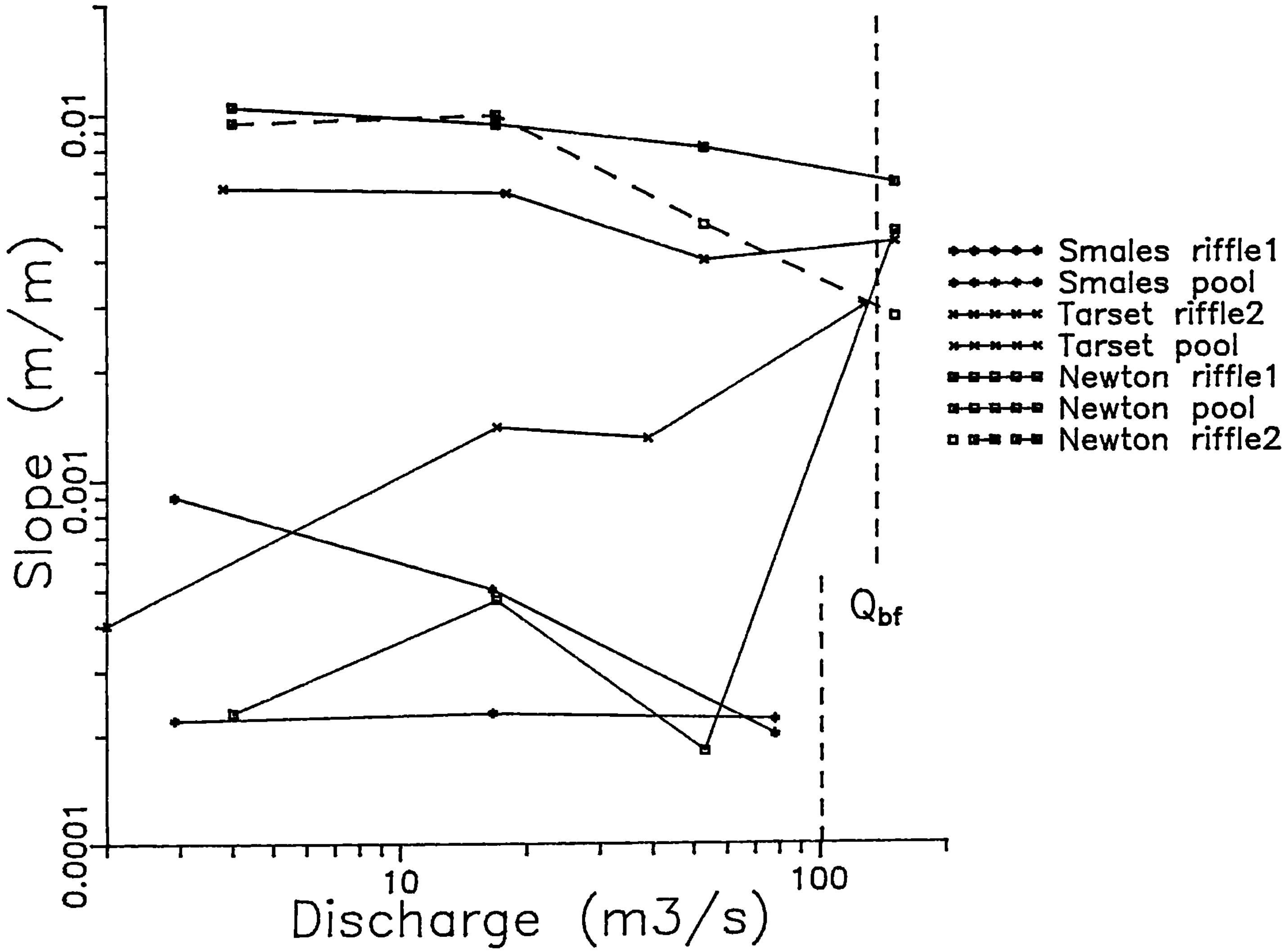
Shear stress was determined using both the DuBoys relationship and the log-velocity Prantl/von Karman law. The DuBoys formula takes the from:

$$\tau_0 = vdS \qquad \text{(Equation 7.1)}$$

Where v is the specific weight of fluid, d is the local flow depth and S is the slope of the energy grade line approximated by the water surface slope. Data for the DuBoys method was collected by determining water surface slope and local flow depth at the velocity profiling sites. Water surface slope was determined by recording the water stage at surveyed stage poles located at 40 m intervals throughout the riffle-pool-riffle sequences. The determination of discharge has been discussed in Chapter 3. Figure 1 illustrates the broadly typical response of water surface slope within the three riffle-pool-riffle sequences studied. In all cases, the water surface slope is much lower in the pools and increases as the stage rises. In contrast, the riffles exhibit variable responses, but all show a tendency to reduce in slope as stage increases. The regression relationships developed for stage/water surface slope enable mean shear stress to be calculated for the section or for the individual point depths (Allen 1977). The calculation of point shear stress in this way, assumes that the water surface slope is constant across the section. Leopold (1982) has shown evidence to suggest that profound cross-section variation in water surface slope occurs, particularly over riffles or inflexion points. However Leopold (1982) documented the major variation in cross section slopes at meander bends or channel curves, which did not apply in all but one of the cross sections monitored in the North Tyne. Water surface slope at higher discharges (above hydropower flows) were measured by surveying trash lines along the reach of channel (Newson 1980). This method is in many ways superior to extrapolation from individual depth gauges, since a continuous downstream record on both channel banks is possible. In this way, verification of a lack of major cross stream slope variation at bankfull discharge was possible.

Point shear stress (τ_p) was determined from velocity profiles measured at 4 positions across the sections. The points were chosen to be representative of the section, for example, in pools a deep and a shallow profile were chosen with two other profiles

7.1 Changes in water surface slope with increasing discharge.



representing depths in between these. The points were also spaced as equally as possible across the sections and away from the banks as these areas were known from observation to remain sedentary and of little consequence to sediment transport. Velocity profiling at only 4 points reflects a compromise between the detail of the sectional flow and the temporal detail during what are rapid stage changes. At the time it was decided to adopt the technique used by Meigh (1987) and to construct a relationship between flow depth at a point and τ_p. Meigh (1987) had achieved successful relationships using velocity profiles at a straight pool site on the river Severn and had then used representative depth values across the section to reconstruct cross-sectional shear velocity distribution. The values for shear stress calculated in this way were consistently lower than those determined by the DuBoys formula. This has been confirmed from flume measurments of direct shear stress using hot-films in comparison with DuBoys estimation based on water surface slope, and log-velocity profiling using the lower 20% of the flow depth. The log-velocity profiles consistently recorded values of shear stress at the bed *similar to* the direct measurments, whilst the DuBoys estimations were overestimated in "pool" regions and under-estimated in "riffle regions" (Tsujimoto et al 1990). Over 240 individual profiles were made, from three pool sites and four riffles, during three separate hydropower releases.

Velocity was measured at 5 points located at 0.01-0.05m above the bed with a further measure made at the surface. Two current meters were used, an Ott C320 with 3-5 cm impellers, depending on flow velocity, and a Braystoke with 5cm impeller which was exclusively used in the pools owing to its greater depth facility. To ensure accuracy of depth readings, the graduated staffs of each current meter were measured against a rope, drawn across the channel, readings could then be made relative to this datum. In the pools, the water surface provided a suitable cross reference datum owing to the absence of turbulence or waves. The sectional measurements were made simultaneously at a riffle and pool within one riffle-pool-riffle sequence. This differs from the earlier work on riffle-pool hydraulics (Lisle 1979; Andrews 1982) who used sites separated by intervening riffle-pool units. Bathurst et al (1979), Beschta (1982) and Clifford (1990) have shown the importance of riffle flows on the immediate downstream pool hydraulics particularly at low discharges when the riffles are not drowned out.

The lowest velocity points were all measured within the bottom 20% of flow depth, as determined by a variety of authors to be the range within which uniform flow (and thus the log velocity law) applies (Bathurst 1979; Bridge and Jarvis 1977). Recent comparisons between shear stress calculated using the near bed velocity gradient and direct measurments of shear stress using a flash-mounted hot film (Gust 1988) have confirmed the validity of the technique. Furthermore, the comparisons, though made under controlled conditions in a flume, were measured over an undulating bed profile, broadly analagous to those in a riffle-pool sequence (Tsujimoto et al 1990). The log velocity law under steady, two-dimensional flow has the form (Yalin 1972)

$$U/U* = 1/k \ln (y/ks) + B \qquad \text{(Equation 7.2)}$$

where U is the velocity measured at a point y from the bed, U* is the shear velocity, k is the von Karman constant (k = 0.4) and ks is the roughness height. For flows in the rough turbulent regime, B is a constant. Meigh (1987) provides an algorithm for determining if conditions ascribe to rough turbulence, which occurs when the thickness of the viscous sublayer is small relative to the size of the roughness elements (large boulders down to small grains depending on the bed) and in which case, turbulence extends below the level of the roughness elements. In this case U* can be calculated from the slope of the semi logarithmic plot of U against log y. Nikuradse (1933) found that rough turbulence (and therefore B in equation remains constant) pertained when the product

$$U*ks/v > 70 \qquad \text{(Equation 7.3)}$$

for coarse gravels ks has been found to be equivalent to between 3 - 4.D_{84} of surficial gravels (Ferguson pers comm). By applying this to equation 7.3, for the range of U* at each section monitored, minimum values were calculated that showed that rough turbulent conditions applied in all cases and therefore B in equation 7.2 remains constant.

Two further sources of error in the velocity profiles (assuming operator and mechanical error were minimised) arise from the determination of the zero bed datum (Flintham and Carling 1988) and from the relative roughness criterion (Bathurst 1982). Flintham and Carling (1988) using a range of gravel from 6-20mm developed a value of 0.5.D84. to define the zero bed datum, above which the values for y are adjusted. In this study, as in the study by Bathurst (1977) and Meigh (1987) the reference level is given as the bed surface. This is largely due to the problems with determining the individual appropriate D_{84} for each point, and due to inconsistency in the literature regarding the appropriate value for reference depth (Flintham and Carling 1988; Einstein and El-Samni 1949; Smith 1975; Bathurst 1977).

Relative roughness refers to the ratio between mean sediment height and flow depth, (d/D_{50}), and Bathurst (1982) has suggested limits to the application of the log-velocity law based upon this criterion. According to Bathurst, when the relative roughness is < 4 then roughness is great and application of the log velocity law is problematic due to interaction of wake eddies disrupting the velocity profile. A relative roughness of 4-15 represents an intermediate state, and values > 15 marks the boundary of small scale roughness and confident application of the log velocity law. Table 1 shows the values of relative roughness in this study, the majority of which lie within the small scale and

Table 7.1: Relative roughness (d/D_{50}) for each site.

Site:	1	2	3	4
Smales riffle	(4.8-11.3)	(5.7-12.2)	(6.0-12.6)	(6.8-13.7)
Newton riffle1	(9.8-15.9)	(9.8-15.9)	(8.7-14.9)	(7.3-13.4)
Newton riffle2	(4.7-9.1)	(4.7-8.1)	(4.1-7.4)	(2.8-7.2)
Tarset riffle2	(1.7-6.3)	(1.4-3.7)	(3.8-8.5)	(1.7-2.3)
Smales pool	(22.8-37.2)	(20.5-33.2)	(13.7-21.7)	(12.3-19.5)
Newton pool	(12.5-22.9)	(18.3-24.4)	(5.7-6.9)	(3.6-6.4)
Tarset pool	(18.9-22.9)	(30.0-38.0)	(21.8-29.8)	(22.7-39.1)

intermediate roughness zones, although some sites on the riffles initially fall below the 4 limit. These values were not maintained for long once the flow began to rise and although at many riffle sites the values do not extend above 15, checks on the validity of the profiles proved that in the majority of cases the log-velocity law applied.

Equation 7.2 can be rewritten as

$$U = 5.75.U* \log_{10}(y/ks) + B \qquad \text{(Equation 7.4)}$$

The slope (U*) is then determined by

$$U* = U_2 - U_1/5.75.\mathrm{Log}_{10}\,(y_1/y_2) \qquad \text{(Equation 7.5)}$$

and shear stress is then calculated from

$$\tau_p = p(U*)^2 \qquad \text{(Equation 7.6)}$$

For each velocity profile, the best fit line was obtained by least squares regression and U* determined from the gradient of the relationship. The values for U* were selected on the basis of Log linearity exhibited by the coefficient of determination, $r^2 > 0.5$ Non-significant relationships were viewed and equation 7.5 applied to 0.05m and 0.01m measurements unless the profile exhibited considerable deviation from a log-linear trend whereupon these were rejected.

Table 2 illustrates the distribution of r^2 for the range of U* experienced in this study.

Table 7.2: Correlation coefficients and standard deviations associated with shear velocity classes in riffle and pools

U_* (m/s)	n	r2 (%)	sd
Riffle			
0 - 0.004	5	0.1	0.1
0.004 - 0.009	2	0.0	0.0
0.009 - 0.017	3	4.7	0.5
0.017 - 0.035	20	35.0	31.3
0.035 - 0.070	31	69.6	23.7
0.070 - 0.139	58	74.0	22.2
0.139 - 0.175	4	67.5	9.8
> 0.175	7	92.6	5.6
Pool			
0 - 0.004	16	7.1	15.4
0.004 - 0.009	30	33.6	31.4
0.009 - 0.017	25	33.8	27.5
0.017 - 0.035	24	53.2	28.2
0.035 - 0.070	27	74.0	13.3
0.070 - 0.139	16	89.3	10.3
0.139 - 0.175	--	----	----
> 0.175	--	----	----

Values of U_* have been accorded to riffle or pool. Two immediate points are obvious. First, there is an increase in r^2 and a decrease in standard deviation of the coefficient as U_* increases, in both the pools and riffles. Secondly, for a given range of U_* values, the pool profiles exhibit higher r^2 values than the riffles. This latter point may be explained by the generally higher relative roughness experienced in the pools. The increase in r^2 value with increasing U_* reflects, in part, the non-loglinearity of the velocity profiles associated with slack water zones in the pools, and high relative roughness on the riffles.

To ascertain the possible error involved in the determination of shear stress a check was made of the sensitivity of shear stress values (estimated from log-velocity profiles) to changes in the reference depth and the number of velocity values used. The reference depth was changed from 0.01m to 0.02m for one check, and the highest velocity reading above the bed removed for a second check. The results of the checks were recorded for riffles and pools and subjected to a one-way analysis of variance (ANOVONEWAY) to compare the possible magnitude of variation within the data with the temporal vararaitions at a site and between riffles and pools.

The affect of altering the reference depth was to increase the shear stress values in pools by an average of 41% (sd = 49%) and in riffles by +53.7% (sd = 12.4%). The effect of using only the bottom four velocity readings was to decrease the shear stress values at pools by -39% (sd = 36.2%) and at riffles by -5% (sd = 23%). The results of the ANOVONEWAY test indicated that in pools the magnitude of variation in the data caused by altering the reference depth was equivalent to the temporal variations resulting from unsteady flow, but were significantly different than the varations between shear stress values recorded at riffles or pools. Subsequent interpretations of the data must bears this point in mind. The same test applied to riffle data indicated that the varaiance imparted to the data was significantly less than either temporal or spatial variations at the 95% confidence level.

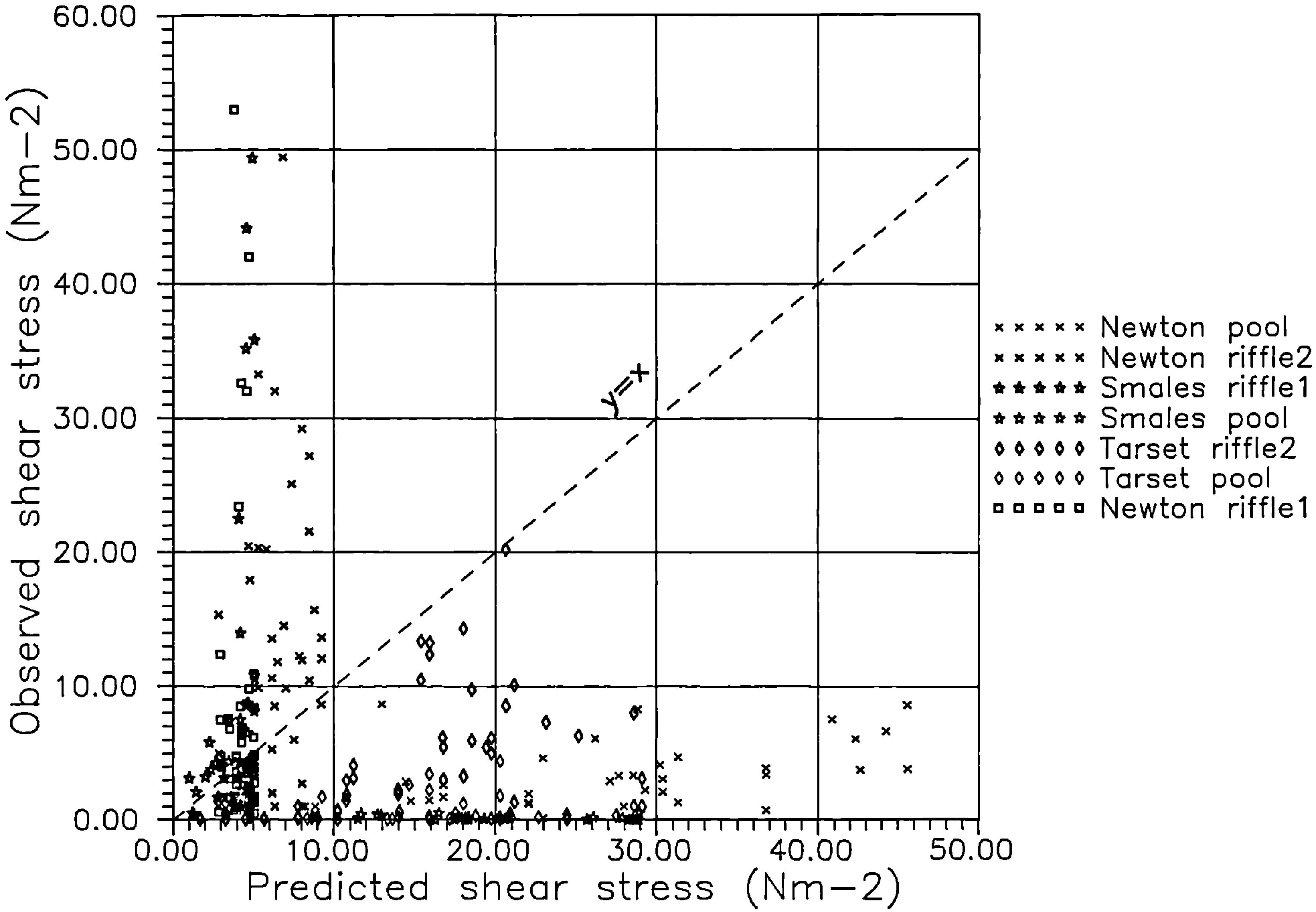
The affects of altering the number of velocity readings used in the estimation of shear stress generated data variance that was significantly different to spatial and temporal data variance at riffles or pools at the 95% confidence level.

The conclusions from this analysis suggest that a variation about the mean of on average 53% and 41% is to be anticipated in the shear stress readings from pools and riffles based on a 0.01m variance of reference depth. Nevertheless, with the exception of the temporal variation in shear stress within pools, the data variance is significantly lower than that between riffles and pools and on riffles. The patterns of shear stress observed between pools and riffles during hydropower discharges are considered to be "real" features of the unsteadiness of the flow field, and not a product of data error.

For logistical (and climatic) reasons it was impossible to measure velocity profiles during floods in excess of hydropower flows, and since the relationships between flow depth and shear stress proved statistically untenable, it was decided not to attempt extrapolation. Instead an approach was adopted based on the ratio τ_p/τ_0 which has been used successfully by Petit (1987) to determine the cross stream variations in τ_p. To whit, the relationship τ_p/τ_0 was applied to local shear stress determined from local flow depth, coinciding with tracer pebbles (see Chapter 12) and water surface slope, measured at compensation flows and hydropower flow. For discharges in excess of hydropower generation, an assumption of τ_p/τ_0 = unity was made. This assumption is valid, as a variety of authors have confirmed a tendency for grain shear stress (τ_p) to equal or exceed (τ_0) at bankfull discharge (Bridge and Jarvis 1976; Bathurst 1977; Bathurst 1982; Carling 1983; Petit 1990). In streams with riffle-pool sequences, shear stress in pools at low flows is consistently lower than estimated from the depth-slope product due to extended velocity profiles resultant of residual depth. The difference between uniformity parameters (τ_0/τ_p) decreases as residual ponding effects are drowned out, Bathurst (1982). Conversely, with decreasing w/d ratio, secondary flow development and micro-turbulence is recorded as increasing and a reduction in τ_0/τ_p would be expected, however, Bathurst (1979) has suggested that secondary flow development is most effective in altering grain shear stress, at medium in-bank flows. Petit (1990) shows that the ratio τ_p/τ_0 tends to increase as Q increases, but does not obtain unity. However a variation between riffles and pools such that τ_p/τ_0 is much nearer unity for riffles even at bankfull Q is compensated in pools by much higher values of τ_0, and therefore τ_p (grain shear stress) is higher than riffles. Furthermore the streams used in Petit's study had low w/d ratios which probably encouraged greater form resistance loss at bankfull discharges. Bathurst (1977; 1982) records for high w/d cobble-bed streams like the North Tyne, an increase in shear stress uniformity across sections that imply a weakening of secondary flow effects and hence a move towards uniform flow. Following this argument it was felt that for bankfull discharges, local grain shear stress could be effectively deduced from the DuBoys relationship applied to local depths Allen (1977).

Figure 7.2 depicts the variation from unity experienced for the ratio τ_p/τ_0 for riffles and pools in the North Tyne during hydropower flows. Pools consistently plot below the line of unity with values for bed shear stress up to 70% lower than predicted from the DuBoys formula. This reflects the residual depth effects alluded to in the discussion above, together with a resistance loss incurred due to near bank zones of slack water. The departure of observed bed shear stress from predicted values, varies per pool and riffle, with the Smales pool experiencing the lowest grain shear stress observed from velocity profiles, despite experiencing the shallowest residual depth. This represents an important departure from the theory expounded by Bathurst 1982, although a review of the velocity profiles from this pool shows that the flow was distinctly non-uniform and therefore the observed trend may well be spurious.

7.2 Comparison between predicted shear stress (DuBoys) and shear stress calculated from velocity profiles measured during hydropower generation.



Riffle sites exhibit the most dramatic variation in τ_p/τ_0, with the majority of values plotting around the line of unity for low predicted shear stress, but increasing rapidly to values up to 70% in excess of predicted values as maximum hydropower discharges are reached. Individual riffles behave differently with Tarset riffle 2 exhibiting consistently lower than predicted grain shear stress than any other of the riffles monitored. It is perhaps significant that it is this riffle that had the lowest relative roughness values, which Ferguson et al (1989) and Wiberg and Smith (1987) suggest, results in the reduction of velocity profile readings below those predicted from the depth slope product, due to the influence of particle form drag. Petit (1990) also recounts lower than predicted shear stress from velocity profiles for riffles on the gravel-bed La Rulles river. Table 7.3, illustrates the geometric mean values for τ_p/τ_0 experienced at the sites monitored in the North Tyne at compensation and hydropower flows, together with those recorded for the La Rulles. All sites experience an increase in τ_p/τ_0 which is contrary to the extrapolation to unity, suggested by other workers, however, the conditions described are for large - transitional roughness when considerable fluctuations in the flow field are known to occur, and for flows of only 12% - 17% of bankfull. Both Figure 7.2 and Table 7.3 show that the decision to measure point shear stress directly in order to interpret the effects of hydropower releases on the sediment dynamics of riffle pool sequences was correct, and is significantly different than the predictions made by depth-slope products alone.

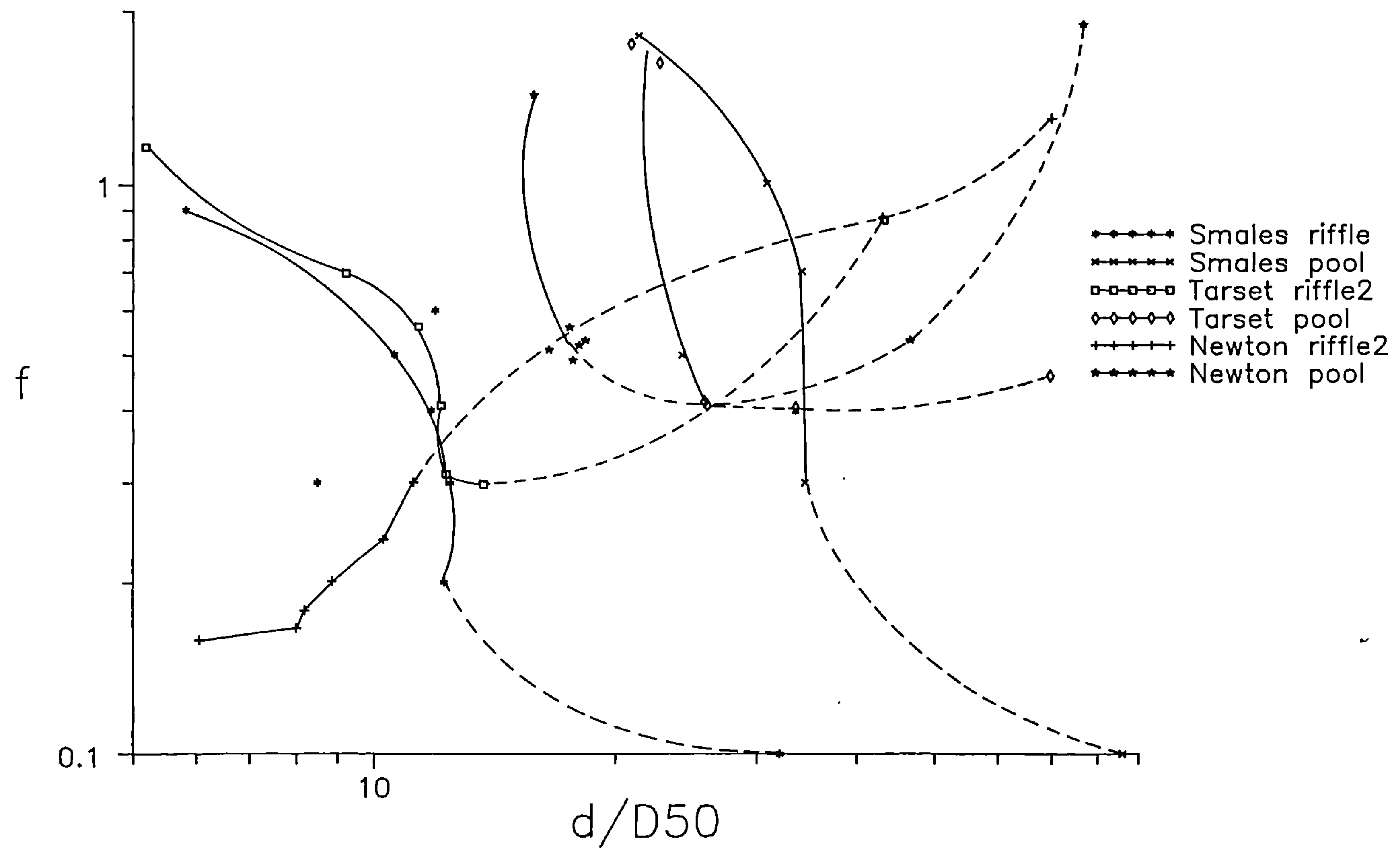
Table 7.3: Comparisons between the range of τ_p/τ_o ratios recorded for riffles and pools in the North Tyne during hydropower discharges and in the La Rulles stream (Petit 1990)

Smales riffle	0.23 - 2.04
Tarset riffle 2	0.03 - 0.79
Newton riffle1	0.27 - 2.42
Newton riffle2	0.28 - 2.13
La Rulles riffle	0.14 - 0.28 (Bankfull Discharge)
Smales pool	0.001 - 0.03
Tarset pool	0.005 - 0.07
Newton pool	0.023 - 0.18
La Rulles pool	0.020 - 0.15 (Bankfull Discharge)

Figure 7.3 illustrates the effect of decreasing relative roughness on total resistance (including grain and form resistance), measured by the dimensionless Darcy-Weisbach friction factor (f). Considerable variability is again evident, with the lower w/d ratio Smales site, reacting quite differently at bankfull discharge than all other sites. However, with the exception of Newton riffle 2, all sites, pool or riffle, show an initial decrease in f as relative roughness increases, suggesting that grain resistance is an important component of total resistance. However this is unexpected for the pools where direct measures of grain shear stress show the opposite, that grain resistance is in fact a minor component of the total resistance; instead f in pools initially decreases with increasing discharge as residual depth and slackwater zones are activated and cease to offer resistance to flow. This transition is apparently more rapid than the decrease in grain resistance experienced on the riffles. The anomalous behaviour of Newton riffle 2, may result from the bifurcation of flow around a central island, such that flow depth and slope increase dramatically as an increasing discharge is funnelled through a consistently narrow cross section.

The tendency for f to increase up to bankfull discharge at all but the Smales site, suggests that additional resistance at high flows is operative which may come from increasing boundary drag as the ratio bed perimeter/wall perimeter decreases (Flintham and Carling 1988) or through the development of significant secondary flows, (Bathurst 1982). Carling (1990) refers to a consistent decrease in f as discharge over pools and riffles

7.3 Variation of Darcy–Weisbach friction factor with decreasing grain roughness

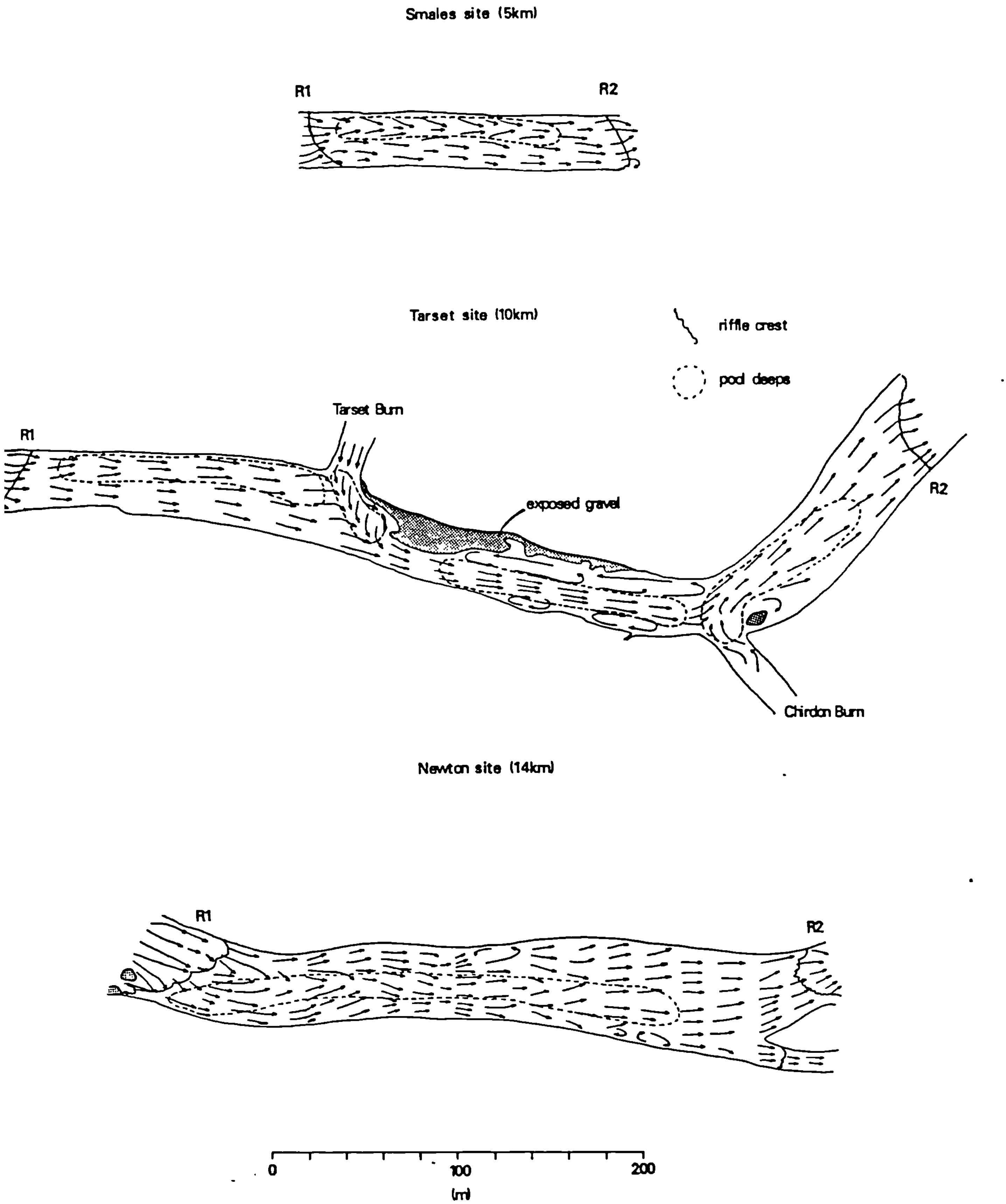


increases to bankfull. A deviation to this trend was related to the inundation of additional bank roughness elements as flow depth increases, which certainly occurs at the Newton and Tarset sites when trees are incorporated into the bank roughness at just below bankfull discharge. This has important ramifications for the assumptions made in estimating local shear stress from the depth slope product, although if increasing resistance is due to an increasing boundary drag and not secondary flow or spill resistance, Markham and Thorne (1992), then the assumption will be tenable. Clearly more research at high flows would be needed to elucidate this further, and indeed a request was made to the Northumbrian Water plc, and the Northumbria National Rivers Authority for a 40+ cumec release along the lines of the scour valve test monitored by Petts et al (1985). However, this request was not granted, largely due to sensitivities during privatisation of the Regional Water Authorities in 1989/90 coinciding with a particularly dry summer.

7.7 Evidence of flow structure

Figure 7.4 depicts the surface flow lines for the three sites monitored for hydraulic and sediment transport data. In each case the deepest sections of the pools are detailed and the flows are recorded for peak hydropower discharge. The patterns of flow into and through the pools is consistently converging as described by Keller (1970), and Keller and Melhorne (1978). Surface flow convergence is associated with bed flow divergence and hence scour of the pool bottoms and the maintenance of the riffle-pool sequence, (Keller and Melhorne 1978; Thompson 1986). The presence of converging flow over pools has also been used to infer secondary flow patterns; Hey and Thorne (1975) suggested the existence of two counter-rotating helicoidal flow cells around a meander bed based on the flow patterns deduced from deviation of string streamers, and detailed velocity profiles. Clearly convergence over the pools in the North Tyne occurs in straight as well as curved sections of channel, which suggests that it is the topography of the long profile controlling flow rather than the other way around. The initial control on the convergence of stream lines is closely related to riffle topography. Riffle 1 at the Smales site and riffle 2 at both the Tarset and Newton sites display crescentic cross stream morphology that at flows shallow enough to be influenced by topographic changes, will cause a convergence of streamlines in to the centre of the channel, (Hey 1990; Sear and Newson 1991). The same effect will be created by the asymmetrical angle of riffle 2 (Smales), and riffle 1

7.4 Surface stream lines at peak hydropower generation



(Tarset and Newton), although the tendency for flow convergence will be concentrated toward one side of the channel (Hey 1990). Analysis of the cross sections of the riffles (Appendix A9) also shows that flow convergence and acceleration is generated at deeper areas of the riffles, where flow is constricted through what amounts to an orifice. Seddon (1900) described the transition in the effect of riffles in terms of low flow weirs and high flow orifices. The orifice analogy is clearly part of the low flow phenomenon as well, and is important for controlling the flow patterns at hydropower discharges.

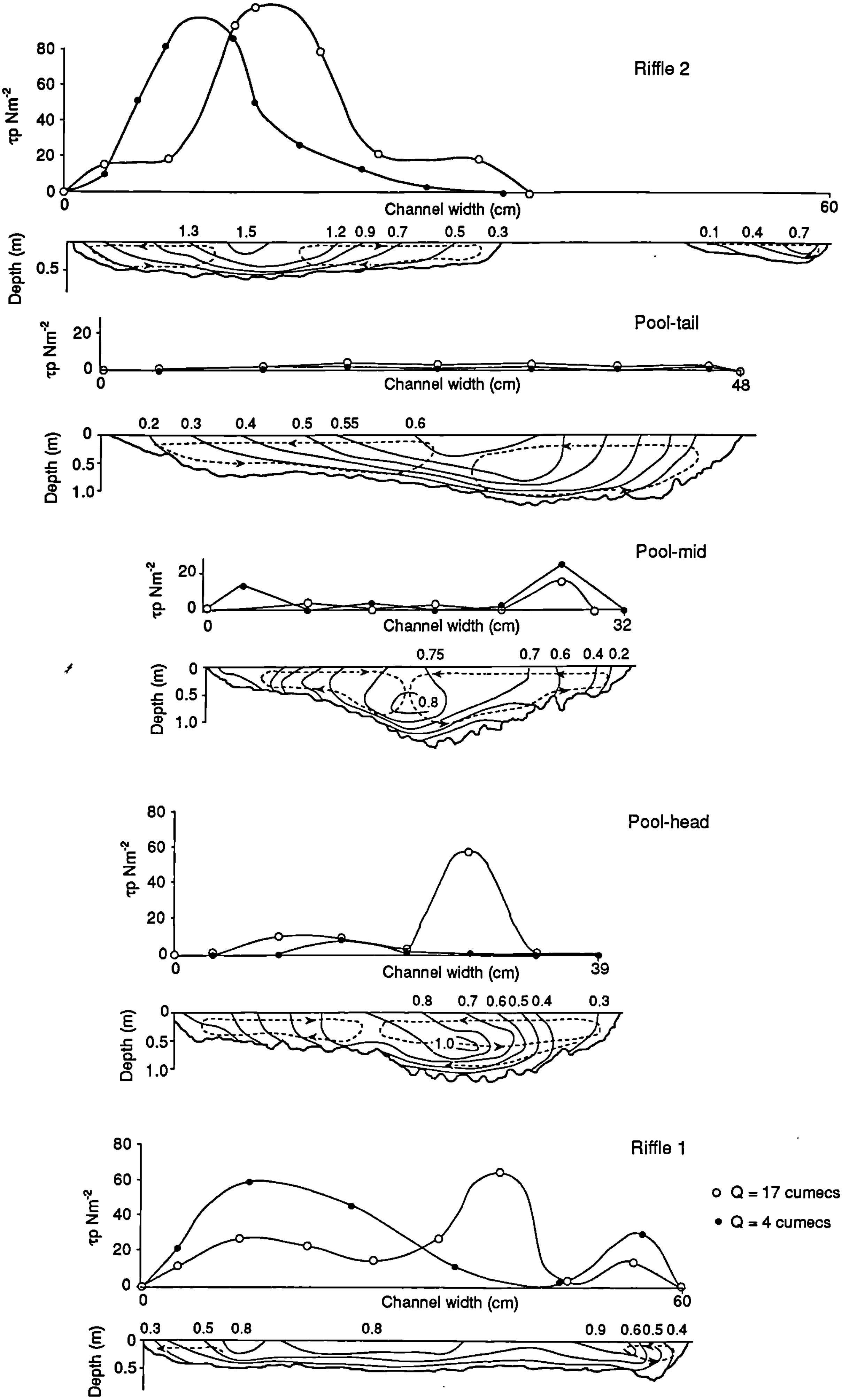
Bathurst (1979) and Knight (pers comm) both identify downwelling flow at the zone where two secondary cells meet, which is confirmed *under ideal conditions by the flume* studies of Studeras (1982). Furthermore, this is associated with relatively high shear stress at the bed due to compression of the velocity field. In contrast, upwelling flow caused by the meeting of two upward rotating flow cells, promotes low boundary shear stress, Thorne et al (1979). Clearly if this was the model of flow circulation in the North Tyne pools then downwelling should create locally high shear stresses. The fact that it does not suggests that what secondary circulation is generated does not reach the bed, or is so weak as to produce higher, yet still very low force on the bed.

The interaction of the bed morphology and the stream flow is particularly marked at the Tarset site. The confluence bar clearly constricts the flow, causing local acceleration which deepens the pool downstream. The sudden widening of the channel below the constriction is marked by the development of reverse cells on both banks. Notably the right bank cells are associated with small embayments, and their effect is to further constrain the central flow lines until the Chirdon Burn confluence. The confluences are also areas of complicated flow structure, associated with the interaction of two opposing flow fields. Best (1987) has described the flow structure at channel confluences in terms of two counter-rotating flow cells, meeting at the junction of the two water bodies. The angle of tributary entry is important for the spatial arrangement of these cells and the ratio of tributary to main channel discharge determines their migration across the channel during a flood event, (Best 1988; Reid et al 1989). Chapter 4 details the development of channel morphology at the Tarset and Chirdon Burn tributaries, however, the flow structure would suggest a pattern similar to the one described by Best (1986). The presence of deep scour pools at the tributary junctions controls the pattern of low flow structure in the North Tyne, and the development of tributary confluence bars, itself a function of the hydropower regulation regime, further alters the flow. Confluence angle clearly determines the presence not only of the tributary bar (Best and Reid 1985) but also the position of the scour pool, and therefore the deflection of the streamlines during hydropower flows. The pattern of stream lines downstream of both confluences at Tarset, shows a clear deflection across the channel and the development of a pool at the left bank. In the case of the Chirdon Burn confluence the entrance at the apex of a bend, alters the theoretical bend streamlines from the right bank convergence to the left bank. At high discharges this will promote the transport of main stream sediment across to the left bank, where the riffle is shown to be have aggraded, (Chapter 4).

Flow structure at hydropower discharges appears to be controlled by the geometry of the riffles and pools. This pattern is likely to affect sediment routing through the riffle-pool sequences through its effect on the distribution of boundary shear stress (Bathurst 1979) and the relative sorting and trajectory of particles, caused by the deflection of the shear stress vector by secondary flows (Dietrich and Smith 1984). Figure 7.5 illustrates the flow structure through the riffle-pool-riffle sequence at Newton. In the absence of EMF data secondary flow cells have been inferred from the isovel pattern after Bhowmik (1982). As discussed above, these can only be best approximations, however several flume studies have confirmed the utility of this technique for straight channels (Muller 1979; Studeras 1982; Tsujimoto et al 1990). In general the flow depths over the riffles at peak hydropower discharges are not sufficient to allow development of full secondary circulation, however some distortion of the isovels near the channel margins suggests the transference of water out from the mainstream; shear stress in these regions are low. Migration of the shear stress peak at the riffles occurs in response to rising discharge (see below) and the distribution cross stream reflects the sectional topography and relative roughness, rather than any flow structure. Flow in NR2 is controlled by the diversion of water created by the central island.

The presence of secondary flows in the pool regions is strongly suggested by both the surface stream lines (Fig 7.4 above) and the distortion of the isovels. The coincident shear stress distribution is not related to these structures except at the pool-head, where at peak hydropower discharge, a jet of high velocity locally increases the shear stress to 58 N/m^2. The presence of this jet confirms the observations of Beschta (1982), and the theory of Bathurst (1982), and it is strongly associated with the acceleration of flow off

7.5 Distribution of boundary shear stress in relation to bed morphology and flow structure: Newton site. (flow structure and isovels are for maximum hydropower discharge)



the upstream riffle converging into the pool. Twin, counter-rotating flow cells are developed in the pool-head and persist throughout the pool to the pool-tail. Beyond this the flow depths are again reduced as the reach widens to NR2, thereby destroying the structure. The twin cells inferred from the isovels, conform to the theoretical pattern of flow structure in straight pools suggested by Thorne (1978). Flow is deflected towards the pool deep, and plunges to the bed before returning to the banks. At the pool margins, flow is transferred outwards towards the banks, which as the discharge rises probably accounts for the initial reduction in friction factor noted below. The distribution of boundary shear stress at hydropower flows does not appear to relate to the secondary flow pattern beyond the pool-head, furthermore the values for shear stress decline rapidly downstream. This is not in line with the theoretical effects of flow structure outlined by Thorne et al (1979) and Bathurst (1979) which indicate that cross-stream shear stress distribution is controlled by secondary flow development. The deviation from this pattern suggests that the secondary flows are extremely weak and do not override the effects of boundary grain roughness and velocity profile extension, (Bathurst 1982; Church and Jones 1982).

Flow structure is clearly a feature of the riffle-pool sequence in the North Tyne at hydropower flows, however the strength of them is insufficient to alter the shear stress distribution significantly except in the pool-head regions. The implications for higher discharges however, would be a pool-head velocity and possibly shear stress reversal promoted by jetting and the increased strength of converging secondary flow cells corresponding to the pool deeps. At higher discharges the secondary flow structure would again weaken relative to the primary flow, (Bathurst 1979) and the jetting would probably subside as the upstream riffles were drowned out. However the routing of sediment, competent at moderate discharges may well be influenced by the flow patterns observed in this study; a point that is explored in Chapter 12. More detailed EMF data should be made in conjunction with velocity profiling to elucidate the relative strengths of the secondary currents over a range of discharges, but this was beyond the scope of this present study.

7.8 Hydraulic characteristics of riffles and pools during hydropower generation.

Cross section variation in near bed velocity has been linked to the movement of sediment through the riffle-pool sequence through the reversal hypothesis described above. The determination of bed velocity has advantages over the estimation of shear stress, since it is a primary data measure, requiring no assumptions other than reference depth. Furthermore, since bed velocity has been used as a measure of reach (or point) competence, (Novak 1974; Keller 1971) it is important to investigate with respect to the passage of the flood wave associated with hydropower generation.

Figure 7.6 - 7.11, depict the development of the cross section bed velocity and associated shear stress fields within sequential riffle-pool sequences at the three sites monitored within the North Tyne. Each individual cross section diagram, shows the changes in bed velocity at 0.02m above the stream bed and the point shear stress determined from velocity profiles during the passage of a typical hydropower flood wave. In all figures, the sequence of diagrams is downstream from top to bottom.

Newton Site:

Figure 7.6 and 7.7 show the comparison between riffle and pool cross section bed velocity and shear stress distribution during a flood wave. What is immediately apparent is the inability of bed velocity data to equate with shear stress data, particularly in the pool, although there is evidence to suggest that lower bed velocities are associated with higher shear stress, reflecting greater grain drag.

The distributions of bed velocity are clearly morphologically controlled in the pool, with a high velocity core associated initially with the deepest part of the section, and declining towards the banks as flow depth shallows. This distribution is relatively uniform across the section, and is achieved rapidly once the flood wave arrives. This would support the view alluded to above, that flow resistance due to slackwater is diminished relatively rapidly. In contrast, the riffles both experience a relatively complex velocity field development, characterised by continual post floodpeak acceleration of near bed velocities. During the passage of the flood wave, bed velocity peaks occur at different points in the riffle sections. Initially these are associated with the deeper parts of the section (towards the left bank in both cases) but this changes as relative roughness decreases on the shallower sections and the flow, being shallow but not affected by turbulence, accelerates to values above the deeper flow regions. This phenomenon is

Fig 7.6: Temporal variation of sectional bed velocity at the Newton riffle-pool-riffle sequence during a hydropower release.

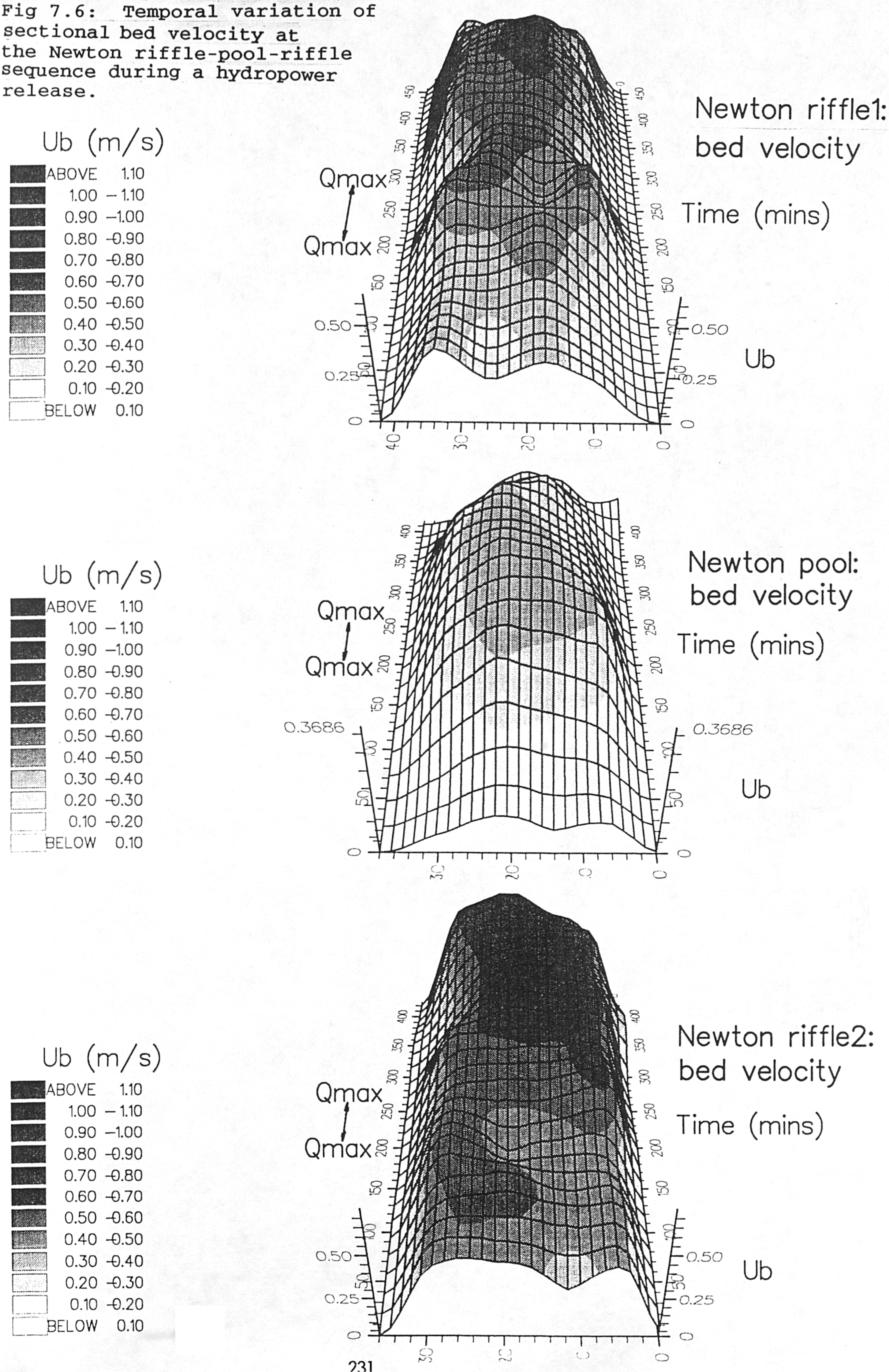
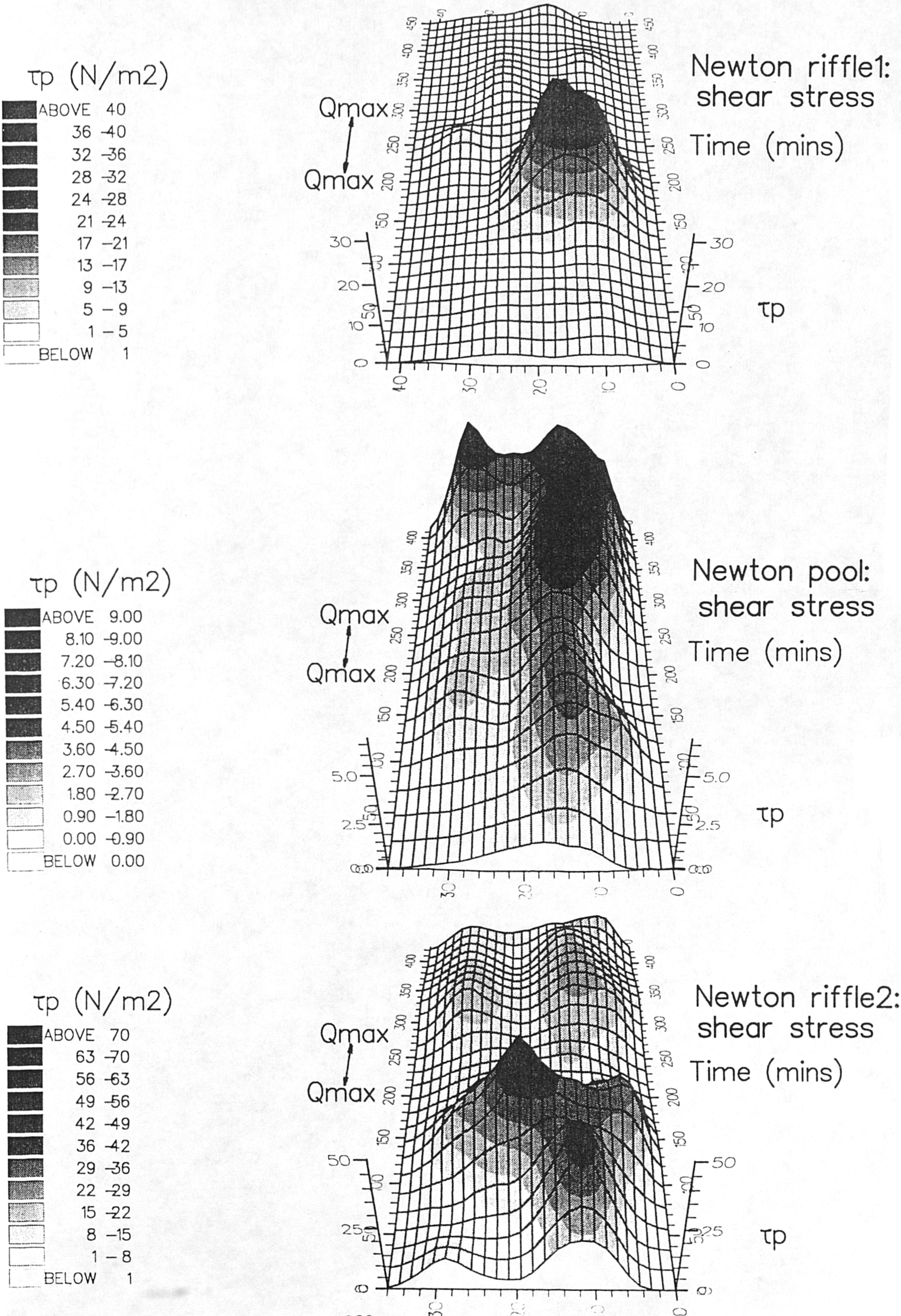


Fig 7.7: Temporal variation of sectional shear stress at the Newton riffle-pool-riffle sequence during a hydropower release.



also apparent in the pool, as the peak discharge passes, the core of maximum bed velocity migrates up the left bank finer gravel bar.

At no time does the bed velocity in the pool exceed that on the riffles. This is also the case for point shear stress, where maximum values in the pool are 80% lower than riffle 1 and 87% lower than the maximum value on riffle 2. The distribution of shear stress, is characterised by the bed roughness. The discrete peak associated with riffle 1, accords with the position of a shallow bar of relative bed stability (Chapter 6), and is manifested only as the flow depth over the bar begins to peak. Similarly, at riffle 2 the shear field is strongest at the left bank channel margin where the bed rises towards a central island. For both riffles, shear stress peaks at or just prior to peak discharge, and declines thereafter. In the pool, the shear field is relatively stable until the flow begins to drop. A discrete peak is associated with the greater drag experienced in the mid-right bank region of relative bed roughness. Shear stress over the finer gravel bar on the left bank is much lower, although as the flood wave passes, this becomes an area of higher shear stress. Lower shear stress over areas of finer bed material (higher d/D_{50}) are recorded by Ferguson et al (1989) and would appear to be important for determining the distribution of shear stress in pools and riffles at low flows.

Tarset Site:

Figure 7.8 illustrates that bed velocity distribution within the Tarset pool is clearly controlled by the channel morphology at the section, but is influenced by the acceleration of flow through the constricted channel upstream, (Chapter 4). Initial bed velocities are amongst the lowest recorded in any of the pools surveyed, and flow at the channel margins is close to zero. As described above, the channel margins at this site are associated with slack water zones, and areas of reverse circulation. These effectively reduce the channel cross-section to a narrow deep profile, with a sand covered bed of gravel, with some boulders. As discharge increases the flow is accelerated through the constricted cross-section upstream at the tributary confluence bar, which is manifested as a rapid increase in bed velocity at the pool section. The increase in bed velocity at the deeper mid-channel section, imparts a downstream momentum to the reverse flow cells at the channel margins, with a concomitant decrease in friction factor. Locally, bed velocities rise to 0.9 m/s, the fastest recorded at any site monitored, a function of the

Fig 7.8: Temporal variation of sectional bed velocity at the Tarset pool-riffle sequence during a hydropower release.

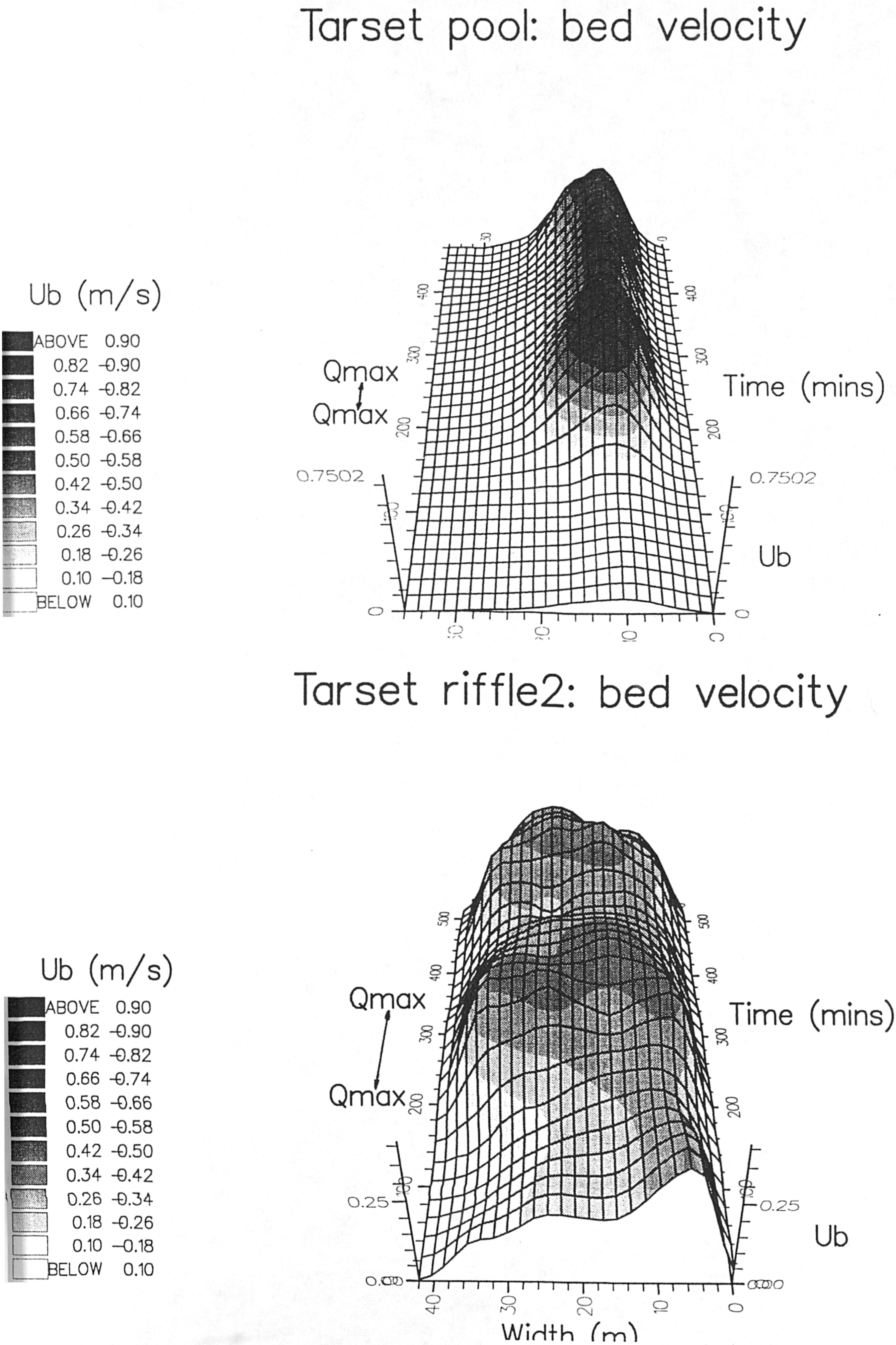
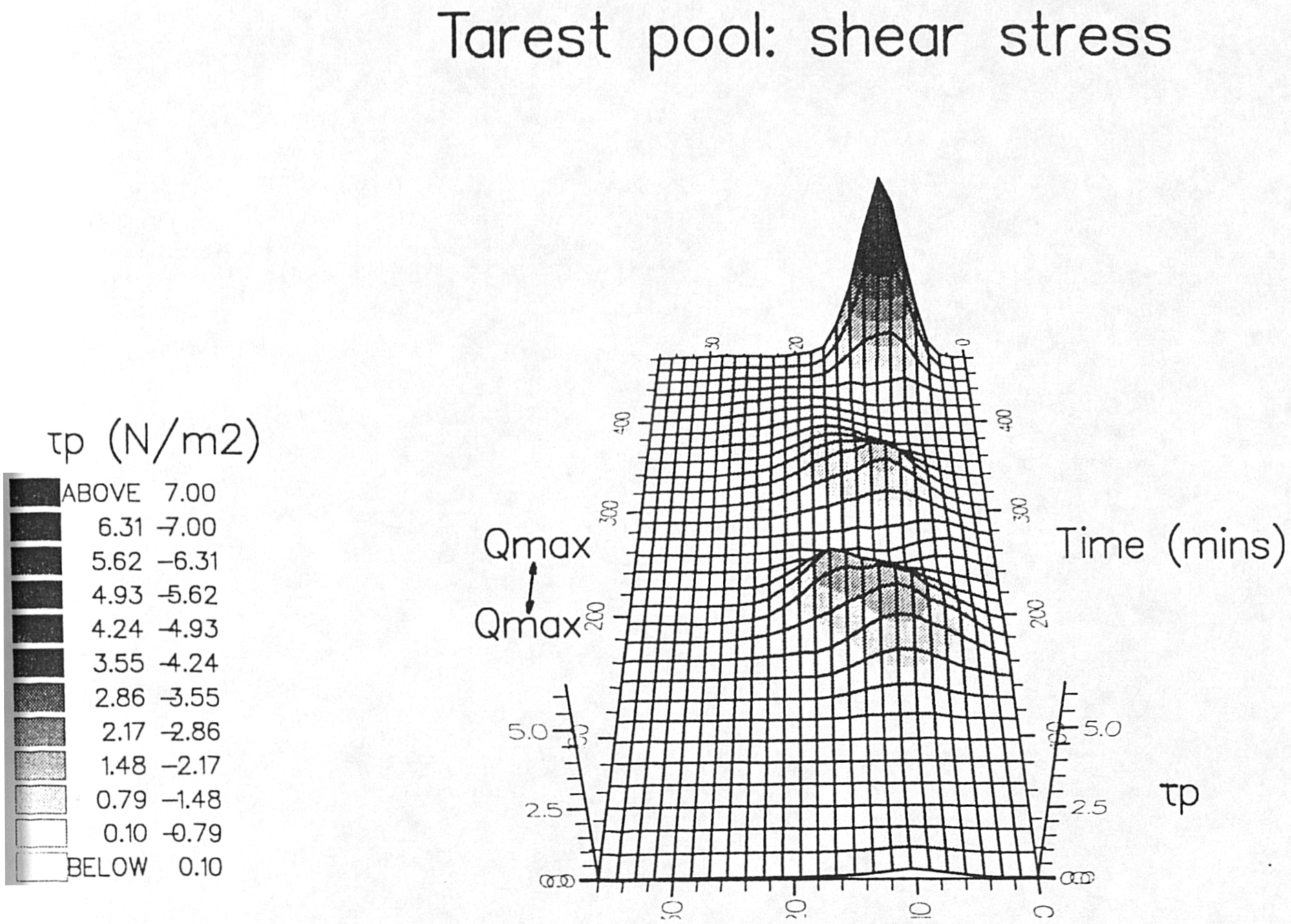
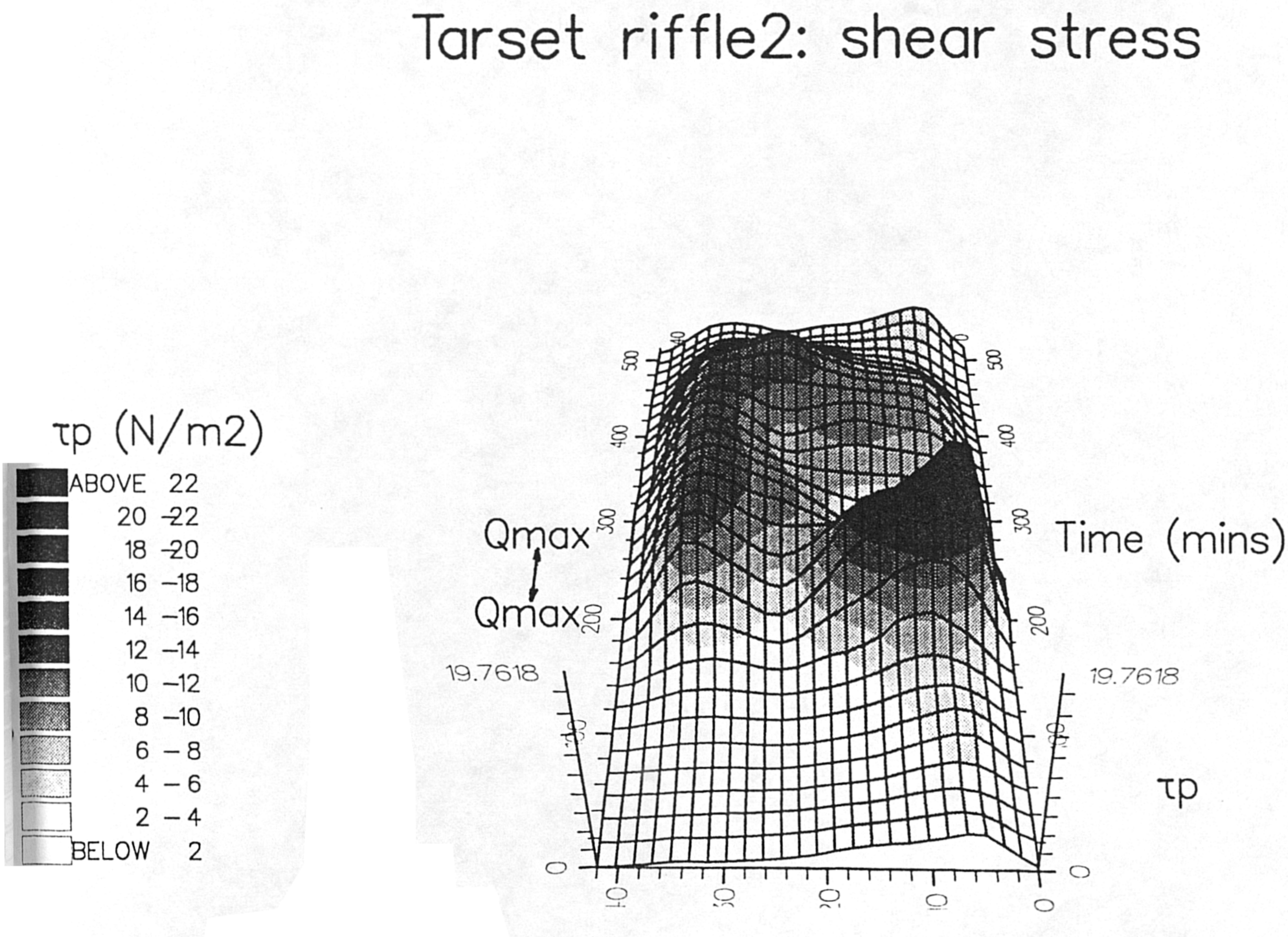


Fig 7.9: Temporal variation of sectional shear stress at the Tarset pool-riffle sequence during a hydropower release.





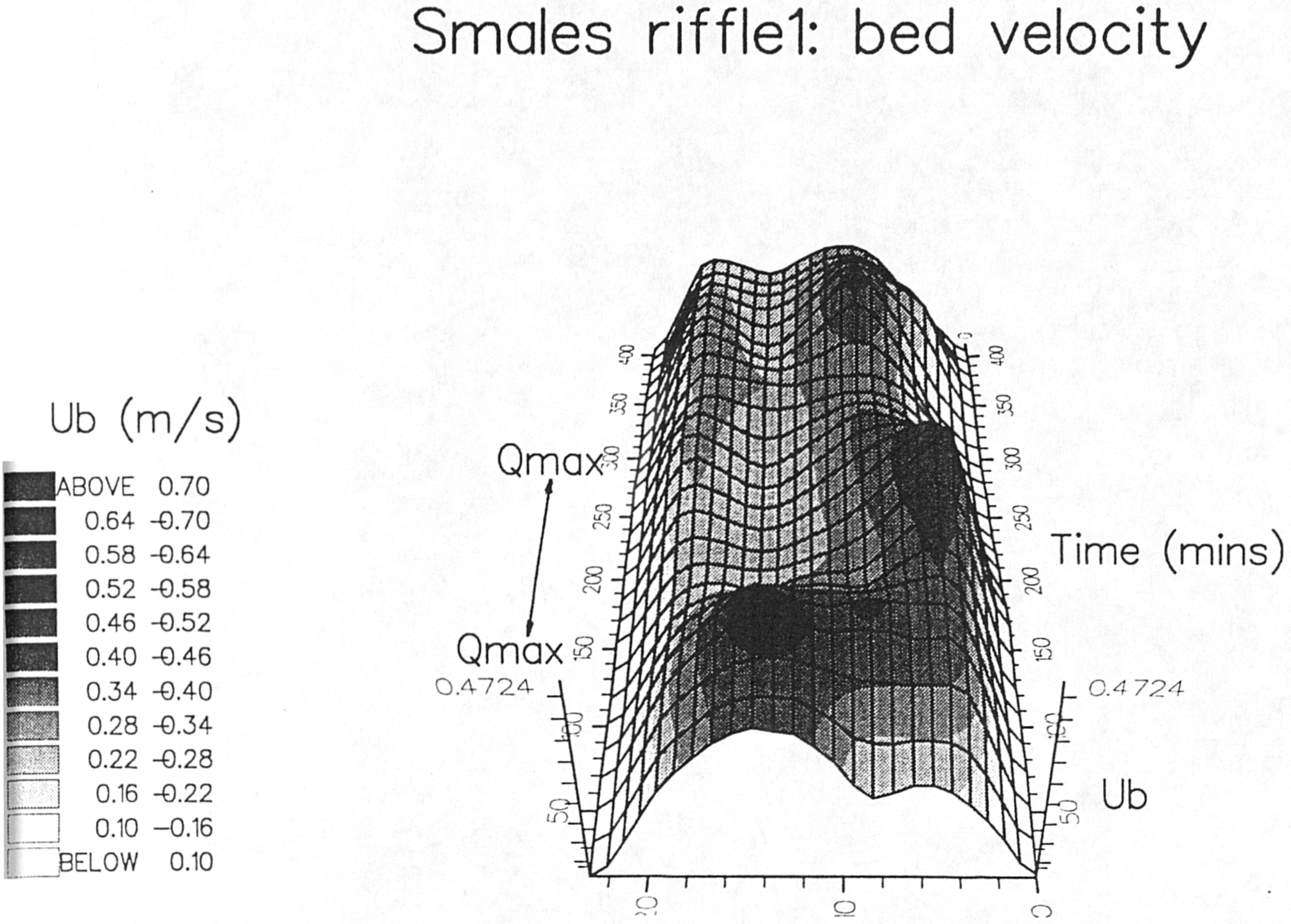
smoothed sand bed and accelerative jet from upstream. Despite the locally high bed velocities, shear stress values are consistently low, reflecting the smooth bed offering little drag in comparison to gravel and boulder beds. A peak in the shear field occurs as the discharge declines, and is possibly the result of the exposure of the gravel bed as the sand is scoured from the surface. This has been observed in pools with high sand content during floods (Lisle 1979) but bed load measurements in the Tarset pool do not equate with this hypothesis. Instead, it is possible, (assuming no operational error) that this represents a decelerating flow phenomenon in unsteady conditions. The shear field is particularly difficult to explain, although it is clearly associated with the pattern of bed velocity. The development of three discrete shear peaks during the flood wave,(albeit of low magnitude), occurs in association with bed velocity peaks at maximum discharge and ass the discharge declines. The reason for these peaks is possibly an upstream jet developed as the flow accelerates through the constricted channel, reaching a peak just below peak discharge. Therefore bed velocity peaks would be expected to occur at around maximum discharge attainment, and as discharge drops.

Bed velocity and shear stress is initially controlled by bed morphology at the downstream riffle, with peak values associated with the deeper right bank region. This is also an area of large roughness elements, and as the flow increases drag created by these produces a localised shear stress peak. As the discharge increases and flow depth rises across the section, the drag effect of the roughness elements is drowned out, and the shear stress drops at the right bank. As this occurs, the left bank bar is accessed by the flow and the bed velocity at maximum discharge, becomes relatively uniform across the riffle. At the same time, as the flow recedes, drag over the bar is increased and the point of maximum shear stress switches across the section to the left bank bar. This continues until the reduced depth of flow creates rough turbulent conditions ($d/D_{50} < 4$) over the bar and the shear field breaks up. At discharges approaching compensation flow levels the distribution of shear stress is similar to the initial pattern, although bed velocity locally remains high across the whole riffle.

Smales Site:

The Smales site is altogether different form the previous sections, both in terms of scale and morphology, (Chapter 4). The distance between the upstream riffle section and the

Fig 7.10: Temporal variation of sectional bed velocity at the Smales riffle-pool sequence during a hydropower release.



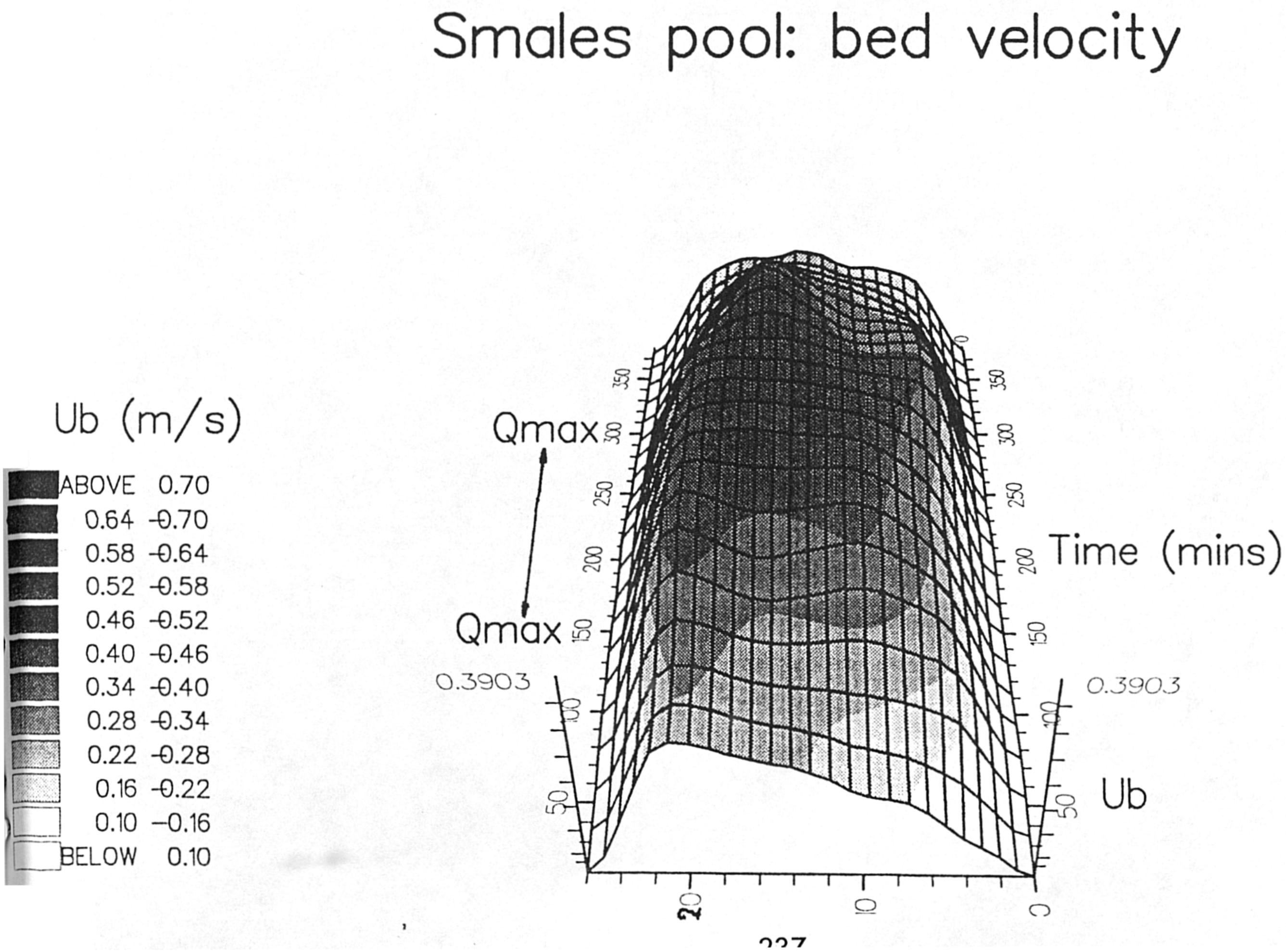
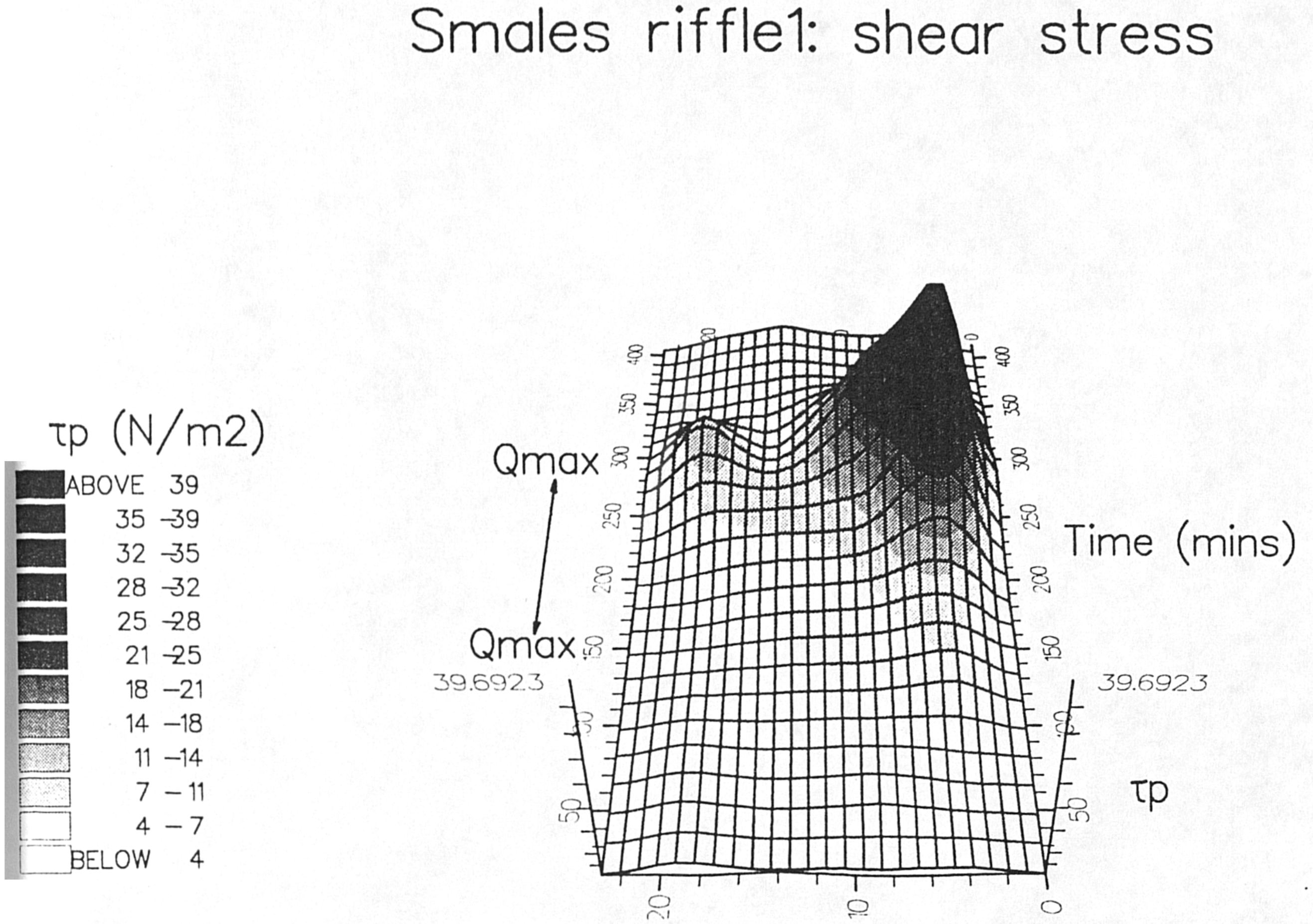
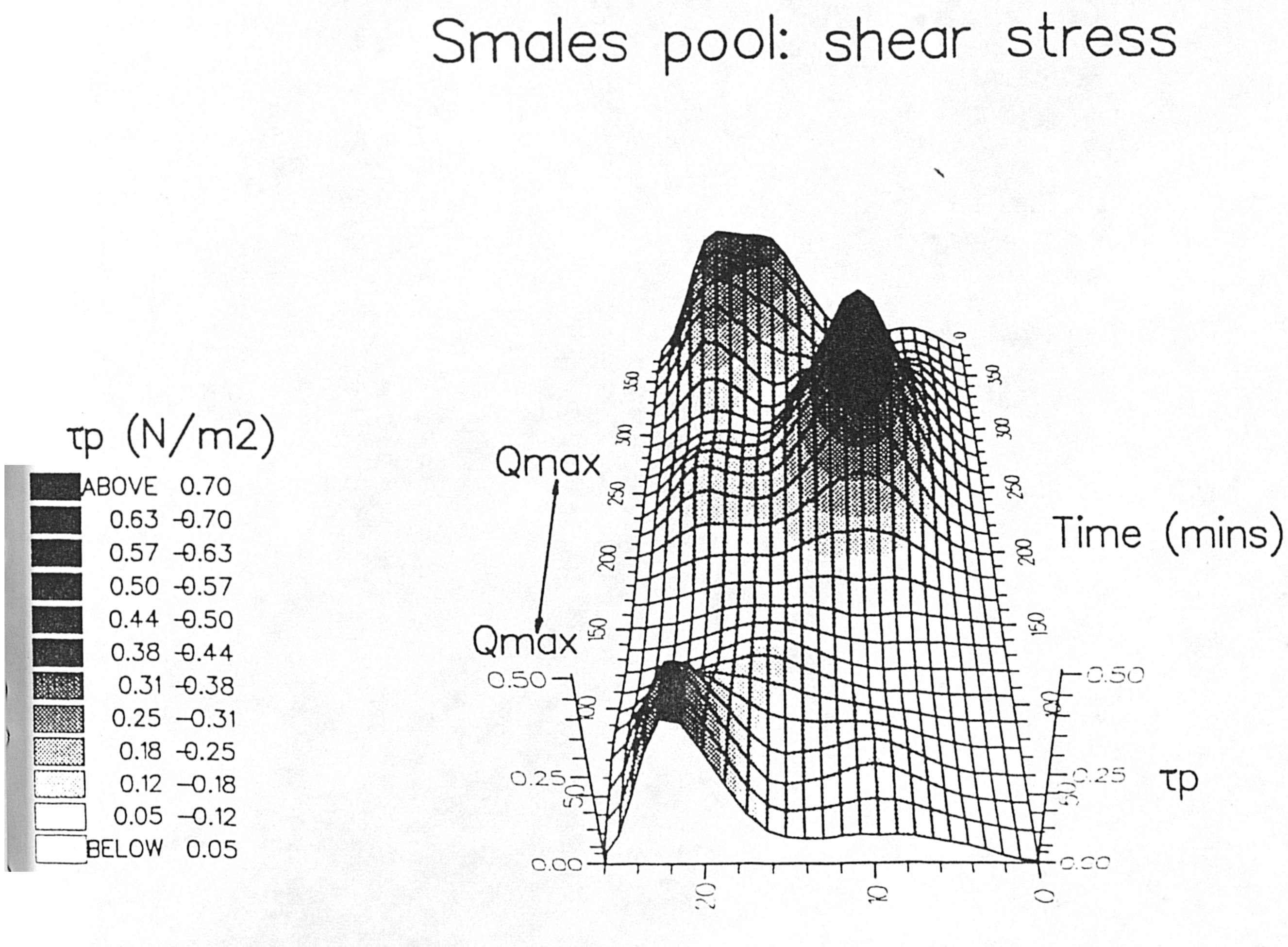


Fig 7.11: Temporal variation of sectional shear stress at the Smales riffle-pool sequence during a hydropower release.



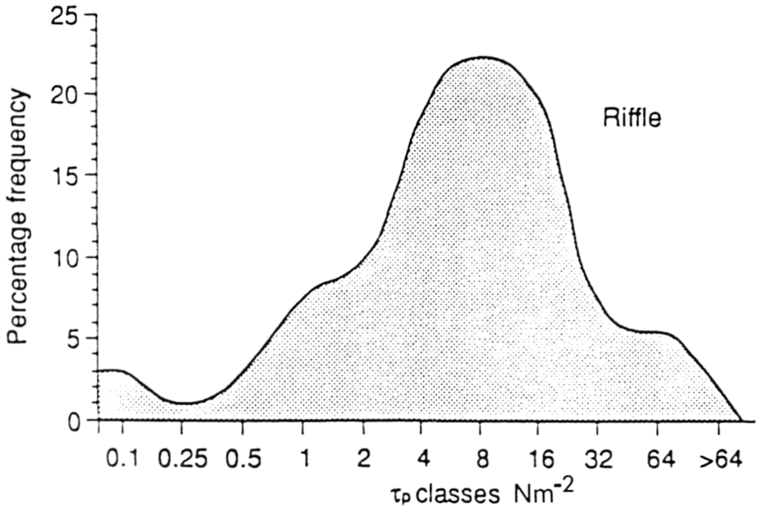


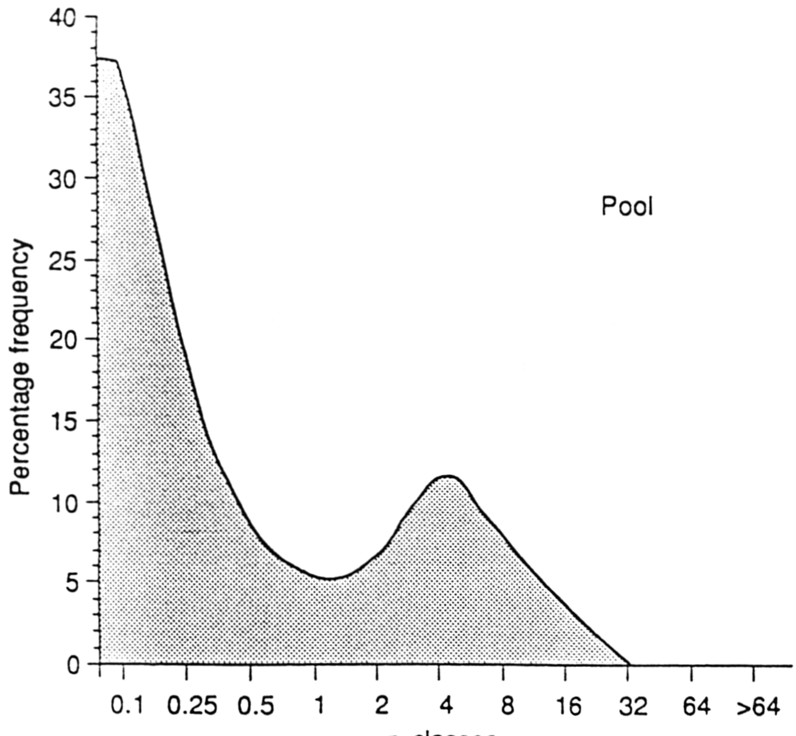
deepest pool section is only 1.8 channel widths compared to 4 and 10 for the Newton and Tarset pools respectively. Furthermore the reach is straight, with no significant width variation between riffle and pool up to bankfull. As a result of this it was expected that pool hydraulics would be influenced by the upstream conditions at the riffle.

Figure 7.10 and 7.11 show the bed velocity and shear stress experienced at the two sections simultaneously. Bed velocity is again controlled by morphology, at both the riffle and pool. Peak bed velocity is experienced in the deepest left bank regions of both sections, indeed the pool sectional distribution is probably influenced by the jet of accelerated flow coming off the upstream riffle (Bathurst 1982; Beschta 1982). Bed velocities at both sections are similar, although the riffle experiences a local maxima at 66% from the left bank. Characteristically, shear stress across the pool section is 80% less than that experienced at the riffle, however the distribution is dominated by a left bank peak associated with the deeper, rougher region of the pool. As water levels rise, the core of maximum bed velocity at the riffle, migrates across the section from left to right bank. This is again a function of the acceleration of flow over an incipient bar. As the discharge peaks bed velocity peaks at the riffle left bank, and pool right bank; the distribution across the sections differs, with a more uniform cross sectional pattern of bed velocity in the pool. Values of bed velocity in the pool are now comparable to the riffle except for a narrow region. Maximum bed velocity in the pool has extended out of the deeper region up the finer gravel bank. Shear stress does not exhibit the same uniformity of cross sectional distribution in the pool, and in fact the bed roughness is clearly lower than the other pools surveyed since at no time do values rise above 1 N/m^2. Shear stress at both riffle and pool peaks as the discharge begins to fall, with maxima, located at the left bank of the riffle, and on the finer gravel bar in the pool. As the discharge falls further, the shear stress peak, again moves to the deeper pool region, and the initial pre-release position on the riffle.

Figure 7.12 characterises the difference in shear stress experienced at riffles and pools during hydropower discharges. The τ_p classes extend from 0 - >64 N/m^2 and the frequency was established for each class based on the 240 determinations made during the three releases monitored. The distribution of shear stress experienced on riffles is unimodal, with a modal value of between 8-16 N/m^2. This contrasts the pools where bi-modality characterises the distribution, although the dominant modal value corresponds

7.12 Percentage frequency of τ_p classes experienced during hydroelectric generation at riffles and pools





to between 0.1-0.25 N/m^2. The range of shear stresses experienced on the riffles is also much greater than that within the pools, with a total range from 0-79 N/m^2 compared with 0-9 N/m^2 experienced within the pools. The variation in the frequency of higher magnitude shear stress on the riffles compared to the pools has implications for the sediment transport rate and competence of the riffle-pool sequence under hydropower. This is especially important when viewed against the frequency of shear stresses predicted from the DuBoys relationship which gives a total variation experienced by the pools as 2-45 N/m^2 and for the riffles as 1.8-29 N/m^2. Clifford (1990) has described a similar pattern of higher frequency, higher magnitude shear stress at riffles compared with pools which he relates to the greater frequency of turbulent events. The data described here would appear to confirm this observation.

7.9 Evidence for bed velocity reversals

Clifford (1990) has described the existence of spatially and temporally varied bed velocity reversals between riffles and pools, at flows up to bankfull. From the discussion above, the reversal hypothesis underpins a majority of sediment transport models of the riffle-pool sequence. In terms of the routing of sediments through the riffle pool sequence under hydropower flows, the existence of a reversal tendency might be important, particularly for the finer sediments.

Figure 7.13-7.15 illustrate the development of bed velocity at sequential riffles and pools at the four monitoring points across each section. The period of maximum discharge is shown in all cases. What is immediately apparent is the presence of localised velocity reversals in 10 out of the 12 sectional readings, although in the case of NR2, there is only a reversal in 1 of the cases.

As described above, the Tarset pool experiences accelerated bed velocities at the channel centre (Fig 7.13). A reversal of bed velocity is achieved at only these sites (B and C), the channel margins remaining below the comparable margin values for the downstream riffle. This would support Keller's (1971) hypothesis that near-bed velocity reversal is a localised phenomenon, generated by jetting off the upstream riffle. Beschta (1982 Fig 1) illustrates the creation of a submerged jet which passes under the static surface flow of the pool, thereby locally increasing the bed velocity. Evidence for this was not found in

Fig 7.13: Bed velocities at individual points across the pool and riffle sections during a hydropwer release: Tarset.

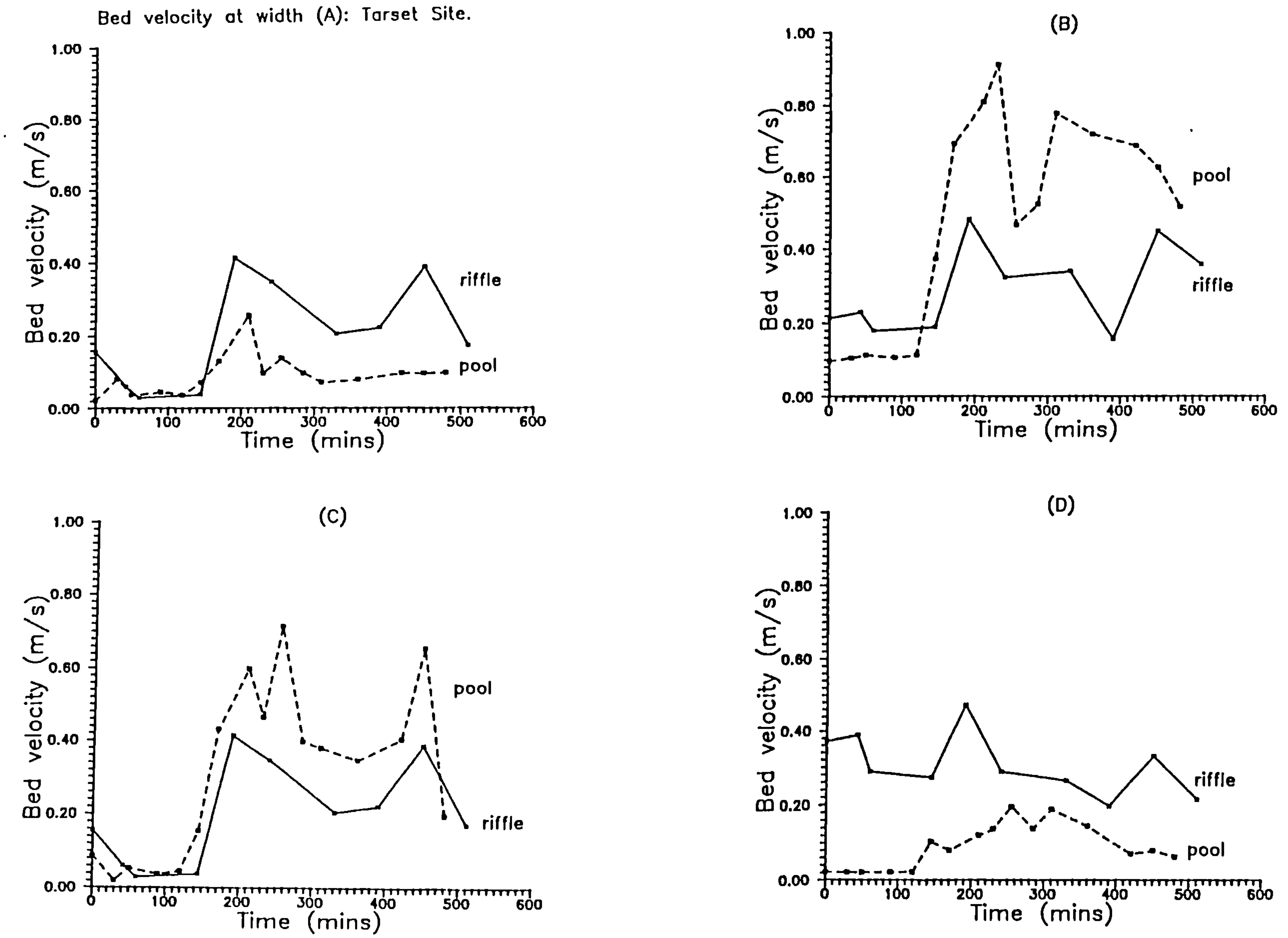


Fig 7.14: Bed velocities at individual points across the pool and riffle sections during a hydropwer release: Smales.

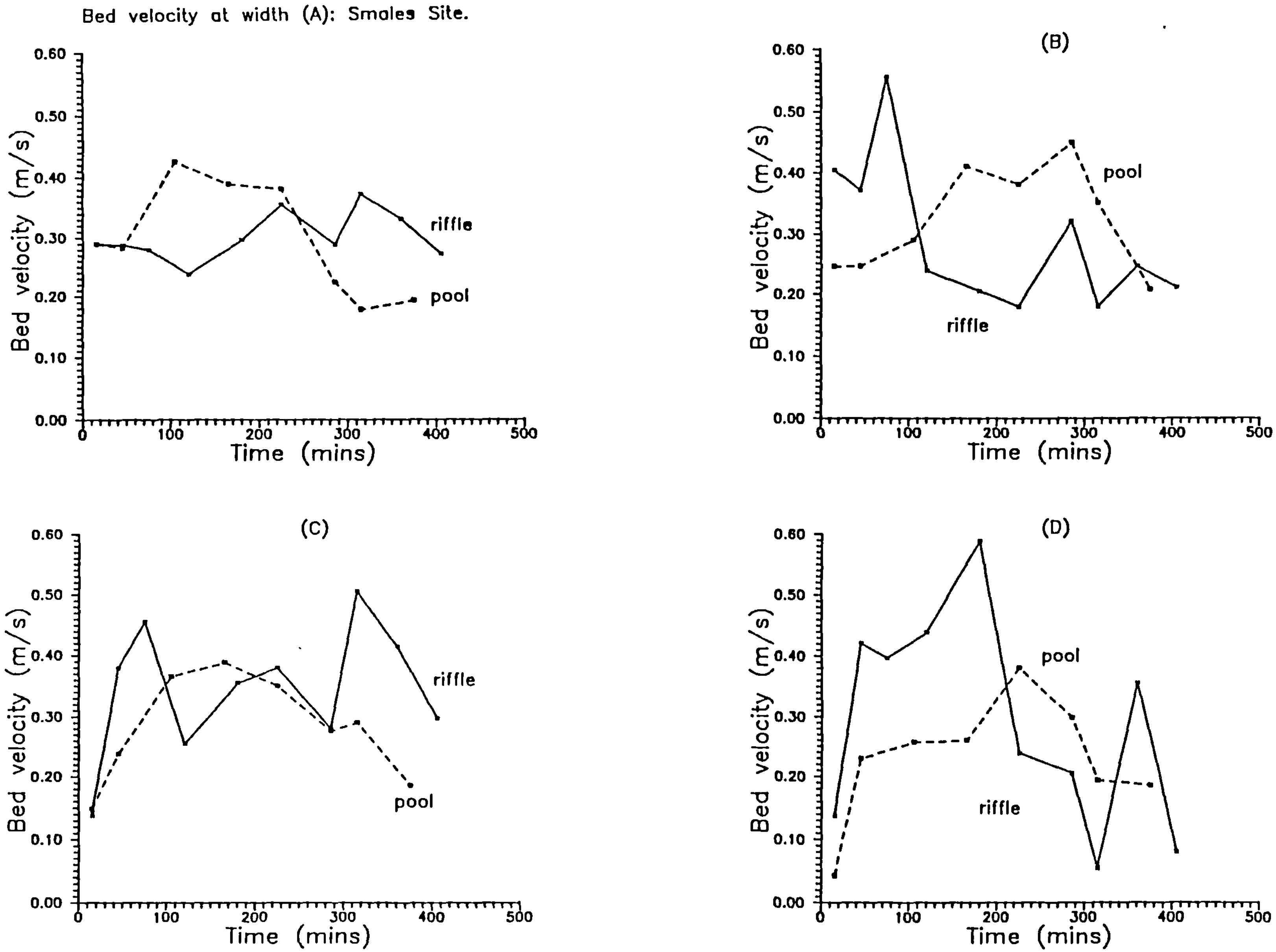
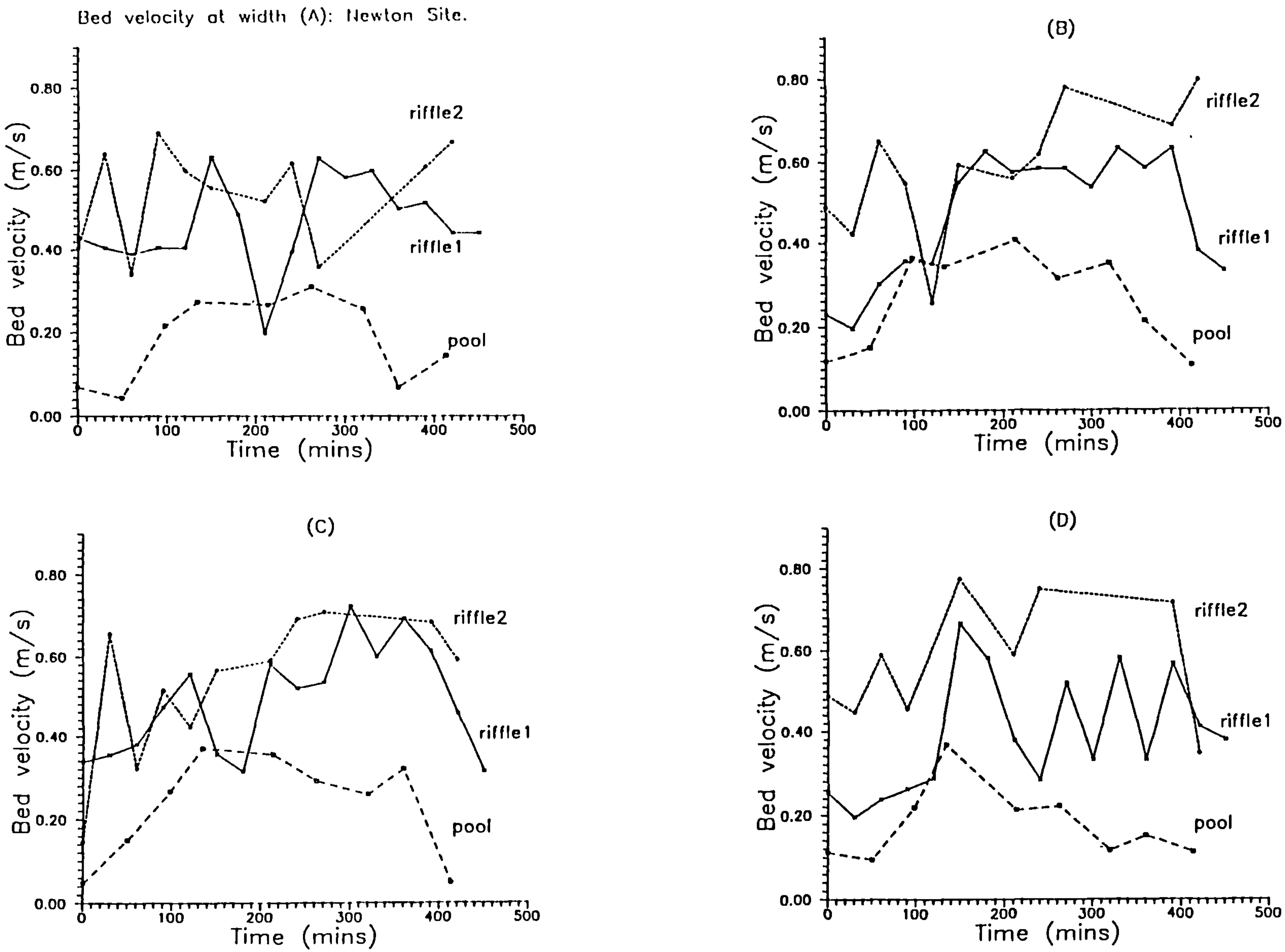


Fig 7.15: Bed velocities at individual points across the pool and riffle sections during a hydropwer release: Newton.



any of the sectional measurements, in all cases the surface velocity was greater than the bed velocity, however, the detailed sections monitored in the Newton section (see evidence of flow structure above) did exhibit a subsurface high velocity core which dissipated downstream. The presence of this jet was strongly associated with a shear stress peak at the pool head although no reversal in shear stress was evident there was a reversal of maximum velocity. This phenomenon did not last to the mid pool region and the jet was no longer evident at the pool tail some 240m downstream. The Tarset situation is more a core of high velocity than a subsurface jet feature, since the surface flow was consistently faster than the near bed.

The development of the pool reversal at the Tarset site is a product of the upstream acceleration of flow through what amounts to a Venturi flume. The zones of slack water downstream of the orifice throat help to maintain the high bed velocities within a constricted core. The importance of upstream bed morphology on low flow (12% bankfull discharge) patterns is exemplified by this section.

The Smales site experiences a localised velocity reversal at all the cross section points monitored, although their timing varies through the hydropower flood, making a total sectional reversal impossible (Fig 7.14). The position of the reversals is again associated with the deeper sections of the pool where the flow converges off the riffle. Analysis of the reversal data, shows that only the deepest point (A) experiences a 'true' reversal due to the greater acceleration of bed velocity over the riffle. The other reversals, are instead a function of a localised retardation of velocity at the riffle. The deeper sections of the Smales riffle are drowned out relatively rapidly as discharge rises causing the bed velocities to drop as the Bernoulli effect is reduced. In contrast the reversal at the shallow section (D) results from the retardation of bed velocity as initial acceleration over the shallow bar falls with the establishment of uniform discharge. This latter point has important ramifications for the inference of sectional hydraulics based upon uniform discharge measurements, since clearly a reduction in bed velocity due to the retardation of flow as the discharge levels off will not truly reflect the maximum attained.

Figure 7.15 depicts the reversal data for the Newton site, unique in that it includes hydraulic data for a riffle-pool-riffle sequence. Although isolated reversals occur between the pool and the upstream riffle 1, these are again not true reversals, but result from the local retardation of flow on the riffle. The contrast between the lack of reversals between the pool and the downstream riffle shows the very site specific nature of the phenomenon, both within the cross section and between adjacent riffles bed velocity reversals are evident at flows of only 12% bankfull. The reversals are themselves, localised and sporadic, with many resulting more from the instability of flow over riffles than a hydraulic trend in itself. Localised reversals are associated particularly with deeper sections of pools, especially when confined by marginal slack water zones. Instability of the riffle flow field is particularly associated with the morphological controls on acceleration and retardation and the attainment of uniform discharge conditions.

At no time does a sectional velocity reversal occur (which is consistent with continuity principles given the relatively limited stage increases) but rather, local reversals occur that are related to retardation on the riffle and local acceleration into pools. Similarly, no evidence of a shear stress reversal was found in any of the sections monitored. Shear stress in the pools remained consistently below the levels monitored on the riffles, a product of the lower relative roughness of the stream bed, and the extension of the velocity profiles over greater depths.

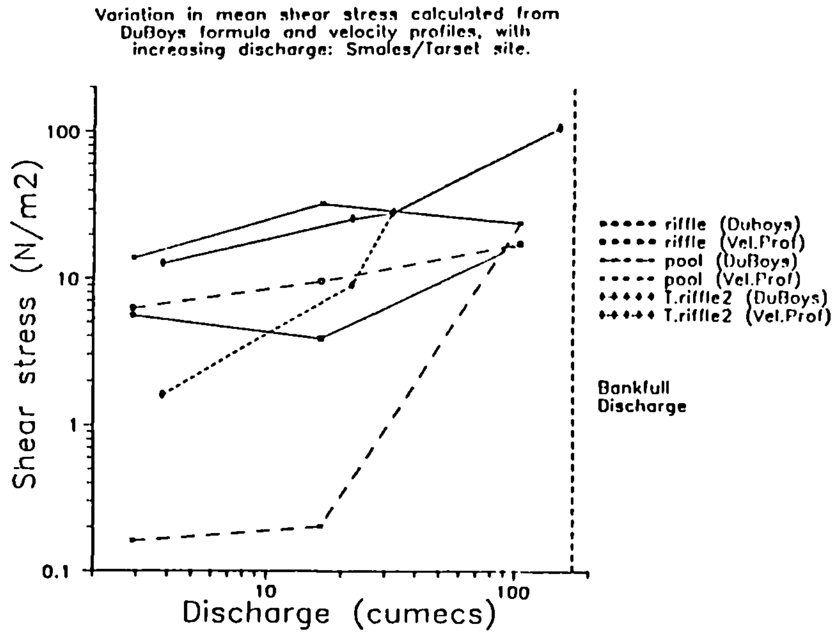
7.10 Hydraulic characteristics during floods

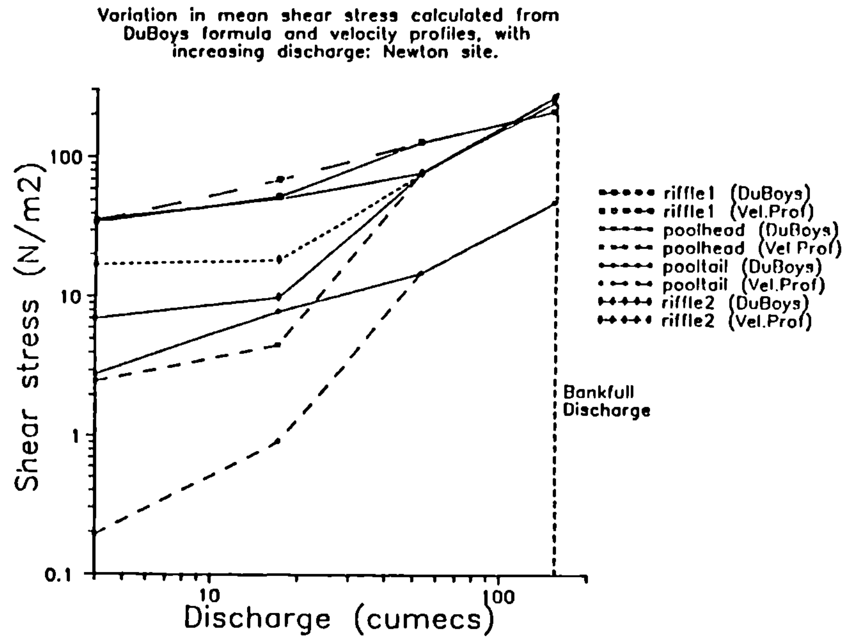
Two sediment transporting events were recorded by the bedload tracing experiments, at flows above hydropower discharges. Using the discharge calculating algorithm developed in Chapter 3 these corresponded to a bankfull event of 151 cumecs and a 53 cumec event of approximately 35% bankfull. Both events left clear trash marks from which water surface slope and boundary shear stress could be determined. Following the discussion above, the shear stress at these higher discharges was assumed to be equivalent to the depth slope product, which in any event was the only method of calculating shear stress available. An attempt to predict the shear stress according to the method used by Petit (1987) which was based on the ratio between τ_p/τ_o, proved to be inappropriate for the pool sections. The ratios developed during hydropower discharges are clearly different to the conditions under higher events. The rejection of this technique was based on the extremely low shear stresses predicted for the pool sections at both discharges, which did not correspond to any other recorded values for the amount and size of bedload transport observed (Ashworth 1987; Carling 1983; Carling and Komar 1991). In order to establish the cross sectional shear stress during hydropower discharges for the individual tracers used in the bed load experiments, the ratios of τ_p/τ_o were applied to the values of τ_o recorded for each individual particle. These were used to generate a sectional distribution, from which a mean value was obtained from sectional integration (Bathurst 1979; Flintham and Carling; 1988).

Figure 7.16 depicts the change in sectional average shear stress with increasing discharge for the tracing experiment cross sections. In each case the values for τ_o and τ_p are shown for compensation flow and hydropower discharges. The relationships are clearly non-linear in many cases and as discussed above, are more likely to have complex functions.

Figure 7.16a shows the development of shear stress at the Smales and Tarset sites. A reversal of mean boundary shear stress is shown between the Smales pool and riffle, for a discharge just below bankfull. The rate of increase in shear stress is relatively constant for the riffle, with a rise of 6-16 N/m^2 over 100 cumecs, (f exponent = 0.276). In contrast the pool experiences a rapid increase from 0.17-22 N/m^2 for 100 cumecs,(f exponent = 1.397). The reversal tendency is explained by an increased slope over the pool at this confined site which enables local shear stress to overcome the change in

Fig 7.16: Variation of sectional averaged shear stress with discharges up to bankfull for tracing sites in the North Tyne.





depth between riffle and pool. The slope change is probably due to the widening of the channel downstream of riffle 2 that reduces the relative height of water between riffle 1 and riffle 2 over the pool. The values of shear stress experienced at this site are on average 70% lower than those at the other sites. This is confirmed by the lower tracer movement and smaller particles moved during the event. Peak shear stress at the riffle during hydropower is greater than during the flood event (41 N/m^2 compared to 17 N/m^2) which implies a reduction in turbulence. This is supported by the reduction in friction factor recorded for this site.

The Tarset riffle 2 exhibits the highest increase in shear stress of any of the riffles monitored (f = 1.148) with a bankfull value of 103 N/m^2, compared to an average hydropower value of 9 N/m^2. Maximum recorded $_p$ at this site was 21 N/m^2 at 17 cumecs, with a bankfull maximum of 112 N/m^2. Cross sectional variation is reduced at bankfull and during the 36 cumec flood with a peak shear stress located at the right bank (Fig c, Appendix C).

The shear stress at the Newton site is shown in Figure 7.16b and Figures d-g, Appendix C. The increase in shear stress with discharge varies through the reach in the order depicted in Table 7.4.

Table 7.4: Documented hierarchies in the rate of increase in τ_o together with the equivalent observations from the North Tyne

Keller	(1971)	pool-mid>pool-tail>riffle
Ashworth	(1987)	pool-head>pool-mid>pool-tail>riffle
Petit	(1987)	pool-mid/pool-head>pool-tail>riffle
Clifford	(1990)	riffle-crest>pool-tail>riffle-mid>poolmid
North Tyne	(N)	pool-tail>pool-head>pool-mid>riffle1/2

Clearly this is variable between individual riffle-pool sequences and between rivers, however with the exception of the river Quarme (Clifford 1990), pools experience a more rapid increase in shear stress than riffles.

At bankfull discharge the order of mean shear stress magnitude in the three study sites is :

Smales

Pool-head (38 N/m^2),mid-pool (22 N/m^2), Riffle 1 (16 N/m^2), Pool-tail (12 N/m^2)

Tarset

Riffle 1 (123 N/m^2), Riffle 2 (103 N/m^2), Pool-head (45 N/m^2), Pool-tail (37 N/m^2)

Newton

riffle 2 (275 N/m^2), pool-head (257 N/m^2), riffle 1 (220 N/m^2), pool-tail (54 N/m^2).

The Newton site indicates a reversal in mean shear stress between riffle 1 and the pool-head, and a near equalisation with riffle 2. Interestingly the pool-tail, despite it's high relative rate of shear stress increment, experiences a force of only 20% that of the pool-head and riffles. The increase in shear stress, and the reversal at bankfull discharges at the pool-head are largely the result of a narrowing cross-section relative to the riffles and pool-mid/tail regions. Ashworth (1987) and Carling (1990) both identify the effects of confinement with velocity/shear stress reversal, which can only occur if the pool sections are narrow enough to compensate for the increased depth relative to riffles. The observations in this study of velocity reversals at 12-16% bankfull are clearly topographic low-flow phenomena, whilst the shear stress (and velocity) reversals at higher flows are a function of reach geometry. The reversal of shear stress within the North Tyne appears to operate in confined pools at discharges approximating 80% bankfull, which is within the region of flows determined from other studies at between 60-90% bankfull (Lisle 1979; Andrews 1979; Ashworth 1987; Petit 1987; Clifford 1990; Carling 1990).

The analysis of the hydraulic data reveals that during hydropower discharges, riffle surfaces experience a complex fluctuating shear field, on average 373% stronger than associated pools with local maxima attaining 40-78 N/m^2. Maximum shear stresses are generally associated with the periods of rise and recession of the hydropower flood hydrograph, with lower values recorded during stable peak discharge.

Localised bed velocity reversals occur within discrete regions of a pool, but many are associated with local flow deceleration on the riffle rather than an increase in pool bed velocities; correspondingly sediment transport is not considered to be significantly

local
influenced by reversals during hydropower events. No shear stress reversals were recorded in the pools for hydropower discharges.

The morphology of the riffle-pool sequence is important for determining the presence of a shear stress reversal during high magnitude flood events. The tendency for the capacity of pool-heads to be smaller and pool-tails to be greater than associated riffles is expressed in the shear stress at these sites. Correspondingly the longstream shear stress tends to decrease downstream to the pool-tail by an average of 55.4 %.

From the discussion of bed structure and strength in Chapter 6 this need not be the discharge at which pool scouring occurs since a lower shear stress will be required to mobilise the particles in pools than on riffles. This hypothesis is explored further in the following chapters.

Chapter 8
Sediment Transport and Sediment Routing in riffle-pool sequences.

The intrinsic controls on sediment transport represented by spatial variations in grainsize, sediment stability and local hydraulics, have been detailed from the literature, and described for the North Tyne. In this section the transport of sediment itself will be detailed and related to the factors above.

8.1: Sediment transport: morphological and extrinsic controls

The effect of bed morphology on the transport of sediments has been observed directly through tracing, and bedload sampling (Butler 1977; Ferguson and Ashworth 1992; Meigh 1987), inferred from direct measurement of boundary shear stress (Bathurst 1977; Thorne et al 1979), modelled in flumes, (Bathurst and Cao 1987; Ashmore 1987), and theorised on the basis of lateral and longitudinal variations in channel morphology (Yalin 1972; Bagnold 1980; Jaeggi 1987). Morphology controls the flow parameters determining shear stress operating at a given point in the river bed. The resultant pattern of erosion potential, in the presence of sediment supply, leads to the development of sediment storage units or zones of net erosion. The input of major sediment supply at a site can overload the balance of supply and transport to change morphology (Harvey 1992, Sear and Newson 1991; Osterkamp and Costa 1974). Conversely, a reduction in sediment supply produces a stability of existing morphology where flows are under-competent (see Chapter 1), or a net erosion of morphological features under competent flows (Petts 1984; Carling 1988).

The morphological control on shear stress distribution alluded to by Bathurst (1977; 1979) is the crux of the riffle-pool maintenance debate (Lisle 1979; Petit 1986; Ashworth 1987; Carling 1990) and is invoked as such with respect to sediment transport. Meigh (1987), in his detailed study of cross-section variation in sediment transport showed that the distribution of shear stress was related to cross-section morphology, and as Thorne and Lewin (1979) showed, that sediment transport was related to this pattern. The preceding sections have exemplified the role of the riffle-pool morphology in conditioning the hydraulics during hydropower generation, and, given the validity of the DuBoys method of calculating shear stress at higher discharges, the direct link between cross-section morphology and shear strength. The patterns of shear stress and near bed velocity constructed in Chapter 7 should, under conditions of uniform sediment supply, be capable of explaining the observed sediment transport within the riffle-pool sequence.

Meigh's study showed that not only was sediment transport rate variable across a section, but also the particle size distribution. Wilcock (1971) described the influence of channel morphology in terms of competence, whereby wide shallow channels (like the North Tyne) increased in competence at a greater rate than shallow channels for the same friction factor and rise in discharge.

Recently, Ashworth and Ferguson (1992) have described the importance of bed morphology in determining sediment transport rates in braided gravel-bed streams. However, there again existed a strong link between the shear stress field generated by the morphology and grainsize distribution of the bed, and the observed sediment transport rate and competence.

In addition to spatial variability, bedload is also variable through time, and is often observed as pulses (Billi and Tacconi 1987,; Meigh 1987; Reid et al 1985) or hysteresis in relationships with measures of flow magnitude (Bathurst 1987). Direction of hysteresis appears to vary in relation to a sediment source, with clockwise hysteresis on the rising limb of a flood when sediment sampling is downstream of a supply, and anti-clockwise in the absence of a supply. This effect is clearly of importance when attempting to interpret morphological controls on sediment transport from spot samples.

Bathurst (1987) lists four conditions under which non-uniform bedload transport occurs:

1. Variation through a flood hydrograph
2. During unsteady sediment transport
3. In the presence of sediment storage
4. Seasonal and interstorm variation

The conditions limiting the first 3 points have been discussed already in terms of intrinsic limitations on sediment supply. However, the last point is largely conditioned by sediment supply resultant from extrinsic catchment processes and differential flood effectiveness (Sear and Newson 1991; Newson 1989). The effectiveness of a given flood is determined by the transgression of the sediment supply/demand threshold for a particular reach of channel and the permanency of the corresponding alteration of the boundary conditions (Newson 1992). In this study, the legacy of past climatic and anthropogenic activity will be important for determining the quantity and calibre of sediments entering tributaries and the distribution of large "residual" elements within the North Tyne channel itself (see Chapters 2 and 4). However, it is the resolution of the particular influence of the Kielder reservoir operating regime from these extrinsic factors that must be addressed. The vegetation of direct sediment supply sources such as active gravel bars, and bank erosion scars that are a feature of the post regulation North Tyne, effectively reduces the influence of extrinsic factors to the tributary inputs (shown to be of local morphological significance only, Chapter 4), the existing suite of sediment within the channel, and the in-channel morphology of riffle-pools and barforms. The effects of sediment supply are likely to be determined by the riffle-pool sequence itself and the barforms within the channel. Furthermore, from the discussions in Chapters 5 and 6 the effects of armouring and bed stability are likely to dominate the supply of sediment in the North Tyne, particularly during hydropower regulation. The object of the following Chapters is then to establish the actual sediment transport in the North Tyne, to isolate the effects of the riffle-pool sequence upon the spatial patterns of bedload, and to account for the observed changes in bed structure, sediment populations and morphology. In addition, it is intended to assess the interrelationship of the observed sediment transport with the hydraulics discussed in Chapter 7 in an attempt to elucidate the effects of hydropower regulation and floods.

8.2 Sediment Transport in riffle-pool sequences

The transport of sediment in riffle-pool sequences has only been quantitatively determined in six published studies, despite some 57 papers addressing the topic of their maintenance and function (Chapter 1). Furthermore, these studies have concentrated on the dynamics of flood related sediment transport, and are therefore of limited comparative use in assessing the effects of low-moderate hydropower discharges. The six studies are:

1. 1971 Keller. Tracing experiment in Dry Creek, single riffle-pool sequence. (D_{50} = 22mm).

2. 1979 Lisle. Measurement of fine sediment scouring in single (isolated) riffle and pool. (D_{90} = 46mm).

3. 1982 Jackson and Beschta. Measurement of bedload transport rate at a single riffle-pool-riffle sequence. (measures at riffle only). (D_{50} = 28 mm).

4. 1985 Campbell and Sidle. Direct measurement of sediment transport rate and particle size of bedload at a single riffle-pool-riffle sequence. (measures at riffles only). (D_{50} = 28 mm).

5. 1986 Petit. Tracing experiment in La Rulles stream. Tracers located in riffle and intra-pool locations. (D_{50} = <40 mm).

6. 1987 Ashworth. Tracing experiment in riffles and intra-pool locations in 5 riffle-pool sequences in two gravel-cobble bedded streams. (D_{50} = 50 - 84mm).

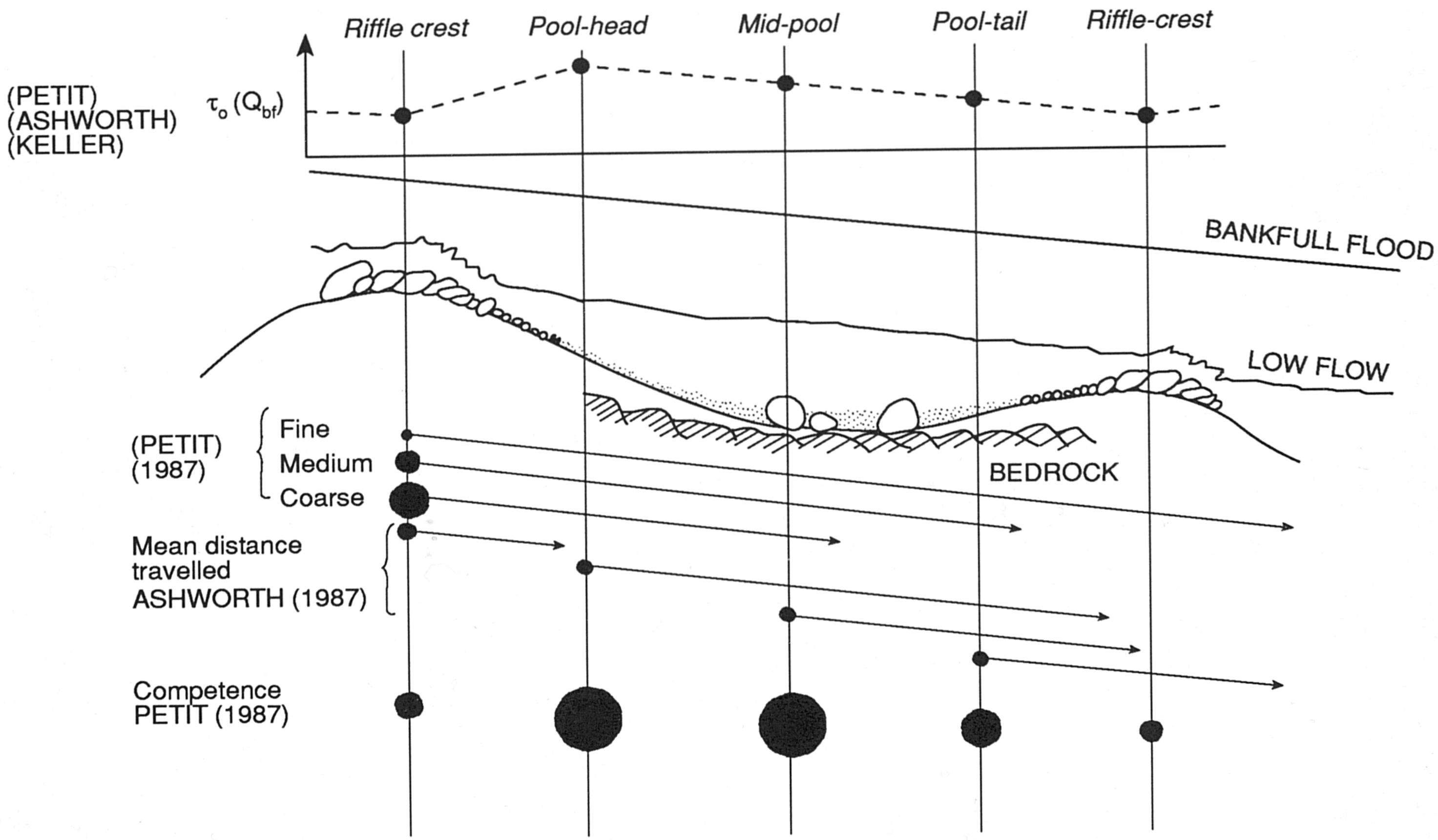
Of these, only four involve measurements in pools, and these are exclusively tracer experiments. The determination of the scour of sand from the pools in Lisle's study was by depth profiling using echo soundings, and therefore does not equate to a transport rate as such. The most comprehensive study to date of the transport rates associated with a single riffle-pool-riffle sequence is that of Campbell and Sidle (1985) and Sidle (1988). A deficiency in this study is the absence of hydraulic measurements within the pool or riffles to equate to the observed transport of sediment at the riffles and the inferred transport in the pool. As with all the sediment transport rate studies, the pool is treated as a "Black Box" from which inputs and outputs are measured.

This approach does not elucidate the routing of sediment through the pool nor the cross section variation at riffles. Furthermore, no indication of the relative roles of the distinct morphological sections within the pool is accomplished by this approach. Keller's (1971) earlier work on the relative hydraulic responses of the pool and riffle sequence showed that the pool-tail reacted differently to the mid-pool (habitually the site of most hydraulic studies, which in itself assumes that the mid-pool behaves differently to other sections). The discussion of Teleki (1972), in refuting the reversal hypothesis of Keller (1970), suggested that for equal channel widths, the difference in depth between pool and riffle would lead to a lower velocity in the pool. By the same argument, the variation in depth and sectional area from pool-head to pool-tail must involve a synthesis of hydraulic response and therefore different sediment transport/routing behaviour. In addition, studies that treat the pool as a black-box are limited in use at low flows, since the recorded sediment transport at each riffle may be the result of local sediment supply, rather than a supply from the pool.

The mechanics of low flow sediment transport in pools is unknown, and merely inferred from hydraulic considerations. However, it is the effect of a regime dominated by low-moderate flows that is important to this study. What "black-box" studies of pools do show is the highly variable nature of the supply of sediment from a pool during floods (Sidle, 1988). This latter point is important to consider in this study in order to put the lower flow effects into perspective, as well as to elucidate the effects of the reduced flood frequency upon sediment transport. The variability of sediment supply from pools tends to relate to the antecedent flood history (in terms of net supply or net scour) and flood magnitude. Campbell and Sidle (1985) found that moderate storms led to a net import of coarse sediment into the pool and a net output for floods of bankfull and above. In contrast fine sediment (<8mm) exhibited a highly variable response to discharge with episodic supply and storage. A similar study by Jackson and Beschta (1982) on a similar stream identified considerable differences between the sediment transport rates (and sizes) of two sequential riffles during flood events. Their results were used to support a theory of two-phase bedload transport in gravel-bed streams exhibiting riffle and pool sequences. Their phase 1 bedload consists of sands and fine gravels scoured from the pool, channel margins and local pockets of fine sediments, moving over a stable armoured riffle-bed. At a further stage, discharge is such that the pool scours and the armour layer at the riffles is breached. The corresponding phase 2 bedload is both coarser and of greater quantity. The downstream routing of phase 2 sediment is hypothesized to be from riffle to riffle, with the intervening pools transmitting sediment efficiently due to a velocity reversal (see Chapter 7). The widely differing sediment transport rates recorded at the two riffles suggests that sediment routing through sequences of riffles and pools is complicated; indeed both Campbell and Sidle (1985) and Jackson and Beschta (1982) suggested that the complex morphological changes, coupled with the effects of large organic debris (an important factor in both their streams, but not on the North Tyne), would complicate the release and storage of sediment. The reliance of both authors on the assumption of a velocity reversal to explain the net output of pool sediments, is not substantiated by recent observations (Clifford 1990; Carling 1990), although for the North Tyne selected pools can exhibit localised reversals in near-bed velocity at flows of only 15% bankfull. In contrast to the studies of sediment transport alluded to above the North Tyne is a different river, both in terms of scale (both streams above were under 10m wide with riffle-riffle spacing of < 50m) and sediment calibre, (D_{50} of the North Tyne riffles approximately twice that of the two streams above)). Given the reports of Carling (1983) on the effects of narrow streams on the transport of sediment (discussed in Chapter 7), the degree of analogy between processes operating in the riffle-pool sequence of small, fine gravel streams and a wide, coarse, cobble-bed stream, is questionable.

Evidence of the role of floods in routing sediment of differing sizes through the riffle-pool sequence, comes from the tracer studies of Keller(1971), Petit (1987) and Ashworth (1987). In particular, the study of Ashworth is important, since the channels studied are of similar sediment calibre. However the ratio w/d is different, with much lower values recorded for the North Tyne at bankfull discharge, despite the smaller scale of the Dubaigh and Feshie channels. The tracing studies of Keller and Petit were made in narrow channels with comparatively low w/d ratios and finer sediment calibre. Furthermore, in both studies considerable channel curvature was present which may have affected the behaviour of the reach hydraulics, and concomitant sediment transport (Thorne and Lewin 1979). Despite these differences a model of sediment transport through riffle-pool sequences during floods can be developed from which to compare the results from the North Tyne. Figure 8.1 schematically depicts the collected results of the six studies described above, for a single riffle-pool sequence. What is clear is that a difference exists not only between riffles and pools, but also within the pool itself, which is of great significance to the downstream sorting of sediments, and the maintenance of the reach morphology (Ashworth 1987). The collective results of the tracing experiments show that surface-sized sediment travels an average distance according to hierarchy, pool-head > mid-pool > pool-tail > riffle - although Keller (1971) found that mid-pool material travelled on average a shorter distance than riffle material. Petit (1987) found that reach competence was also determined by the morphological position in which the

8.1 Schematic representation of sediment transport through a riffle-pool-riffle sequence at bankfull Q. (after Keller, 1971, Petit, 1987, Ashworth, 1987)



tracers started, such that pool-head and mid-pool regions > pool-tail > riffle. The competence of the mid-pool was limited, however, and large residual elements were not transported.

The implications for the sorting of bedload within the riffle-pool sequence has been discussed by all three authors in terms of their observations of sediment within the streams studied; however their conclusions differ. Ashworth (1987) despite recording four out of five pools with finer pool-tails, suggests that the pool-head will be finer as a result of greater competence. Petit (1987) records that the pool-tail is both durable and yet finer than the pool-head, which is attributable to the inability of this region to transmit the finer sediment. Keller (1971) does not discriminate between individual pool regions, but concludes, in unanimity with the other authors, that riffles are the coarsest regions of the riffle-pool sequence, (see Chapter 5). From the discussion of results in Chapter 5, the pools in the North Tyne and associated tributaries are often coarser than the riffles on account of the large residual elements within them. Furthermore, the sequence of downstream fining is the converse of what Ashworth describes in his model, but is equivalent to the observations made by Petit (1986). What all the studies of sediment transport in riffle-pool sequences show is the importance of floods in moving sediment out of the pools and, through intra-pool variation in hydraulics, for the sorting of sediments. The concentration of studies on the role of floods in transporting sediment through the riffle-pool sequence is founded on the belief that not only are floods responsible for the majority of sediment transported, but that the maintenance of the riffle-pool sequence, and the sedimentology of the sequence, is generated during flooding. Recently, Clifford (1990) has suggested that the maintenance of the riffle-pool sequence results from the low flow hydraulic variation between riffle and pool effecting greater sediment transport on the riffles which is expressed in the coarser surface material and a more stable and durable bed. The results of Chapters 5 and 6 confirm these observations. Furthermore, the hydraulic patterns described in Chapter 7 would support the notion of their low flow origin.

Chapter 9
Infiltration and the transport of fine and medium bedload

9.1 Introduction: infiltration processes

The transport of fine-medium sediment (<16 mm B-axis) in gravel-bed rivers is complicated by the number and extent of storage areas within the channel. Fine sediment including suspended load, is stored within the bed as matrix material (Chapter 5) and in areas of flow separation and slackwater (Carling and Reader 1982; Church et al 1987). The storage of fine-medium sediment in slackwater and wake deposits has been quantified in Chapter 6 and accounts for less than 1% of the total storage of fine-medium sediment in the river channel. The majority (97%) of this size range is stored below the protective armour layer as matrix material. The composition of fine matrix sediment is important for the effective spawning and gestation of salmonid fish eggs (Kondolf 1992; Crisp and Carling 1989; Milhouse, 1982), as well as characterising the grainsize of transported sediment upon armour breaching, (Jackson and Beschta 1982). In the context of regulated rivers, it is the motion of fine-medium sediments that dominates the sediment transport regime of the river. Furthermore, the release and storage of this sediment component often characterises the post-regulation sedimentology of a stream (Leeks and Newson 1988; Petts 1988b).

The processes by which fine-medium sediment arrives within the framework gravels is complex, involving infiltration, particle overpassing, and simultaneous deposition with coarse bedload, during waning floods, (Frostick et al 1984; Carling and McCahon 1987). Recent studies however have tended to concentrate on the infiltration of fines into the bed of gravel streams, and view this as the dominant mechanism for matrix development. A review of the literature reveals the following state of knowledge of the infiltration process:

The rate of infiltration is independent of the reach hydraulics, but is related more to the sediment supply (Diplas and Parker 1992). However, Einstein (1968) found that turbulence and high velocity inhibits infiltration, although during floods, Carling and McCahon (1987) found infiltration to be greatest at areas of high velocity. In contrast Welton (1980) observed lower infiltration during a flood in the high velocity thalweg.

Sources of infiltrated material vary with discharge. During baseflows and summer floods, suspended sediments are the dominant source. During floods, bedload becomes the dominant source. The nature of the dominant source determines the correlation between local hydraulics and infiltration rates, with bedload correlating better than suspended load (Carling and McCahon 1987; Frostick et al 1984; Diplas and Parker 1992).

The grainsize of infiltrated sediments increases with discharge, but is constrained by the pore throat dimensions at the surface (Frostick et al 1984; Carling and McCahon 1987). The presence of an armour layer encourages clogging of the immediate subsurface pores, and thus inhibits further infiltration.

Infiltration is highest in pools and at bar-tails, and in slack water areas, in the presence of supply (Diplas and Parker 1992; Carling and McCahon 1987; Welton 1980).

Infiltration affects bed load transport by consolidating the surface particles and increasing their threshold of motion, at the same time producing a smoother bed that promotes higher particle velocities and transport rates of exposed grains (Frostick et al 1984; Diplas and Parker 1992).

Scouring of infiltrated fines is deepest in areas of high velocity and increases with disruption of the armour layer. Typical depths of scour are between 1-3 D_{90} surface sediment.

Typical infiltration rates show considerable variation according to the type of sediment into which a channel is cut; however, all show highest rates during floods. Typical values from the literature are:

Gravel/Cobble upland streams:	0.0079	(Baseflow)
(Carling and McCahon 1987)	0.29 - 2.5	(Flood)
Gravel/Clay lowland streams:	0.24	(Baseflow)
(Frostick et al 1984)	4.43	(Flood)
Chalk lowland streams:	5.0 - 10.0	(Flood)
(Welton 1980)		

(all figures in $Kg/m^2/day$)

Of the latter, the study of Carling and McCahon (1987) is most comparable to the North Tyne study, and provides a useful background value from which to gauge infiltration rates.

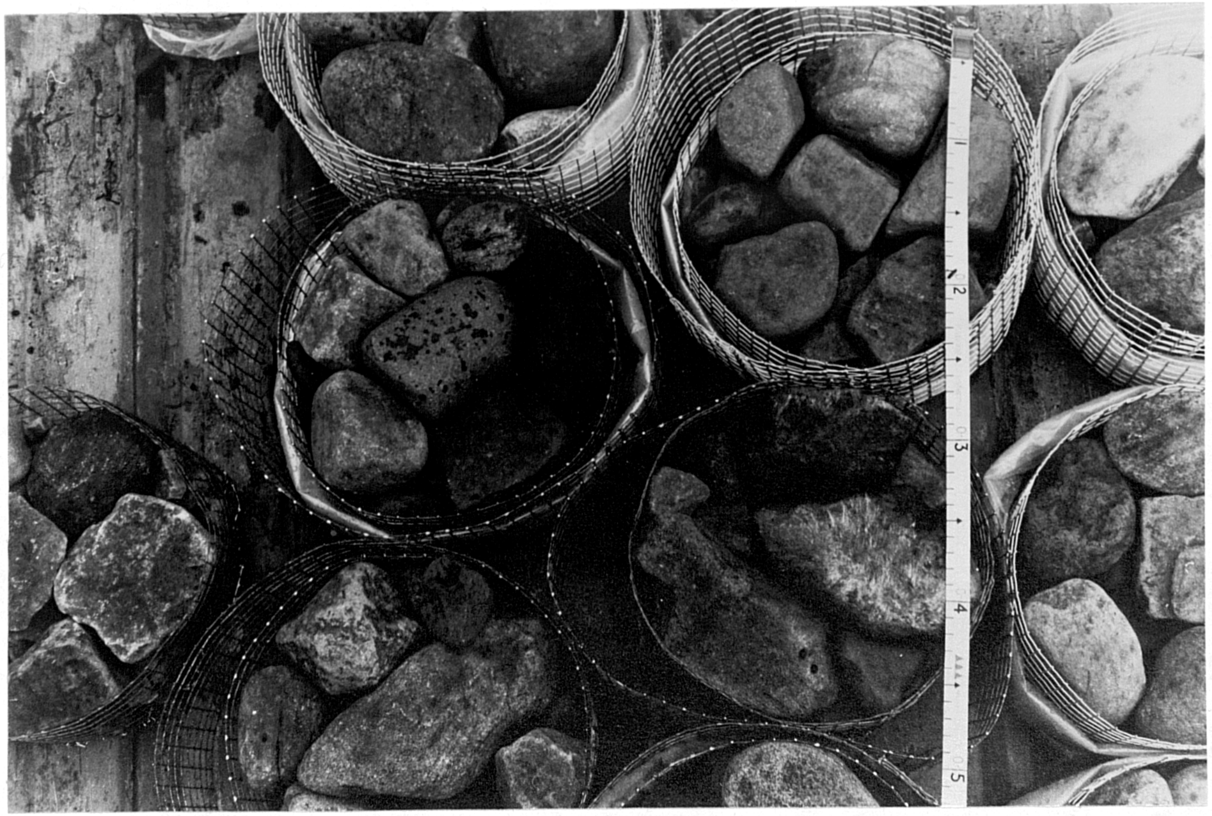
9.2 Methodology

Given the discussions of the sedimentological changes in the post-regulation North Tyne, it is evident that an increase in the fines content of the bed is most likely the result of infiltration into an otherwise static armoured/compacted bed. Chapter 5 describes such an increase in the fine sediment < 2mm within the bed of some riffles, and Petts (1988) describes a similar scenario for two regulated rivers, below tributary inputs.

In addition to investigating the process of infiltration within the North Tyne, it was considered that by monitoring the quantity and calibre of the sediments entering uniform infiltration baskets, some indication of the longer term bedload transport rates and characteristics could be deduced. Furthermore, the cross section variation in sediment transport could be discerned for a variety of discharge conditions that were otherwise difficult to record.

The infiltration baskets were constructed along the lines of those described by Carling (1984) and Davey et al (1987). Each basket was 10 cm deep with a surface area of 25 cm^2. Figure 9.1 illustrates such baskets, together with a view of one in situ. The gravels were collected from the North Tyne riffles according to armour and sub-armour. The latter was passed through a 16mm sieve and the material retained was returned to the

Fig 9.1: Infiltration baskets showing the armour layer and surface porosity.



basket. A representative armour layer was reconstructed above the cleansed finer framework (Figure 9.1). Table 9.1 defines the characteristics of the basket samplers in relation to the gravel-bed of the North Tyne.

Table 9.1: Basket dimensions: 10 cm deep x 500 cm^2 surface area.

Grainsize (% by weight):	**Armour**	**Sub-armour**
64mm	25	11
45mm	25	12
32mm	18	12
22mm	5	10
16mm	4	8

Void density :		
Baskets:	16.5%	SD = 7.2%
Bed:	13.7%	SD = 6.4%

Mean pore diameter:		
Baskets:	7.3mm	SD = 5.5mm
Bed:	6.3mm	SD = 4.2mm

Values for void density (Carling and McCahon 1987), and mean pore diameter, were obtained by direct measurement from exploded photographs such as Figure 9.1 and photographs of the bed. Each basket was placed within a wire frame, which prevented collapse of surrounding sediment upon extraction of the basket, and yet allowed intra-gravel movement of fine sediment < 10mm. This latter phenomenon has been found to be an important source of fines infiltrating the bed, particularly during high discharges when intra-gravel velocities may be competent for sand-sized sediments (Lisle 1989; Carling 1984). To overcome the problem of fines loss from impermeable baskets when drawn through the water column, a polythene bag was folded down around each basket and secured with a foam collar (Davey et al 1987; Coleman and Hynes 1970). Upon sampling, the foam collar was removed and the bag pulled up around the pot, thereby reducing the loss of infiltrated sediments to a minimum. Carling (1984) found that impermeable baskets reduced trapping efficiency by 62% in a flume study, whilst Lisle (1989) found a 3% increase in the quantity of infiltrated sediment in an impermeable basket. In this study an initial experiment was carried out, to assess the importance of the intragravel component of fine sediment infiltration. Out of 32 baskets, two had no polythene bags and were open to intragravel sediment sources; 15 were open and had polythene bags; and 15 were sealed against intragravel sediment sources but had polythene bags. The results of 40 days' infiltration (involving 25 days of hydropower) indicated that on average, sealed baskets had a 20-25% reduced trapping efficiency (ie a quarter of the infiltrated sediment came from intra-gravel sources, assuming no loss to re-suspension), and that without polythene bags to protect the fines upon retrieval, 26-40% were lost.

Four baskets of identical sediment composition, were emplaced at eight riffle sites below the dam site at YR1/2, TR1/2, NR1/2 and at a site in the Countess Wood Gorge downstrean of the river Rede. Each set of two riffles corresponded to input and output from a single pool, although the Tarset site was complicated by the input of two major tributaries. The Yarrow site represents the first riffle-pool-riffle sequence below the dam, whilst the Tarset riffle 2 and the Newton and Rede sites represent morphology still affected by flooding.

The sampling frequency was variable at first, depending on whether the prevailing discharge was dominated by compensation flows or hydropower. In June 1988, a flood event of approximately 54 cumecs maximum, occurred, after which sampling was continued on a monthly basis. In total, some eight samples were made from April 1988 to November 1988, after which time the baskets were retained for a long term sample which was subsequently terminated by the loss of 60% of the baskets during a bankfull flood, and the further loss of baskets through weed growth.

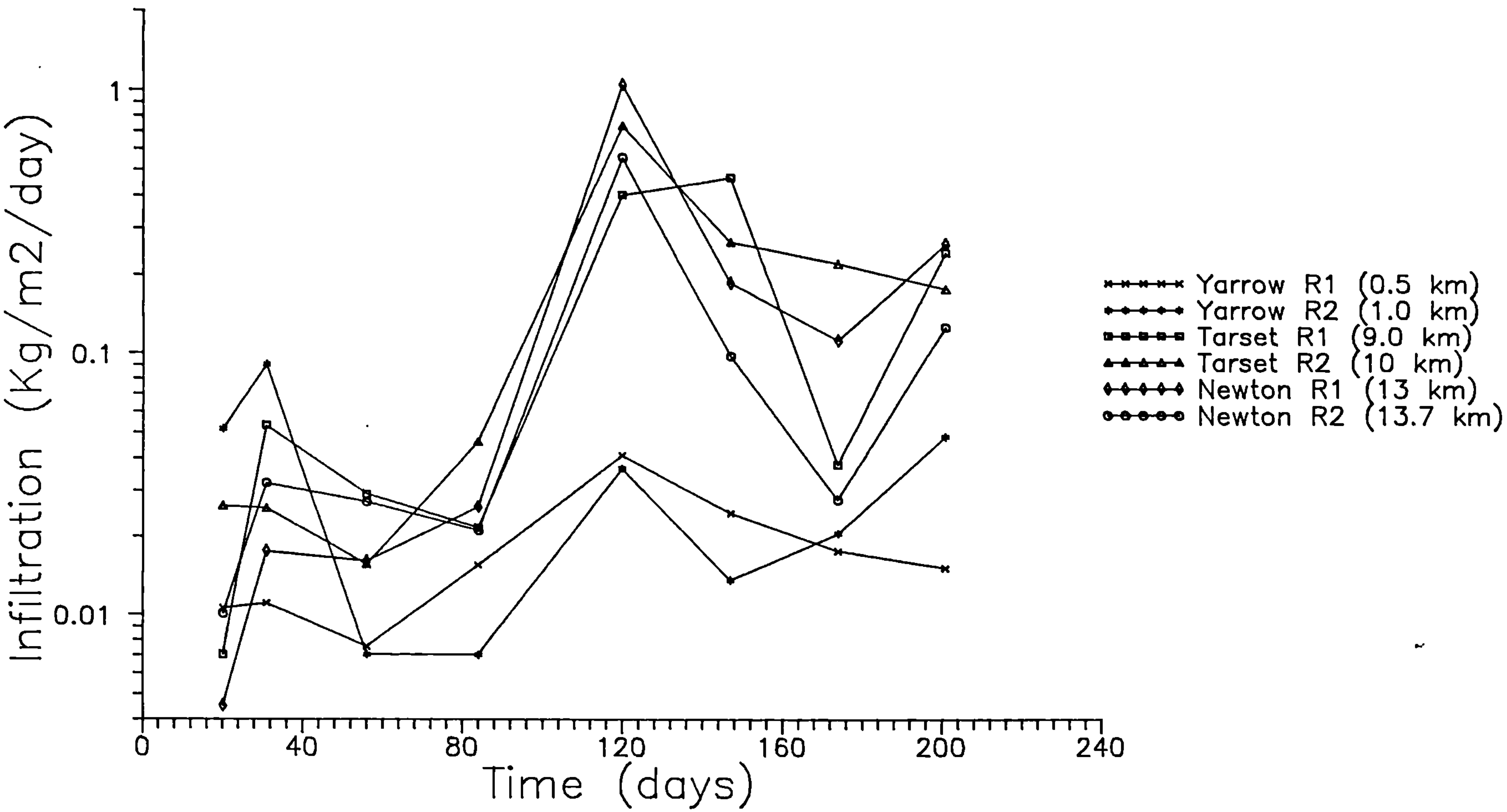
Upon withdrawal from the bed, the basket sediment was flushed through a 16mm sieve into a bucket, using clean water. The water and sediment mix was returned to the laboratory and evaporated to dryness. After weighing, the air dried sediment was submerged in water and the organic component floated off (Meigh 1987). This technique was preferred to combustion as results from heating experiments had shown evidence of particle disintegration, which in the small samples could affect the size distribution. After air drying again, the inorganic sediment was sieved for particle size analysis. The infiltration rates expressed in this section in Kg/m^2/day, represent the inorganic fraction only, unless otherwise stated.

9.3 Fine sediment infiltration into stable gravel-beds

Figure 9.2 illustrates the variation in total inorganic infiltration over the period of study. The logarithmic y axis scale reflects the wide variation in infiltration rates experienced at individual riffles. The variation in infiltration rates between sites is particularly evident during compensation and hydropower regulation (0 - 90 days), and during the period after the flood event of July 28th 1988, (120 - 180 days).

Two distinct populations exist, which are particularly differentiated by the effectiveness of the flooding; these equate with the two sites immediately below the dam site (Yarrow riffle 1 and 2) and those sites downstream of the confluence of the Tarset and Chirdon Burns. Application of a Kruskal-Wallis test for population difference indicated, with 95% confidence, that the Yarrow sites experience a different infiltration regime to the sites further downstream. The Tarset and Newton sites were not significantly different from each other suggesting that infiltration is controlled by similar factors at all sites. An exception is the Tarset riffle 1 site, which is upstream of the significant tributary inputs, but which is 9 km downstream of the dam site. Several small tributaries, including the Smales Burn, discharge into the North Tyne upstream of this site and it is possible that these will be cumulatively effective (particularly during hydropower flows) in increasing the discharge. The gauging station at Tarset unfortunately ceased to operate at the beginning of this study, and no gauge of the discharge was possible. However, observation of the trashlines associated with this event suggested discharges only marginally increased above hydropower. An alternative reason for the accentuated infiltration rates associated with this site comes from the availability of fine sediment. The analysis of pre-regulation grainsize data, described in Chapter 5, suggests that much of the fine sediment from sites closer to the dam site, is currently stored in the bed at or upstream of this site. Furthermore, immediately upstream, is an island, which has local deposits of fine sediment trapped in bank shadows, which may become available as Phase 1 bedload (see Chapter 8 for definition) during discharges in excess of hydropower. This latter point is supported by the direct measurements of bedload transport during hydropower discharges described in Chapter 11, which were the highest recorded for any of the sites monitored. In addition, cross section patterns show accentuated infiltration rates immediately downstream of the island (see below).

9.2 Variation of infiltration rates per site, through time.



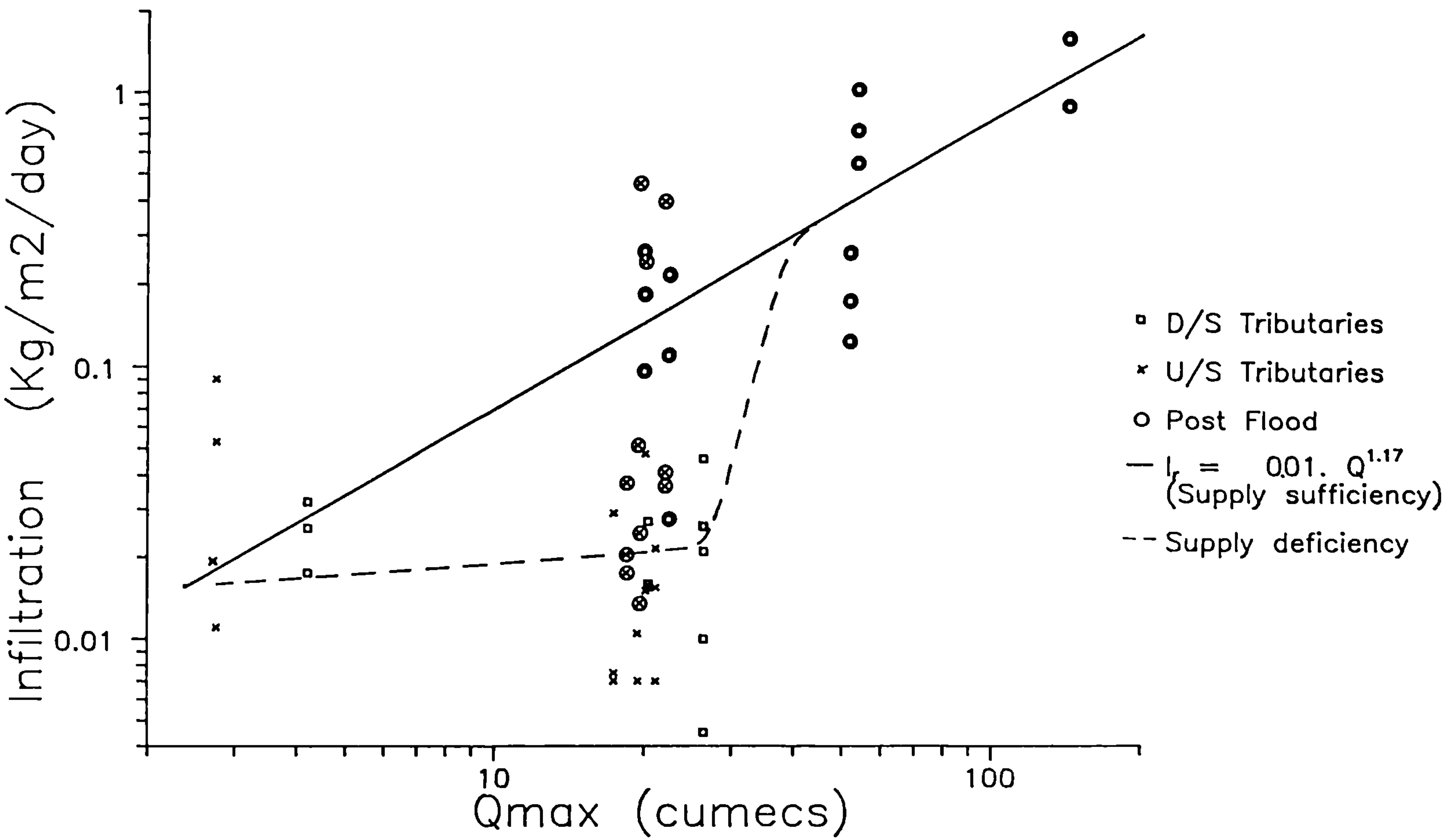
Inter-riffle variations decrease as the discharge increases for all sites during major flood events (t = 120 and 210 days), suggesting an equality of supply and a more uniform rate of infiltration. In contrast, during hydropower discharges the inter-riffle variation is most prominent, suggesting more local controls on infiltration rates. This pattern has been identified in the local hydraulics at a site. Inter-riffle variation in bed velocity and shear stress (τ_p) are greater during hydropower and compensation flows than during floods (Chapter 7). This suggests that infiltration rates are influenced by local hydraulics at low-moderate discharges; a point that is explored below.

Post-flood recovery following a flood of 54 cumecs (1/3 bankfull) is illustrated by the Tarset and Newton sites. Carling and McCahon (1987) have shown that for small freshets in a small upland stream, post-flood re-attainment of background infiltration rates takes less than two weeks. In contrast, the North Tyne exhibits accentuated infiltration rates up to 55 days after a flood event of 1/3 bankfull, although this is variable per site. The longevity of post-flood recovery in this instance results from a major increase in available sediment, derived from pool-scouring, armour disruption and higher intragravel sediment loads. The local controls on infiltration rates evident during hydropower discharges are also apparent in the variable post-flood recovery times, suggesting that riffles, whilst experiencing broadly similar infiltration of fines during floods, are differentiated most clearly during post-flood recovery.

The discussions above suggest that one of the dominant controls on infiltration rates is sediment supply, particularly at high discharges. This is supported by the observations of other workers in this field, who all report increased infiltration rates during flood events. In this context, the North Tyne during floods exhibits infiltration rates of 50 times the compensation levels, in comparison to 37-318 times baseflow levels in upland cobble-bed streams (Carling and McCahon 1987), and 18 times baseflow levels in clay/gravel streams (Frostick et al 1984).

Figure 9.3 depicts the relationship between infiltration rate and maximum discharge experienced at a site. A similar analysis, on the basis of the percentage of time flows were at hydropower discharge during the period of each sampling, produced no statistically significant relationship ($r^2 = 0.02$), suggesting that infiltration rates are not cumulative, but rather supply restricted until higher discharges access new sources. Two

9.3 Variation of total infiltration rate with discharge magnitude.



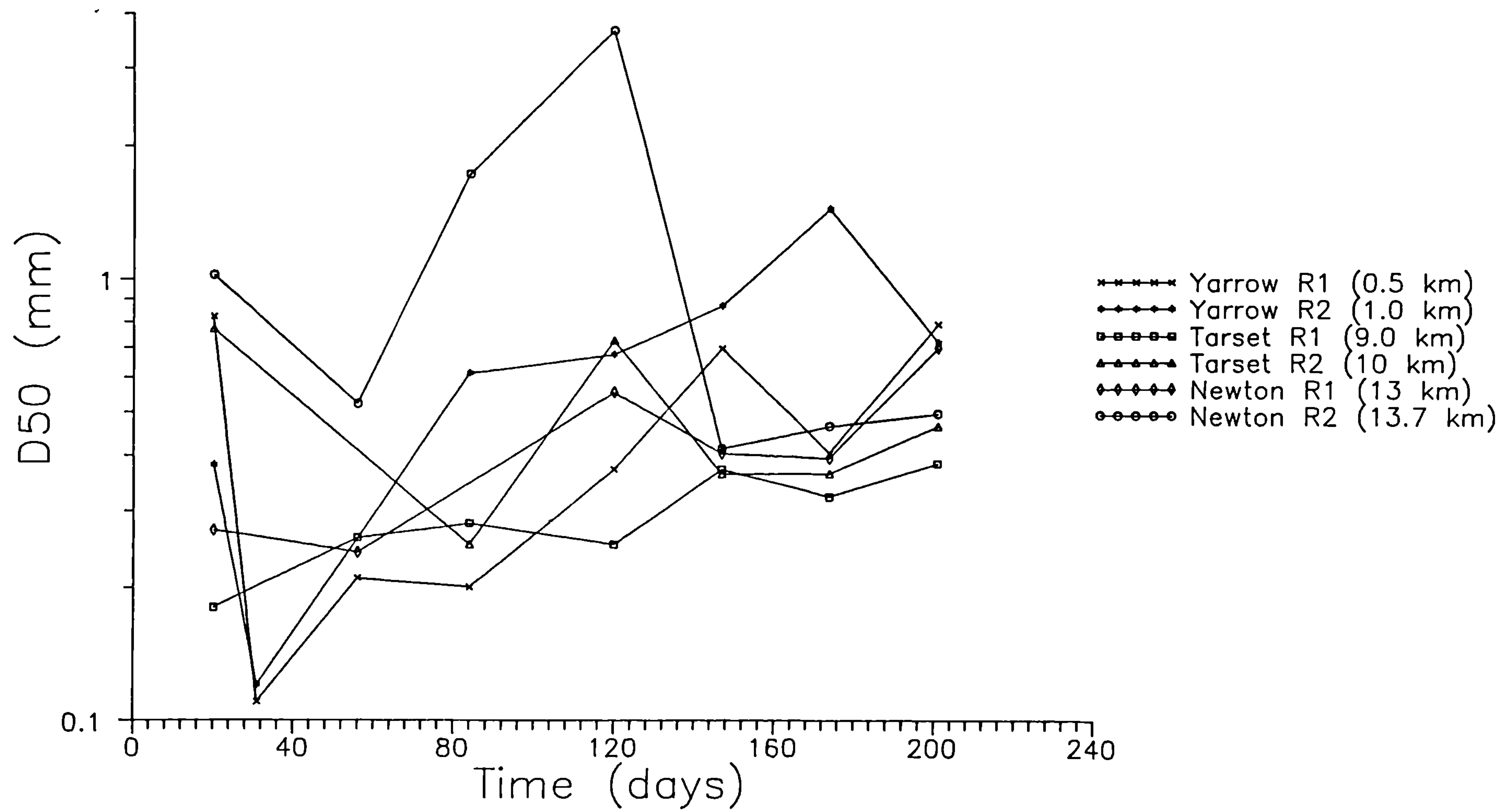
patterns are evident: a sediment-deficient scenario experienced at all riffles following prolonged periods without flooding, and particularly apparent up to 5km from the dam; and a supply-sufficient scenario which occurs during and after flood events of 50 + cumecs. The curve for supply deficiency shows a marked increase between 28 - 52 cumecs. This discharge is suggested here to be the threshold flow at which material < 16mm is scoured from pools, and at which sporadic armour breaching occurs at the riffles. The latter points are supported by the tracing experiments discussed later. The site nearest the dam site clearly did not experience a competent discharge, and consequently the minor increase produced little variation in the infiltration rates. The effect of sediment supply is clearly evident in the infiltration rates experienced at 20 cumecs for sites at 9 km + from the dam site. The curve for supply sufficiency is extrapolated back to compensation flows on the basis that sediment at such low discharges is limited not so much by supply as by competence. The curve accounts for 78% of the variance in total infiltration rates, and can therefore be used to prorata infiltration rates in salmonid spawning gravels under conditions of supply sufficiency.

9.4 Infiltration rates on a particle size basis

An important consideration in the quantification of infiltration rates is the relative proportions of suspended load and bedload. These in turn give some indication of the sediment dynamics operating at different discharges (Frostick et al 1984). In addition, analysis of the particle size of infiltrated sediments from a range of discharges can aid in assessing the processes of matrix formation. In the North Tyne, it is also important to examine the particle size composition of sediments, to investigate the impact of river regulation in producing the observed changes in bulk river bed granulometry (Chapter 5). Furthermore, given the importance of the salmonid fishery in the river, it is important to consider the dynamics of material < 1mm (Crisp and Carling (1989)).

Figure 9.4 depicts the changes in median particle size of infiltrated sediments recorded during the period of study. With the exception of Newton riffle 2 during flood conditions, all infiltrated sediments have a D_{50} less than 1 mm (sand size and below). The mean size for all infiltrated riffle sediments is 0.31 mm. There is a general increase in median particle size over time at all sites, largely, but not exclusively the result of the July 28th flood event. Newton riffle 2 shows the greatest response to the flood event in

9.4 Variation of D50 (mm) of infiltrated material per site, through time.



terms of median particle size, with flood infiltrated sediments dominated by fine gravels of 4 mm. The significantly coarser nature of infiltrated sediments at this site probably results from several factors, but observations from total infiltration rates (see above) indicate lower quantities of infiltrated sediments compared with other sites downstream of tributary inputs. This either means a deficiency of fine sediment supply, or the scouring of fines from the inter-gravel pores. Hydraulically this riffle consistently experiences the most rapid near bed velocities due to the constriction of flows by a mid-channel island (Chapter 7). Carling (1984) has demonstrated that siltation rate is dependent, in part, upon turbulent exchange at the sediment water interface, and Lisle (1989) has described how in areas of higher energy fines are pushed deeper into the gravel framework. Jackson and Beschta (1979) record scour depths of 1cm below surface gravels for flume studies of infiltration, whilst Frostick et al (1984) record values of 8 cm below the bed surface for thalweg positions, in a small gravel stream. Diplas and Parker (1992) standardised scour depths (or depth to which fines are depressed below the surface - there is no differentiation in the literature) in terms of the D_{90} of bed, and suggest that in areas of sporadic bedload motion scouring occurs up to $3.D_{90}$. This scenario for the North Tyne would mean a scour depth of approximately 27 cm, or twice the depth of the infiltration baskets in thalweg positions. This point is examined in the following section, but it is assumed here that in the case of Newton riffle 2, fine sediments are preferentially removed from the subsurface layers, leading to coarser infiltrated sediments.

For sites experiencing increased sediment supply, D_{50} becomes finer post flood, in contrast to the riffles closest to the dam. This can be explained by the increased competence of the flood discharges at sites furthest from the dam leading to coarser infiltrated material, which is not available under post-flood hydropower flows. At sites closest to the dam, flood flows were not significantly greater than at hydropower and therefore no significant increase in the size of infiltrated sediments was observed. However, reference to Figure 3.3 (Chapter 3) indicates that the latter period of the infiltration study was characterised by longer periods of hydropower generation, which results in coarser infiltrated material.

A comparison of the grainsize frequency curves for infiltrated material, subsurface bed material and bedload is depicted for each site monitored for infiltration. Each sample was truncated at 11.2mm b-axis to enable comparison; subsurface material and bedload both contained substantial quantities of sediment above these sizes. The grainsize frequency curves for each infiltration site are depicted in Appendix D for convenience, and only Tarset riffle 2 is illustrated in Figure 9.5. Additional comparative grainsize data is given in Table 9.2 below.

9.5 Grainsize comparisons for Tarset riffle 2.

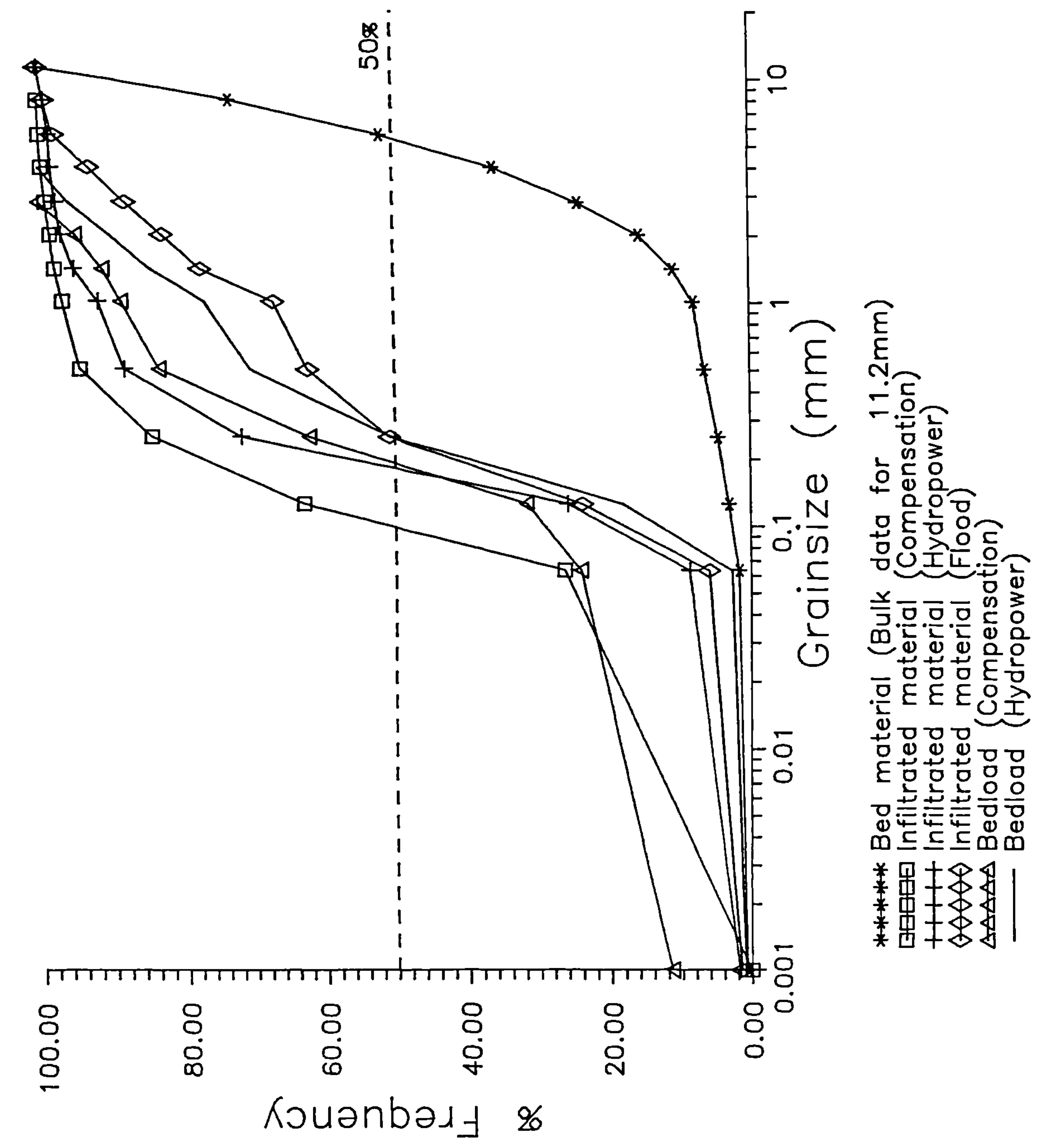


Table 9.2: Comparison between infiltrated sediments and subsurface material truncated at 11.2mm

Sediment	D50(mm)	Sorting	Skewness
(Yarrow riffle 1)			
Subsurface (< 11.2mm)	1.0	-5.3	-0.55
Infiltrated (Compensation)	<0.063	-2.28	1.00
Infiltrated (Hydropower)	0.1	-2.99	-0.40
Infiltrated (Flood)	0.15	-1.60	0.39
(Tarset riffle 1)			
Subsurface (< 11.2mm)	4.3	-1.98	-0.65
Infiltrated (Compensation)	0.13	-3.09	-0.51
Infiltrated (Hydropower)	0.16	-1.77	-0.15
Infiltrated (Flood)	0.11	-1.15	-0.16
Bedload (Compensation)	0.17	-0.74	0.01
Bedload (Hydropower)	0.30	-3.30	0.50
(Tarset riffle 2)			
Subsurface (< 11.2mm)	5.6	-1.08	-0.38
Infiltrated (Compensation)	0.09	-2.58	-0.61
Infiltrated (Hydropower)	0.17	-1.15	0.14
Infiltrated (Flood)	0.23	-2.36	0.37
Bedload (Compensation)	0.18	-2.98	-0.52
Bedload (Hydropower)	0.23	-1.74	0.35
(Newton riffle 1)			
Subsurface (< 11.2mm)	5.5	-0.85	-0.48
Infiltrated (Compensation)	<0.063	-2.83	1.00
Infiltrated (Hydropower)	0.16	-1.04	-0.09
Infiltrated (Flood)	0.20	-1.96	0.47
(Newton riffle 2)			
Subsurface (< 11.2mm)	6.5	-0.91	-0.47
Infiltrated (Compensation)	0.25	-3.75	0.47
Infiltrated (Hydropower)	0.25	-3.49	0.23
Infiltrated (Flood)	4.4	-1.57	-0.63
Bedload (Compensation)	1.4	-2.91	0.51
Bedload (Hydropower)	1.4	-2.76	-0.29

Table 9.2 shows that, without exception, infiltrated sediments, bedload and subsurface material all exhibit very well-sorted distributions (Briggs 1984); however, this varies

between dominantly fine and coarse sediments. This latter point is illustrated by the values of sample skewness, which show that, without exception, the subsurface matrix material (< 11.2 mm) is negatively skewed, indicating a dominance of coarse particles. All other sediment populations are distinctly variable, with no pattern of graphical skewness, suggesting considerable local controls on sediment supply and infiltration.

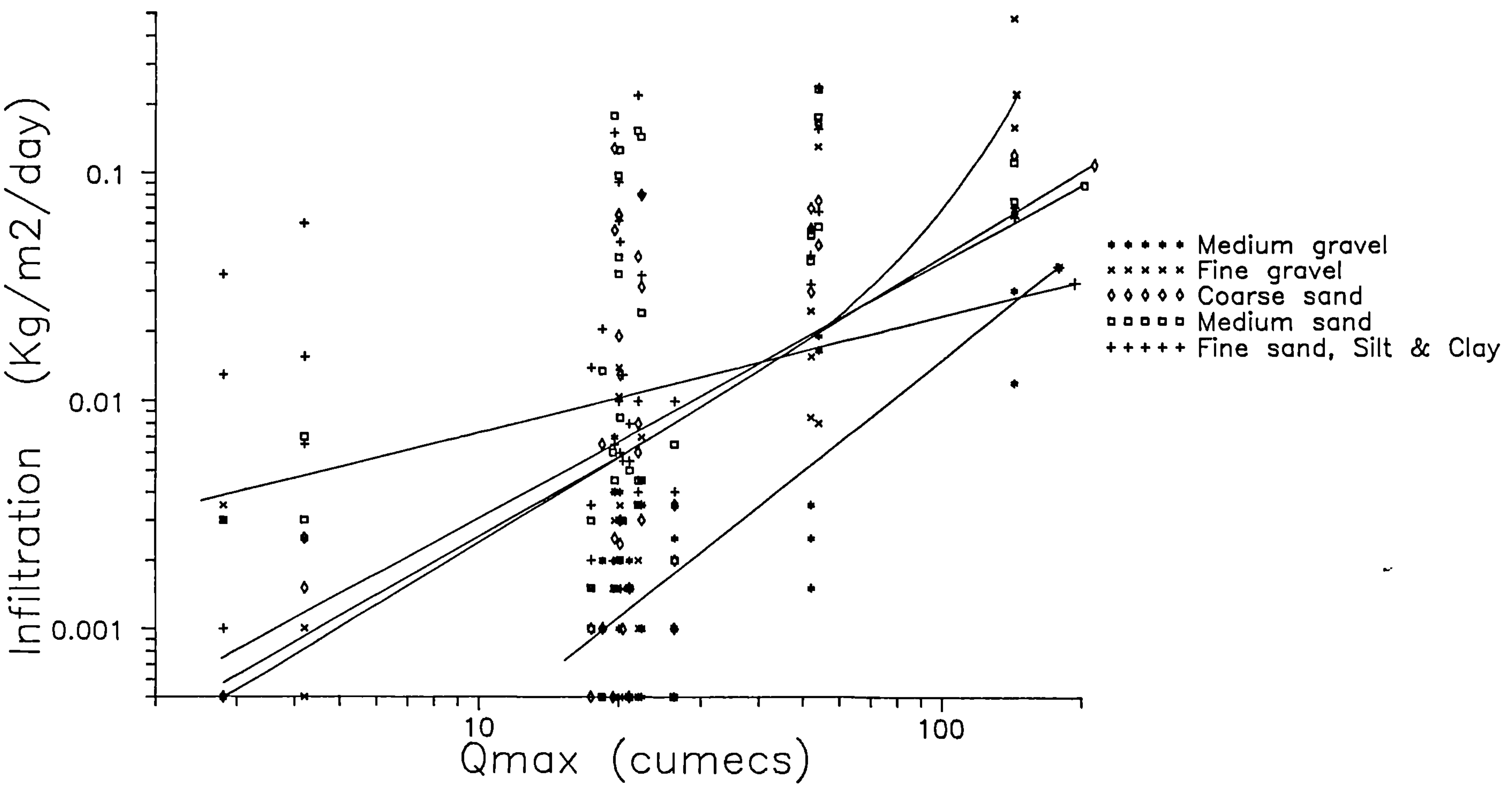
Table 9.2 also depicts the median grainsize for the different sediment samples. Subsurface matrix material is dominated at all sites, except Yarrow riffle 1, by fine gravel. In contrast, sediments infiltrated during compensation flows (Qmax = 2 cumecs) are dominated by sediments in the fine sand, silt and clay size ranges. These are the size ranges included in suspended sediments, suggesting that this represents the dominant source of infiltrated material under compensation flows. This size category also dominates the bedload measured during compensation flows, suggesting that suspended sediments are indeed the source of infiltrated material.

Sediments infiltrated under hydropower flows are also dominated by suspended sediments, although the proportion of bedload material has increased (Figure 9.5 Appendix D). Consideration of the size distributions of bed load collected under hydropower flows shows that the infiltration process is size selective, since the potential source of infiltrated sediments is much coarser. Clearly, as other studies have shown, the process of infiltration involves a form of sieving, conditioned by pore size, which in the case of the North Tyne riffle sediments preferentially selects material finer than 0.2mm. Results from the experiments to determine the contributions from intra-gravel sediments suggest that up to a quarter of the infiltrated sediments comes from this source, which Carling's (1984) flume experiments show is largely composed of fine sands, silts and clays. Unfortunately the process of basket retrieval largely destroyed the vertical structure described in other studies, therefore no assessment of the stratification was made, although visual observations indicated a concentration of coarse material at the surface. This latter feature has been observed in other studies, and has been attributed to the inability of coarse material to penetrate the finer pores of the subsurface framework (Frostick et al (1984); Lisle 1989). The observation that much of the coarser fraction of the bedload moved during hydropower flows is not trapped in the subsurface gravels suggests that it is routed through the riffles and into the downstream pool, with entrapment within structural elements such as wake deposits providing the only source of protection during competent discharges.

Material infiltrated during floods is generally coarser than that associated with hydropower and compensation flows. An exception to this is at Tarset riffle 1 (Appendix D, Figure 2), the reasons for this being discussed above. Infiltrated flood sediment at Newton riffle 2 closely approximates the grainsize composition of the subsurface matrix sediments, suggesting that it is during these conditions that these sediments are formed. This is not the case with the other riffles, suggesting that the preferential deposition of fines within the bed is scoured out at a later stage during hydropower flows. The evidence for a significant intra-gravel source of fines suggests this latter point. The scouring of fine sediments from Newton riffle 2 has been alluded to above, and is clearly operative during and after flood discharges.

The discussions above clearly hint at a relationship between the composition of infiltrated material and the discharge in the channel. Figure 9.6 plots the infiltration rates of five particle size classes against the maximum discharge experienced during sampling. Two points are immediately apparent; first there is a general tendency for the infiltration rates of all size classes to increase with discharge, but secondly, the rate of increase varies according to particle size. This second point is important for predicting the composition of infiltrated sediments under flood conditions, which characterised the pre-regulation North Tyne. Considerable scatter is evident within the relationships, and from the discussion of total infiltration rates above, it is evident that sediment supply is of considerable importance. However, it is evident that the infiltration of medium gravel is competence driven, and increases in proportion until, during bankfull flows (measured at a site below the River Rede confluence), infiltration rates exceed those of fine sands, silts and clays. Evidence from the Countess Wood Park site showed that for the 143 cumec event, much of the surface framework gravels was removed, and replaced with a veneer of medium-coarse gravel. This suggests that in order to achieve the infiltration of significant proportions of coarse sediments, bed mobilisation is required. Clearly this will be reduced as a result of the regulation of the North Tyne (Chapter 3). At discharges experienced at the Tarset and Newton sites (54 cumecs), sands, silts and clays still dominate the infiltrated sediments. With a further increase in discharge, fine gravels increase in proportion, until these dominate the material. The degree of scatter associated with a given discharge is greatest under compensation and hydropower flows, when

9.6 Variation of infiltration rate with discharge magnitude on a particle size basis.



hydraulics show the differentiation of sites is greatest, and supply of sediment is limited. The higher infiltration rates during hydropower flows are of course associated with post-flood conditions.

From the discussions above, it is evident that the process of infiltration is controlled by sediment supply, which in turn is controlled by flood competence (and vice-versa). However, even under conditions of supply sufficiency such as occur during floods of 54 cumecs plus, the selectivity of infiltrated material is governed primarily by pore size, and the ability of flows over the riffles to route sediments through the gravel bed. The increase in the proportion of coarse and fine gravels infiltrated during flows above 54 cumecs suggests that the production of the coarse fraction of the matrix sediments within the North Tyne riffles is achieved during bed mobilising events. Infiltrated sediments from lower discharge events, and particularly during hydropower and compensation flows will produce an increase in the fine sediments < 1mm where fine sediment is available. This is in agreement with the evidence for increased fine sediments within some of the post-regulation riffle sediments discussed in Chapter 5. The ability for a riffle to scour the fines infiltrated during protracted periods of low flows, is locally dependent upon reach hydraulics and sediment supply.

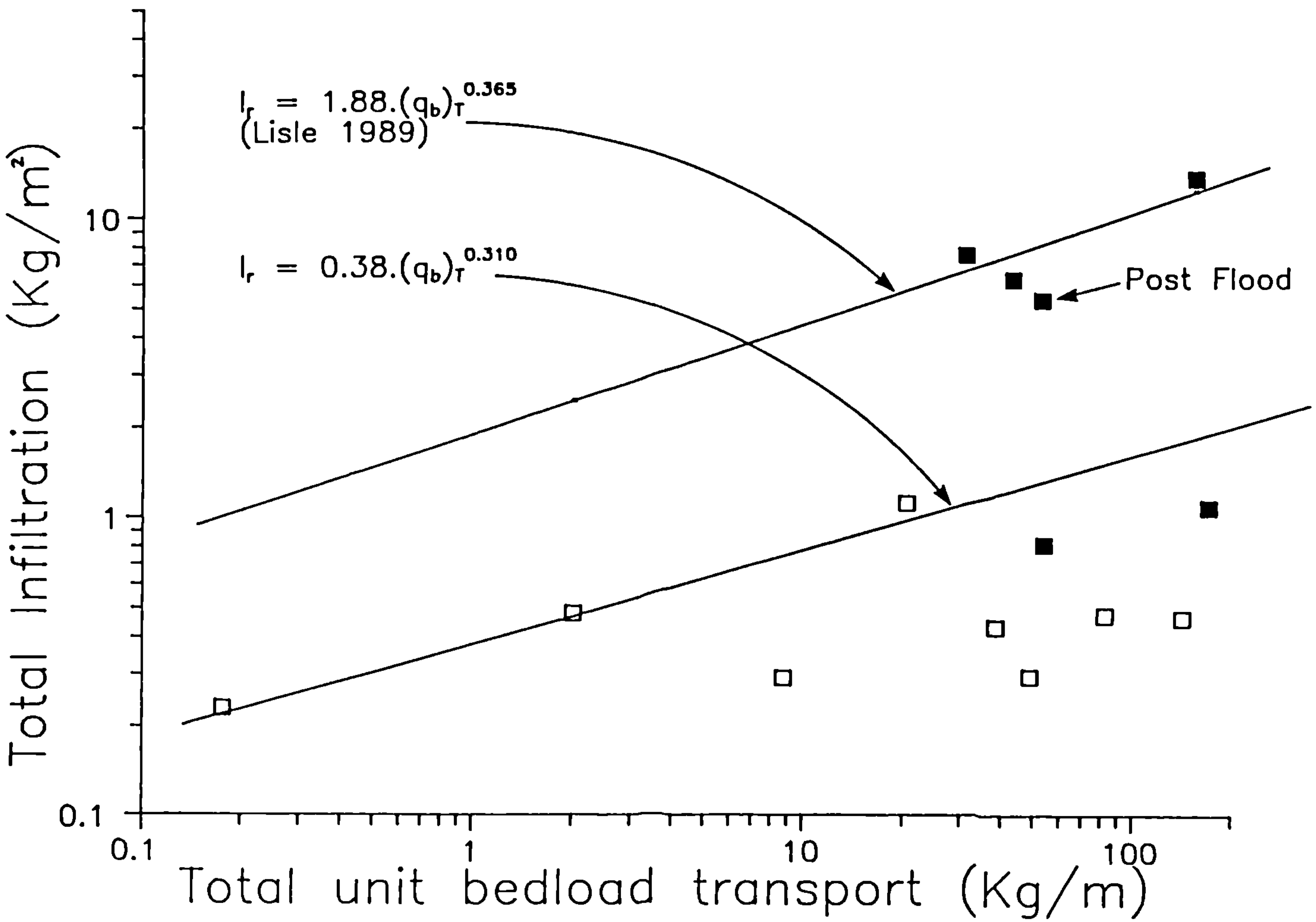
9.5 Cross-section variation and implications for bedload transport.

Infiltration rates have been shown to vary according to the sediment supply and maximum discharge experienced at a site. In addition these factors have been shown to vary, per riffle in the North Tyne, particularly during hydropower generation. Furthermore, the contributions of different grainsizes varies, both at a site and through time - again, according to discharge and supply. These variations in the components and rates of infiltrated sediments produce opportunities for variable matrix development at individual riffles, which in turn may influence the selection and recruitment of spawning salmonids (Petts 1984; Crisp and Carling 1989; Mackintosh pers comm). Reference to the results of the re-survey of F.B.A. sites in Chapter 5 shows that 64% of the riffles surveyed have a higher percentage of fine sediments < 1mm in their matrix material although the quantities were not statisically significant. These include the Yarrow riffle 1 site, Tarset rifle 1 site, and Newton riffle 2 site. The latter site exhibits coarser infiltrated sediments than all other sites monitored; therefore the enhanced fines recorded for this site would suggest that the fines in the infiltration baskets are scoured, leaving coarser material in situ. In the bed itself, the fines are infiltrated lower into the bed - a feature of riffle sites experiencing higher energy conditions (Lisle 1989; Diplas and Parker 1992). This latter point is supported by the results of egg basket monitoring, which are buried between 10 - 20 cm beneath the surface gravels. The Newton riffle 2 site consistently experiences high siltation rates, which destroys salmon eggs within the basket (Haile et al 1989; Haile pers comm).

Cross section variations in infiltration rates at riffle sites are considered to be as great or greater than the variation between individual riffles (Adams and Beschta 1980; Frostick et al 1984; Lisle 1989). Furthermore, the variation is most apparent in the coarser size fractions; those derived from the bedload (Carling and McCahon 1987).

The variation in cross-sectional infiltration rates has been attributed to a number of factors, including local velocity, bedload transport rate and sectional morphology. Carling and McCahon (1987) concluded that there was no meaningful correlation between time averaged infiltration rates and detailed bulk hydraulic data, but that "useful patterns" could be observed. Lisle (1989) produced a significant relationship between total bedload transport and total accumulation of infiltrated sediments at a section; the inference being that sediment supply will condition infiltration rates. This is supported by the flume study of Carling (1984) who determined that the only parameter which infiltration rate was related to significantly was suspended sediment concentration. Figure 9.7 shows the equivalent relationship between total unit bedload transport and cumulative infiltration rate for the Tarset riffle 1 and 2 and Newton riffle 2 sites. The relationship does not correlate as well as Lisle's ($r^2 = 0.22$, $r^2 = 0.93$ (Lisle)), largely because of the effects of sediment deficiency prior to the July 28th flood, and also due to errors in the calculation of total unit bedload. This latter method involved the use of data measured four months after the infiltration experiments, and is based on the assumption of continuity of transport rates at a site over time. Given these constraints, it is remarkable that the rate of infiltration should so closely approximate that determined by Lisle (0.310, 0.365 (Lisle)). Clearly the results from the sediment sufficient streams in Lisle's experiments show infiltration rates of almost an order of magnitude higher than those experienced in the North Tyne, but this serves to indicate the low sediment transport rates existing under the hydropower generation regime. It is notable that three

9.7 Variation in total infiltrated sediment with mean total unit bedload



of the post flood points (where sediment supply is in sufficiency) plot on the line derived by Lisle for sandy-gravel streams in the USA, suggesting that at least gross infiltration rates are perhaps consistent under conditions of supply sufficiency.

The literature provides conflicting reasons for the cross sectional variation in infiltration rates. These result from the balance between supply of sediments into the bed and the ability of flows to scour the fines from the bed. Hence Frostick et al (1984) record maximum infiltration rates in the areas of fastest flow, whilst simultaneously recording the deepest scour. Carling and McCahon (1987) identify areas of slackwater and high velocity filaments with accentuated infiltration rates, which although seemingly contradictory, may be explained by the differences in grainsize composition of the infiltrated material. In general, the literature agrees that coarser (bedload sized) infiltrated material is best correlated with local hydraulics, and that suspended sediment sized material is more equably dispersed across a section, due to secondary flows and turbulent mixing. Frostick et al (1984) and Carling and McCahon (1987), both show accentuated bedload sized material in areas of highest velocity, and finer sediments in areas of slackwater. However, Lisle (1989), and Diplas and Parker (1992), both note that in regions of high energy flow, the depth of penetration of fines increases; therefore some of the results from infiltration surveys utilising shallow baskets may preferentially encourage the sorting of fine sediments from coarse by the action of scour (see above discussion of egg baskets).

Table 9.3 lists the average values of infiltration rates for individual baskets during the three discharge conditions that prevail within the North Tyne. Considerable cross section variation occurs at all flows, which suggests that the composition of riffle matrix sediments, in as much as they are altered by infiltration, will be complex.

Table 9.3: Average infiltration rates for individual baskets across riffle sections. (kg m^{-2} day^{-1})

Site:	Q:	1	2	3	4
Yarrow R1	Comp.	0.0077	**0.0118**	0.0073	0.0055
	HEP.	**0.0123**	0.0110	0.0098	0.0111
	Flood.	**0.0522**	0.0395	0.0156	0.0222
Yarrow R2	Comp	0.0089	**0.0328**	0.0077	0.0093
	HEP	0.0052	0.0063	**0.0098**	0.0083
	Flood	**0.0564**	0.0128	0.0167	0.0222
Tarset R1	Comp	0.0048	0.0693	0.0135	**0.0860***
	HEP	0.0037	0.0391	0.0212	**0.0420**
	Flood	0.1141	0.4500	0.3400	**0.5778**
Tarset R2	Comp	0.0202	0.0229	0.0124	**0.0278**
	HEP	**0.0507**	0.0303	0.0247	0.0279
	Flood	**1.0134**	0.4030	0.3710	0.3887
Newton R1	Comp	**0.0188**	0.0110	0.0171	0.0106
	HEP	**0.0288**	0.0125	0.0216	0.0272
	Flood	**1.5740**	0.3130	0.4674	1.3415
Newton R2	Comp	**0.0584**	0.0100	0.0190	0.0180
	HEP	**0.0640**	0.0071	0.0071	0.0230
	Flood	**0.9930**	0.2790	0.0680	0.9500

* Bold equals maximum infiltration rate

The position of maximum infiltration rate remains constant from hydropower discharges up to flows of approximately 36% bankfull, with the exception of Yarrow riffle 2. Furthermore, at half the sites monitored the position of maximum infiltration rate remains constant from compensation flows. Continuity of the sectional distribution of infiltration rates is particularly associated with the sites affected by the July 28th flood event. This implies that, given a sufficient sediment supply the balance between infiltration and rate of scour from the bed is controlled by hydraulic factors (assuming the equality of pore density and size is relatively constant in the baskets). At the sites closest to the dam site, sediment supply and hydraulics merge to generate fluctuations in the cross sectional distribution of infiltration rates.

Figure 9.8 illustrates the relationship between the cross-sectional distribution of shear stress and infiltration rates at the Tarset riffle 2 site. Information for the other sites where these measurements coincided is contained in Appendix D. Infiltration rates at this riffle are highest for the basket nearest the left-hand bank. Consideration of the reach hydraulics for this site, described in Chapter 7, shows that the input from the Chirdon Burn, immediately upstream of this site, deflects sediment laden flood water across to this bank. In addition, observation of the riffle morphology show this to be a depositional incipient bar area. In contrast, the basket nearest the right-hand bank was located in a region of high velocity at low flow, as evidenced by the accentuated shear stress readings in Figure 9.8. Correlation of shear stress and bed velocity with infiltration rates reveals that a greater strength of relationship exists for shear stress (r^2 = -0.635 p = 0.01 n = 16).

Multiple regression of infiltration rate on bed velocity and shear stress accounts for only 44% of the variation, indicating that other factors are dominant in conditioning the observed distributions. The correlation coefficient between shear stress and infiltration rate exhibits a hierarchy according to flow strength; Hydropower>Flood>Compensation. This results from the greater cross section variation in hydraulics at hydropower, coupled with a higher competence than at compensation flows. Clearly at flood flows, the balance between scour and sediment supply across the section is not equal. The correlation coefficients for both bed velocity and shear stress are negative with respect to infiltration rate for all flows. This confirms Carling and McCahons (1987) observation that areas of slackwater are sites of accentuated infiltration, and from morphological considerations are also areas of deposition. Tables 9.3 and Appendix show that for both the Newton riffle sites, maximum infiltration rates are associated with the channel margins (shallow depositional areas), whilst minimal infiltration rates are associated with the thalweg. Clearly scour is operative in the regions of maximum flow strength which, given the 10cm depth of the baskets, probably removes much of the infiltrated fines through resuspension.

Table 9.4 lists the ratio of bedload:suspended load for compensation and hydropower flows. No individually sieved data was available for flood sediments due to loss of samples.

9.8 Cross-section variation of fine sediment infiltration in relation to shear stress. Tarset riffle 2

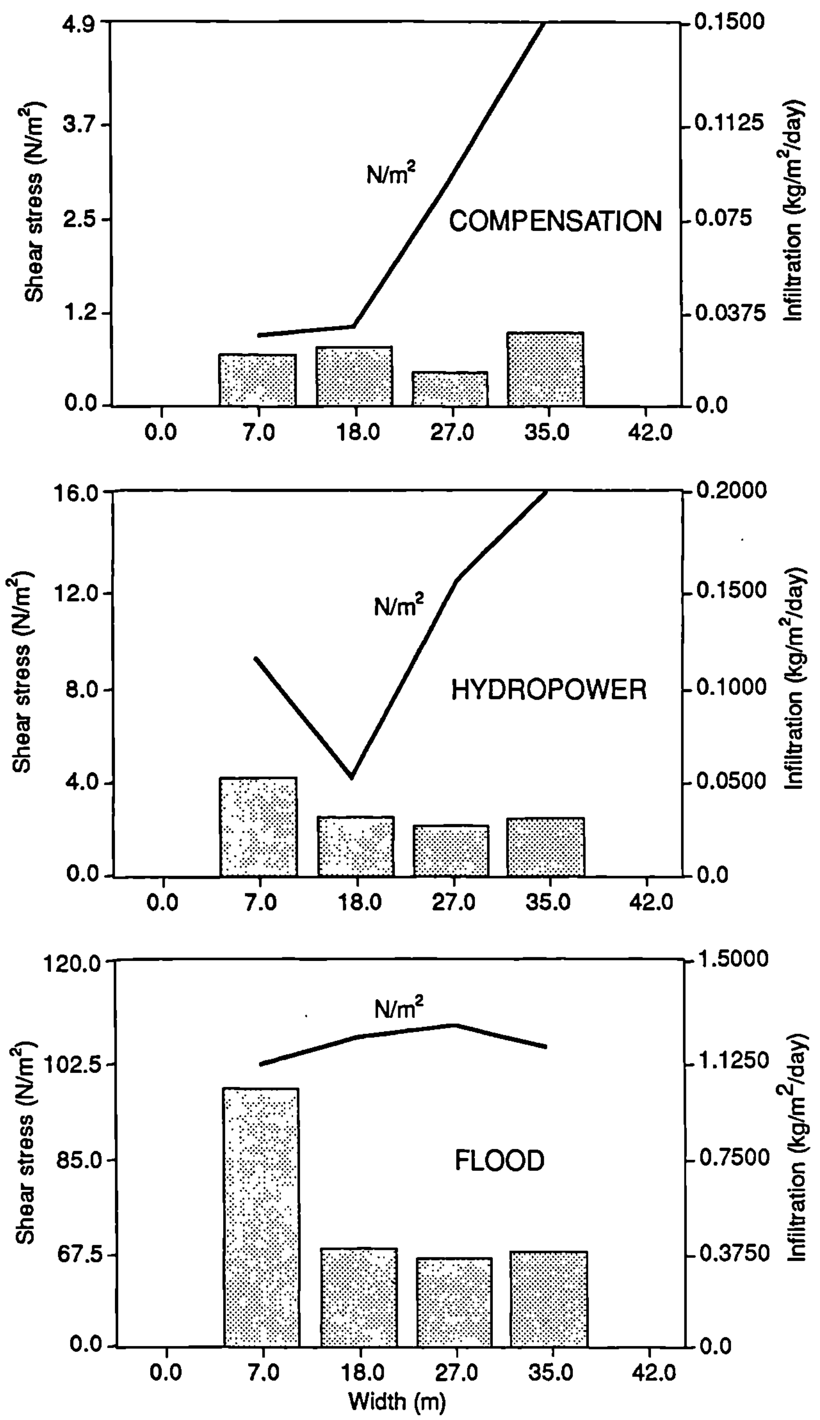


Table 9.4: Ratios of Bedload:Suspended load in infiltrated sediments

Yarrow R1	Comp	0.15	0.47	0.39	0.35
	HEP	1.38	0.69	0.47	1.86
Yarrow R2	Comp	0.37	2.85	0.19	0.47
	HEP	0.49	1.10	1.94	1.27
Tarset R1	Comp	4.88	6.10	0.82	9.00
	HEP	0.85	5.25	1.86	9.00
Tarset R2	Comp	1.44	0.47	0.47	1.17
	HEP	2.85	0.85	2.03	2.70
Newton R1	Comp	0.47	0.43	0.56	0.10
	HEP	1.08	2.23	1.86	2.23
Newton R2	Comp	0.27	3.17	2.57	1.94
	HEP	1.94	2.70	1.44	0.49

Reference to Tarset riffle 2 and the two Newton riffles shows that in areas associated with highest shear stress, the amount of bedload is greatest in proportion to suspended load. This appears to confirm the hypothesis that turbulent resuspension is largely responsible for the low infiltration rates in these regions. Shear stress correlates negatively with suspended sediment infiltration rates at compensation flows. Furthermore, the relationship, though weak, is stronger than that for bedload ($r^2 = -0.457$ $p = 0.05$, $r^2 = 0.072$). At hydropower discharges, bedload correlates positively with shear stress ($r^2 = 0.570$, $p = 0.001$), whilst suspended sediments correlate negatively ($r^2 = 0.623$, $p = 0.001$). Clearly, at hydropower discharge, matrix ingress by infiltration varies according to the capacity for turbulent resuspension of fine sediments (<0.25mm) at a site, which in turn is significantly related to the distribution of shear stress. Accordingly, finer matrix sediments should be expected at channel margins and in regions of deposition, and coarser matrix material in the thalweg and in other regions of high shear stress. According to Diplas and Parker (1992), the depth to which fines are ingressed is also likely to be greater in regions of high velocity, which would help explain the presence of excessive fines within egg boxes placed in the centre of the Newton riffle (Haile et al 1989).

9.6 Infiltration rates in relation to salmonid spawning gravels

The infiltration of fine sediments into spawning gravels is particularly problematic when the eggs are present within the redds. Carling and McCahon (1987) utilised their values for infiltration rates to determine the likely time for the siltation of Brown Trout (*Salmo trutta* L.) redds. This exercise is repeated here in order to assess the ecological importance of infiltration rates during the discharge regime operated by Kielder Reservoir, and during natural flood flows.

Carling and Reader (1982) provide equations for determining the porosity of Carboniferous sandstone/limestone sediments (the same as the North Tyne, see Chapter 5) based on median grainsize. Using their equation 6, for a median North Tyne riffle sediment of 59 mm produces a porosity value of 0.165. Carling and McCahon (1987) assume that the porosity of gravels cut by salmonids are approximately twice that for more consolidated gravels, which would give a value of 0.33 for salmonid redds within the North Tyne.

The size of salmonid redds have been shown to vary according to the length of the fish, such that larger fish construct bigger redds largely as a result of deeper excavation (Crisp and Carling 1989; Kondolf 1992). Using the equations developed by Crisp and Carling (1989), and the values for mean Atlantic Salmon (*Salmo salar* L.) size documented by the Northumbria NRA (Mackintosh pers comm), it is possible to approximate the volume of a typical Salmon redd at 400000 cm^3. For the Brown Trout (*Salmo trutta* L.), Carling and McCahon (1987) quote a figure of 10000 cm^3. The respective void volumes (V_v) for these redds would therefore be:

Atlantic Salmon $V_v = 400000 \times 0.33 = 132000\ cm^3$

Brown Trout $V_v = 10000 \times 0.33 = 3300\ cm^3$

Using the relationship between discharge maxima and infiltration rate developed for the North Tyne, it is possible to calculate representative infiltration rates for a range of discharges, compensation flow to bankfull. From these it is possible to calculate the volume of sediment infiltrated per day (Table 9.5).

Table 9.5: Infiltration rates and the volume of void space filled under different discharge conditions.

Discharge	I_r (Kg/m^2/day)	Volume/day (cm^3)
Compensation	0.023	10
Hydropower	0.238	107
36% Bankfull	1.100	495
Bankfull	3.54	1593

The time taken to fully silt the redds of spawning salmonids are detailed below:

Discharge	No. Days to silt redd	
	Atlantic Salmon	Brown trout
Compensation	13200	330
Hydropower	1233	31
36% Bankfull	267	7
Bankfull	83	2

These values are based on the assumption of post-flood sediment supply, which is reasonable given the necessity for a flood to enable the larger salmonids to reach the spawning grounds. Under these conditions, it is clear that during hydropower and compensation flows, siltation of salmon spawning redds is unlikely. However, under hydropower conditions the smaller redds of the Brown Trout are capable of being siltated in under a month. Continuous hydropower flows for periods of 30 days are not uncommon, particularly post flooding when reservoir levels are high (Johnson 1988). Furthermore, enhanced infiltration rates have been recorded for periods of up to 55 days after a flood event. Even during flood events of the size monitored in July 1988, salmon redds are unlikely to become fully silted. However, the infiltration of fines into smaller redds will be detrimental, particularly during post flood hydropower flows. The bankfull rates clearly pose a threat to the smaller redds, but in reality, mobilisation of the gravels, already loosened during spawning, will be the dominant problem, followed by siltation during the falling limb of the flood. The discharges at which given sizes of gravel are moved are discussed in later sections.

What is not clear from these calculations is the depth of infiltration, since Crisp and

Carling (1989) describe a tendency for fine sediments to collect at the base of the redd, around the egg burial depth. During hydropower flows, there is clear evidence that scour of fines from the surface layers is operating in regions of high shear stress, but other authors have shown depth of infiltration to be greatest in these areas. Furthermore, Lisle (1989), Diplas and Parker (1992) and Frostick et al (1984) all describe the infiltration process as occurring from the bottom up. Under these conditions, it would not take the siltation of the total redd to become detrimental, as evidenced from the egg basket surveys of Haile et al (1989).

9.7 Conclusions: Infiltration and sediment transport from pools

The experiments to determine the infiltration rates of fine sediments within the North Tyne riffles have highlighted the influence of regulation in reducing infiltration rates during floods. Furthermore, the values of infiltration experienced as a result of hydropower generation are sufficiently low as to pose little or no threat to salmonid eggs. In contrast, the levels of fine sediment infiltration experienced during floods attain levels which are detrimental to salmonid eggs, and particularly the smaller fish. This is an important consideration, given the relatively long relaxation times (up to 55 days) during which infiltration rates remain high. The dominance of fine sediments < 1mm in the infiltrated sediments recorded at all sites, is undoubtedly the cause of the accentuated fine sediment levels recorded in some of the post-regulation riffle sediments. However, the dominant affect of hydropower flows is to scour flood deposited fines from the surface layers of the riffle sediments. This accounts for the general reduction in the percentage < 2mm recorded in the sediment re-surveys (under the equipment constraints described in Chapter 5). The particularly accentuated levels recorded at Yarrow riffle 1 are the result of boulder clay immediately beneath the fluvial gravels. The infiltration rates at this site are not sufficient to account for the high levels of fines. Unfortunately the experiments cannot allow inference of cross-sectional sediment transport rates, but rather indicate that fine sediments are trapped most effectively in areas of slackwater and on incipient bars. Finer sediments are routed through the thalweg and regions of high shear stress, promoting a deeper penetration of fines, and entrapping a significantly coarser grainsize.

Infiltration rates are clearly determined by sediment supply, which is derived (in the absence of bank erosion and the proximal deposition of coarse sediment at the mouths of tributaries) from the upstream pools and riffle beds. Consideration of tracing evidence (discussed later in this section) suggests that substantial disruption of riffle armour does not occur at discharges of 54 cumecs, and therefore the high sediment loads recorded at riffles during the July 28th flood are largely derived from upstream pools. Infiltration data for the site downstream of the Rede confluence, which experienced a discharge of 143 cumecs, showed that armour disruption promoted coarser infiltration sediment. Clearly for fine sediment (< 16mm), this implies that pool scouring occurs at discharges between 25 and 54 cumecs (17% - 36% Bankfull discharge). This sediment would be analogous to the phase 1 bedload described by Jackson and Beschta (1982). The following section will endeavour to elucidate the routing of fine sediments (<22.4mm) through the Newton riffle-pool-riffle sequence, and provide supporting evidence for the scouring of pools.

Chapter 10

The routing of fine and medium-sized sediment in riffle-pool sequences using magnetic tracing.

The determination of infiltration rates on riffles within the North Tyne has shed light on the discharges at which fine - medium sized sediment (<0.063 - 16mm) is scoured from pools, and when disruption of riffle surface sediments occurs. However, no evidence as yet exists for the routing of fine - medium sized sediments through the intervening pools. This section discusses the application of magnetic tracing techniques to the routing of sediment ranging in size from < 0.063 - 22.4mm, through a single riffle-pool-riffle sequence.

10.1 Tracing sediments in gravel-bed fluvial systems

Techniques for the determination of the routes that given sizes of sediment take when progressing through a channel, have been elucidated by the use of labelled particles, whose distance, direction and rate of motion have been monitored over time. Arkell (1985) lists the optimum attributes that such tracers should possess as:

1. stable against premature loss of tagging,

2. reasonably inexpensive,

3. detectable at low concentrations,

4. non-toxic to aquatic or human life,

5. the method of tagging should allow repeated experiments within a reach either by the decay of the original tracers or through a readily identifiable characteristic,

6. tracers should accurately mimic the size range, density and shape of the natural sediments.

To date, a plethora of techniques has been developed for the tracing of fluvial sediments, which largely reflects the variety of conditions for which they have been developed. Arkell (1985) lists a table to which has been added some of the more recent innovations in tracer technology (Table 10.1). It is clear that different technologies are required for the determination of the routing of fine sediments from those used for coarse materials. Painting, arguably the cheapest (dependent upon numbers painted!) and most widely used technique, is clearly inefficient for sizes much below 8-11mm, although this will depend upon the grainsize population of the river bed, and the concentrations of tracers inserted. This methodology is expanded further in Chapter 12.

The experimental objectives and economies of scale are important considerations in the adoption of tracing techniques. The determination of thresholds of motion within a small narrow channel requires a different approach to that for the routing of particles through a large, wide channel. The former can be achieved using relatively few particles whose subsequent collection need not include documentation of distance or direction of travel, whilst the latter will need far larger concentrations to offset the dilution effects of a large channel reach. An example is given by the experiments of Reid et al (1984b), who used fewer than 100 particles to determine the initiation of motion of particles within a channel of only 3m width, while Hassan and Church (1992) suggest that painted particles of 1000+ are required for the statistically sensible determination of transport lengths within actively-transporting reaches of large channels.

A further consideration in the adoption of a suitable tracing technique is the efficiency of the method in terms of recovery rates. Arkell (1985) argues that the efficiency of tracing using painted particles is low in comparison with magnetic tracing technology, largely as a result of the loss to recovery by burial. Clearly the activity of the scour zone of the channel bed is important when considering the choice of tracing technique (Hassan et al 1984; Schick et al 1987; Drew pers comm). The efficiency of a tracing technique is also dependent upon the size of the tracer relative to the bed sediments. Fine particles are notoriously difficult to detect due to burial beneath the armour layer and dilution in the dispersion process during transport (Larrone and Carson 1976; Arkell et al 1983; Arkell 1985). Tacconi et al (1992) record for the same flood, a recovery rate of 3.6% for painted tracers of 16mm as opposed to 60% for particles 128mm in size. Typical recovery rates from upland gravel-cobble bed streams for tracing experiments to

Table 10.1 **Techniques for the Tracing of Fluvial sediments**

Technique	**Size(mm)**	**Number**	**Recovery**	**Source**
Painted Particles	22 - 128	500	8 - 98%	Takayama (1965)
" "	75 - 150	100+	0 - 88%	Leopold et al (1966)
" "	20 - 120	134	48%	Keller (1970)
" "	cobbles	35	85 - 100%	Slaymaker (1972)
" "	32 - 512		2 - 57%	Schick & Sharon (1974)
" "	15 - 100	200		Hey (1975)
" "	4 - 256	100+	5%	Larrone & Carson (1976)
" "		500	38 - 57%	Thorne (1978)
" "	15 - 130	205	78 - 98%	Carling (1987)
" "	26 - 235	877	30 - 96%	Ashworth (1987)
" "	16 - 128	3935	4.7 - 8%	Tacconi et al (1992)
Magnetic: Metal Strips	32 - 137	156	35%	Butler (1977)
" : Magnets	50			Ergenzinger & Conrady (1982).
" : Exotic Pebbles	16 - 64			Ergenzinger & Custer (1983)
" : Enhancement	1.4- 90	300kg	63%	Arkell (1985)
" : Magnets	29	100	100%	Reid et al (1984)
" : Magnets	45 - 180	532	55 - 93%	Hassan (1988)
" : Magnets	21 - 180	970		Larrone & Duncan (1992)
" : Magnets	16 - 180	250	80%	Church et al (in press)
Radio Transmitter	32 - 100	24	80 - 84%	Emmett et al (1992)
Exotics: Limestone	8 - 256		5%	Moseley (1978)
" : Dolerite riprap	32 - 300			Kondolf & Matthews (1986)
Flourescence: dyes	0.125-1			Nordin & Rathbun (1971)
" : dyes	0.125-1			Nordin & Kennedy (1978)
Radioactivity: Ir^{192}	Sand			Hubbel & Sayre (1963)
" :	11 - 32	few	100%	Stelczer (1981)

determine sediment routing, range from 5 - 96% for painted tracers, and 35-93% for magnetic (Hassan and Church 1992; Butler 1977; Arkell 1985). Tracing of sediments < 4mm within gravel-bed streams is impossible by painting, since visibility is poor at these sizes, and furthermore the application of paint changes the characteristics of the individual particles. Similarly, the use of inserted magnets (Reid et al 1984) or radio transmitters (Emmett 1992) cannot be adopted for sizes < 16 mm. Arkell et al (1983) document the routing of sediments as fine as 1.4mm in gravel-cobble rivers in mid-Wales, using enhanced magnetism of the natural sediments. This process was selected for the purposes of routing sediments of < 22.4mm through a riffle-pool-riffle sequence within the North Tyne.

10.2 Magnetic tracing of fluvial sediments

The use of magnetically-enhanced sediments for tracing in fluvial environments can be split into two methodologies: the use of magnets inserted into relatively few coarse particles, and the enhancement of the full range of particles in bulk by heat treatment. The variety of magnetic techniques used are listed in Table 10.1 above, and are clearly dominated by the use of inserted magnets. This reflects the prevalence of coarse sediment routing studies made within gravel-cobble bed rivers.

Butler (1977) used 156 particles tagged with strips of aluminium and located by commercial metal detector. The purpose of the experiment was to identify the transport distances of particles in relation to bar morphology, and also to elucidate the quantities of particles that were buried. The technique was reasonably successful, with a recovery rate of 35% following a flood event of 15 - 20 year recurrence interval. Some 86% of particles were buried, up to 0.2m beneath the surface.

Ergenzinger and Conrady (1982) inserted permanent magnets into particles and sealed them with resin. The detection equipment consisted of 9000 windings of wire wrapped around an iron core buried in concrete and submerged in the stream bed. The passage of magnetic particles over this equipment induces an electric current (Lenzs law), which can be detected. The advantage of this technique is for the continuous detection of sediment transport which enables thresholds of motion and cessation to be discerned. In a similar experiment Reid et al (1984) used magnetised particles of representative D_{90} grainsizes to investigate initiation of motion. In addition they investigated the constraints on particle motion determined by particle structure (Brayshaw 1985). Ergenzinger and Custer (1983) in an attempt to cover a broader range of particle sizes, introduced naturally magnetic sediments (magnetite and Pyrrhotite) into the stream. In practice the technique is incapable of differentiating particle sizes below 32mm, or indeed resolving particle size variations above this. A major problem with this technique is the variability of the induced signal as a result of factors other than grainsize or sediment transport rate. Particle velocity, orientation to the sensor, and height of saltation above the sensor severely limit the interpretive qualities of the technique. Furthermore vibration of the sensor created "ghost" particles on the trace (Custer et al 1987).

Hassan (1988) describes the use of implanted magnets for tracing coarse particles downstream from an insertion point. Hassan's study utilised a commercial pipe detector which enabled particles to be detected upto 0.6m beneath the surface. The method enabled discrete coarse particles (45 - 180mm) to be located over relatively large reaches of channel and over long periods of time (Hassan et al 1984).

Arkell et al (1983) describe the tracing of sediments ranging in size from 1.4 - 90mm within large sections of gravel-cobble bed channels in mid-Wales. The technique uses a commercially manufactured search coil similar to a metal detector, to monitor the downstream motion of particles. The particles themselves are located by exhumation and detailed searching of the sediment with a hand-held ferrite probe. Finer sediments are located by analysing seived subsamples of the recovered sediment for volumetric susceptibility (m^3kg^{-1}) which can be calibrated with sediment weight (Arkell 1985) (see Appendix E). The susceptibility readings from the field coil can be used to indicate the presence or absence of tracer as it progresses downstream, although care must be taken to identify if there is any metal present which could cause a false trace.

10.3 Methodology

The purpose of this study was to determine the movement of sediments < 22.4mm through a reach of channel some 365m in length with an average width of 35m. Both painted tracers and inserted magnets are impracticable and the use of exotic fluorescent or radioactive tracers was not possible under the constraints of equipment. Furthermore the use of radioactive tracers would have caused problems with the access to land (the North Tyne is a major salmon fishing river). The best available and most suitable tracing technique for this size range is that used by Arkell (1985) for the tracing of fine sediments in large gravel-bed channels. The process involves the heat treatment of material taken from the river bed in order to enhance the "apparent low field reversible in phase magnetic susceptibility" (X) of iron rich sediments. The details of the determination of the optimum enhancing "recipe" for North Tyne sediments together with the calibration for tracer weight are given in Appendix E.

Some 230 kg of North Tyne bed material < 22.4mm b-axis was taken from the Newton riffle 1 (NR1) section and heated at 700 C for 40 minutes in a preheated glass furnace at the Lemington glassworks. The grainsize data for tracer material together with bulk bed material truncated at 22.4mm is shown in Figure 10.1. The tracer is clearly much finer than the bed material, a decision taken in order to increase the concentration of fine sediments which were suspected to be mobile during hydropower conditions. The relative lack of coarser material is made up for by its ease of identification owing to a pink colouration (see Appendix E).

The heated sediment was left to cool then taken to NR1 and trodden into the bed over the full 40m section. Field susceptibility (X) readings were made using a modified MS2D search loop manufactured by Bartington Instruments. The handheld probe was extended from 0.75m to 1.5m depth capability in order that readings could be made in the pool at compensation flow. Even at this extension capillary rise within the plastic sheathing of the probe caused water to penetrate into the electronics house at the top of the probe producing spurious results. This was noticed immediately but required a time consuming refit. This is clearly a problem inherent to the search for tracer material in deep water.

Background field susceptibility (X) readings had been made prior to tracer emplacement throughout the 365m riffle-pool-riffle downstream. X readings were made every 2m across full width sections at the emplacement site and at sections located at 5, 10, and subsequent 20m intervals downstream. Four readings of X were made at each point across the sections and average values determined for that point. The average values for field susceptibility are depicted below together with the those of the tracer material at emplacement. All readings were taken with the search coil submerged.

Figure 10.1 Comparison between bed material (<22.4 mm) and magnetic tracer grain size emplaced at Newton riffle 1

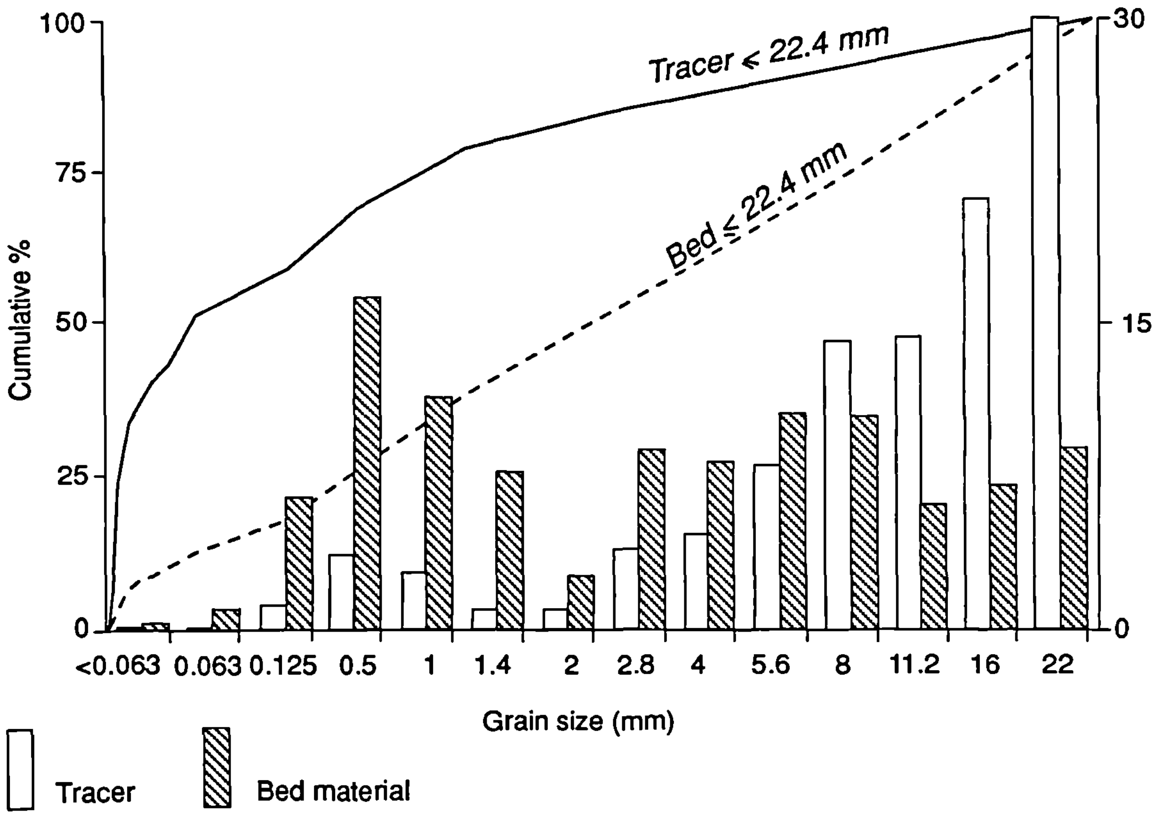


Table 10.2 Field susceptibility readings for background and tracer material in situ.				
Background:	$\bar{X}$ = 2.5	S.D = 4.2	Min = 0	Max = 12
Tracer:	$\bar{X}$ = 38	S.D = 30	Min = 15	Max = 122

Susceptibility surveys were made immediately after emplacement of the tracer and following a monitored hydropower release the next day (see Table 10.3). Table 10.3 and Figure 10.2 display the survey dates in relation to the prevailing hydrological conditions. Full surveys were carried out at all sections on 6 occasions and at sites immediately downstream of the emplacement site on 8 occasions. A final post-bankfull flood survey failed when the instrument ceased functioning after 3 cross sections; results for this survey are therfore largely estimated (see below). Table 10.3 and Figure 10.2 show that the hydrological conditions throughout the survey were dominated by hydropower generation with only three peaks greater than 20 cumecs prior to the bankfull events of February 26th which mobilised most of the river-bed throughout the riffle-pool-riffle sequence. Although the initial survey recorded the movement of tracer material during one hydropower event the material should be considered as structurally weak and in an exposed situation. Consequently the period of continuous hydropower immediately following the monitored release was one in which the tracer material was spread over the riffle and stabilised. The period of time between surveys 4 and 5 was characterised by intermediate discharges of 5-6 cumecs with a small flood of 30.2 cumecs 6 days prior to the survey of 17/11/89. The survey conducted on the 14/1/90 followed a relatively dry winter with a peak discharge of 21 cumecs and only 5% hydropower generation. In February a sequence of large flood events including two in succession of bankfull capacity caused a major reworking of the river bed throughout the study reach. This was followed by an extended period of continuous maximum hydropower release in an effort to reduce the levels in Kielder Reservoir. This delayed the survey until 24/5/90 when a compensation flow day was arranged with the Northumbrian Water Authority for the purpose of monitoring the post-flood effects. Unfortunately the equipment failed and further high flows prevented a return survey within the time scale of this project.

The determination of particle size was made on only one occasion (7/7/89) since the

10.2 Maximum discharge hydrograph for period of magnetic tracer survey: Survey dates are shown.

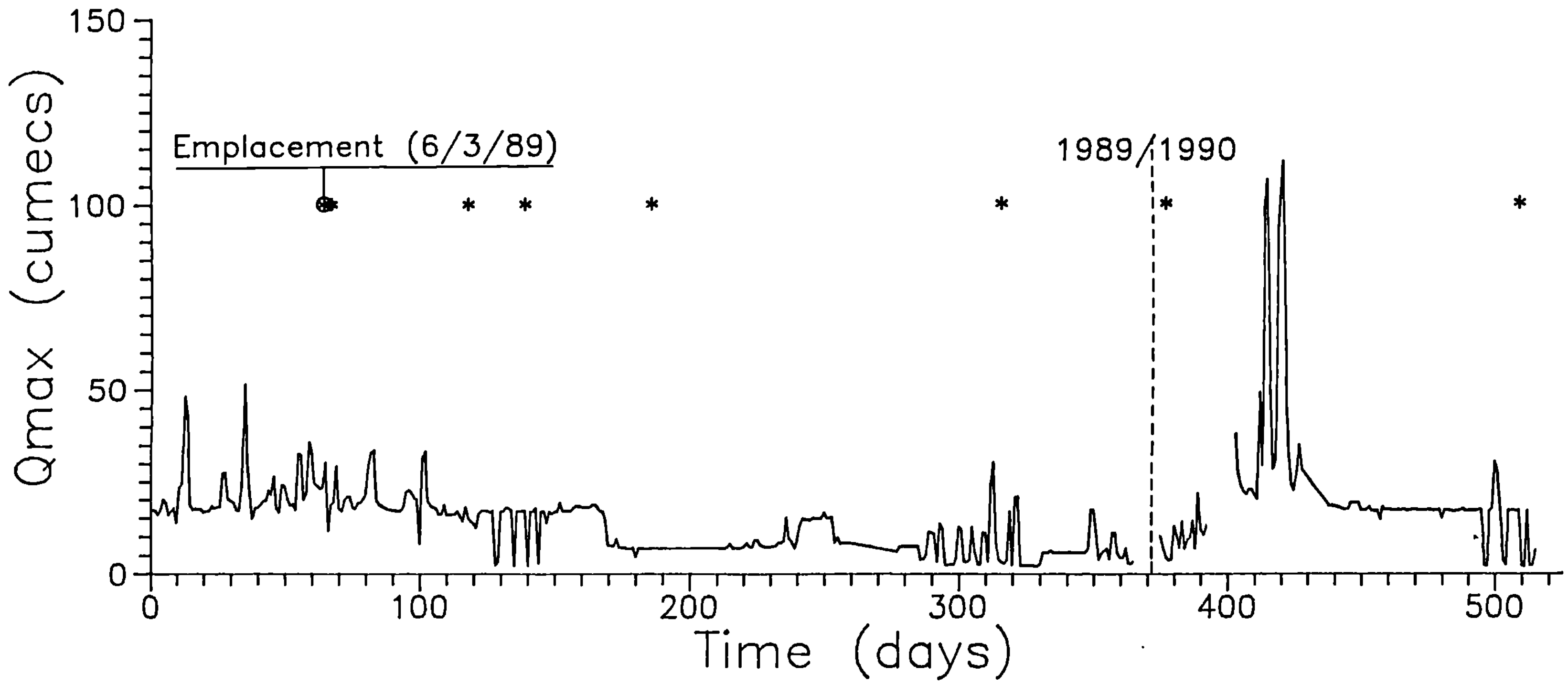


Table 10.3 Hydrological conditions associated with the magnetic tracing surveys

Survey	Days	Maximum Discharge (cumecs)	% Hydropower regulation
Background	0-2	51	100
Emplacement (7/3/89)	0	30.2	50
(9/3/89)	1	18.7	50
(30/4/89)	52	33.1	100
(21/5/89)	73	17.5	81
(7/7/89)	120	19.1	64
(17/11/89)	253	30.2	20
(14/1/90)	311	21.0	5
(24/5/90)	441	151.0	86

process was found to be very difficult to conduct in pool locations, requiring frequent total immersion to collect the sediment in a modified surber sampler (see Chapter 5.0). The submergence was effected by clutching a large boulder, held in a plastic carrier bag, and sinking, "pearl fisher" style to the bottom of the pool. Once sediment was collected in the surber sampler it was possible to carry it to the bank by walking out of the pool. The use of a freeze corer, modified to cope with deep water would be a preferable method or alternatively the availability of diving equipment (Klingeman and Emmett 1982).

10.4 Results: Fine sediment routing through a riffle-pool-riffle sequence.

Figure 10.3 depicts the results of the 6 surveys together with the partially completed survey following the bankfull event. The values are shown as the percentage number of readings made per section above the background values taken prior to emplacement. The choice of a percentage value results from a need to correct for unequal numbers of readings per section. The technique has been shown by Arkell et al (1981) and Arkell (1985 Figure 6.10) to correlate significantly with the concentration of tracer material at a point although no indication of the particle size is obtained. The sequence of graphs shows the progression of fine sediment (< 20mm as indicated by the grainsize survey) downstream through the pool. Also shown on the graphs (and formalised in Table 10.4) is the "centroid position" (Crickmore 1967) which is the point where the concentration of tracer material is equal upstream and downstream. Whilst the progression of the tracer is obvious from the graphical representations the centroid position responds to more subtle changes in the dynamics of dispersion and release of tagged material. The calculation of the centroid position is effected by the spatial integration of the tracer concentration with respect to the distance from emplacement site:

$$\frac{\int_0^\infty S(x)x\,dx}{\int_0^\infty S(x)\,dx}$$

Where S is the concentration of tracer material at a point x from the emplacement site. Though algebraically correct this formula is in practice difficult to apply analytically given the complexity of the curves represented by S(x). To simplify the approach a probabalistic method based on the assumption that the curve represented by the concentration of tracer downstream is actually analogous to a probability distribution is used, consequently a sample based formula for the centroid becomes:

$$\frac{\sum x_i . S_i}{\sum S_i}$$

which is essentially a mean. The technique can also be applied to calculating velocity or discharge of material, however the results obtained from these surveys rely too heavily on the time between successive surveys for the derivation of velocity to reflect any realistic rates.

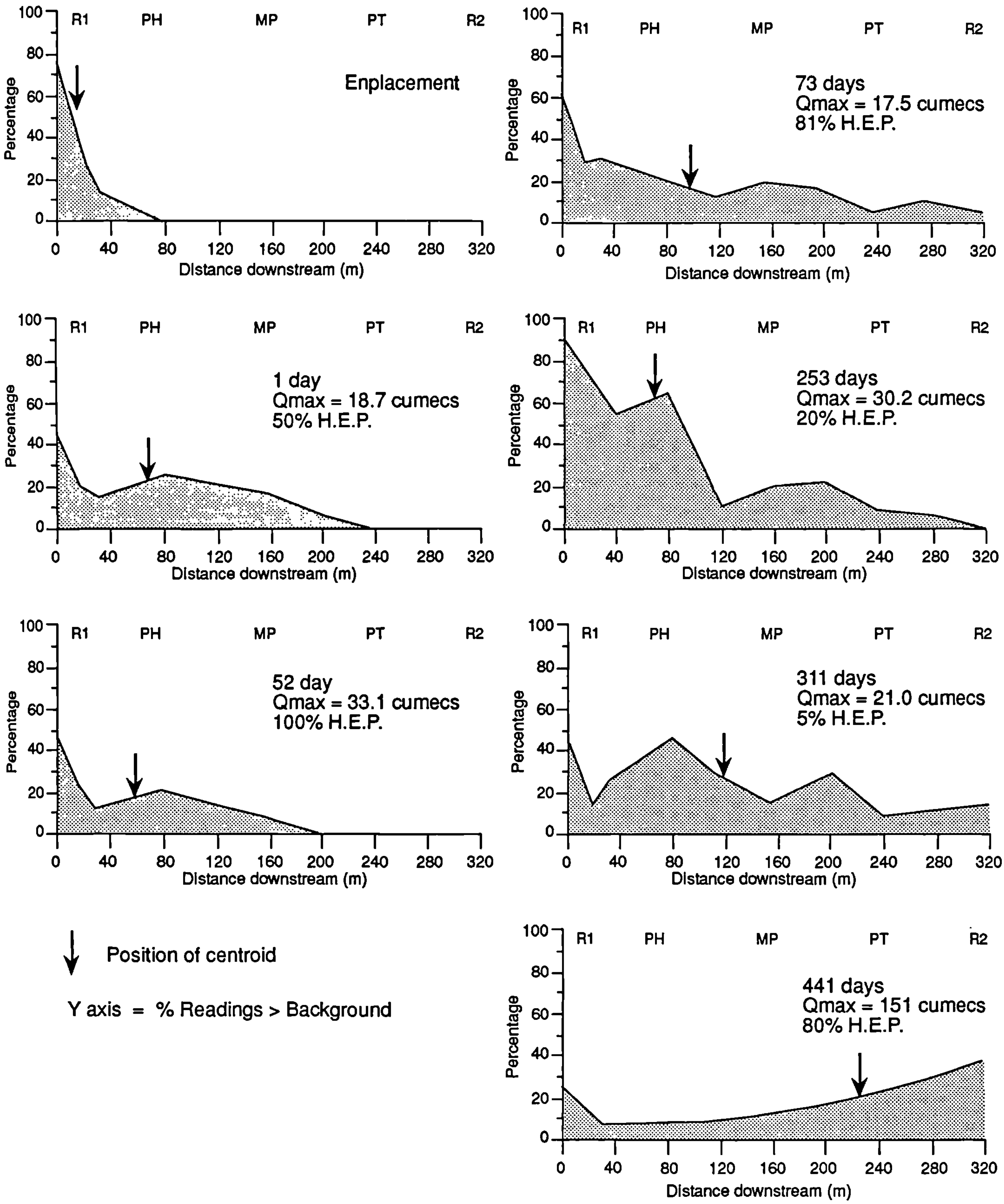
Table 10.4 Centroid positions of the tracer cloud dispersed dowmstream through the pool at Newton.

Date	Centroid Position	Movement	Previous peak discharge
8/3/89	17.9m	17.9m	5.6(m^3/s)
9/3/89	74.1m	56.2m	18.7 "
30/4/89	56.8m	-17.9m	33.1 "
21/5/89	95.6m	38.8m	17.5 "
17/11/89	77.2m	-18.4m	30.2 "
14/1/90	118.2m	41.0m	21.0 "
24/5/90	214.8m	96.6m	151.0 "

Figure 10.3 and Table 10.4 all show that some local movement of tracer material occurred immediately after emplacement such that the centroid position is located 18m downstream of the emplacement site and some material was evident from the susceptibility surveys up to 70m downstream. This is to be expected since the material (containing sediments fine enough to be suspended) would be loose and the finer fractions would be competent even under compensation flows.

The previous section suggests that much of the fine sands and gravels would be infiltrated below the armour layer particularly in regions of low shear stress. The following survey, conducted after a controlled release of 18.7 cumecs maximum, resulted in the movement of tracer material up to 220m into the mid-pool region. The centroid position also moves some 56m reflecting not only movement of tracer downstream, but also infiltration of material into the riffle site. The process of tracer burial has been

Figure 10.3 Progressive movement of magnetic tracer (<22.4 mm) through Newton riffle-pool-riffle sequence showing location of centroids



described by Arkell (1985) and Hassan et al (1988) but this scenario clearly differs since little new material is received on the riffle during hydropower releases; instead scouring dominates (Chapters 4 and 13). Consequently a net loss of tracer concentration at the riffle site (subsequently regained after larger flows) indicates that material is most likely infiltrated into interstices and positions of structural shielding (Chapeter 6.0).

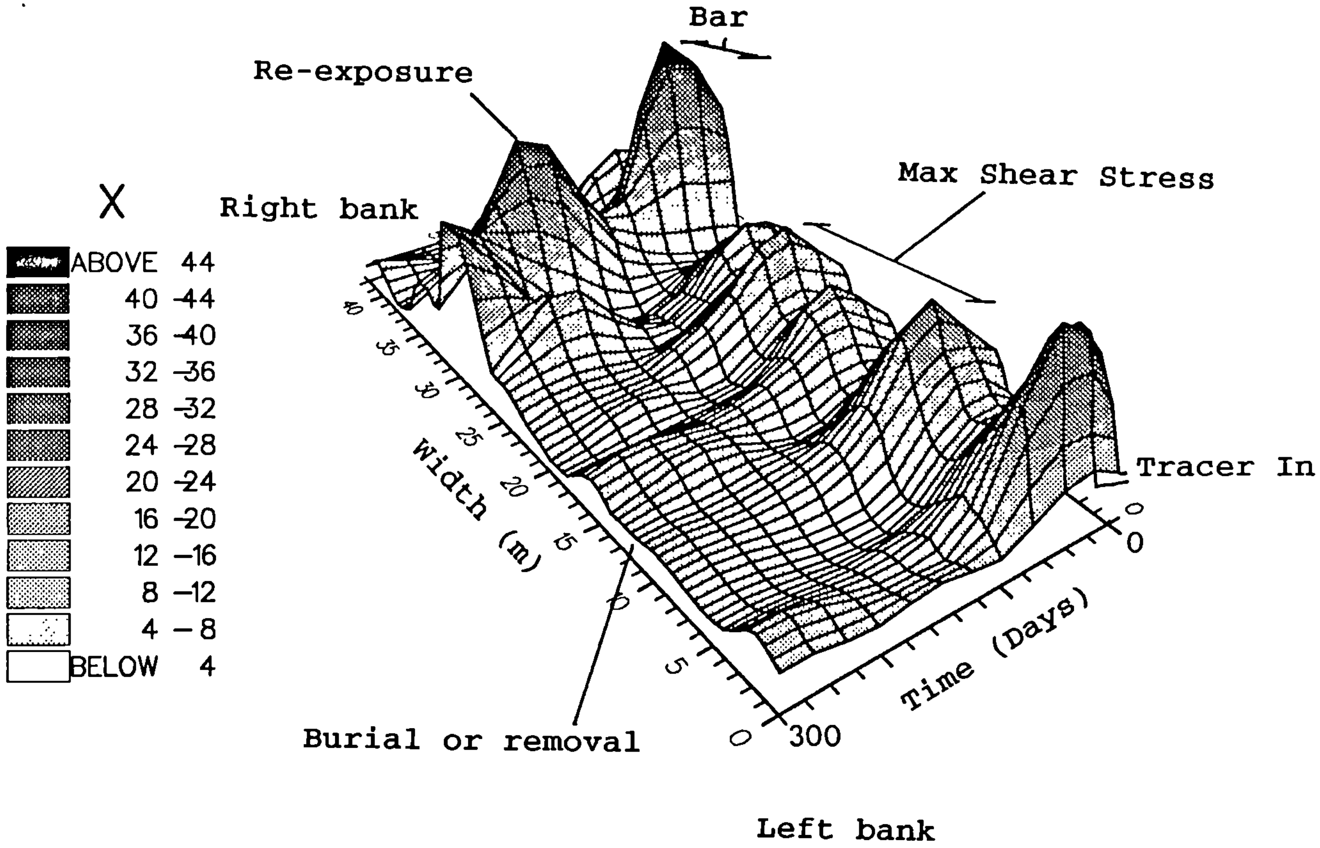
The following survey after a small flood of 33 cumecs reveals an upstream movement of the centroid position and a reduction in the downstream presence of tracer. Two processes are in operation: a re-emergence of tracer at the emplacement site as evidenced by the increased number of readings above background and a dilution of tracer in the pool-head to mid-pool region. This latter phenomenon is a feature of subsequent surveys which show this region to be consistently lower in X readings than mid-pool or pool-head regions. The presence of material downstream of this point suggests that tracer is either routed through quite rapidly or is diluted by material depositing over the tracer. A further consideration is the possibility that tracer material is present but is trapped between the large boulders at this point in the channel and which given the nature of the search loop precludes the accurate determination of X. Reference to the following survey reveals that material is routed through the pool-head to collect in the mid-pool to pool-tail region. Consequently the loss of tracer following the 33 cumec event is largely due to the downstream progression of tracer and its subsequent dilution from material derived from the left bank. A period of hydropower generation promoted transport of tracer through the pool with a subsequent deposition on the downstream riffle. This indicates that fine sediment (in this case material < 5.6mm) can traverse a riffle-pool unit in under 73 days during predominantly hydropower regulation.

The pattern of tracer concentration is not uniform and deposition is evident in the mid-pool and pool-tail regions together with the immediate face of the upstream riffle. This latter point was observed by Arkell et al (1981) who describe the preferential concentration of tracer material on the forset slope of a prograding bar. The deposition in the North Tyne is analogous to the observations by Hack (1957) of fine sediment "fans" downstream of riffles which Hack interpreted as resulting from low-flow winnowing. The morphology of the riffle shows that a deep section exists at this point which is storing winnowed fines and releasing them slowly downstream. The centroid position was moved to 96m downstream during the hydropower generation despite re-exposure of material on the riffle. Transport dominates this period until a flood of 30 cumecs results in the upstream movement of the centroid as a result of a major re-exposure of tracer at the emplacement site.

Figure 10.3 shows that values of the number of susceptibility readings above background approach those at the emplacement date, however this hides the fact that actual values for X are substantially lower (Average X = 32.2 (6/3/89); X = 14.7 (21/5/89)) which suggests that much of the tracer is still below the armour layer. Nevertheless, tracer material is clearly moved off the riffle and into the pool-head and a build up is also apparent in the mid-pool. The downstream riffle experiences a reduction in tracer which suggests that infiltration or scour has occurred. The survey conducted in January 1990, following a period of intermediate flows of 5 cumecs, clearly routes the sediment downstream re-supplying the riffle and collecting in the mid-pool. The centroid position moves some 41 meters downstream as a result of tracer transport. The survey after the bankfull flood revealed for the downstream riffle and the pool-tail, considerably enhanced levels of X and numbers of readings above background. A decline in values progressed upstream suggesting that much of the tracer was deposited on the downstream riffle and pool-tail. Evidence from the painted tracers suggested that much of the bed had been mobilised, although the incipient bar on the upstream riffle remained stable. Slightly higher readings are therefore inferred for this site but low values are considered appropriate for the pool-tail and mid-pool region. The result would mean a shift in the centroid position to the pool-tail and a net transference in tracer concentration downstream to the next riffle. On the basis of these results it is clear that the mechanics of fine sediment transport over riffles is complex and is characterised by a series of storage by infiltration and re-emergence through local bed disturbance and censoring.

Figure 10.4 illustrates the temporal fluctuation in supply and storage at the emplacement site throughout the period of surveys. Tracer material is rapidly infiltrated and dispersed from the riffle region 0-20m width. This corresponds to a region of high shear stress and low bed strength characterised by sporadic breaching of the armour. Infiltration rates are low which reflects the depth of resuspension in this section of the riffle. Discussion in Chapter 9.0 suggests that fines will be forced deeper into the bed which given the 10-20cm depth constraints of the search loop (Arkell 1985) would be compatible with the reduced X values. In contrast the region characterised by an incipient bar, high bed

Figure 10.4 Temporal fluctuations in X values across the emplacement riffle, illustrating the re-exposure and storage of magnetic tracer.

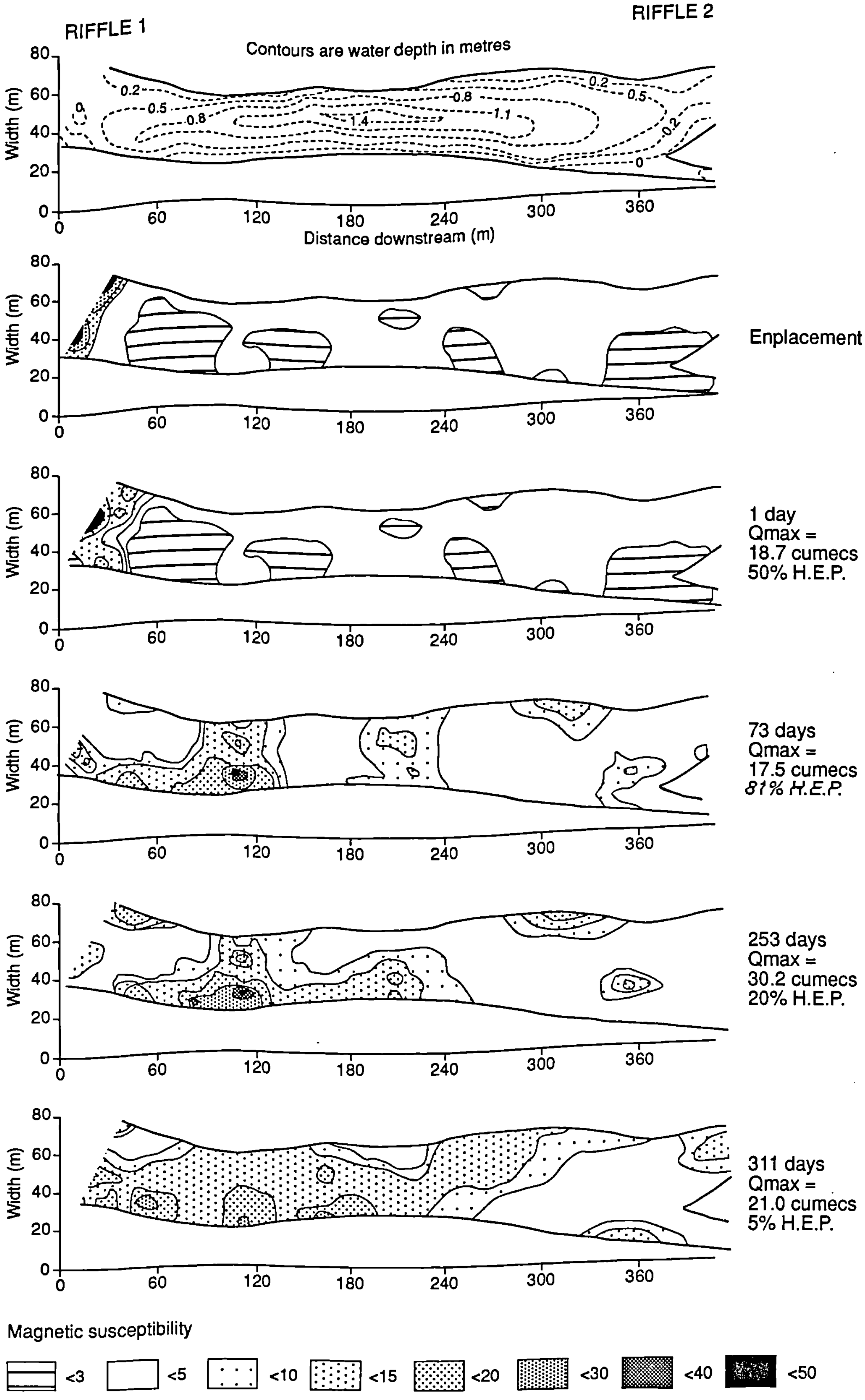


strength and low shear stress exhibits a storage and supply function depending on discharge. Fine sediment in this section is stored in structural positions and is not infiltrated so far into the bed (infiltrations rates are high). Correspondingly during higher discharges the tracer is scoured from the bed and re-exposed. The evidence from the behaviour of the centroid position suggests that 30 cumecs represents a threshold of fine sediment winnowing from beneath the armour layer.

Although the longitudinal dispersion of tracer material is clearly defined the spatial patterns in relation to the topography of the riffle-pool-riffle sequence is not. Figure 10.5 depicts the spatial patterns of tracer material as revealed from the sectional surveys. The results were put through a Unimap 2000 computer mapping package and the contours interpolated from a grid described by the sections. As with the previous longitudinal interpretation, the value of the susceptibility plot is considered to be indicative of the concentration of tracer at that point. This is open to debate since Arkell (1985) found considerable scatter in the relationships between field coil readings of X and the number and weight of tracer material. This is largely the result of differential burial depths, relationship to the sensor field, and the size and concentration of the tracer. However it is reasonable to assume that high readings are analogous to high concentrations, given the existence of enhanced X at the emplacement site where tracer material is most concentrated. Emplacement of the tracer produced a relatively even concentration of tracer across the section, with some downstream motion evident towards the right bank, reflecting dispersal over the incipient bar. Typical background X values were between 0 and 5 for the remaining channel.

Following a single hydropower event the pattern of dispersal shows a discrete movement of material over the riffle, with the furthest progression associated with a narrow channel between the incipient bar and the small tributary input at the right bank. Tracer is clearly routed into the pool downstream of the tributary which is the pattern of sediment transport throughout the surveys. In contrast the left-bank side of the riffle shows little downstream movement which supports the contention that much of the finer material was infiltrated below the armour layer. Further hydropower generation coupled with a flood of 33 cumecs begins to show discrete zones of tracer accumulation associated with the pool-head and mid-pool regions. Tracer is routed off the riffle and into the pool-head providing a cross channel deflection which follows the riffle topography. Material in the

Figure 10.5 Spatial distribution of magnetic tracer dispersal through the Newton riffle-pool-riffle sequence



faster flowing riffle section is routed downstream to the pool-head but leaves a region of low susceptibility behind. Deposition of tracer at the forset face of bars is described by Arkell (1985) and Hack (1957) for riffles. Subsequent grainsize surveys showed this region to be dominated by coarse and medium tracer gravels. A definite accumulation of tracer is associated with the shallow rougher areas of the left bank of the pool-head. Material here was found to be trapped between large boulders and particularly in wake deposits. The hydraulics described in Chapter 7.0 show the presence of secondary flow cells in this region which clearly cause a net movement of fine tracer towards the right bank. Recent studies of the mechanics of sediment movement in gravel bed bends illustrates the effect of secondary flow cells on the direction of fine sediment transport (Markham and Thorne 1992; Deitrich and Smith 1984). The absence of tracer in equivalent concentration on the gravel bank reflects the preferential routing of sediment towards the right bank from the riffle, together with the dilution effect of a copious fine sediment supply. Tracer is still evident on the incipient bar of the emplacement site although the forset face of the riffle is now relatively clear of surface tracer concentrations. This may reflect the infiltration of fine sediment into a deposit downstream of a negative step as observed by Carling and Glaister (1988). A discrete deposit of fine sediments is associated with the shallow left bank and upstream of the island at the pool-tail. This suggests that tracer sediments have been routed through the system and have concentrated in storage elements associated with regions of shallow weak flows in the pool-tail.

A further flood of 30 cumecs re-exposes tracer material at the pool-head and emplacement site and particularly at the incipient bar. Material has again collected in the pool below this bar and values for X are accentuated throughout the upper region of the pool-head. Downstream tracer accumulations have changed although their position remains constant, reflecting local redistribution rather than wholesale movement. Fine sediment accumulated upstream of the island has been moved downstream onto the shallow right bank of Newton riffle 2. In contrast, material in the mid-pool has been distributed across the total channel width but has decreased in concentration. No reason for this pattern is evident but it serves to illustrate the complexity of the supply/storage/tranport mechanism at low-medium flows.

Considerable movement of tracer occurred over winter 1989/90 despite low flows and a maximum discharge of only 21 cumecs. The dominant pattern is one of redistribution of the sediment stored in the pool-head across the total channel width. The region of apparent absence of tracer mid-way along the left bank of the pool represents the entry of a large field drain. This drain discharges considerable quantities of fine sediment into a delta which clearly dilutes the tracer for some distance downstream. The pool-tail presents a barrier to sediment progression downstream which forces material to be routed across towards the left bank. Accordingly a concentration of tracer is built up on the opposite side of Newton riffle 2, a region of accentuated infiltration, and hence fine sediment deposition.

The apparent concentration and wider dispersal of tracer material during a period of relatively low flows suggests that much of the tracer is stored in the channel sediments or routed through the reach when discharges are higher. The low-flow pattern tends to route fine sediment through the pool-head and mid-pool only to accumulate on the rising bed of the pool-tail. The importance of local hydraulics is evident when the patterns of sediment transport are viewed in associated with the hydraulics and topography of the reach. Accumulation in the interstices between larger roughness elements of the bed and in wake deposits within the deeper regions of the pool are further evidence that sediments are preferentially routed towards and through the pool deeps and right bank zone. The routing of fine sediment off the upstream riffle is controlled by the presence of a higher velocity jet which impinges on the right bank approximately where tracer concentrates and reference to the streamlines at hydropower flows shows that even flow from the left bank region of the emplacement site is carried across to the right bank. Consideration of the shear stress patterns show that the tracer, whilst routed by locally accentuated shear stresses, concentrates preferentially in regions of low force. Spearmans rank correlation of shear stress at a point at compensation and hydropower flows against X value at that point reveals a significantly negative value for hydropower conditions ($r^2 = -0.30$, $N = 104$, $p = 0.01$). This suggests that magnetic tracer is preferentially concentrated at sites associated with low shear stress and that the observed patterns of X are more strongly related to hydropower discharge conditions than compensation whose equivalent correlation coefficient was not significant although still negative ($r^2 = -0.09$, $n = 104$).

10.5 Observations of size sorting through a riffle-pool-riffle sequence

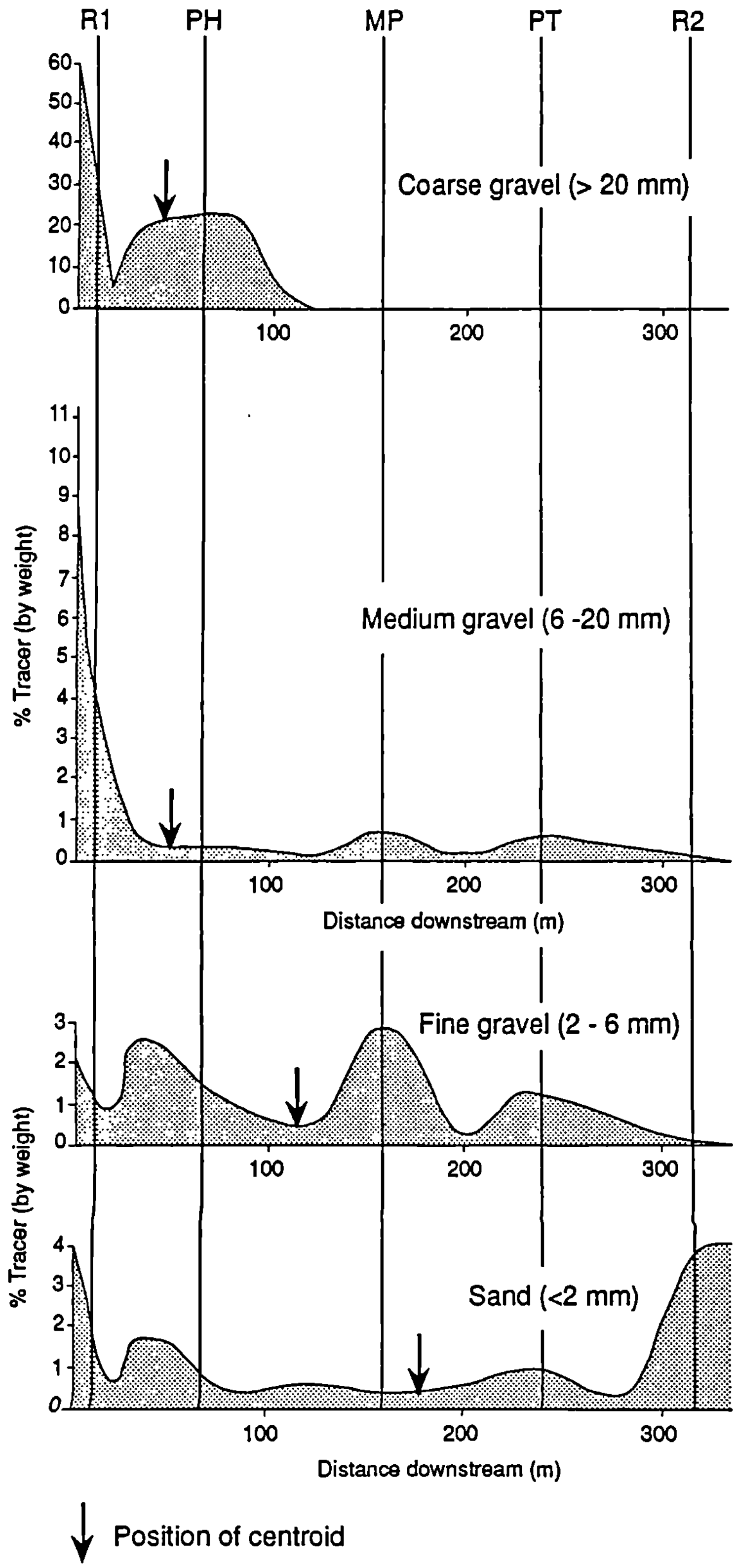
Figure 10.6 shows the downstream distribution of tracer material by granisize recovered from the Newton site on 7/7/89. Wherever X values were high a sample of sediment was recovered using a modified surber sampler that enabled the collection of fine sediment underwater. Sediment was dug down to approximately 15 cm beneath the surface layer and the sample taken back to the laboratory for detailed analysis. Some 48 samples were collected and assigned a percentage of tracer by weight according to the grainsize classes depicted in Table 10.5. Centroid position was calculated for each size class and raw data was processed through the Unimap 2000 package. Table 10.5 shows how the centroid position downstream increases with decreasing grainsize.

Table 10.5 Centroid position downstream of the emplacement site (NR1) according to grainsize class.

Size Range (mm)	Centroid position (m)
Coarse Gravel (> 16)	41
Medium Gravel (5.6 - 16)	50
Fine Gravel (2 - 5.6)	116
Sand (< 2)	171

This is clear evidence of downstream fining within a riffle-pool-riffle sequence based on the weight of tracer material recovered. Sediment > 5.6 mm is concentrated on the emplacement riffle and within the pool-head. Material in the medium gravel category is found up to 300m downstream from the emplacement site but is brought to rest on the pool-tail. Fine gravel is distributed throughout the pool though with discrete regions of concentration. Finer sediments appear to be removed from the pool-head and deposited in the mid-pool and pool-tail leaving a dominance of coarse and medium gravel. This implies a coarser sedimentology in the pool-head than the mid-pool or pool-tail. This is in accordance with the grainsize data described in Chapter 5.0 and 6.0 although in contrast to that described by Ashworth (1987). Sand is clearly competent throughout the

Fig 10.6: Tracer distribution downstream of the emplacement riffle on a grainsize basis. Positions of centroids are shown.



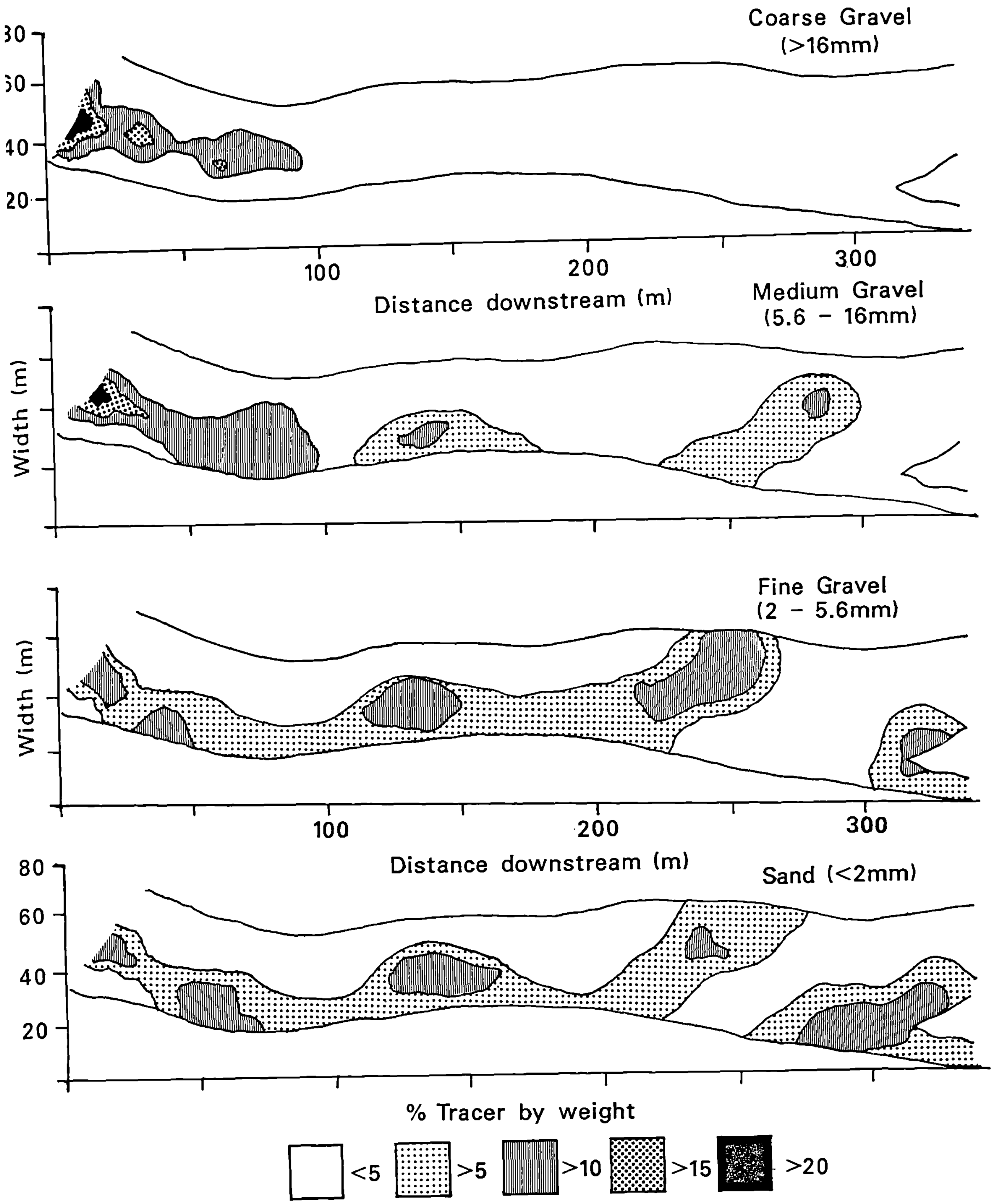
pool during hydropower discharges. A marked concentration is apparent at the downstream riffle which is associated with the island. Sand deposition at the downstream riffle coincides with a region of low shear stress and exposure at compensation flows. Trapping of fine sediments at the head of the island is evident from visual observations of sand splays which clearly develop during discharges in excess of compensation flows. Sand is also present in the foreset face of the emplacement riffle together with fine and coarse gravels. Sediment in the pool-tail region will be poorly sorted which is clear from the grainsize data described in Chapter 5.0.

Figure 10.7 reveals the spatial pattern of sediment routing according to grainsize. The tendency for routing along the right bank and storage in the interstices and wake deposits of the coarser pool regions is clearly evident. The localised nature of the coarse gravel transport is apparent and like the rest of the grainsizes is associated with a gradual release from the incipient bar attached to riffle 1. Downstream routing of coarse gravel is linked to the patterns of flow convergence off the riffle although less cross channel motion is evident than in the finer sediments. Medium gravels are concentrated in the pool immediately below the bar on riffle 1 and local concentrations occur along the right bank until the pool-tail. Sediments from 2-5.6mm are competent over the pool-tail and follow a similar pattern as the sand. The barrier effect of the pool-tail has been described by Petit (1987) and is the result of the combination of positive slopes out of the deeper pool and low shear stresses even at bankfull flows. Deposition of sediments of all sizes are associated with regions of low shear stress and low flow depth. Observations during the collection process, revealed that almost all the samples taken in the pool-head and mid-pool were associated with wake deposits in the lee of large roughness elements. This not only shows that sediment was in transport through the deeper pool sections but also that the trapping of sediments is effected by the interaction of the local micro-morphology and the flow field.

The total weight of recovered tracer amounted to 1.64 kg or a recovery rate of only 0.7%. Continuation of the survey of wake deposits downstream of Newton riffle 2 revealed no monitorable tracer concentrations which suggests that all the material is within the survey riffle-pool sequence. Furthermore the recovery of this small amount implies that some 227 kg of sediment is still stored locally within the emplacement site or in such low concentrations within the pool that they were undetectable. However, it is clear that

10.7

Distribution of tracer material according to particle size: 7/7/89, Qmax = 33 cumecs.



riffles act as reservoirs for the storage and release of fine sediments within the North Tyne and that the pattern of release is clearly determined by the local hydraulics, discharge maximum and sedimentology of the site. The storage of fine sediment beneath the armour layer in areas of low shear stress at the channel margins or on bars is in accordance with the results of the infiltration experiments and the observations of increased levels of sediments <2mm recorded at some riffles since regulation. In addition a value of 30-33 cumecs recorded for the scouring of fines from the subsurface riffle sediments and the routing of fines through the pool, is in accordance with the value of between 25 - 52 cumecs recorded for the initiation of pool scouring on the basis of inflitration data.

Arkell (1985) describes the limitations on detectability of tracer on the basis of concentration and burial depth. If sediment is infiltrated below 10-15cm below the armour layer then it is unlikely to be detected. Similarly the fine sand fractions which would form part of the suspended load would become widely dispersed across the pool and hence may become too diluted for detection. Given the propensity for detectable tracer concentrations to be associated with local concentrations of fine sediments (eg wakes/intersices) the loss of dilute finer material is entirely probable. The rate of recovery is clearly linked to the particle size with coarse gravel and medium gravel both exhibiting recovery rates of 0.25% whilst fine gravel and sand record 0.07% and 0.18% respectfully. The magnetic tracing technique described above is clearly limited in its efficiency by the equipments inability to penetrate far into the channel bed and by the rapid dilution of material finer than 2mm. Larger quantities of tracer could be used, however this may lead to spurious results determined more by the addition of a large volume of structureless sediment than by any naturally-occurring process. Despite the limitations of this technique it does provide a method of tracing fine sediments over large channel distances/areas. Improvement of the sampling methodology to include freeze coring techniques and more powerful field coils would be suggested recommendations for future projects.

The observations that fine sediments can be routed through pools during hydropower flows is expanded in the following Chapters which seek to record the rates of sediment transport and conditions for the initiation of sediment transport for riffles and associated pools.

Chapter 11

Direct sampling of fine and coarse bedload in riffle-pool sequences during hydropower generation

11.1: Intoduction

The previous sections have detailed the routing and infiltration of fine to medium sized sediment within riffles and pools for discharges up to 36% bankfull. Sediment up to 22mm (Phi scaling) is known to be competent at riffles during hydropower generation; however, the transport rates are typically supply limited. Consideration of the grainsize characteristics of the surface and subsurface sediments reveals that the supply limitation is predominantly the result of bed armouring and the development of structure. Bed structure is important for limiting the availability of all sizes of sediment depending upon the prevalence of a given structural assemblage. Results of a structural survey of riffles and pools within the North Tyne reveal that whilst supply limitation on the riffles is to be expected as a result of the enhanced bed structure, the pools are characteristically replete in sediments of all sizes and exhibit only discrete areas of structural development. This section aims to quantify the actual sediment transport rates and grainsize characteristics in relation to the hydraulics at associated riffle and pool sections during hydropower generation. In addition, this section aims to produce information on the relative thresholds of sediment transport associated with riffle-pool morphology, and to assess the implications for sediment routing. Thresholds of initial motion of individual particle sizes will be discussed in Chapter 12, when a larger range of data will be used.

11.2: Bedload transport in gravel-bed rivers: some observations

The factors influencing sediment transport within gravel-bed streams have been described in the previous sections. However some considerations of actual transport measurements from a variety of sources is required, to put the current study into context.

Carling (1989) provides an extremely lucid statement on the current status of sediment transport studies, suggesting that, " complete theoretical and deterministic models of the bedload transport process which successfully predict observed transport rates in a range of natural streams are presently unavailable". Some of the reasons for this have been addressed already and include the intrinsic properties of the bed sedimentology and form, and extrinsic properties associated with sediment supply. A further consideration of the inability to predict the transport of bedload in gravel/cobble bed streams is the difficulty associated with obtaining reliable datasets (Reid et al 1985; Bathurst 1987; Church and Gomez 1989). The incidence of bedload mobilising events is unpredictable, and the reliable sampling of what is apparently a spatially and temporally irregular phenomenon is problematic (Hubbell 1987).

The datasets of bedload transport resolve into a picture of great complexity, revealing a process which is largely stochastic in nature, but which under conditions of supply sufficiency yields tantalising glimpses of determinism. This is probably one of the major reasons for the continuing research into a "globally" representative solution (Church and Gomez 1989).

One of the few directly analogous studies of bedload transport rates within a regulated gravel-bed river are described by Beschta et al (1981). The results indicated that sediment transport was dominated by fine sediments (0.79mm) although material up to 14mm was in motion. Riffle armour (D_{50} = 16 - 25mm) remained static and sediment transport rates were supply limited. The bedload transport rates measured at two riffle sections were different for each riffle, although peak bedload transport occurred at peak discharge in both cases. A similar scenario was described by Davoran and Moseley (1986) for a regulated braided channel in New Zealand. Supply limitation and variable sediment transport rates at different sections led the authors to conclude that a relationship between sediment transport and hydraulic conditions could not be achieved.

Reid et al (1985) using a continuous recording bedload trap in the unregulated Turkey Brook, observed supply limitation, bedload pulses and variable thresholds of initiation and cessation of motion. In addition, they recorded unequal transport rates across a section, and unequal sizes of sediment recorded for thalweg and channel margins. Their observations were supported by detailed bedload sampling at a pool section in the River Severn, by Meigh (1987). Meigh concluded that cross sectional bedload transport was variable, and influenced by upstream supply as well as local sources of sediment. Discrete zones of bedload were observed, which were characterised by different particle sizes. The rate of sediment transport was significantly related to local shear stress estimated from velocity profiles, and particularly so for locally-entrained material (Meigh 1987). Meigh also found that stream power, calculated using grain shear stress, accounted for up to 88% of the variance in bedload transport rates for locally entrained material.

Carling (1989), in a discussion of the transport of sediment within two small gravel/cobble-bed streams, concluded that although the rate of increase in bedload transport approximated a 3/2 exponential increase in excess stream power, the large variations observed were likely to be resolved only through consideration of the structure and packing of the sediment supply within a given stream. Reid and Frostick (1984; 1986) discussed the effects of armouring and bed structure on the transport of sediment, in terms of an hysteretic loop between the sediment load:fluid-force relationship. This conceptually allows for lower than expected sediment transport rates in association with rising discharge due to higher thresholds of motion caused by bed armour and structure. When the armour and structure is disrupted, then sediment transport rates are increased, although discharge may be falling. Correspondingly, two values of sediment transport rate can be associated with a single discharge, depending on the strength of the bed surface.

The discussions in previous sections have identified variable bed strength throughout riffle-pool sequences that might be expected to result in a difference in the relationship between fluid force and sediment transport for riffles and pools. However, as Chapter 7 resolved, a considerable difference in the strength of the shear stress operating on the bed exists between riffles and pools, which might result in little or no sediment transport in the pools. Implicit in the observations of bedload transport:fluid-force hysteresis is the consideration of differential thresholds of motion of individual particles. Bedload transport cannot occur until individual particles are moved by a requisite shear stress. The value of this shear stress is a function of the particles' submerged weight, and a series of resisting forces which are determined by the drag coefficient of a given grain and the strength of the packing arrangement within which it is positioned. Although this is relevant to the discussion of sediment transport processes, further consideration of the relative thresholds of motion with respect to riffle-pool morphology and hydropower generation will be made in the following Chapter (12) when data will include a wider grainsize and shear stress field. This Chapter will concentrate on the thresholds of initiation and cessation of bedload transport as defined by Reid et al (1985) and Reid and Frostick (1986). Their studies, using a continuous bedload recorder, resolved up to five-fold differences between the specific power and shear stress required to initiate bedload transport and that associated with its cessation. This phenomenon was explained by the greater force required to break up the consolidated, structured stream bed and as a result of the difference between static and dynamic friction (Reid and Frostick 1986). The shear stress or stream power at which sediment is deposited has received little attention, with the majority of studies concentrating on the initiation of sediment transport (Reid et al, 1985). The force at which material is deposited is important to consider with respect to the development of sediment storage units and the generation of particular grainsize populations. The variability of shear stress within the riffle-pool sequences monitored in the North Tyne would suggest that deposition would be preferentially disposed in pools and at channel margins; the finer sediments found in these locations would seem to confirm this hypothesis. As a result these locations have a higher percentage of fine sediments available for transport. Consideration of the grainsize population of the bedload measured at a site can be used to infer the typology and degree of size sorting within a channel reach (Ashworth et al 1992). Ferguson and Ashworth (1992) describe the spatial variability of bedload associated with braided channel morphology, and Ashworth et al (1992) describe the sorting of sediment around a medial bar on the basis of sediment in transport measured at a variety of points. Although not directly analogous to the riffle-pool sequences in this study, their observations of downstream fining associated with the change from converging to diverging flow patterns, and the finer bedload associated with regions of lower shear stress, are both applicable to conditions that occur within the North Tyne riffle-pool morphology.

The grainsize composition of bedload has been studied with respect to indices of flow strength in an attempt to model the development of individual particle populations within bedload associated with a given fluid force or quantity (Parker et al 1982; Diplas 1987; Shih and Komar 1990; Komar and Shih 1992). Two conflicting theories have been developed to explain the presence of a wide range of grainsizes within bedload samples taken during different discharges. Equal mobility theory assumes that the effects of a coarser bed armour, together with the relative protrusion effect on larger particles (Fenton and Abbott 1977), will equalise the mobility of all grainsizes, such that the maximum particle size of a bedload sample will remain constant with variable discharge or shear stress (Parker et al 1982; Andrews 1983). Wilcock and Southard (1988) further strengthened the evidence for equal mobility through a series of mixed-sediment flume experiments and concluded that the critical shear stress for the initiation of transport rate of a given sediment size remained equal for all sizes.

Size selectivity represents the antithesis of the equal mobility theory, and assumes that a different shear stress is required to initiate the motion of different particle sizes (Carling 1983; Ashworth and Ferguson 1989; Shih and Komar 1990). If equal mobility exists, then grainsize populations of bedload would be expected to remain constant over a range of discharges or shear stress. Conversely, if size selectivity exists, then the grainsize population of bedload will become progressively coarser as the fluid force increases (Komar and Shih 1992).

The implications of these opposing theories of bedload transport for the development of the grainsize population of the bed of a river have been discussed by Ashworth and Ferguson (1989). Precise application of the equal mobility hypothesis to sediment transport in all reaches of a channel would produce a uniform mix of sediment sizes with little evidence of preferential sorting. Clearly experience of natural gravel channels suggests that this is not the case, particularly in the presence of variable bed morphology (Ashworth and Ferguson 1989). Whilst the presence of a variable bed morphology produces marked deviations from the uniform ideal of the equal mobility hypothesis (Parker et al 1982), evidence from coarse gravel/cobble bed streams with high shear stress fields show that surface sediment size is controlled by the strength of fluid force operating on the bed (Ashworth 1987; Ashworth and Ferguson 1989). Deitrich et al (1989) have recently suggested that the coarsening of a river bed is a function of the balance between supply and transport capacity of a stream. A decrease in sediment supply is associated with a coarsening of the surface layer due to selective entrainment of finer particles. As this surface layer coarsens, the ratio between the critical shear stress of surface and sub-surface median sediment sizes increases, thereby increasing the fluid force required to disrupt the stream bed. Analysis of the armour ratios and structural development in this study would support this hypothesis, suggesting that size selectivity dominates the bedload transport mechanism within the North Tyne.

11.3 Methodology

The determination of bedload transport rate involves the application of a representative formula or the direct sampling of material in motion. The deficiencies in the capability of sediment transport formulae to predict anything like the actual transport rate at a point or across a section was considered preclusive to their application to this study (Meigh 1987; Gomez and Church 1989). Consequently a methodology was designed that was based on direct sampling of bedload in transit.

The variety of bedload sampling techniques that are available to the field worker are reviewed extensively by Hubbell (1987), Klingeman and Emmett (1982), and Bathurst (1987). Four basic techniques exist for the sampling of bedload transport:

in-situ traps that are emptied after flood events or longer.

continuous samplers; eg vortex tubes, Birkbeck bedload samplers, conveyor belt samplers.

accoustic or electromagnetic detectors (continuous)

hand-held or wire operated samplers, designed to take real-time sub-samples of bedload; eg VUV or Helley-Smith basket samplers.

In addition, Neill (1987) and Ferguson and Ashworth (1992) have described techniques for the determination of sediment transport rates based on sediment budgeting the erosion and deposition rates over time through quite large channel reaches. Sediment transport calculated this way provides bedload transport rates of similar orders of magnitude to those established using Helley-Smith sampling. Difficulty arises in establishing the age and sequence of deposited material.

The availability of equipment, together with the scale of the North Tyne, precluded the use of in-situ traps. The lack of wire supports, together with the desire to sample two or more sections, rapidly meant that the larger VUV samplers were not applicable. Acoustic or magnetic detectors were considered unsuitable since they give no indication of the grainsize composition of the bedload and in the latter case would have required considerable financial input and large structures on the banks of a renowned Salmon river - a politically unsuitable option.

Ferguson and Ashworth (1992) and Ashworth et al (1992) have championed the spatial sampling of bedload to determine the sorting and hydraulic characteristics associated with a reach of river. Spatial sampling methodology differs from the classic, single-section sampling used to establish relationships with hydraulic parameters. However, the spatial sampling of bedload is prone to assumptions of temporal stability, to the extent that what is monitored at a point is assumed to reflect the total transport of sediment and grainsize population of bedload at that point for a given discharge. In reality this method overlooks the temporal variability of bedload at a site which has been identified as a major cause of scatter in bedload transport formula (Meigh 1987; Reid et al 1985). Furthermore, the aims of this study revolve around the impact of an altered hydrological regime upon a characteristic morphology, which necessitates both a spatial and hydraulic approach to the study of bedload. Consequently the spatial component was satisfied by the simultaneous determination of bedload at discrete cross sections in a riffle-pool sequence, which in turn enabled the sectional hydraulic characteristics to be elucidated at the same time.

A hand-held Helley-Smith sampler was chosen which was based on the modification according to the design of Newson (Bathurst et al 1986) to accommodate larger gravel sizes. The sampling efficiency of the Helley-Smith bedload sampler has been shown to vary according to transport rate and particle size:

100 % efficient for all particle sizes at transport rates of < 0.1 Kg/m/s (Hubbell 1987).
100 % efficient for particle sizes up to 8mm at transport rates of 0.1-1 Kg/m/s, 70% for material > 8mm (Hubbell 1987).

175% efficient for particles 0.25 - 0.5mm
100% efficient for particles 0.50 - 16mm
70% efficient for particles 16.0 - 32mm (Emmett 1980).

Meigh (1987) assumes a 100% trapping efficiency for material up to 32mm using the

150mm modified Helley-Smith, but provides little evidence, concluding that efficiencies for material larger than 32mm remain unknown. It is important to this study that the trapping efficiencies of 175% have been recorded for material 0.25-0.5mm, since this represents a significant fraction of the bedload trapped in the pools. For the purposes of this study, however, 100 % trapping efficiency is assumed for all particle sizes, since the calibration of the modified 150mm Helley-Smith is unknown and was beyond the scope of this study.

Observations of the rate of rise of hydropower flows had indicated that the sampling time (per sample) would have to be short in order to achieve a representative sample of bedload during a release. Meigh (1987) has reported sampling times of 2-3hours for a 30m cross section sampled at every 2m for a duration of 3-6 minutes per sample. Clearly with a rate of rise of the order of 45-90 minutes, full sectional sampling was unlikely to be representative of conditions per section for a given individual discharge. Instead of full sectional sampling, four points were monitored simultaneously with velocity profiles to quantify the transport rates associated with characteristic zones of the bed at single cross sections at riffles and pools. Two modified Helley-Smith samplers (150mm orifice) were available for each release. This enabled continuous, simultaneous monitoring at a riffle and pool section, and at one riffle-pool-riffle section during the Tarset release. An experiment was conducted at a single point at Tarset riffle 2, to determine the likely rates of transport, and hence the sampling time that would collect a measurable size of sediment for particle size analysis. A time of three minutes per sample was found to produce measurable quantities of sediment throughout the discharge range 2 - 16 cumecs, as well as allowing for multi-section sampling as the hydropower wave passed. Sections in the pool were monitored from a tethered boat, with sampling positions marked on a rope. Riffle sections were sampled on foot, again demarcated by a rope. Total sampling time per section was greater for the pool sections due to the difficulty in operating from a tethered boat, but averaged 30 minutes during low discharges, increasing up to 45-50 minutes at peak flows. The time to sample riffle sections depended on the roughness of the bed, since mobility at high discharges over rough slippery beds considerably increased the sampling time. Tarset riffle 1 averaged 30 minutes per section, and represented the "smoothest" section sampled. Unfortunately, no hydraulic measurements were made at this section due to a lack of equipment.

Transport rates at individual points were found to be typically within the range 10^{-7} - 10^{-5} Kg/m/s, which necessitated the combining of samples to provide a single sectional value of transport rate and grainsize. A note was made of the point at which the obviously largest particle was recorded, although this was not achieved at all of the sites, due to the different operators per section. However, the major purpose of the sediment transport monitoring was to give quantitative information on the relative transport rates between pools and riffles during hydropower generation; the spatial patterns of sediment transport were investigated through the use of tracers. Consequently the individual point shear stress measurements were averaged. It is these values which are discussed in this section.

The bag used on the Helley-Smith samplers had a mesh size of 0.25mm. Consequently the results of grainsize analysis below this size are liable to be underestimates. However, organic deposits tended to block the end of the mesh bags, with a corresponding increase in the recovery rate of finer particles, as noted by the retention of water in the bottom of the bag upon retrieval. Clogging of only the lower 10-20cm of the bag was not considered to affect the overall trapping efficiencies, since a free flow was still possible through the entry nozzle. Clearly a detailed calibration for these types of sampler is required before any firm conclusions can be made on their performance at low transport rates.

The placement of the sampler on the river bed is important to consider with respect to the grainsize of the bed (Bathurst et al reply to discussion in 1987). Bathurst et al (1987) discussed the effect of large boulders in channelling finer bedload into threads, concluding that estimates of the true bedload transport rate should take account of the number and size of intra-boulder "troughs" when determining the active transport component of a section. Meigh (1987) cautions the method of sampler emplacement, suggesting that a nozzle-up attitude to the bed, followed by careful lowering onto the surface reduces the likelihood of "scooping" up bed material; this method was adopted during this study. The "threads" hypothesis was pertinent for the Smales riffle, and in the deeper parts of pools, where large boulders up to 310mm were present. The sampling points in these regions were chosen to represent the broad conditions reflected in the section, but also, where possible, to be located in troughs between the larger boulders. Despite this attention, it is considered likely that bedload transport was underestimated in the Tarset pool due to an inability to determine the positioning of the sampler with respect to the bed.

After sampling, the bedload was returned to the laboratory, where the organics were floated off by sequential decanting. This method was preferred to combustion, since the magnetic experiments had shown a propensity for the larger sediments to fracture. The inorganic fraction was then oven dried, and weighed, prior to sieving at 1/2 Phi intervals to determine grainsize.

Sediment transport rate was calculated according to:

$$I_b \text{ (Kg/m/s)} = \frac{\text{Total weight of sediment trapped (kg)}}{\text{Sampler width (m) x Sampling time (s)}} \qquad \text{Equation 11.1}$$

Where I_b is the transport rate of bedload, the sampler width was 0.15m and the total sampling time was (4 x 180) seconds.

In total, 188 measurements of bedload were made at four riffles, which was equal to 47 total sections. In comparison, some 108 individual samples, equal to 27 total sections, were sampled in three individual pools. Hydraulic measurements were available for 32 of the 47 riffle sections, giving a total database of 52.

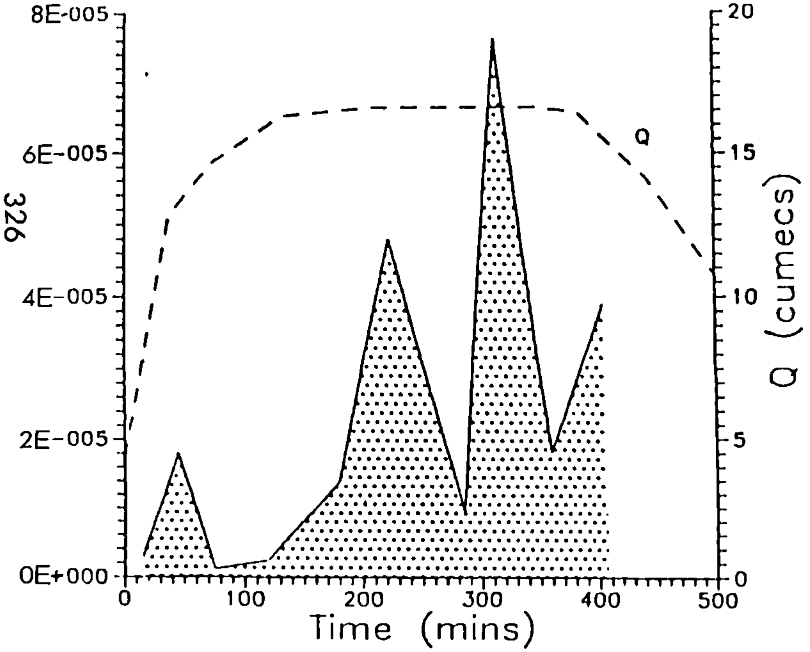
11.4 'Bedload transport rates in riffles and pools during hydropower discharges

Figures 11.1 - 11.3 illustrate the relative sediment transport rates monitored at the three sites, Newton, Tarset and Smales, during identical hydropower releases (Chapter 3). Any resulting variation in the discharge hydrograph is caused by attenuation and acceleration as the wave passes downstream (Petts et al 1985; Gilvear 1989), together with variable inputs from the tributaries.

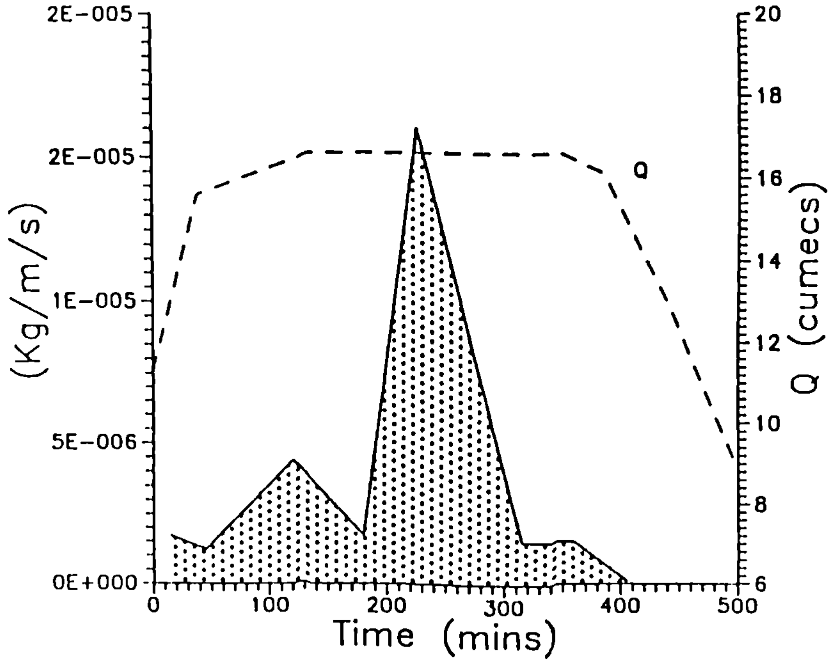
The transport of bedload within riffles and pools is characterised by temporal instability, largely out of specific synchronisation with the prevailing discharge conditions, although the gross changes from compensation to hydropower flows is clearly expressed in the

11.1 Smales Bedload Transport

Variation in bedload transport during a controlled hydropower release. Smales riffle 1. (16/11/89)

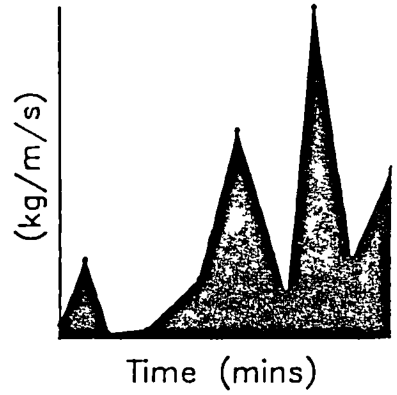


Variation in bedload transport during a controlled hydropower release. Smales pool. (16/11/89)

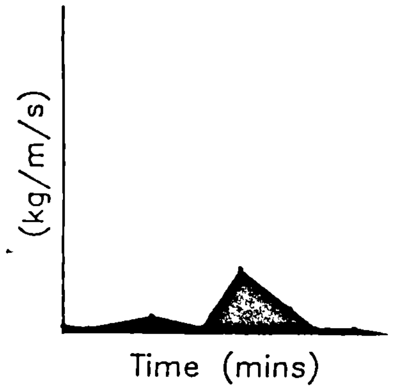


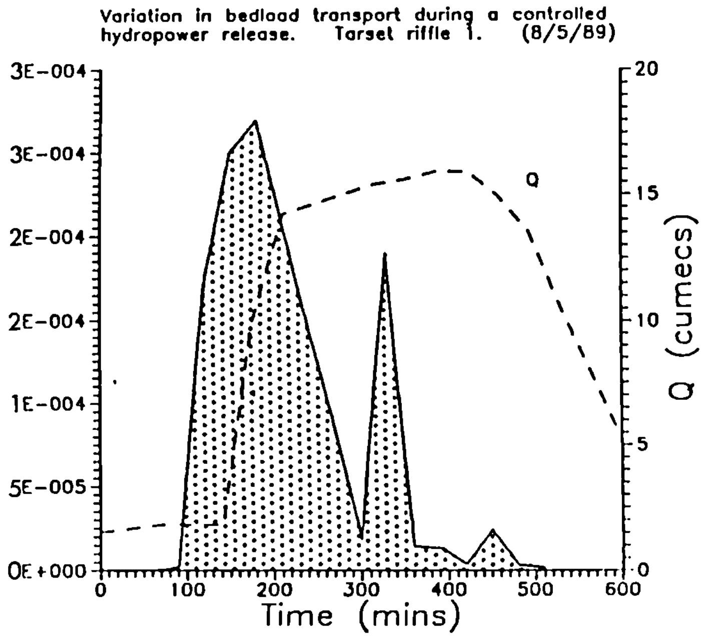
Equal Scale

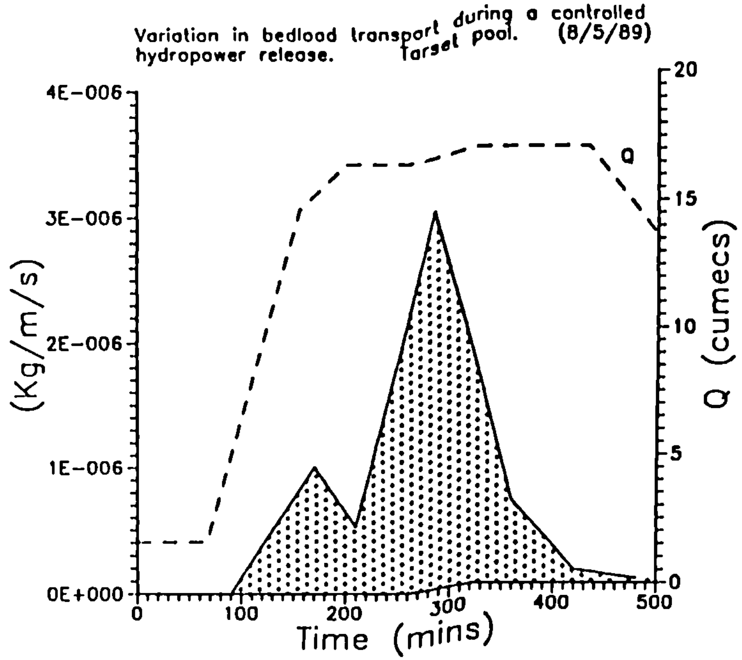
Riffle

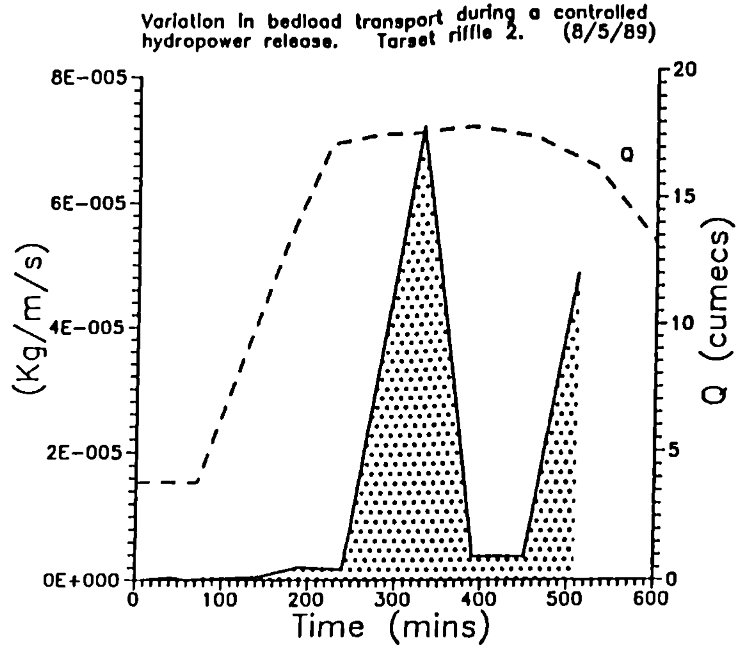


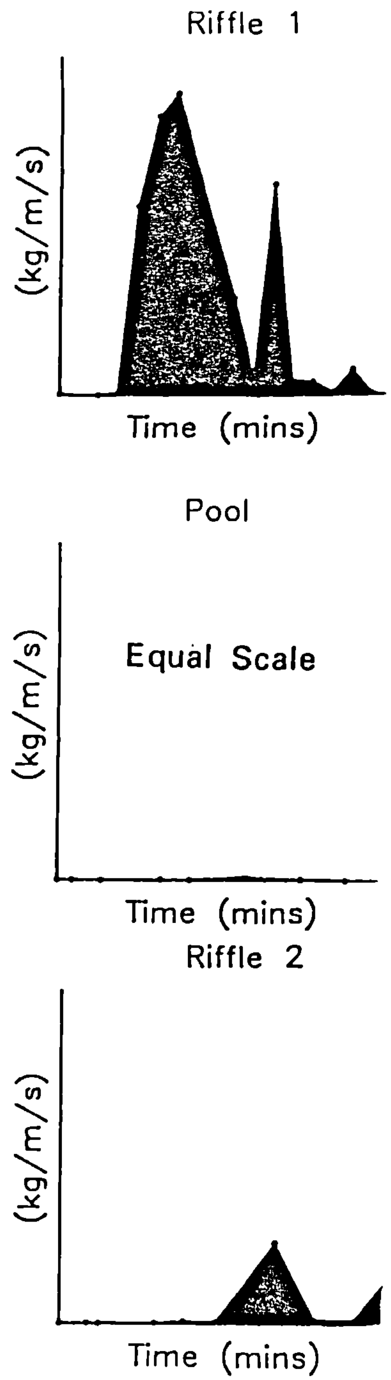
Pool





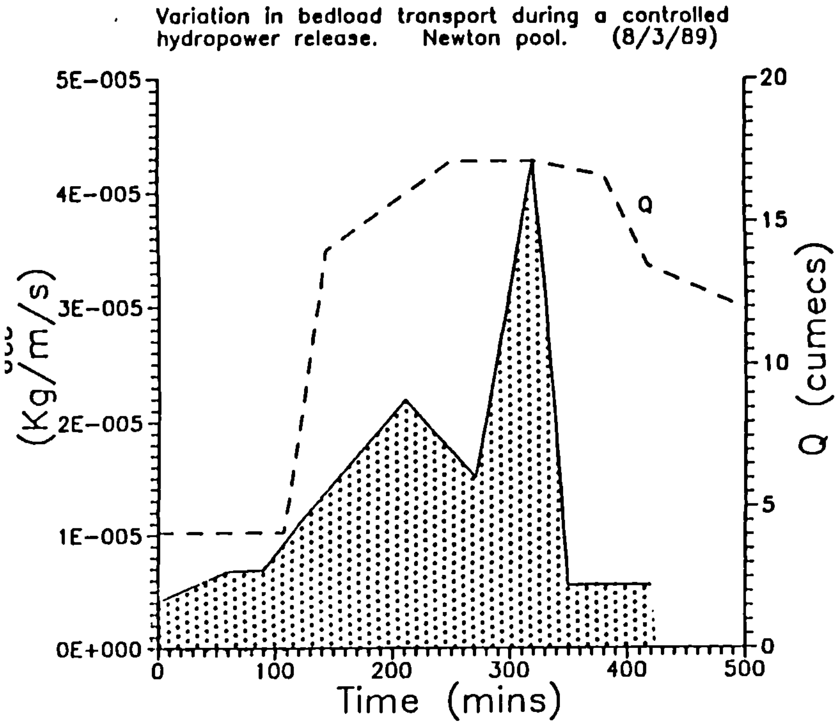


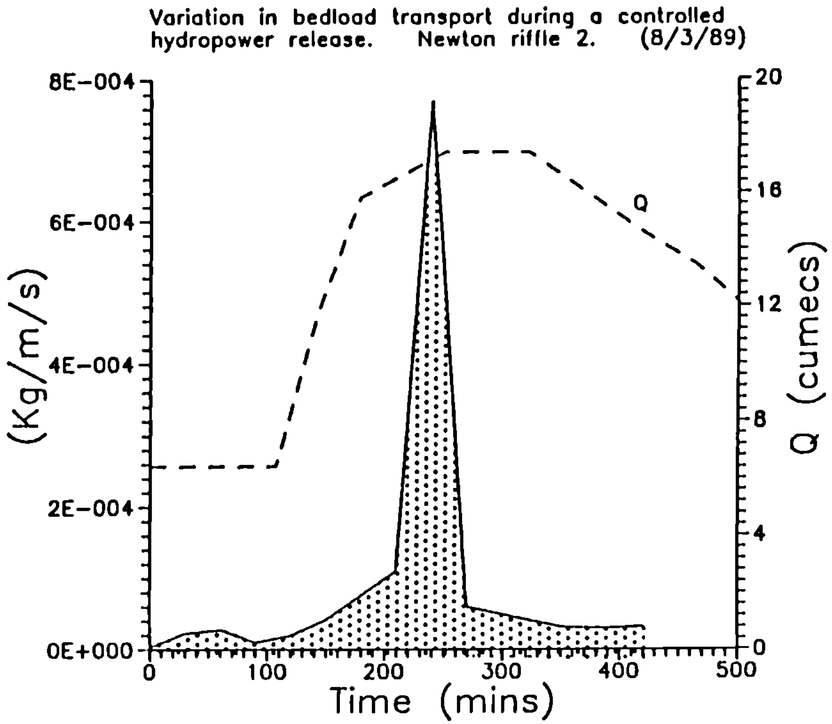


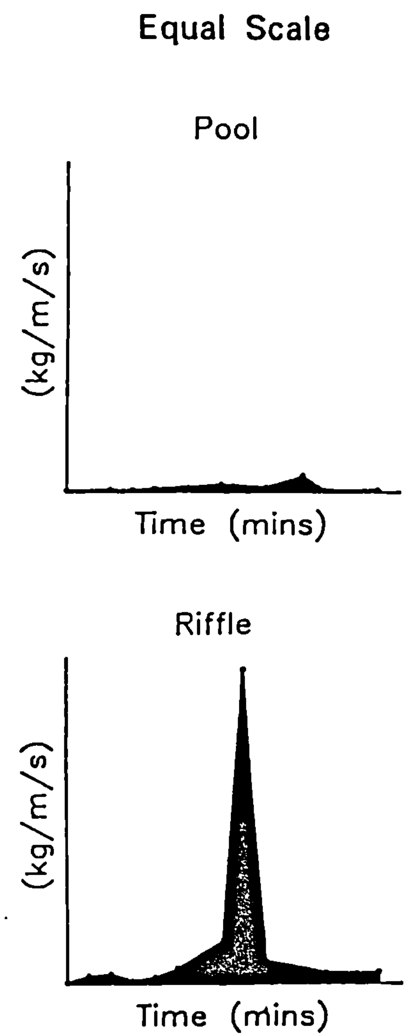


11.2 Tarset Bedload Transport

11.3 Newton Bedload Transport







magnitude of the sediment flux. The plots of bedload transport, depicted at equal scales, show the dramatic difference between pools and riffles during identical discharge conditions. The difference between pools and riffles is variable according to the individual sites:

Table 11.1: Average values for sediment transport, flow depth and shear stress experienced during hydropower discharges at riffles and pools.

Site	I_b (Kg/m/s)	Depth (m)	τ_p (N/m^2)
NR2	$9.7 * 10^{-5}$	0.35	17.2
NP	$1.3 * 10^{-5}$	0.83	3.2
TR1	$6.5 * 10^{-5}$	0.41	---
TR2	$1.3 * 10^{-5}$	0.49	5.1
TP	$5.9 * 10^{-7}$	1.20	0.4
SMR	$2.3 * 10^{-5}$	0.71	8.2
SMP	$3.8 * 10^{-6}$	1.10	0.3

The variation between bedload transport rates at riffles with respect to pools appears to be related to the depth of the pool, with deeper pools experiencing lower transport rates with respect to riffles. In reality, the depth of pools affects the transport rate of bedload through the extension of the velocity profile over greater flow depths, therefore decreasing the shear stress acting on the bed. Correspondingly, there is also a relationship between shear stress and transport rates for pools and riffles, such that the lowest shear stress is associated with the lower transport rates. The Tarset pool is anomalous, displaying higher transport rates for a lower shear stress, but this may result from operator error in the sampling procedure rather than a phenomenon in itself. Sediment transport rates recorded at associated riffles and pools show that pools experience, on average, bedload transport rates between 6.1 - 110 times lower than corresponding riffles during hydropower discharges. This depends upon the sediment supply available at a given riffle and the shear stress experienced in the given pool. The Newton site differs from both the Tarset and Smales sites, since the shear stress and bedload transport monitored at the riffle and pool are greater than all other sites with the exception of Tarset riffle 1. This may be explained by the shallower flow depths, lower bed strengths and bed structure, and finer sediment size relative to all other sites except Tarset riffle 1 (see Chapters 4, 5 and 6).

Reference to Figures 11.1 - 11.3 shows that in terms of the sediment balance between input and output from pools, all pools experience a net input of sediment during hydropower discharges, which corresponds to the morphological changes identified in Chapters 4 and 13. Riffles experience a progressive degradation as a result of competent hydropower flows, whereas pools experience a net aggradation. However, the low rates of bedload transport, together with the short transport lengths of sediment during periods of hydropower, result in low rates of morphological change to the riffle-pool sequence.

Considerable variation exists between individual riffles and pools in terms of the timing and magnitude of bedload transport rate. This is most notable at the Tarset site (Figure 11.2) where Tarset riffle 1 experiences maximum bedload transport as hydropower wave arrives, followed by a reduction in transport rates as maximum discharge is attained. Tarset riffle 2, in contrast, experiences maximum bedload transport rates at peak discharge, with little transport during the rising limb of the hydrograph. The Tarset pool experiences little bedload transport, but what was sampled shows a relationship with the discharge, rising as the discharge rises, and peaking at maximum flow rate. This latter point is pertinent to all pools, with maximum bedload transport relating to maximum discharge.

In contrast, the riffles display very variable transport rates, characterised by pulses of high bedload transport. This latter phenomenon has been reported in many studies of bedload transport in gravel-bed streams, and has been related variously to sporadic break-up of the armour layer, destruction of structural elements, flow instability or inherent dynamics of the riffle-pool sequence (Gomez 1983; Reid et al 1985; Meigh 1987). The pulses recorded in this study are almost all associated with the presence of larger particles in the bedload (Table 11.2) and are independent of the unsteady flow conditions expressed as shear stress, (see Table 11.3). This implies that the pulses are a function of either local shear stress fluctuations upstream, or, rather, the destruction of individual structural units. This latter hypothesis is supported by the increase in transport rates of a range of grainsizes associated with each individual pulse (see below). The pulses in the transport of bedload observed in this study are a function of the low transport rates in general, influenced by the sporadic dislocation of individual large clasts, which exposes fine sediment to the flow field. All other observations of bedload pulses have been conducted under conditions of relatively high bedload transport rate, where the addition

Table 11.2: Grainsize data for bedload samples collected at riffles and pools during hydropower discharges.

Q (m^3/s)	D_{84}	D_{50}	D_{16}	Sort	Skew	Kurt
Smales Riffle						
4.3	0.81	0.27	0.17	1.25	-0.33	1.38
12.8	11.30	3.30	0.38	2.21	0.25	0.77
14.7	0.62	0.27	0.19	1.12	-0.54	1.92
16.3	0.62	0.29	0.19	0.99	-0.31	1.39
16.6	6.06	0.93	0.27	2.10	-0.24	0.74
16.6	19.69	5.66	0.62	2.30	0.30	1.11
16.6	12.12	3.73	0.25	2.40	0.33	0.50
16.4	39.40	29.86	5.66	1.78	0.77	4.64
14.1	0.87	0.35	0.15	1.50	-0.21	1.40
10.7	25.99	14.92	2.30	1.84	0.63	1.20
Smales Pool						
11.3	0.66	0.29	0.13	1.23	-0.01	1.07
15.6	0.38	0.22	0.11	0.94	0.05	1.20
16.6	0.71	0.35	0.23	0.90	-0.37	1.17
16.6	0.76	0.31	0.20	1.21	-0.37	1.47
16.6	0.38	0.22	0.12	0.93	0.00	1.39
16.6	1.87	0.41	0.20	-0.91	-0.41	1.29
16.1	0.47	0.25	0.15	1.01	-0.14	1.76
12.8	1.62	0.57	0.23	1.64	-0.17	1.36
8.8	0.74	0.37	0.19	0.93	-0.06	1.16
Tarset Riffle 1						
1.5	0.50	0.33	0.18	0.85	0.03	1.26
1.8	0.44	0.29	0.17	0.64	0.19	0.78
1.8	0.54	0.33	0.19	0.97	-0.12	1.48
1.8	32.00	11.31	0.44	2.72	0.50	0.99
9.8	51.98	36.76	0.33	3.13	0.85	0.81
14.2	78.80	51.98	6.06	2.16	0.75	1.21
15.4	3.73	0.54	0.27	1.78	-0.42	0.80
15.6	4.29	0.41	0.22	1.97	-0.53	1.45
15.9	52.00	22.63	6.10	1.91	0.41	1.84
15.9	0.87	0.33	0.17	1.38	-0.37	1.69
14.9	0.93	0.38	0.20	1.19	-0.26	1.43
13.5	0.47	0.29	0.17	0.77	0.00	0.91
10.6	11.31	3.73	0.29	2.32	0.38	0.56
7.9	0.50	0.31	0.17	1.17	-0.21	2.03
5.2	0.47	0.31	0.17	0.74	0.04	1.00
Tarset Pool						
2.0	0.00	0.00	0.00	0.00	0.00	0.00
2.0	0.00	0.00	0.00	0.00	0.00	0.00
2.0	0.00	0.00	0.00	0.00	0.00	0.00
15.3	0.33	0.14	0.05	1.17	0.04	0.87
17.1	0.33	0.14	0.05	1.30	0.04	0.90
17.1	0.66	0.33	0.15	1.01	0.01	1.04
17.1	0.41	0.18	0.07	1.49	-0.12	1.21
17.1	0.33	0.18	0.07	1.11	0.22	1.04
13.6	0.38	0.22	0.11	0.85	0.11	0.85
Tarset Riffle 2						
3.8	0.00	0.00	0.00	0.00	0.00	0.00
3.8	3.73	1.42	0.23	1.94	0.37	0.86
3.8	0.00	0.00	0.00	0.00	0.00	0.00
13.2	0.50	0.31	0.15	0.97	0.03	1.19
17.4	0.87	0.41	0.06	1.69	0.37	0.72
17.8	0.41	0.18	0.07	1.23	0.09	0.97
17.8	34.30	19.70	1.07	2.33	0.69	0.80
17.4	3.03	0.54	0.20	1.78	-0.26	0.80
16.2	1.30	0.47	0.25	1.19	-0.20	1.00
13.2	6.96	2.64	0.57	1.68	0.25	0.77
Newton Pool						
4.1	0.71	0.35	0.17	0.92	-0.01	0.76
4.1	0.56	0.17	0.05	1.52	-0.01	0.75
4.1	0.56	0.17	0.05	1.52	0.00	0.75
13.9	1.84	0.47	0.08	2.09	0.15	0.72
17.1	10.10	1.59	0.16	2.71	0.17	0.72
17.1	2.35	0.72	0.10	2.13	0.26	0.79
16.6	7.41	1.52	0.31	2.30	0.15	1.02
13.4	0.62	0.25	0.05	1.63	0.25	0.97
11.9	0.32	0.12	0.05	1.23	-0.01	0.74
Newton Riffle 2						
6.4	0.36	0.18	0.09	0.92	-0.01	0.73
6.4	5.59	2.64	0.37	2.02	0.41	1.31
6.4	6.87	2.70	0.28	2.30	0.43	1.17
6.4	1.93	0.35	0.07	2.16	-0.01	0.66
11.8	2.00	0.47	0.07	1.93	-0.01	0.95
15.8	8.28	1.24	0.15	2.66	0.10	0.86
17.4	36.50	13.64	1.19	2.41	0.50	1.12
17.4	49.20	29.80	0.97	2.67	0.75	0.96
17.4	2.64	0.62	0.15	2.05	0.05	1.00
14.6	15.24	4.23	0.28	2.70	0.41	0.83
13.4	6.28	2.04	0.48	1.79	0.17	0.89
12.1	3.18	0.75	0.14	2.12	0.13	0.87

Table 11.3 Bedload transport rate and hydraulic parameters recorded at riffles and pools during hydropower generation.

Q (m^3/s)	I_b (kg/m/s)	U_b (m/s)	p (N/m^2)	w_o (W/m^2)
Smales Riffle				
4.3	3.1 x 10-6	0.23	1.57	0.09
12.8	1.8 x 10-5	0.36	2.48	0.21
14.7	1.1 x 10-6	0.42	2.37	0.20
16.3	2.4 x 10-6	0.29	4.10	0.36
16.6	1.4 x 10-5	0.36	5.66	0.50
16.6	4.8 x 10-5	0.29	15.18	1.34
16.6	9.4 x 10-6	0.27	27.00	2.38
16.4	7.6 x 10-5	0.28	15.61	1.37
14.1	1.8 x 10-5	0.34	4.10	0.33
10.7	3.9 x 10-5	0.22	4.28	0.38
Smales Pool				
11.3	1.7 x 10-6	0.19	0.36	0.026
15.6	1.2 x 10-6	0.25	0.24	0.014
16.6	4.4 x 10-6	----	----	-----
16.6	1.7 x 10-6	0.34	0.34	0.019
16.6	1.6 x 10-5	0.36	0.10	0.006
16.6	6.3 x 10-6	0.37	0.30	0.017
16.1	1.5 x 10-6	0.31	0.29	0.016
12.8	1.5 x 10-6	0.25	0.14	0.008
8.8	1.0 x 10-7	0.19	0.26	0.014
Tarset Riffle 1				
1.5	4.5 x 10-7			
1.8	2.5 x 10-7			
1.8	2.4 x 10-6			
1.8	1.7 x 10-4			
9.8	2.5 x 10-4			
14.2	2.7 x 10-4			
15.4	8.7 x 10-5			
15.6	1.8 x 10-5			
15.9	1.9 x 10-4			
15.9	1.4 x 10-5			
14.9	1.3 x 10-5			
13.5	3.6 x 10-6			
10.6	2.4 x 10-5			
7.9	3.0 x 10-6			
5.2	1.4 x 10-6			
Tarset Pool				
2.0	0	0.06	0.15	1.0700
2.0	0	0.06	0.04	0.0003
2.0	0	0.05	0.02	0.0001
15.3	1.0 x 10-6	0.33	1.19	0.0500
17.1	5.2 x 10-7	0.44	1.65	0.0700
17.1	3.0 x 10-6	0.38	0.24	0.0100
17.1	6.4 x 10-7	0.32	0.39	0.0170
17.1	1.0 x 10-7	0.36	0.26	0.0110
13.6	3.5 x 10-8	0.22	0.08	0.0030
Tarset Riffle 2				
3.8	0	0.23	2.49	0.08
3.8	5.4 x 10-7	0.22	0.55	0.02
3.8	0	0.18	2.06	0.07
13.2	6.6 x 10-7	0.21	4.77	0.28
17.4	2.1 x 10-6	0.27	9.45	0.55
17.8	1.7 x 10-6	0.40	6.83	0.40
17.8	7.2 x 10-5	0.37	7.33	0.42
17.4	3.7 x 10-6	0.28	10.28	0.59
16.2	3.6 x 10-6	0.41	3.12	0.18
13.2	4.8 x 10-5	0.24	3.60	0.21
Newton Pool				
4.1	4.1 x 10-6	0.09	0.61	0.011
4.1	6.8 x 10-6	0.11	1.32	0.025
4.1	6.9 x 10-6	0.26	2.74	0.051
13.9	1.1 x 10-5	0.34	3.91	0.214
17.1	2.2 x 10-5	0.31	2.50	0.157
17.1	1.5 x 10-5	0.28	4.50	0.283
16.6	4.3 x 10-5	0.25	3.61	0.225
13.4	5.5 x 10-6	0.19	3.60	0.187
11.9	5.5 x 10-6	0.10	6.30	0.317
Newton Riffle 2				
6.4	4.2 x 10-6	0.38	10.10	0.910
6.4	2.3 x 10-5	0.54	10.90	0.980
6.4	2.8 x 10-5	0.47	24.00	2.200
6.4	9.8 x 10-6	0.55	9.80	0.890
11.8	2.0 x 10-5	0.42	53.50	6.100
15.8	4.2 x 10-5	0.62	11.10	1.300
17.4	1.1 x 10-4	0.55	13.40	1.600
17.4	7.7 x 10-4	0.65	7.10	0.850
17.4	5.9 x 10-5	0.65	22.80	2.720
14.6	3.1 x 10-5	----	-----	-----
13.4	2.9 x 10-5	0.57	12.70	1.470
12.1	3.2 x 10-5	0.66	13.60	1.540

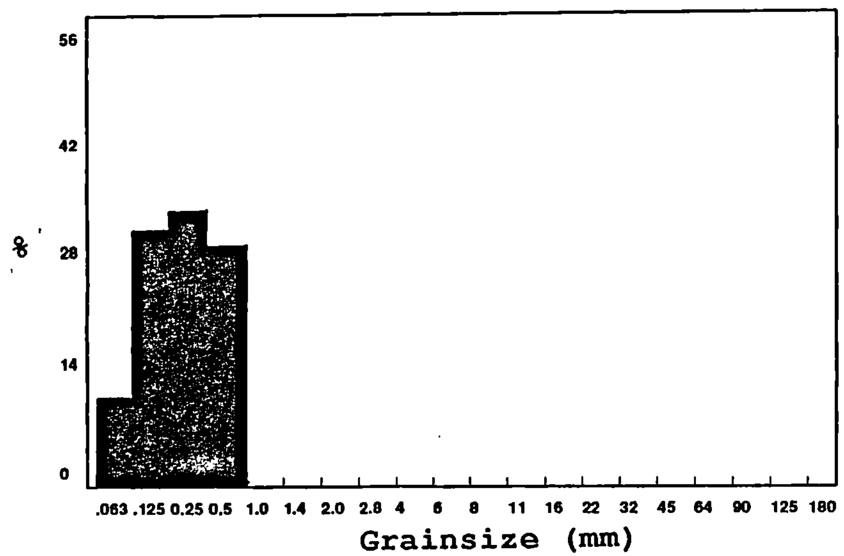
or absence of an individual clast would not significantly affect the overall transport rate, (Meigh 1987; Frostick et al 1985; Tacconi and Billi 1987). The existence of pulses in this study confirms the lack of a relationship between bedload pulses and "pulses" in the flow field, expressed as shear stress. Furthermore, there is no evidence of an association at low bedload transport rates between the supply of sediment from a riffle and the transport of bedload in a pool. This is confirmed by the magnetic tracing experiments discussed in Chapter 10 which indicated that little riffle sediment was moved further than 20m per hydropower event. Therefore the pattern of bedload transport at a site can be considered to independent of the bedload transport at sites in excess of 20m upstream during hydropower discharges; in effect, the sediment transport dynamics of the riffle-pool sequence are dislocated and operate in isolation, only affecting the total sequence over periods of time in excess of 100 days (see Chapter 10).

11.5 Grainsize characteristics of bedload transport during hydropower discharges

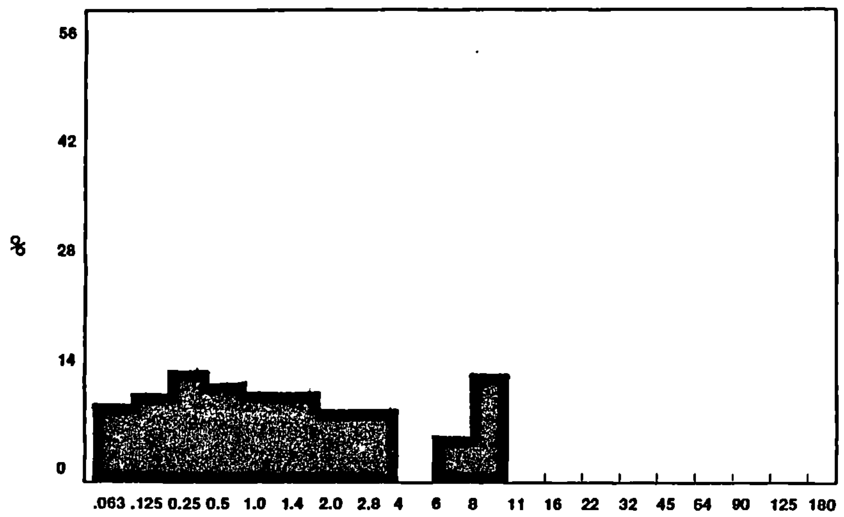
The total transport rates of bedload have been shown to be variable both spatially and temporally within riffle-pool sequences and at a site. Similarly, the grainsize composition of the bedload in transit is dependent upon the prevailing hydraulic conditions. Figures 11.4-6 depict the average grainsize composition of bedload at compensation and peak hydropower discharges for associated riffles and pools. This was calculated by combining the grainsize data for compensation and hydropower discharges at each site to provide a general value for the dominant discharge frequencies within the North Tyne (Chapter 3). Results for the Newton site, located below significant tributary input, and possessing a relatively shallow riffle and pool, are depicted in Figure 11.4. For an equivalent compensation discharge, the grainsize distributions of the pool and riffle are substantially different, with the pool experiencing a competence of 0.5mm in comparison to 8mm at riffle 2. Sediment of 0.125-0.5mm exists in almost equal proportions in the bedload within the pool, whereas 0.063 and 0.125mm material dominates the riffle bedload. The coarser elements of the riffle bedload are clearly derived from local sources, probably the wake, and infill deposits, and are sporadically in motion, dependent upon the magnitude of the shear field. The dominance of fine sand and silt/clay at the riffle reflects the reach competence of this size range which includes suspended sediments.

11.4 Bedload Grainsize for Newton pool

Compensation flow (Q = 2 cumecs)

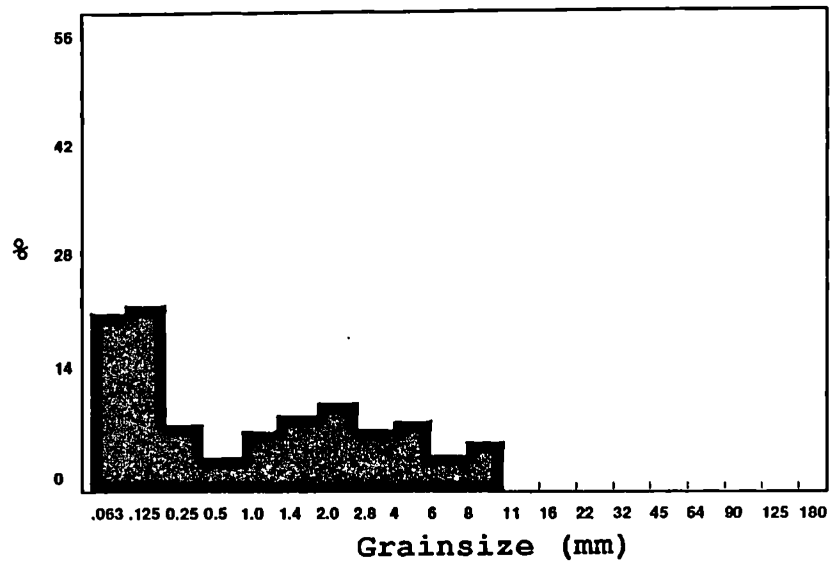


Hydropower flow (Q = 17 cumecs)

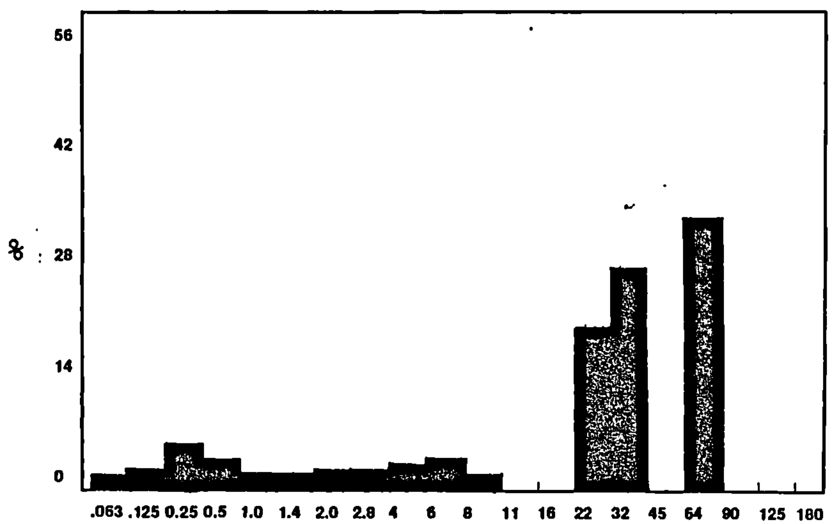


Bedload Grainsize for Newton riffle 2

Compensation flow (Q = 2 cumecs)



Hydropower flow (Q = 17 cumecs)



As the discharge rises to hydropower levels (16 - 18 cumecs), both pool and riffle bedload incorporate progressively coarser particles, such that competence becomes 8mm in the pool and 64mm on the downstream riffle. A bi-modal distribution characterises both sediment populations, with accentuated frequencies of 0.25mm particles at both sites. Riffle sediment has become skewed towards the coarser particle sizes, a transformation from the fine skewness exhibited during compensation flows. Reach competence is now 8mm (assuming the pool-tail is equivalently competent). This value is in accordance with the routing of medium gravel identified using magnetic tracers.

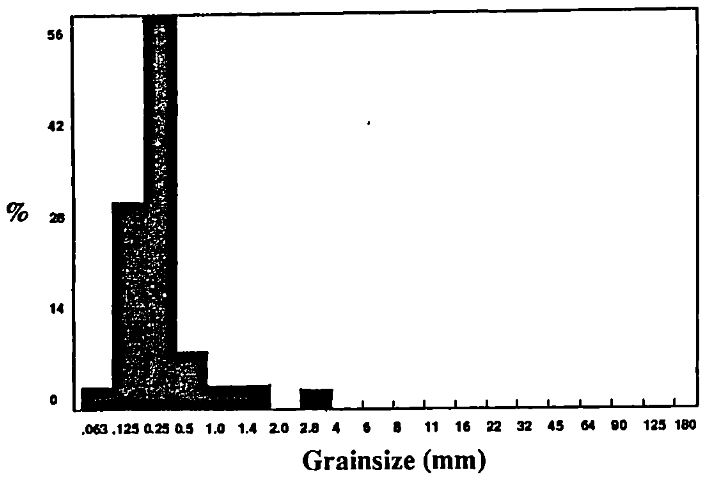
The position of the largest particles trapped in the Helley-Smith bedload sampler (identifiable on two occasions) was associated with the deeper point of the left-bank gravel bar, and the deepest section as indicated by the magnetic tracing experiments (see Chapter 4). No comparable data was collected by the team at riffle 2.

Figure 11.5, depicts the grainsize populations associated with the Tarset riffle-pool-riffle sequence. At compensation flows the transport of sediment is limited to material < 4mm at riffle sites only. The pool experiences shear stresses of < 0.5 N/m2 which are incapable of transporting sediment. The absence of material < 0.125mm suggests that suspended material is not present in the flow near the pool bed, since it is clearly present in samples taken at higher discharges. The pool is therefore a sink for fine sand and silt/clay which is in accordance with the grainsize data recorded in this pool (Chapter 5). The bedload at Tarset riffle 1 (TR1) is finer and better sorted than that at Tarset riffle 2 (TR2), again reflecting the finer nature of the riffle sediment at TR1, and the relative lack of bed structure within which finer sediments can be trapped (Chapter 6). The reach competence is characterised by suspended sediments, with no bedload transport possible through the pool.

At hydropower discharges, the grainsize population of TR1 becomes similar to TR2 in distribution, characterised by bi-modality and an extended size range. TR1 bedload is in fact more coarse and slightly poorer sorted than TR2, with a competence of 32mm compared to 22mm for TR2. The secondary mode is associated with material in the 0.125-0.25mm grainsize range, which is the modal value of bedload in transit through the pool. The riffle-pool-riffle sequence is linked up at hydropower discharges for material

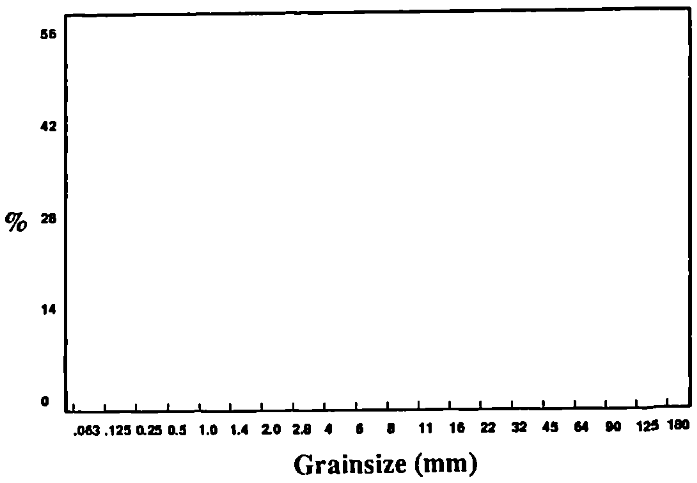
11.5 Bedload Grainsize for Tarset riffle 1

Compensation flow (Q = 1.4 cumecs)



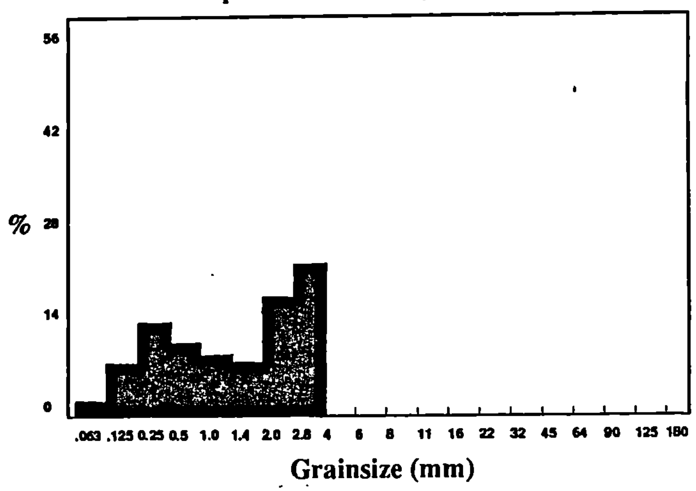
Bedload Grainsize for Tarset pool

Compensation flow (Q = 1.8 cumecs)

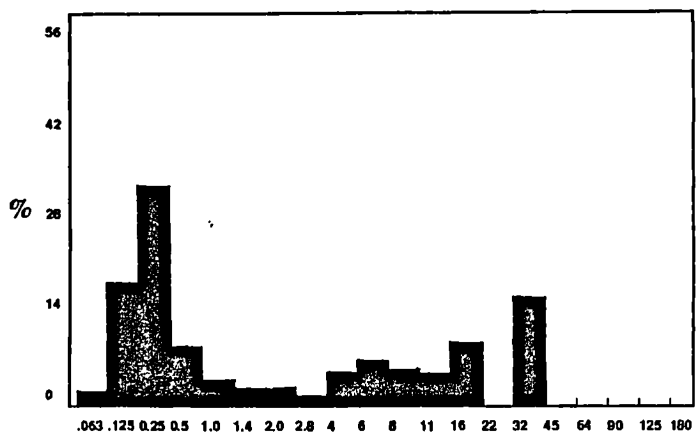


Bedload Grainsize for Tarset riffle 2

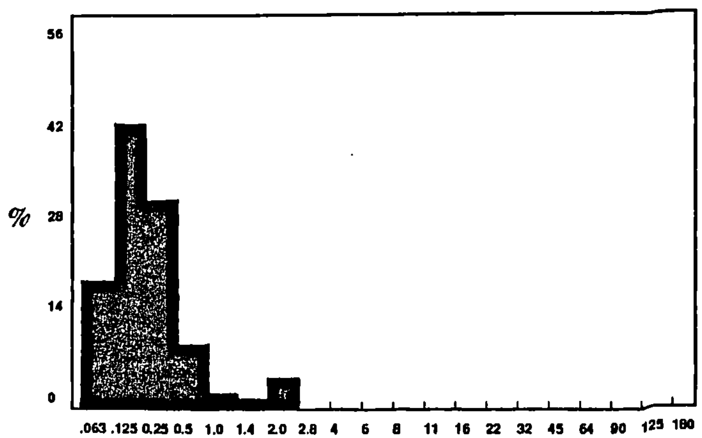
Compensation flow (Q = 2.8 cumecs)



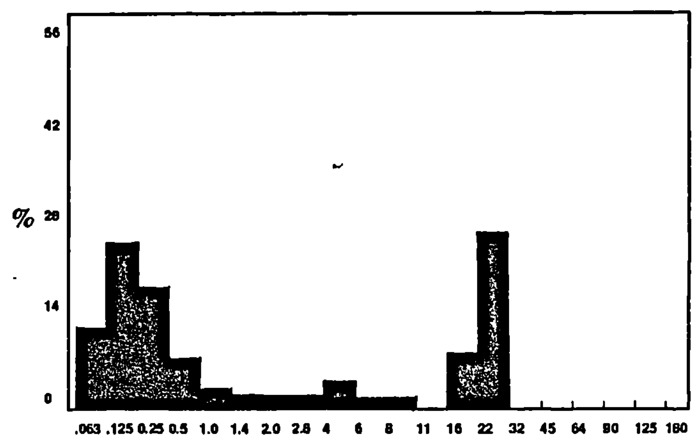
Hydropower flow (Q = 16.4 cumecs)



Hydropower flow (Q = 17.1 cumecs)

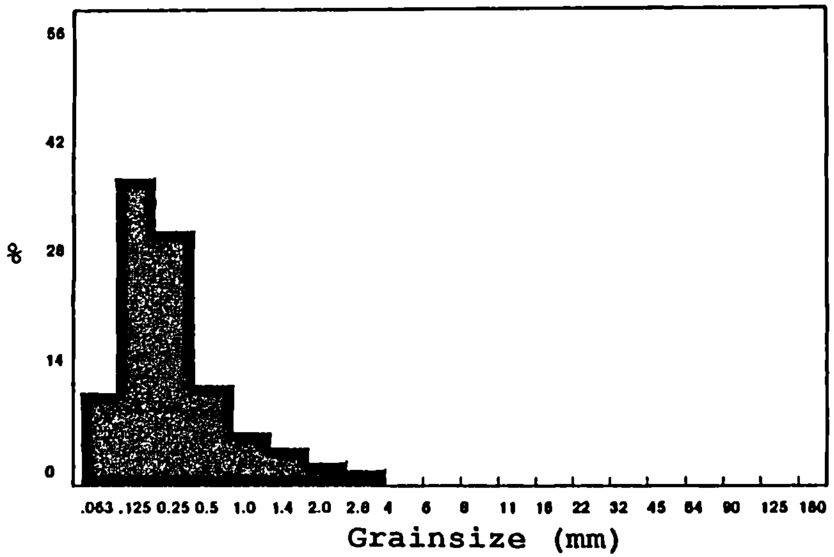


Hydropower flow (Q = 18.7 cumecs)



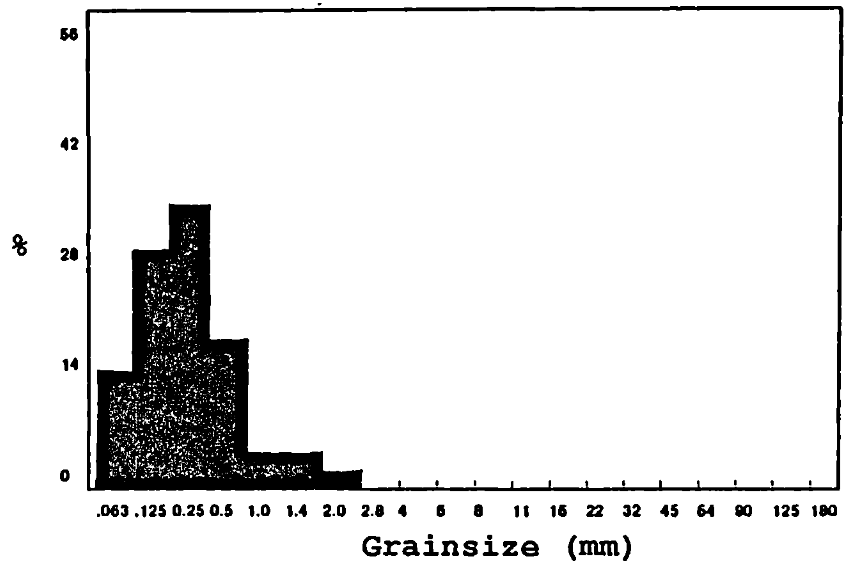
11.6 Bedload Grainsize for Smales riffle

Q = 4 cumecs

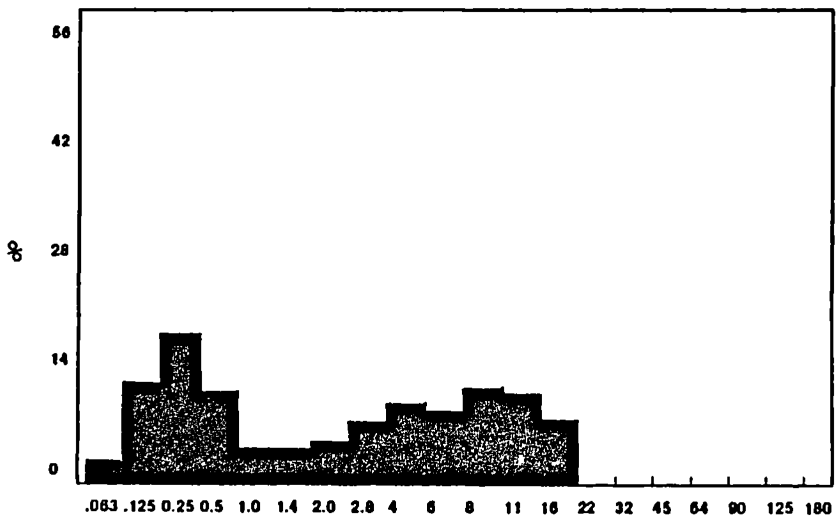


Bedload Grainsize for Smales pool

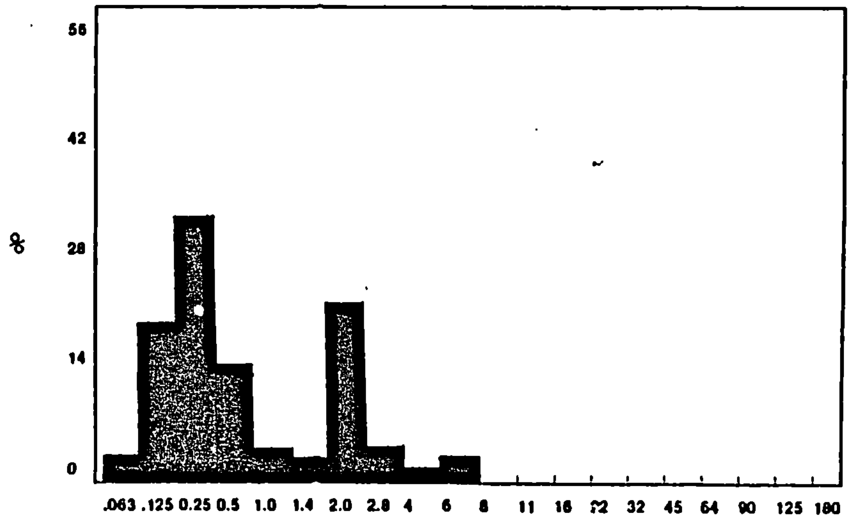
Q = 4 cumecs



Hydropower flow (Q = 16.6 cumecs)



Hydropower flow (Q = 16.6 cumecs)



up to 2mm b-axis, providing a reach competence in the coarse sand size. The presence of accentuated levels of sediments < 2mm in some post-regulation riffles is explained by the competence of pools within this size range during hydropower releases.

The position of largest grainsize trapped in the Helley-Smith bedload sampler was recorded for TR2 (3 observations), and fluctuated between the second and first points located on the incipient left bank bar, rather than in the deeper sections towards the right bank. The increase in sediment transport competence associated with this region of TR2 corresponds to the position of highest infiltration rate, and suggests that sediment supply is responsible for the observed patterns of bedload fluctuation.

Figure 11.6 illustrates the grainsize populations associated with the hydropower release monitored at the Smales site. The bedload for Q = 4 cumecs was made as the discharge was rising, and consequently does not represent compensation flow per se. The grainsize populations for riffle and pool at this discharge are similar, in being characterised by unimodal, finely skewed distributions, dominated by particles < 0.25mm b-axis. Competence is only .8mm different (2.8mm SMR, 2mm SMP) and D_{50} is in fact greater for the pool (see Table 11.2). The absence of the coarser sediments at the riffle are perhaps accounted for by the high levels of bed structure associated with this riffle, coupled with a lower shear stress. Similarly, the coarser sediment population of the pool may be accounted for by the proximity of the pool section to the riffle, which may enable bedload from the riffle to influence the pool sediment transport. The equivalence is not explained by the shear stress, which exhibits the characteristically low values for the pool, relative to the riffle. It should be noted that the shear stresses determined for this pool, were the least reliable in terms of the methodology outlined in Chapter 7, and as such may be underestimates of the actual value.

As the discharge attains maximum hydropower levels, the grainsize populations of riffle and pool become more distinctive. The riffle grainsize population becomes more poorly sorted than the pool, with a competence of 16mm. The pool is only half as competent at 8mm, and the distribution is distinctly bi-modal. Both grainsize populations exhibit a dominant frequency of particles of 0.25mm b-axis, again suggesting some connectivity between riffle and pool.

The position of maximum competence was noted irregularly for SMP and not for SMR. The position of maximum competence in the pool was associated with the second and third points monitored from the left bank. These correspond to a relatively fine gravel bank, marginal to the deepest right bank region. This is similar to the pattern observed in the Newton pool, and reflects the availability of sediment in this region, together with the higher shear stress values located away from the banks (Chapter 7).

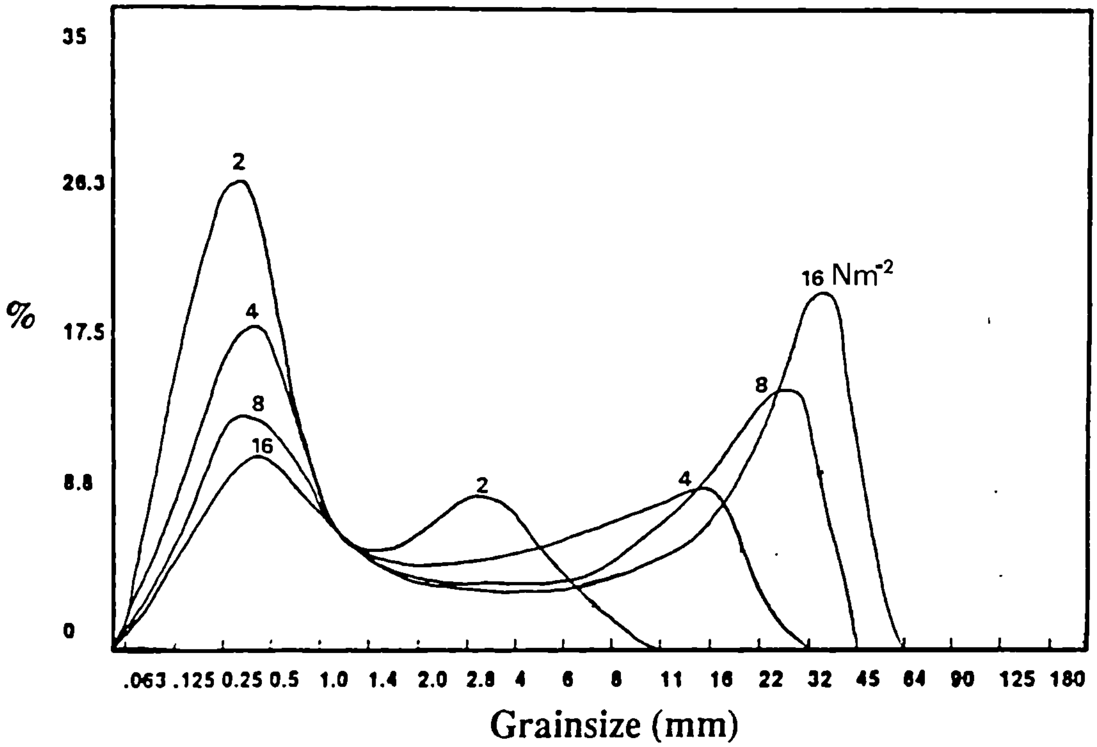
Sorting within the riffle-pool-sequence is clearly apparent within all three sites monitored, suggesting a generally applicable process. All riffles exhibit the winnowing of sediments within the coarse gravel size range, in accordance with magnetic tracing results, and all pools exhibit a competence at peak hydropower discharge of only half or less, the associated riffles. Fine sediments < 2mm are the dominant bedload within pools and the grainsize populations are considerably narrower than that at riffles. Clearly coarse sediments greater than 11 mm must be deposited preferentially in the pool-head and mid-pool regions, whilst pool-tail regions are likely to experience a preferential input of sand sized sediment. Sorting of sediment under hydropower regulation within the North Tyne is dominated by intra-pool downstream fining, the amount of sediment transmitted through the pools being dependent upon the supply of sand and fine gravel from the upstream riffle and pool-head.

The previous discussion gave the average grainsize populations for the individual sites; however, the actual picture of sediment transport with respect to the individual size fractions is more complex. Table 11.3 gives the actual grainsize changes with discharge as determined by the D50, D84 and D16 percentile classes, together with the sorting coefficient, which is a measure of the population standard deviation (Briggs, 1980). The development of the grainsize characteristics of the bedload at a site is difficult to interpret, and does not relate clearly to any measure of flow strength. Rather, the pattern is determined by the stochastic motion of individual clasts, which is in turn moderated by the opportunity for a particle to become trapped in a structural position. In the pools, shear stresses are too low for any general bed motion, and consequently, despite a supply of fine - coarse sediments, bedload is characterised by sporadic increases in particle size, broadly related to the prevailing discharge conditions. These fluctuations in the grainsize components of the bedload are possibly related to the burst-sweep cycle of turbulence associated with an unstable boundary layer which has been observed in regions of upwelling flow (see Chapter 7). More detailed research would be required to fully investigate the reasons for the sporadic nature of the grainsize composition of the bedload which was hoped to be addressed by the aborted 40 cumec request from Northumbria Water plc. The aims of this proposed release were to have observed the mobilisation of pool (and riffle) sediments at discharges shown to coincide with movement of magnetic tracer and high infiltration rates indicative of pool scouring. In the absence of this event it remains to be stated that bedload grainsize composition is highly variable at both riffle and pool locations, but for different reasons. In general, bedload becomes coarser and more poorly sorted as discharge increases and grainsize range widens which is in keeping with the observations of Komar and Shih (1990) for bedload monitored during flood events. The data presented in this study has amongst the lowest transport rates monitored, and as such, is highly influenced by the addition of single particles.

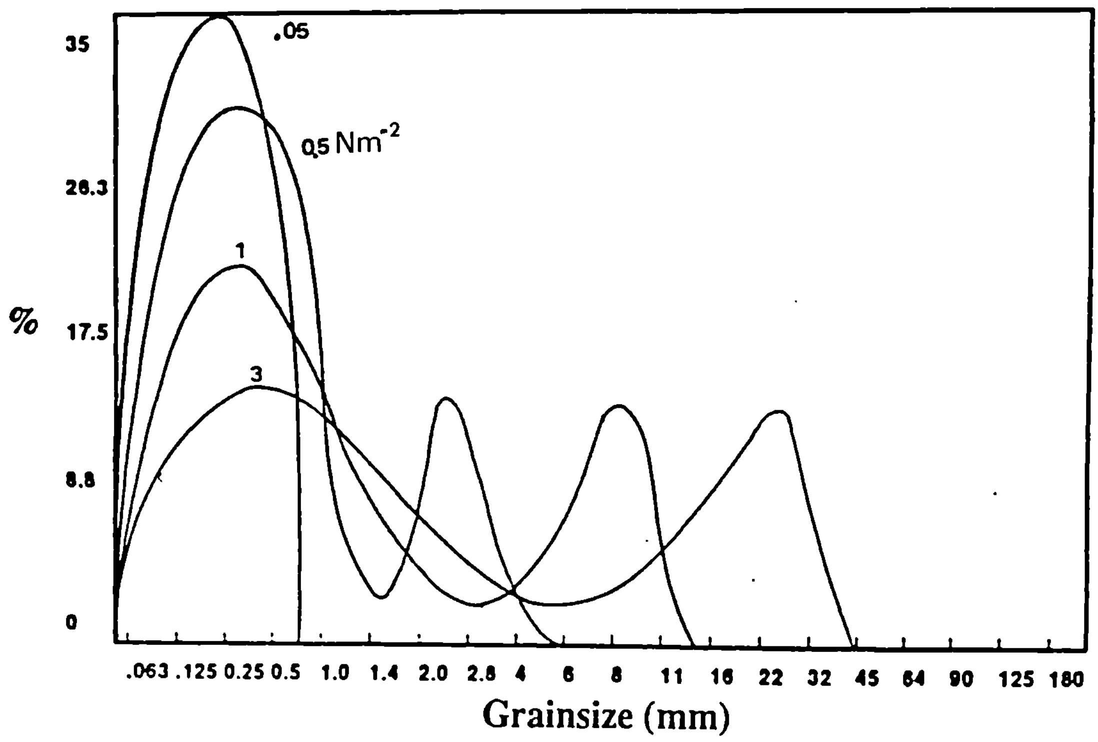
Figure 11.7 illustrates schematically the development of grainsize frequencies for pools and riffles at varying shear stress. The generation of these Figures is based upon the assignation of a bedload sample to an appropriate shear stress class, and the combining of those samples to provide a single representative population. The broad outline of the distribution was then traced by eye. The resulting grainsize distribution therefore represents an idealised representation of the actual data, which enables the determination of changes in bedload composition with increasing shear stress. The complexity of the actual distributions (in particular the bi-modality) precluded the use of simple descriptive statistical approaches such as those used by Komar and Shih (1992) to model the bedload grainsize monitored in the Oak Creek. Furthermore, the aim is not to provide a predictive model, but rather to provide a simplification of the complex patterns observed in the natural state at low transport rates.

Figure 11.7 indicates that equal mobility is not operative in the riffles or pools of the North Tyne at low transport rates, but rather selective transport that incorporates a wide range of grainsizes, but which includes progressively coarser particles as shear stress increases (Komar and Shih 1992). The development of grainsize in both pool and riffle locations is characterised initially by high proportions of fine sand, silt/clay, which increases as shear stress rises, but begins to decline as more and coarser sediment is entrained. The bi-modality of the pool bedload population is characterised by a progressive equalisation of the modal values, and a shift in modal value towards the

11.7 Schematic representation of the variation in Bedload grainsize with increasing shear stress: Riffles



Schematic representation of the variation in Bedload grainsize with increasing shear stress: Pools



coarser size sediment. Whilst equal mobility is implied for a given shear stress by the existence of a coarse and fine modal value, the progressive increase in the value of these modes suggests size selectivity. A similar sequence is apparent at riffle sites, whereby a bi-modal distribution is maintained though with progressively coarser size fractions. In the case of the riffles, the skewness actually reverses from fine to coarse, and the form of the bedload frequency curve begins to approach that of the bed material itself, although truncated at 64mm maximum particle size. The sediment transported at riffles corresponds to the beginning of Phase 2 bedload transport as defined by Jackson and Beschta (1982) in terms of the transport of riffle armour sized sediments. However, for most of the time sediment transport in the North Tyne is dominated by Phase 1 bedload , which involves the local redistribution of material stored in wake deposits, bank shadows, or as infill or isolated unprotected particles.

11.6 Relationships between bedload transport and hydraulic variables.

It was hoped at the beginning of this study that bedload transport rates could be associated with direct measures of bed shear stress. In the event, the transport rates were so small that bulked sectional values had to be used. Nevertheless, the discussion in Chapter 7 proved that the shear stress determined by velocity profiles, even when averaged for the section, provided a more accurate picture of the disparity between riffles and pools than the DuBoys method. Furthermore, initial observations suggest that sectional values of shear stress do explain the broad variation in bedload transport rates between riffles and pools; this is now considered in greater detail.

Given a uniform and constant supply of sediment with no structural assemblages it should be possible to explain the observed patterns of bedload transport from the force exerted by flowing water on the bed itself. This is the basis of sediment transport formulae based upon the Shields entrainment function (Shields 1936). Wolcott (1989) has identified a consistent departure from the ideal conditions described above, which he interprets as resulting from the development of bed structure. Wolcott's experiments were conducted in a flume where sediment supply effects were not an issue; however, this is clearly not the case in the North Tyne. Bed structure controls supply through the development of an armour layer, as well as structural assemblages; correspondingly, considerable scatter in the hydraulic/bedload transport relationship is to be anticipated.

Despite this, it is hypothesized that the lack of armouring and structure within the pools will provide a stronger relationship between sediment transport and hydraulic parameters.

Table 11.4 depicts the statistical strength of the relationships between sediment transport rate (I_b) in Kg/m/s, and a range of hydraulic variables which were measured simultaneously at a site; each site is represented individually.

With the exception of the Newton riffle 2 and Smales pool sites, no statistically significant relationships exist between local hydraulics and the bedload transport rate. Those that perform significantly ($p = 0.05$) are associated with the discharge at NR2 and SMP, although only 58% and 60% of the variation in bedload transport is explained in each case respectively. Clearly error in the sampling procedure may account for some of the variance, but recourse to Chapter 7, together with the care taken in sampling bedload, would suggest that this was minimised. Rather, the supply of sediment is controlled by the development of bed structure and armouring on the riffles, together with a depleted supply of surface fine sediment < 8mm as a result of hydropower regulation (Chapter 5). Sediment transport in the riffles exhibits some deterministic trends (with Q), but is clearly site specific, and of stochastic nature, dependent upon the structural control of sediment supply despite relatively high shear stress fluctuations. This is in accordance with similar observations by Beschta et al (1981) during a regulated release from the Electric Lake reservoir; in this case sediment supply was clearly limited at the riffles.

The inability to predict sediment transport rates from hydraulic variables using at-a-site hydraulic data in the pools is more difficult to explain. As explained above, the actual transport rates, relative to the riffles, is in accordance with the comparative magnitude of shear stress, but specifically the relationships are weak. The transport of fine sediment up to 22mm is supported by the magnetic tracing experiments, and therefore suggests that the measured transport rates and grainsize are not a function of the over-efficiency of the Helley-Smith sampler, (see above). In addition, the replicate measures of bedload transport conducted at compensation flow and hydropower flows were broadly similar in grainsize composition (the major differences being related to rising and falling stage conditions) which suggests that the sampling time of 3 minutes per sample enabled the collection of a representative population of sediment in transit. It is entirely possible that the bedload transport, moving as threads between the larger elements in the deeper pool

Table 11.4: Regression coefficients, Spearmans rank correlation (S_r) coefficients and the statictical significance of relationships developed between bedload transport rate (I_b) and a range of hydraulic variables.

Variable	a	b	r^2	p	S_r	p	df
Smales Riffle							
Q (m^3/s)	-5.92	0.88	0.07	NS	0.135	NS	9
U_b (m/s)	-5.96	-1.97	0.09	NS	0.278	NS	9
τ_p (N/m^2)	-5.54	0.82	0.31	NS	0.552	NS	9
w_o (W/m^2)	-4.64	0.76	0.31	NS	0.532	NS	9
Smales Pool							
Q (m^3/s)	-11.3	4.88	0.63	0.05	0.777	0.05	8
U_b (m/s)	-3.49	4.05	0.56	NS	0.751	0.05	8
τ_p (N/m^2)	-6.58	-1.29	0.16	NS	0.063	NS	8
w_o (W/m^2)	-7.66	-1.02	0.11	NS	0.074	NS	8
Tarset Pool							
Q (m^3/s)	-13.4	5.84	0.18	NS	0.223	NS	8
U_b (m/s)	-4.99	2.82	0.25	NS	0.290	NS	8
τ_p (N/m^2)	-6.13	0.51	0.18	NS	0.276	NS	8
w_o (W/m^2)	-5.44	0.50	0.19	NS	0.203	NS	8
Tarset Riffle 2							
Q (m^3/s)	-7.10	1.51	0.19	NS	0.499	NS	9
U_b (m/s)	-4.23	2.19	0.11	NS	0.497	NS	9
τ_p (N/m^2)	-5.83	0.66	0.12	NS	0.480	NS	9
w_o (W/m^2)	-5.04	0.59	0.13	NS	0.480	NS	9
Newton Pool							
Q (m^3/s)	-5.75	0.76	0.42	NS	0.757	0.05	8
U_b (m/s)	-0.43	0.99	0.45	NS	0.753	0.05	8
τ_p (N/m^2)	-5.17	0.38	0.12	NS	0.251	NS	8
w_o (W/m^2)	-0.47	0.33	0.26	NS	0.351	NS	8
Newton Riffle 2							
Q (m^3/s)	-6.65	2.09	0.50	0.05	0.900	0.001	11
U_b (m/s)	-3.18	4.83	0.43	NS	0.780	0.001	11
τ_p (N/m^2)	-3.89	-0.49	0.04	NS	0.360	NS	11
w_o (W/m^2)	-4.43	-0.10	0.01	NS	0.450	NS	11

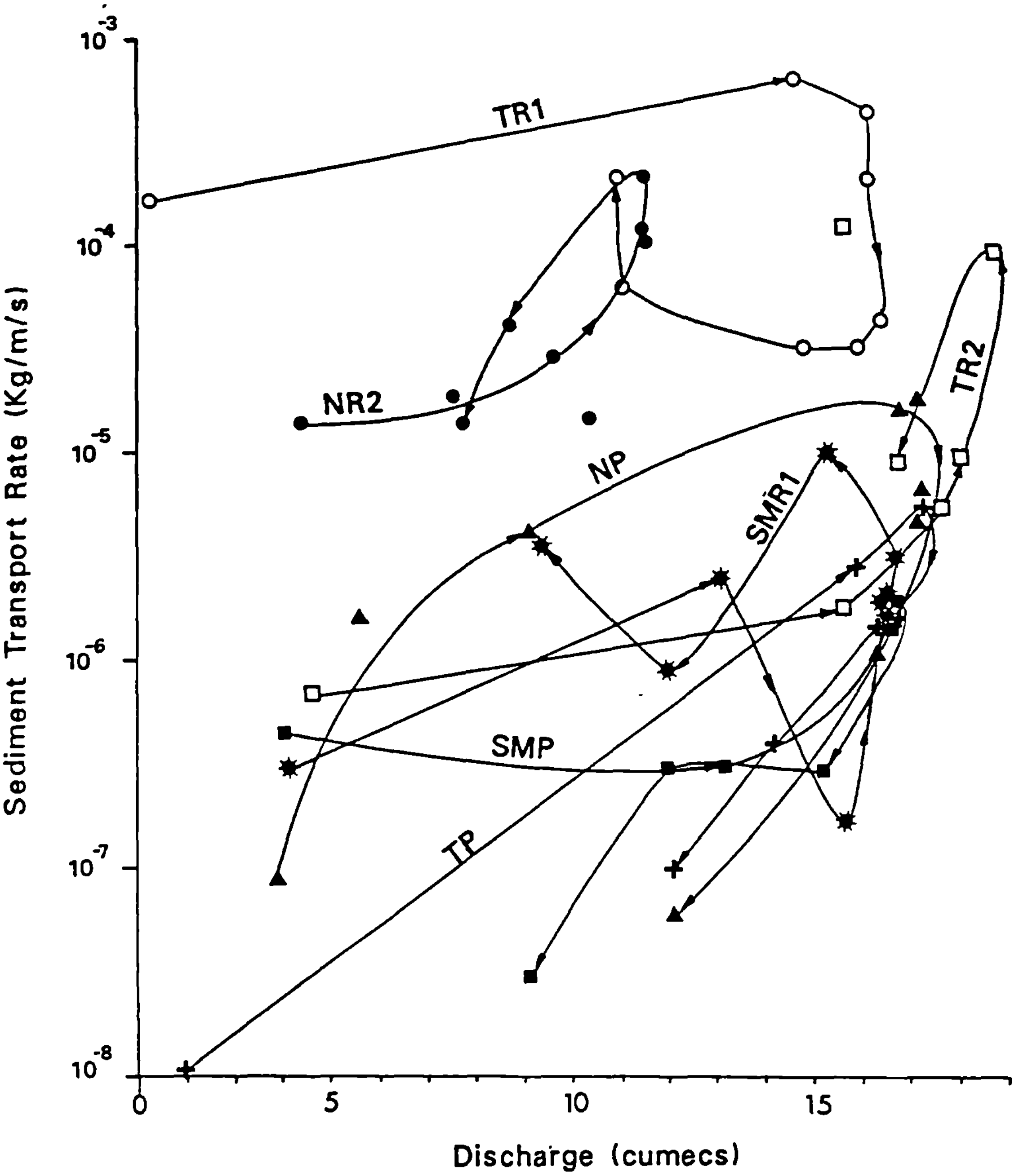
NB: **a** and **b** are the regression coefficients for equation $I_b = a\,X^{b}$.

regions, was not sampled, and therefore the patterns of sediment transport do not reflect the actual conditions at a site. At the low shear stresses monitored in the pools, it is also conceivable that the sediment transport monitored represents the very beginnings of transport, and is composed of infill and isolated unprotected particles, which become entrained only where the shear stress is at sufficient magnitude. The conclusion at this stage therefore becomes one in which at low shear stresses, bedload transport in pools is a stochastic phenomenon, dependent upon the coincidence of exposed particles with high shear stress, supply being deemed to be replete; the lack of measurements at each site being insufficient to establish the nature of the controlling mechanism.

Figure 11.8 depicts the hysteresis observed at each of the sites monitored during this study. This provides a clue to the apparent lack of a relationship between bedload transport rate and hydraulic variables. Hysteresis is complex and site specific, reflecting the individual hydraulic and supply conditions per riffle or pool. General patterns are evident, however, which suggest that pools tend to exhibit higher transport rates on the rising limb of a hydropower release than on the falling, and vice versa for riffles. Tarset riffle 1 is anomalous and exhibits clockwise hysteresis similar to pools. Klingeman and Emmett (1982) have interpreted hysteresis of this type as resulting from sampling downstream of a sediment supply; Tarset riffle 1 is immediately downstream from an island, with a deposit of fines associated with its distal end (Chapters 4 and 5). The anti-clockwise behaviour of riffle bedload hysteresis probably results from the loosening of surface sediments during the high shear stresses experienced on the rising limb of the release wave (Chapter 7); but unlike most sediment transport studies, the armour layer was not breached, and therefore rates remained low and supplies exhaustable.

The clockwise hysteresis and low transport rates in the pools suggest that sediment supplies were limited, particularly in the Newton pool, where shear stresses increased as discharge waned. This also strengthens the hypothesis that shear stresses were not sufficiently high to cause general mobilisation of the bed, but rather represented local redistribution of particularly exposed particles. Shear stress maxima in the pools tend to be localised and as such the transport of bedload is confined to these areas, despite a high percentage of exposed clasts on the pool bed.

11.8 Hysteresis in sediment transport rates for riffles and pools



Meigh (1987) together with many other writers, aggregates the information on transport rates to produce a larger database for statistical analysis, working on the basis that by increasing the population of the sample, a statistically (and deterministically) significant trend will be more likely to be discernible (Andrews 1983; Gomez and Church 1989; Komar 1987; 1989). Correspondingly, the data collected in this study have been combined to provide a database for riffles and one for pools.

The combined data for riffles and pools was log transformed to account for the wide range of data values, and a least squares regression procedure applied between bedload transport rate and a variety of hydraulic parameters. Statistically significant relationships were developed between bedload transport rate, shear stress and stream power, calculated using velocity profile determination of shear stress:

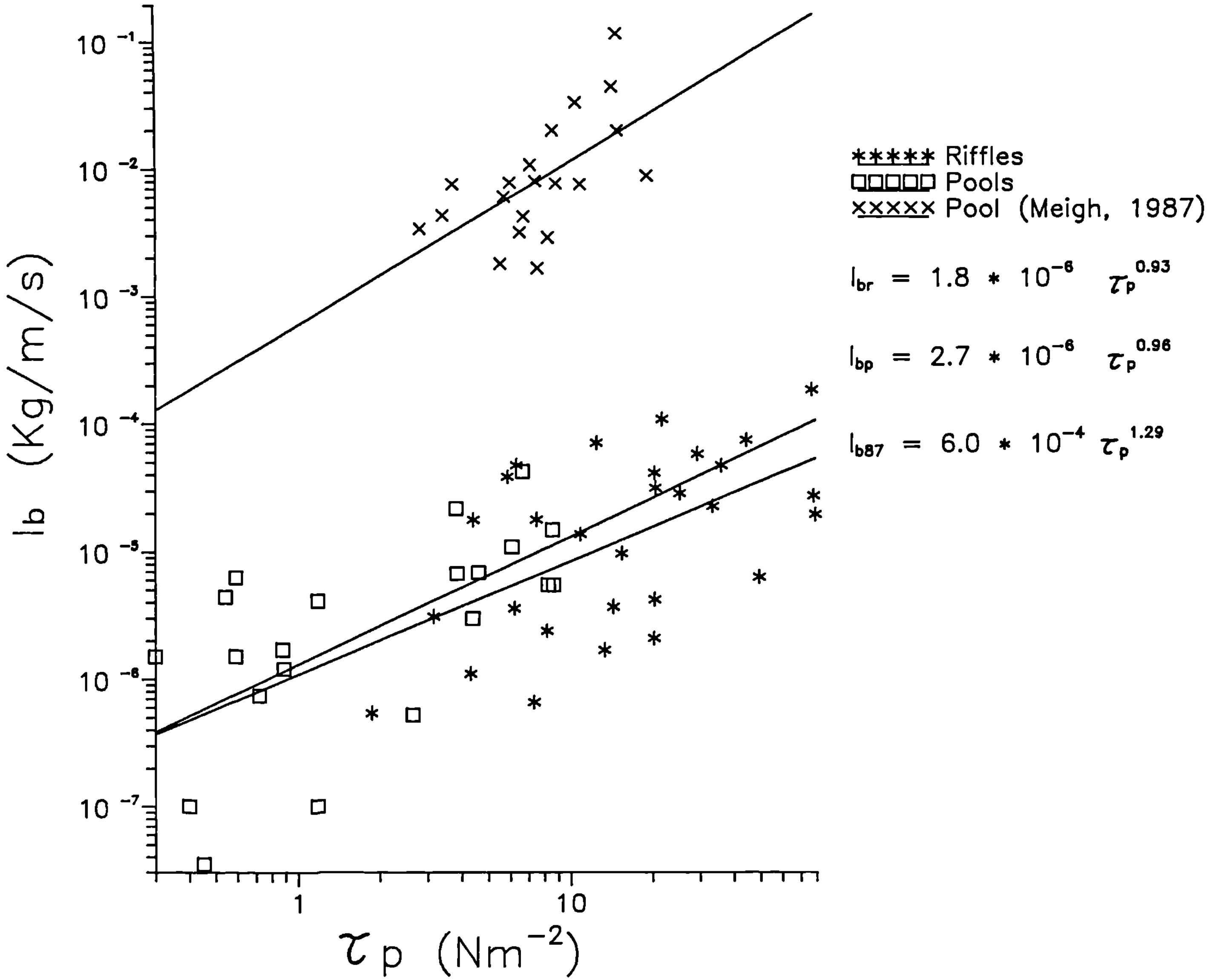
$$w_p = \frac{\tau_p . U}{g} \qquad \text{Equation 11.2}$$

Figure 11.9 depicts the form of the relationships developed for bedload transport rate (I_b) and shear stress. Data collected during floods from a pool in the River Severn by Meigh (1987) is shown for comparison, since the methods of sampling shear stress and bedload transport were the same as adopted in this study.

The low transport rates found in this study for a given shear stress are exemplified by the disparity between Meigh's results and the pool (and riffle) data from the North Tyne. This is to be expected, since the grainsize of the Severn is much finer than the North Tyne (D_{50} = 18.4mm (Severn), D_{50} = 45mm (North Tyne)) and was not strongly armoured (Meigh 1987). In addition, the shear stress range within the pool extended up to 30 N/m^2, compared to 9 N/m^2 in the North Tyne. However, the Severn site was located immediately downstream of a sediment source, which undoubtedly increased sediment loads through the reach. The rate of increase is higher in the Severn pool than those in the North Tyne, which is explained by the arguments developed above concerning low shear stress and sediment supply.

Sediment transport rate increases at a greater rate for a given shear stress in the pools than at the riffles, but only marginally. However, reference to Table 11.5 shows that a

11.9 The relationship between shear stress and sediment transport for riffles and pools. Comparable pool data from Meigh (1987)



greater percentage of the variation in bedload transport is explained by shear stress in the pools than in the riffles. This would be expected, given the lack of bed structure and the relative availability of sediment in the pools.

Table 11.5: The percentage of variance explained by log-log regression of bedload transport rate on shear stress and stream power for riffles and pools. (Data for the River Severn after Meigh 1987)

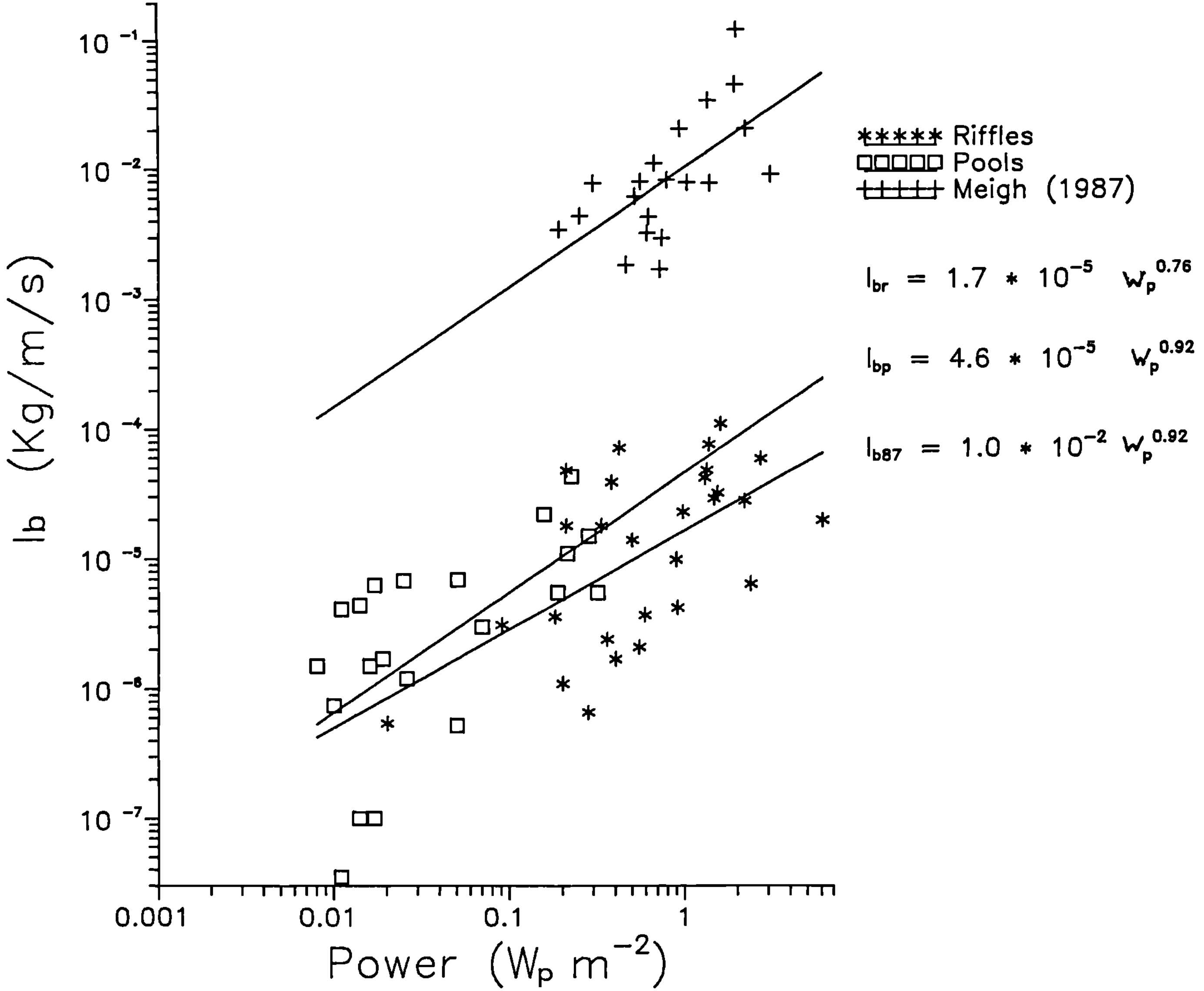
	Shear stress (N/m^2)	Power (W/m^2)
Riffles	$r^2 = 0.31$ $p = 0.05$	$r^2 = 0.36$ $p = 0.05$
Pools	$r^2 = 0.38$ $p = 0.05$	$r^2 = 0.42$ $p = 0.05$
Severn pool.	$r^2 = 0.58$ $p = 0.01$	$r^2 = 0.63$ $p = 0.01$

Figure 11.10 depicts the relationship between stream power and sediment transport rate in riffles and pools during hydropower generation. The values of stream power in the pools are much lower than those recorded during floods in the Severn at Caersws; however, the rate of increase is exactly the same. This implies that the lower rate of sediment transport is clearly the result of controls on sediment supply (since material of the grainsize of the Severn was available on the pool bed), or a function of the much lower stream powers. Unfortunately, the discrepancy was not possible to elucidate further under conditions of hydropower regulation.

The rate of increase of sediment transport with stream power is greater in the pools than on the riffles, which again reflects the greater control on sediment supply resulting from a well developed armour layer and enhanced bed strength/structure. Furthermore, the percentage of variation in bedload transport explained by stream power is greater for the pools, which is in accordance with the structural control hypothesis.

Table 11.5 shows that stream power explains more of the variance in bedload transport rate than local shear stress, which confirms the findings of Meigh (1987) and extends the observation to low transport, low stream power conditions in channels of coarser bed material.

11.10 The relationship between sediment transport rate and stream power for riffle and pool sequences. Comparable pool data from Meigh (1987)



Although significant at the 0.05% level, the relationships between shear stress, streampower and bedload transport rate still only account for between 31-42% of the variance. Put another way, 69-58% of the variation in bedload transport is not explained by local hydraulics.

Meigh (1987) found that the relationship improved when only locally entrained bed material was used. The definition of what constitutes locally entrained material (as opposed to material derived from upstream sources as well) is specific to a given location, but must include particles of local bed material size. The magnetic sediment experiments showed that medium gravel was incapable of transport over the pool-tail due to the low shear stresses. Consequently locally-derived material is likely to include sediment > 5.6mm. Similarly, material < 5.6mm (but larger than coarse sand) though competent within the pool, did not travel as far as finer sediments. Material < 0.25mm is included in the suspended sediment size range, and is likely to be derived from upstream sources. For the purposes of this study, four divisions have been chosen for which their individual relationships to shear stress and stream power are assessed.

Figure 11.11 depicts the sediment transport rate by grainsize class, against shear stress, and Table 11.6 illustrates the relative percentage of variance explained in each case.

Fig 11.11: Relationships between bedload transport rate and shear stress on a particle size basis.

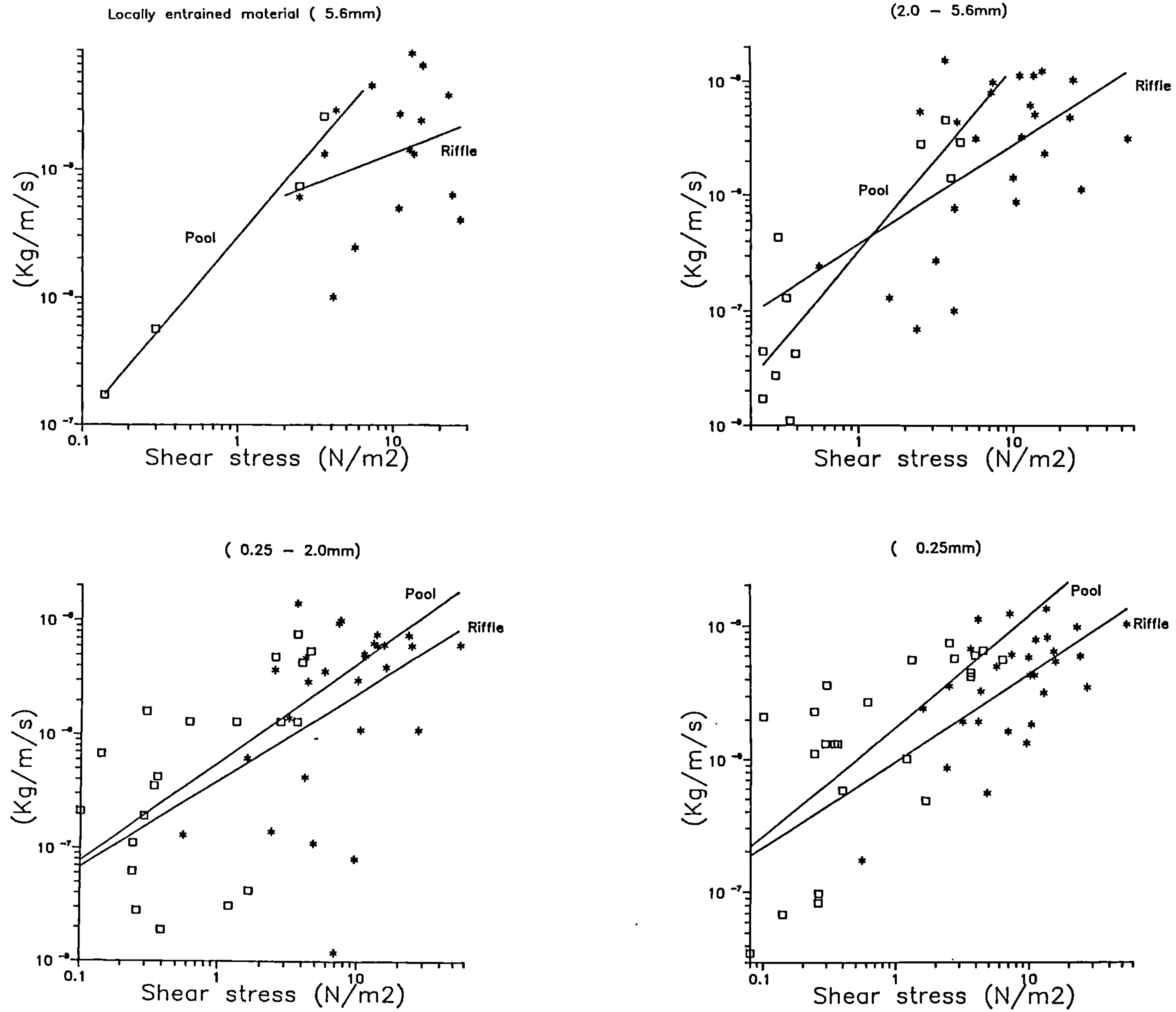


Table 11.6: The percentage variance explained in log-log regression of sediment transport rate and shear stress based on four categories of size class.

	Shear Stress (N/m^2)	Power (W/m^2)
R (> 5.6mm)	$r^2 = 0.05$ NS	$r^2 = 0.08$ NS
P	$r^2 = 0.98$ $p = 0.01$	$r^2 = 0.99$ $p = 0.01$
R (2-5.6mm)	$r^2 = 0.03$ NS	$r^2 = 0.12$ NS
P	$r^2 = 0.86$ $p = 0.01$	$r^2 = 0.67$ $p = 0.01$
R (0.25-2mm)	$r^2 = 0.28$ NS	$r^2 = 0.24$ NS
P	$r^2 = 0.21$ NS	$r^2 = 0.31$ NS
R (< 0.25mm)	$r^2 = 0.16$ NS	$r^2 = 0.19$ NS
P	$r^2 = 0.34$ $p = 0.05$	$r^2 = 0.56$ $p = 0.05$

Where NS is not statistically significant at 0.05% level, **R** = riffle and **P** = pool.

Clearly there is a strong relationship between locally entrained sediment in the pools and both shear stress and stream power. Interestingly, shear stress is the better predictor, accounting for 99% and 86% of the variance in bedload transport rate of material > 5.6mm and > 2mm. No such relationship exists for the riffles, which suggests that the process of bedload transport of even locally-derived sediment is stochastic in nature, whereas locally entrained pool sediment is clearly controlled by local hydraulics. The strength of the relationships developed for the pools declines as the sediment size of bedload decreases, and presumably more material is derived from upstream sources. The converse exists at the riffles, but none of the relationships are significant.

Bedload transport in the pools increases at a greater rate than the riffles, especially for the locally derived gravel. This is to be expected, given the structural constraints on gravel transport at the riffles. Furthermore, it is consistent with the hypothesis that much of the pool bedload is derived from isolated unprotected particles and infill.

The results described in this section confirm the observations of Meigh (1987) that point shear stress and power are the best predictors of sediment transport rate at a site, and particularly so for locally-derived material. However, at low transport rates, large numbers of observations are required to confirm the existence of any relationships between sediment transport and hydraulic parameters. In addition, sediment transport is clearly site specific, particularly at low transport rates and on riffles, with controls on sediment supply overriding the net effect of local hydraulics. This situation represents a positive feedback loop, whereby the strength of shear stress developed at riffles during hydropower regulation effectively depletes fine sediment stores, and strengthens the riffles beds, leading to supply deficient bedload transport regime, characterised by random dislocation of weaker structural elements.

11.7 Thresholds of Sediment transport in riffles and pools: problems of prediction.

The initiation of transport (sensu stricto Carling 1983) of individual grains will be considered in the next section, when transport of sediment during flood conditions can be included. However, Reid et al (1985) discuss the thresholds of sediment transport (independently of grainsize) and cessation. In the context of this study, this is important to consider with respect to infiltration rates and possible morphological change in the riffle-pool sequence. Furthermore, it is of general use to other workers to assess the performance of available bedload transport formulae under conditions of supply limitation and low transport rates.

Table 11.7 shows the thresholds of sediment transport, defined as the point on the I_b/time graph at which a major increase in transport rate occurs, above compensation flow levels. This is similar to the technique employed by Reid et al (1985). In addition, the threshold of gravel transport is determined as the point at which particles of 5.6mm appear in the bedload. Carling (1989) chose this to represent the beginning of fine sediment winnowing from a stable surface of coarser particles, in a stream of similar lithology to the North Tyne. The local shear stress, local stream power and discharge, at initiation of transport and cessation, are shown for each site.

Predicted values of shear stress, stream power and discharge are shown for comparison. These have been derived using some of the standard formulae applied to gravel-bed streams. The critical shear stress for the initiation of material 5.6mm diameter was calculated using the Shields entrainment formula modified by Miller et al (1977):

$$\tau_{ci} = 114 d_i^{0.4} \qquad \text{Equation 11.3}$$

where d_i is the size of reference sediment in metres. This formula was chosen since it is derived from a wide range of gravel bed streams, and is of more general application than those derived from individual channels (Carson and Griffiths 1985).

Stream power was determined by using the formula of Bagnold (1980), which was employed by Carling (1989) to predict the stream power at which material of 6mm would come into motion. This formula takes the form of:

$$\omega_o = 2844\ d_i^{1.5}\ (\log 12\ h/d_i) \qquad \text{Equation 11.4}$$

where d_i is the chosen size of sediment, in this case 0.0056m, and h is the flow depth at which it is entrained.

Values for critical discharge for the onset of bedload transport, analogous to the movement of fines over a stable gravel bed (Newson and Bathurst 1990), were obtained using the Schokolitsh equation in the form modified by Bathurst et al (1987) and applicable only to Cobble/Boulder-bed streams with a slope > 0.1%. This applies only to SMR and TR1 in the North Tyne. The equation takes the form of:

$$q_{ci} = 0.21\ g^{0.5}\ D_{16}^{1.5}\ S^{-1.12} \qquad \text{Equation 11.5}$$

where q_{ci} is converted to discharge in cumecs, by multiplying by the full channel width. S is the channel slope and D_{16} is the value of the 16th percentile of surface sediment, sampled by a size by number method.

The determination of the critical discharge for material of 5.6mm was made by using the formulae:

$$q_{ci} = q_{c50}\ (D_i/D_{50})^b \qquad \text{Equation 11.6}$$

$$q_{c50} = 0.15\ g^{0.5}\ D_{50}^{1.5}\ S^{-1.12} \qquad \text{Equation 11.7}$$

$$b = 1.5\ (D_{16}/D_{84}) \qquad \text{Equation 11.8}$$

where D_{16}, D_{50} and D_{84} are the percentile grainsize values of the surface sediments. The value of q_{ci} is converted to discharge in cumecs by multiplying either by full channel width, or by the actively transporting width, which Newson and Bathurst (1990) assume is equal to half the full channel width.

Table 11.7 shows that the critical conditions for sediment transport, and the transport of material of 5.6mm, are specific to a given riffle or pool. This has important ramifications for the application of sediment transport formulae, since it implies that no two portions of the bed, albeit of similar morphology and function, will behave similarly. This is intuitively what a geomorphologist knows already, since this must occur in order for river bed morphology to evolve. Importantly, it is evident that the shear stress and stream power for the initiation of sediment and gravel transport in pools occurs at much lower values than at riffles. This is contrary to existing models of riffle-pool sediment transport, which assumes the need for a velocity reversal or equalisation to occur before a pool can scour, or cope with an equivalent competence to a riffle (Keller 1971; Ashworth 1987; Petit 1987). This important point is examined in greater detail in the following Chapter 12.

Evidence of supply limitation is apparent at NR2 for bedload in general, and at the NP for material of 5.6mm, where the shear stress and stream power at cessation of bedload is higher than at initiation. At all other sites the critical conditions for cessation of sediment transport are lower than initiation, by a factor of 3.1 and 5.1 for riffles and pools respectively. This compares with a value of 2.8 times lower for the Turkey Brook experiments. Reid et al (1985) conclude that the lower critical shear stress and stream power required for the cessation of bedload transport stems from the difference between overcoming static resistance and dynamic resistance of a particle in motion. The pattern is similar for gravel transport and cessation, with much lower values recorded for pools than riffles.

The performance of the initiation of motion formula are characteristically poor, with shear stress values over-predicted by 3-15 times, and stream power over-predicted by 3 -

Table 11.7: Thresholds of sediment and gravel transport and cessation in riffles and pools during hydropower regulation, including predicted values based on Komar, (1989); Bagnold,(1980) and Bathurst et al (1987).

Site	τ_{pi}	τ_{pc}	Predicted	ω_{pi}	ω_{pc}	Predicted	Q_{ci}	Q_{cc}	Predicted
Initiation ($_i$) and cessation ($_c$) of general bedload transport									
SMR	4.1	---	---	0.40	----	---	10.9	14.8	11.6
TR2	6.8	3.1	---	0.28	0.18	---	16.0	----	55.0
TR1	---	---	---	----	----	---	15.7	17.6	16.9
NR2	10.9	13.6	---	0.98	1.54	---	8.5	16.7	53.0
SMP	0.34	0.14	---	0.02	0.01	---	6.0	16.7	---
TP	1.19	0.10	---	0.05	0.03	---	17.3	16.1	---
NP	3.91	3.60	---	0.21	0.19	---	15.8	16.5	---
Initiation ($_i$) and cessation ($_c$) of fine gravel winnowing (5.6mm)									
SMR	2.5	2.4	3.59	0.21	0.20	4.10	12.8	14.7	3.3- 6.6
TR2	7.3	3.1	3.59	0.42	0.18	4.12	17.8	16.2	--------
TR1	---	---	----	----	----	----	15.7	17.6	8.3-16.7
NR2	10.9	9.8	3.59	0.98	0.89	3.57	6.4	6.4	5.4-10.8
SMP	0.30	0.26	3.59	0.02	0.014	4.35	16.6	8.8	--------
TP	----	----	----	----	----	----	----	---	--------
NP	3.06	4.50	3.59	0.21	0.23	4.26	16.9	13.4	--------

217 times. The degree of over-prediction is greatest in the pools. The values for the critical discharge predicted by the modified Schokolitsch formula, are reasonable, with values for general bed motion and the initiation of 5.6mm gravel both within 7-8 % of the actual value. This only applies to the conditions experienced at two of the sites, where the slope conditions were within the parameters of the formula. No satisfactory prediction of initiation criterion is available for pools, though evidence in this study suggests that sediment transport begins at much lower shear stresses and stream powers than at riffles. This is considered in more detail in the following Chapter (12) which examines the initiation of sediment transport on a particle size basis, together with the routing of coarse sediment (> 22mm) at discharges up to bankfull.

Bedload transport in riffles and pools at hydropower discharges is characterised by poorly sorted material at low transport rates. Pools experience much lower transport rates than riffles, although the force required to initiate motion is much lower than on riffles. Shear stress and stream power, determined from velocity profiles, explains up to 42 % of the variation in sediment transport rates in pools and 36% at riffles. The relationship is particularly strong for locally entrained material, which confirms the observations of Meigh (1987). Selective entrainment occurs, with progressively coarser bed material resulting from increasingly higher shear stress; however, the grainsize populations are complex, and generally bi-modal. Pools experience a maximum competence of only half the value on the riffles. There is no connectivity between sediment transport in pools and associated riffles during hydropower regulation.

Sediment transport is clearly supply limited on the riffles. The transport of sediment in the pools is more difficult to explain, since sediment is clearly available for transport. At low discharges,transport rates and shear stresses, it is hypothesized that fluctuations in the turbulence at the bed of the pools governs much of the apparent supply deficiency. Predictive techniques fail to account for the transport conditions observed at riffles, and particularly at pools. An exception appears to be the modified Schokolitsh formula, providing it is used within its design parameters.

The following Chapter investigates the transport of coarse particles (> 22mm) over a range of discharges up to bankfull. In addition, information on the thresholds of transport of individual particles will be looked at in more detail.

Chapter 12.0

Tracer studies of coarse sediment transport in riffle-pool sequences.

12.1: Coarse sediment transport in riffle-pool sequences: path lengths and critical conditions for particle motion at discharges up to bankfull.

Many of the factors that influence the transport of sediment have been dealt with in the previous sections. This section describes the movement of sediment coarser than 22mm from positions on riffles and in pools, during discharges up to bankfull. In addition, bedload data and tracer data is combined to provide information on the threshold of transport (sensu stricto Carling 1987) of grainsizes up to 150mm.

Chapter 8 described the application of tracing techniques to the study of sediment transport (Table 8.1). Tracing experiments have been conducted in gravel-bed rivers since the 1960's (Takayama 1965), and have fallen into three basic groups: studies of initiation of motion (Hey 1975; Carling 1983; Petit 1990); Studies of path length in relation to hydraulic variables (Butler 1977; Ashworth and Ferguson 1989; Carling 1987; Hassan and Church 1992); and studies of structural and morphological controls on transport (Wilcock 1967; Keller 1971; Larrone and Carson 1976; Thorne and Lewin 1979; Brayshaw 1985; Petit 1987; Ashworth 1987; Hassan 1989). Recently, Hassan and Church (1992) have reviewed the information provided by tracer experiments and "confirmed the lack of a relationship between the distance of movement and the particle size", although with sufficiently large size ranges, evidence exists to suggest that coarser material travels shorter distances.

Milhous and Thorne (1982) conclude from individual tracing experiments that channel morphology controls the pattern of tracer (coarse sediment) motion through the pattern of shear stress (see Chapters 8.0 and 10), a point corroborated by Ashworth (1987) and recognised by Hassan and Church (1992). In addition, Milhous and Thorne (1982) provide 7 observations of tracer (coarse sediment) behaviour:

1. Probability of motion is greatest for smaller particles.

2. For larger particles the distance of transport increases with size, whilst for smaller particles the converse situation pertains.

3. The longer the duration of discharge above the critical threshold, the higher the probability of a particle being moved.

4. The recovery rate of tracer particles increases with tracer size.

5. Coarser particles (> 37mm) are most often found in the armour layer.

6. Finer particles (< 37mm) are most often found at channel margins or buried.

7. Recovered particles tend to be located at riffles or "intermediate locations" not in pools.

Experiments conducted by Hey (1975) on the River Severn, at flows just above the critical threshold conditions for bed motion, indicate that selective entrainment occurs. The median size particles travel furthest, whilst finer particles are sheltered, and larger particles are too heavy for transport (Hey 1982). This represents the opposite conclusion to that deduced from bedload measurements, where the presence of a broad range of sediment sizes is used to "prove" equal mobility (Wilcock 1992; Andrews 1983). Ashworth and Ferguson (1989) use tracer data to illustrate selective entrainment on the basis of the percentage of tracer particles moved. Using data collected from 9 different environments (including riffles and pools), they showed that for particles coarser than the bed D_{50} the percentage entrained decreased rapidly, and that particles much finer than the bed also exhibited reduced entrainment. This supports the earlier observations of Milhous and Thorne (1982), and Hey (1982). A major tracing programme conducted in the Virginio Creek involving 3935 painted tracers showed a similar pattern of motion to earlier experiments (Tacconi et al 1992). Fine sediments were preferentially "embedded" in the armour layer, whilst coarser sediments tended to remain in exposed locations. Transport of tracers was approximately similar over three floods, with finer particles travelling furthest (and fastest). However, no simple relationship to discharge was observed; instead, the authors concluded that the dynamics of the bed over time conditioned the transport of particles.

Hassan et al (1984), highlight the main limitations of painted pebble tracing through their experiments using magnetic tracers. The dynamics of the scour layer introduces a vertical dimension to the dispersal of tracer particles through burial and re-exposure. Painted tracers cannot of course be found below the surface layer, and hence are lost to the survey. Hassan and Church (1992) document the loss of tracers as a result of burial, concluding that up to 66% of tracers can be buried in the scour layer after a single event, and that with time this number eventually increases. Nevertheless, the data from tracing experiments that document surface mobility have indicated the complexity of the transport process and have provided important evidence for morphological controls on sediment transport.

12.2: Methodology

For the purposes of this study, sediment was taken from 6 riffles and 3 pools for the size range 22mm - 150mm. The lower limit represented the upper limit of magnetic tracer material and the upper limit represents the size of material that could easily be removed back to the laboratory for painting. In addition, the larger size of painted pebble was considered the maximum that could be emplaced without incurring objections from local fishermen and landowners, (no small consideration in a popular salmon river).

Each stone was weighed and the b-axis measured. No account of particle shape was made, since no significant differences between riffles and pools had been observed in the sedimentological analysis. Each tracer particle was painted with bright yellow oil-based road paint, and an alphanumeric identifier drawn on all sides in permanent black marker pen. Each tracer particle was trodden into the bed along surveyed sections, in groups of four, consisting of a 22, 32, 45 and 64mm particle (N.B. phi scale). Every second group contained a particle within the 90mm size range, and at least 4 particles per section were in the 125mm size range. This system was designed to ensure that the behaviour of a given size of particle could be discerned for different regions of the cross section, ie pool deeps, channel margins, riffle shallows .

Particle positions were re-surveyed after suspected flood events, after an initial survey confirmed that little motion was associated with hydropower flows once the tracers became incorporated into the surface material. Relocation of tracers within pools up to 1.5m deep at compensation flows was achieved by walking through the pool in a series of repeated sections, peering underwater with a facemask and snorkel. The tracer was located by surveying from a fixed datum, using a theodolite and Electronic Distance Meter.

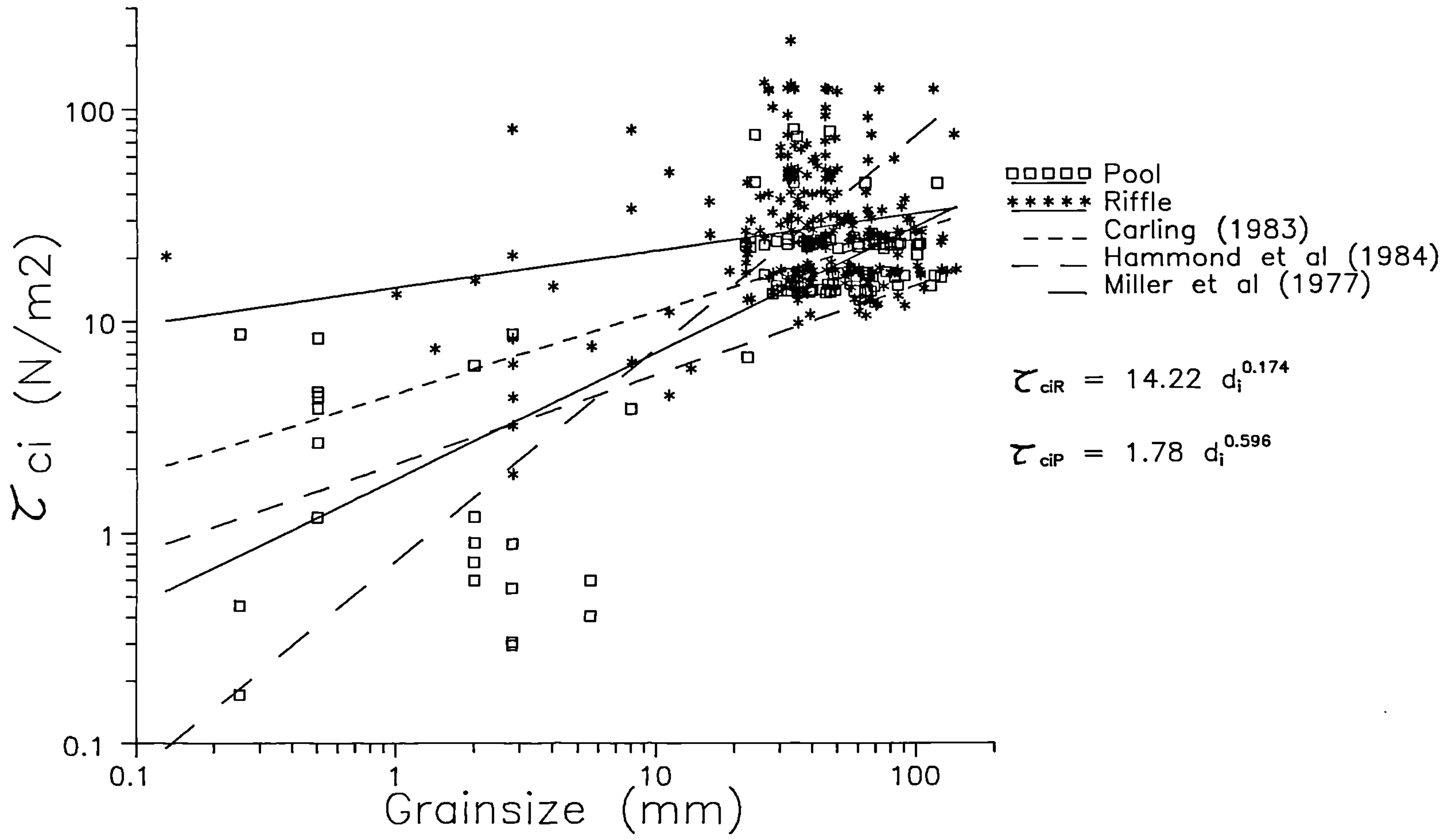
The bright yellow road paint proved to be visible in the deepest peat stained water, provided turbidity was low. Each survey was drawn-up and the distance travelled, together with the trajectory of each particle, was recorded. The movement of each particle was assumed to be associated with the maximum discharge experienced in the reach during the period between surveys. This data, together with the data from trash-line surveys and stage readings, were used to construct the shear stress at-a-point according to the methods outlined in Chapter 7.0.

12.3: Initiation of transport for individual particle sizes.

The previous section detailed the debate concerning the equal mobility, or selectivity of gravel entrainment. Data collected from tracer surveys enabled values for the maximum shear stress at which a particle did not move, and a value for the minimum shear stress at which a particle moved, to be identified. This approach will tend to under-estimate the shear stress at which particles did not move, and over-estimate the shear stress associated with transport. Nevertheless the results are not outside the typical values recorded for similar gravel-bed streams (Carling 1983; Ashworth and Ferguson 1989; Petit 1990), and serve to illustrate the differences between riffles and pools under these constraints.

Figure 12.1 depicts the log-log, least squares regression relationship between grainsize and shear stress at initiation of transport. The tracer data is combined with the data from bedload transport measurements in order to extend the size range. The shear stress values associated with the transport of a given grainsize in the bedload data is the maximum value associated with a given section, unless the position of the sample containing the largest particle was noted (see Chapter 11). Values of shear stress associated with maximum bedload grainsizes are close to those recorded for tracer particles. The choice of units for the axis reflect those used throughout this study.

12.1 The relationship between critical shear stress for transport and particle size for riffles and pools in the North Tyne at discharges up to bankfull. Three equations for the initiation of sediment transport are shown for comparison.



Three empirically-derived curves are also plotted for comparison with those developed for the riffles and pools. The curve of Carling (1983) is based on the motion of tracer particles into a bedload trap, and includes material up to 440mm. Extrapolation of the data to below 10mm takes it beyond the empirical conditions. This is similarly the case with the curve of Hammond et al (1984) whose data spanned the size range 5 - 20mm. The modified Shields curve of Miller et al (1977) spans the full size range present within the North Tyne data.

The data from Great Eggleshope Beck (Carling 1983) was derived from a substrate of similar geology, although the scale of the channel is much smaller. The data of Hammond et al (1984) was derived from visual observations of marine gravel motion, and was notable for the lack of bed armour or structure, a fact that was considered analogous to the sediments in the North Tyne pools. The data from the modified Shields curve, is based on flume experiments using uniform grainsizes (Miller et al 1977).

The equations of each curve are shown below, adjusted for the units used in this study:

North Tyne Riffles:	$\tau_{ci} = 14.22\ D_i^{\ 0.174}$	$D_{50} = 54mm$	Equation (12.1)
North Tyne Pools:	$\tau_{ci} = 1.78\ D_i^{\ 0.596}$	$D_{50} = 42mm$	Equation (12.2)
Carling (1983):	$\tau_{ci} = 4.51\ D_i^{\ 0.380}$	$D_{50} = 20mm$	Equation (12.3)
Hammond et al (1984):	$\tau_{ci} = 2.09\ D_i^{\ 0.420}$	$D_{50} = 8mm$	(Equation 12.4)
Miller et al (1977):	$\tau_{ci} = 0.72\ D_i^{\ 1.000}$		(Equation 12.5)

If equal mobility was operative, then each grainsize would be entrained at the same shear stress and the curve would be horizontal (the exponent value would equal 0). Alternatively, selectivity based on grainsize would result in a steeper curve so that grainsize increased in proportion to shear stress. The evidence from Figure 12.1 indicates that size selectivity is expressed more within the pools, where bed structure, armour and compaction are lowest, than on the riffles, where a combination of these factors, produces a near equality of mobility. This observation runs contrary to that proposed by Bathurst

(1987), who suggested that the complexity of packing and structure in gravel-beds would limit the application of equal mobility theory to loose, unconsolidated sediments. It is the very presence of this structure that results in coarse material being entrained at shear stresses comparable (though much enhanced) to fine particles .

In comparison with other studies, the pool data corresponds best with the relationship developed for fine marine gravels (Hammond et al 1984). In contrast, the riffle data plots closest to the curve of Carling (1983) which is to be expected, given the similarity of geology and environment. The fact that the Great Eggleshope Beck data is best described by a function lying between those of North Tyne pools and riffles, is in accordance with Carling's description of the bed as lacking a well developed armour, but exhibiting compaction (Carling 1983; 1987).

The effect of increased bed structure/compaction is evident from the higher shear stresses required to initiate the transport of riffles sediments of the same calibre as the pool. Of interest is the tendency for the discrepancy between riffles and pools to equalise at grainsizes above 2.D_{50}. Presumably, as the grainsize increases above the D_{50} of the bed, relative exposure effects begin to override the structural restraints on transport, or inertial effects of the larger particle mass, dominates any other factors. In any event there is an order of magnitude difference in the shear stress required to initiate the transport of fine sediments (< 1mm) from riffles than from pools. In addition, although the relationships tend to converge, riffle data consistently plots above the curve for grainsizes equal to or below the D_{50} of the bed. The scatter in both relationships, but particularly apparent in the riffle data, is indicative of the complexity of particle arrangements and the instability of the flow field (Chapter 7), and explains the fluctuating bedload transport rates alluded to in Chapter 11.

The effects of bed structure on sediment transport have been identified in Chapter 6; Table 6.1 reviews some of these. The documented discrepancies between structured and unstructured sediments are of the same order of magnitude as those recorded between riffles and pools. It is clear that not only is structure/compaction a retardent on the initiation of transport, but it also affects the transport lengths, and rates of entrainment of individual particles.

The variation between riffle and pool entrainment can be expressed in a dimensionless format, through the Shields entrainment parameter, which is shown in its modified form in Chapter 11, equation 11.4 (Miller et al (1977). The Shields parameter for a selection of grainsizes is shown in Table 12.1, which illustrates how it varies with increasing grainsize, for both riffles and pools the rate of decrease being greatest for the riffle material. The variation in Shields parameter is well documented, and is a feature of the entrainment of material from a mixed sized bed where relative protrusion effects are experienced (Carling 1983; Komar 1989).

Table 12.1 Shields entrainment parameter for different grainsizes in riffles and pools

Grainsize (mm)	θ riffles	θ pools
10	0.131	0.043
20	0.074	0.033
50	0.035	0.022
125	0.016	0.015

Wolcott (1989) identified the component of "geometric structure" within the Shields parameter as tending to increase the value above that predicted for structureless sediments. Furthermore, his diagram 4.5 shows an apparent convergence towards coarser particles, indicating that structural effects reduce for larger clasts. This is also the case for the riffle and pool data in this study and may be related to relative protrusion effects.

Recently, Komar (1986; 1987; 1989) has sought to produce a general entrainment function for gravel bed rivers by using the dimensionless data from a range of studies, including those of Hammond et al (1984) and Carling (1983). This avoids the site specific problems encountered by using dimensional values. By plotting the Shields parameter against the D_i/D_{50} on logarithmic axis, Komar achieved an equation:

$$\theta = 0.045\ (D_i/D_{50})^{-0.63} \quad \text{(Equation 12.6)}$$

A similar analysis for the riffle and pool data reveals two separate formula:

$$\theta_r = 0.054\,(D_i/D_{50})^{-0.275} \quad \text{(Equation 12.7)}$$

$$\theta_p = 0.031\,(D_i/D_{50})^{-0.117} \quad \text{(Equation 12.8)}$$

Ashworth and Ferguson (1989) using data from three separate gravel-bed rivers with grainsizes and shear stresses similar to those in the North Tyne (D_{50} = 23-98mm, p = 7-406 N/m^2), observed a relationship of:

$$\theta = 0.089\,(D_i/D_{50})^{-0.740} \quad \text{(Equation 12.9)}$$

According to Andrews (1983), equal mobility would be expressed by an exponent of -1.00. Correspondingly, not only is the pool data in the North Tyne entrained at a Shields stress on average 39% lower than comparable riffle sediments, but the process is decidedly size selective for both riffles and pools at discharges up to bankfull.

12.4: Entrainment thresholds, critical discharge and the effects of regulation on their exceedence frequency

Individual site relationships have been developed in addition to the general model presented above. These have been developed in order to produce values of discharge associated with a given shear stress based on the relationship between discharge and shear stress outlined in Chapter 7. From the discharge it was hoped to produce values for the frequency of exceedence based on the discharge duration curves developed in Chapter 3.

Table 12.2 depicts the associated equations and statistical significance (determined by least squares regression analysis) for the site specific relationships between the threshold of transport and grainsize. The distribution of data is influenced by the lack of data fo a range of discharges, correspondingly the r^2 values, although significantly high, are a function of the data distribution. This would have been rectified had the 40 cumec release plan gone ahead. Nevertheless, the resultant equations were used in preference to the general model, since they produced realistic discharge values for most sites (Table 12.2), whereas the general model tended to produce discharges in excess of those ever recorded in the North Tyne.

Table 12.2 Equations for the initiation of transport for individual riffles and pools.

SMR: (Equation 12.10)	$\tau_{ci} = 6.50.\ D_i^{\ 0.237}$	$r^2 = 0.21$,	$n = 44$
SMP: (Equation 12.11)	$\tau_{ci} = 0.28.\ D_i^{\ 1.090}$	$r^2 = 0.75$,	$n = 53$
TR2: (Equation 12.12)	$\tau_{ci} = 6.37.\ D_i^{\ 0.409}$	$r^2 = 0.34$,	$n = 52$
NR1: (Equation 12.13)	$\tau_{ci} = 53.84.\ D_i^{\ 0.294}$	$r^2 = 0.10$,	$n = 87$
NP13: (Equation 12.14)	$\tau_{ci} = 7.80.\ D_i^{\ 0.375}$	$r^2 = 0.48$,	$n = 57$
NR2: (Equation 12.15)	$\tau_{ci} = 20.81.\ D_i^{\ -0.002}$	$r^2 = 0.05$,	$n = 50$

Table 12.2, indicates that entrainment thresholds are site specific, which supports the use of the individual site models, (however weak), in preference to the general model. The tracer data for the Newton pool-head site was not used due to a lack of data for discharges less than bankfull. Instead, the pool-tail data, and the bedload data from the mid-pool region were combined to provide an indication of the entrainment thresholds of sediment in the actively transporting reach of the pool. However it is notable that the tracers emplaced in the region of large roughness elements ($D_i/D_{50} = 0.085 - 0.488$) withstood a calculated shear stress of up to 235 N/m^2.

Table 12.3 shows that in accordance to the observations of the general model, pool sediments for 10 and 20mm material, are entrained at lower shear stresses than riffle sediments of equal size. However, for Smales pool and for the Newton pool in relation to Newton riffle 2, a higher shear stress is required to initiate the transport of pool sediments of 50 and 125 mm. The same reasoning as used above to explain the equalisation in the general model can be invoked in these cases. However, for these individual site models

Table 12.3: Critical Shear stress, associated discharge, and their exceedence frequency based on pre and post dam flow duration curves for 5 grainsizes (10-125mm) computed for individual riffles and pools.

SITES
(Shear Stress (N/m^2))

Grainsize (mm)	SMR	SMP	TR2	NR1	NPH	NPT	NR2
10	11.2	3.5	16.3	58.1	18.5	18.5	20.7
20	13.2	7.3	21.7	59.4	24.0	24.0	21.0
50	16.4	19.9	31.6	61.3	22.8	22.8	20.6
125	20.4	54.0	45.9	63.1	47.7	47.7	20.6

Discharge (cumecs)

Grainsize (mm)	SMR	SMP	TR2	NR1	NPH	NPT	NR2
10	26.0	51.0	15.0	12.0	29.0	57.0	19.5
20	38.0	68.0	28.0	13.0	33.0	77.0	20.0
50	67.0	97.0	35.0	15.2	38.0	105.0	19.0
125	200.0	150.0	56.0	18.0	44.0	150.0	19.0

Percentage of time flow is exceeded (1 = pre dam, 2 = 1987-1990)

	SMR		SMP		TR2		NR1		NPH		NPT		NR2	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	14.0	1.2	7.0	0.3	31.0	63.0	36.0	69.0	22.0	9.0	10.0	1.2	27.0	20.0
20	8.0	0.6	4.3	0.2	22.0	9.0	34.0	67.0	21.0	6.0	6.0	0.9	25.0	14.0
50	4.5	0.2	2.2	0.1	20.0	6.0	31.0	64.0	18.0	4.2	3.2	0.3	28.0	21.0
125	0.0	0.0	0.3	0.0	10.0	1.5	26.0	26.0	13.0	2.1	1.2	0.1	28.0	21.0

Percentage of time flow is exceeded for non-structured riffle sediments

	SMR 1	SMR 2	SMP 1	SMP 2	TR2 1	TR2 2	NR1 1	NR1 2	NPH 1	NPH 2	NPT 1	NPT 2	NR2 1	NR2 2
10	68.0	94.0			31.0	63.0	89.0	100.0					82.0	98.0
20	26.0	16.0			27.0	34.0	82.0	98.0					71.0	95.0
50	3.8	0.3			23.0	9.0	74.0	96.0					70.0	95.0
125	0.0	0.0			18.0	6.0	71.0	95.0					22.0	7.0

it should be noted that much of the inter-site variation is a function of the discharge range available for analysis. The NR1 site did not have bedload measurements available for lower discharges, and therefore only tracer data was used. In this case, tracer movement data was available from discharges of 2, 20, 36, 51 and 151 cumecs. As a result the relationship was maintained.

The discharges at which the given particle sizes are entrained relate to the mean shear stresses developed in Chapter 7.0, and consequently equate to the condition of general bedload motion of a given particle size at a section. The transport of individual particles would be expected in areas of locally high shear stress below the discharges produced in Table 12.3.

In Chapters 6 and 7 the question of when the pools scoured in relation to the riffles was posed, based on the consideration of differential bed structure. From the data contained in Table 12.3 it is clear that general motion of sediment of all sizes takes place on the riffles at discharges on average half that of pools, and that this discrepancy increases with particle size. This is important for considerations of riffle-pool maintenance since it implies riffle degradation during moderate discharges and contrasts the recent theories of the role of bed structure in riffle-pool maintenance which require riffle sediments to remain stable during floods (Clifford in press). Structure and bed strength, do cause an accentuation of transport thresholds, but the rate of shear stress increase clearly compensates for this. It is also clear that pools, and particularly pool-heads, scour at discharges less than bankfull, although bankfull discharge is required to entrain larger elements of the bed material from the pool-tail.

Importantly, a shear stress reversal is not required for the transport of sediments up to 125mm b-axis from the pool within a bankfull flood event. However, the filling of riffle sections during bankfull flood events (discussed later in Chapter 13) is not explained by these models . This must relate to the inability of even the most ambitious field measurement to fully calibrate the hydraulics at riffles and pools at high flows, and the effect of different transport path lengths and particle velocities of individual particles which are discussed below.

The selectivity of entrainment based on the range of discharge increases from the riffle to pool-head and pool-tail. This confirms the observation of Ashworth (1987) that different parts of the bed through a riffle-pool sequence are mobile at a given discharge and that they are differentially competent to transport a given grainsize. However, whilst Ashworth (1987) describes the rate of increase in shear stress as similar throughout the pool, and bankfull shear stress magnitudes occupying a "narrow range", the Newton pool at least exhibits a broad variation between the discharge at which elements of the pool are competent to transport a given grainsize. The slow rate of increase in shear stress at the pool-tail clearly compensates for the lower threshold of transport for bed sediments. This conclusion satisfies the observations from magnetic tracing experiments (Chapter 10) which suggested that the pool-tail formed a barrier to further sediment transport from the pool-head and mid-pool regions and confirms the observations of Petit (1986) . In addition, the downstream fining observed within pool-tails (Chapter 5) is accounted for by the preferential deposition of fines translocated from upstream during low-moderate discharges.

Clearly, the scouring of coarse sediments from within pools can only be effected during discharges greater than those experienced during hydropower generation. The exact values for critical discharges will vary per individual riffle-pool-riffle sequence, according to the local reach morphology, and hydraulics, nevertheless there is a tangible effect of the river regulation for hydropower evident in the frequency at which critical discharges are exceeded.

Table 12.3 also illustrates the exceedence frequency for the critical discharges calculated for the given grainsizes. Values for the percentage frequency at which a discharge is equalled or exceeded were derived from the maximum flow duration curves generated in Chapter 3. The values of the frequency of discharge exceedence for riffles are given for structured/compacted sediments as well as loose sediment, the latter calculated using the pool entrainment data from the general model (Equation 12.2).

For the Smales riffle-pool sequence (upstream of the Tarset/Chirdon Burns) the effect of hydropower regulation has been to increase the frequency of flows competent to erode "overloose" material of 10mm from 68% to 94% of the time, but to decrease the flows for eroding > 20mm material. For structured riffle sediments hydropower regulation has decreased the frequency of flows competent to erode all grainsizes illustrated. The result will be a depletion of the fine sediment sizes (as revealed by the direct sediment transport monitoring; Chapter 11) unless in structured positions. Similarly, since regulation the frequency of pool scouring discharges for 10mm and larger particles has been decreased although clearly there is some transport of sediment finer than 10mm as shown by direct sediment sampling. The decrease in pool scouring discharges and the increase in fines scouring discharges on the riffle has important implications for scour and fill which will be discussed later in Chapter 13.

Downstream of the Tarset/Chirdon confluences, the hydropower regime is still affected by unregulated tributary floods. Nevertheless, Table 12.3 shows that for the three riffles for which results exist (TR2, NR1 and NR2), there has been an increase of 32,11 and 16% respectively for discharges competent to erode loose 10mm sediments, and a 7,16 and 24% increase in competent discharge frequency for 20mm material. The Newton riffle 1 site shows an increase for all the size ranges given but this is not reflected in the tracer results.

In addition, there has been an increase in the percentage of time material < 10mm is eroded from structured positions on all three riffles and a decrease for TR2 and NR2 for all other grainsizes shown. In contrast to the sites nearer the dam site, discharges competent to scour pools and riffles of sediment up to 125mm still occur, although at a frequency reduced from 1.2 - 0.1% of the time. The percentage duration that pool scouring discharges are exceeded, varies between pool-head and pool-tail. The Newton pool-head experiences a reduced frequency to 9% for 10mm particles whilst the pool-tail experiences a reduced frequency to 1.2%. Correspondingly, pool-tails will be areas of preferential aggradation particularly for fine sediments that are routed from the upstream riffle and pool-head. This process has been altered by regulation so that the pool-head receives an increase in the frequency of sediment input from the upstream riffle and a reduction in scouring flows. However a greater reduction in the frequency of pool-tail scouring has occured. The expected results will be aggradation in the pool, and particularly in the pool-tail. The system of intra-pool sediment routing observed in the Newton pool provides an efficient process for maintaining the riffle-pool sequence since the collection of sediment in pool-tails in between floods ensures an increased sediment supply to the downstream riffle durin - g rare pool-tail scouring discharges. This is confirmed in the later discussion of scour and fill in Chapter 13.

The development of bed structure/strength, was related to the shear stress at a site and hypothesized to be less well developed at sites where either the shear stress (and therefore particle mobility) was low (the pools) or relatively high (regions of frequent bed mobilisation). The hierarchy of bed structure/strength development at the sites discussed above (prior to the bankfull flood) was SMR > TR2 >> NR2 > NR1. From the discussion above it can be seen that the hierarchy of frequency of bed mobilising discharges for particles of all sizes is SMR < TR2 << NR2 < NR1. This supports the contention that bed structure/strength is not well developed at riffles experiencing frequent mobility of the bed above the threshold for structural development, and suggests that sites closest to the dam site will experience accentuated development. The same argument explains the accentuation of structure/strength of riffle sediments in the regulated North Tyne relative to riffles in the unregulated tributaries since these are more frequently mobilised by unregulated flood events.

Chapter 6 revealed that bed structure also affects the path lengths and transport rates of sediment. Reid et al (1992), have shown how particles in different structural elements travel shorter distances depending upon the degree of protection. Furthermore, by delaying the entrainment of a particle, bed structure and compaction effectively reduces the time during which transport can occur, further reducing transport distance. Another factor which will tend to reduce transport distance is the density of bed structural elements through which a particle travels. If a given particle travels into a region of relatively dense bed structure then the probability of entrapment will increase and the transport length (and transport rate, Hassan and Reid 1990) will be less than a particle which moves into a region of low structural density.

Part of the variation in entrainment is due to relative exposure effects, which tend to reduce the shear stress required to move larger particles (Fenton and Abbot 1977). Ferguson et al (1989) have shown how the spatial variation in bed roughness (and therefore the degree of relative protrusion) effects the entrainment threshold of a given grainsize range as well as the sediment transport rate. The cross-sections in Appendix A show how the roughness of the bed (indexed by high resolution echo-soundings) exhibits a pattern of asymmetry in the pools which varies downstream and between flood events. Table 12.4 summarises the data from individual cross sections. The values for bed roughness are a calculated by subtracting adjacent values for depth from each other, which with a resolution capacity of 0.01m , effectively delineates the larger individual particles.

Table 12.4: Bed roughness heights as determined from high resolution echo-soundings through the Newton riffle-pool-riffle sequence: (all values in (m)).

Section	$\bar{x}$	max	sd	
1	0.019	0.119	0.021	
NR1				
3	0.032	0.172	0.035	
5	0.032	0.200	0.036	**PH**
7	0.036	0.180	0.040	
9	0.029	0.284	0.038	**MP**
11	0.026	0.211	0.033	
13	0.020	0.168	0.026	**PT**
15	0.014	0.089	0.016	
NR2				

Bed roughness, defined by increasing values for echo-sounded depth change, varies across sections, and downstream. Pool-tails possessing lower roughness values in the Newton pool than pool-head regions. This is maintained post-bankfull flood. The values of echo-souded bed roughness do not correlate significantly with the D50 recorded from particle size analysis, although the broad cross section trends are compatible (refer to Chapter 5). This is not unexpected since the echo-soundings are essentially recording differences in the C-axis, and exposure of the c-axis relative to each other. More research should be conducted to refine the interpretation of high resolution echo soundings, since these may hold the key to investigating bed behaviour in flood events. In the context of this study, they provide evidence of the relative roughness of the bed surface, which are complentary to the broad patterns of sedimentology discussed in Chapter 5.

Ashworth (1987) states that the transport of a particle through a riffle-pool sequence will involve a change in the relative protrusion as the roughness of the bed varies. Correspondingly, the transport of sediment should be at a maximum on the loosest, and hydraulically smoothest parts of the bed (assuming that an upstream supply of sediment exists). If this premiss is accepted then the maximum transport rates (and particle velocities) will be found on the finer gravel banks of pools and in pool-tails, whilst the converse will be true of riffles and in the rougher parts of pools.

12.5: Transport path lengths and percentage movement of tracers in riffle-pool sequences.

Appendix F , contains Tables 12a-c of individual site data, delimiting the mean and maximum distances and percentage entrainment of particles in given grainsizes. The three Tables cover discharges from hydropower maxima (up to 20 cumecs) to bankfull at 151 cumecs. No movement was observed at any site during compensation flows. The average values for riffles and pools are summarised in Table 12.5.

During hydropower discharges of 16.4 - 20 cumecs, the transport of particles is limited solely to the riffles, with the exception of the constricted pool at TP2 (see Chapters 4 and 7). Table 12a (AppendixF) shows the site specific response of riffles which is dominated by the preferential transport of particles within the 32-90mm size ranges. Transport lengths broadly decline with increasing particle size, although this is only obviously expressed in the maximum transport lengths. Clearly, there are site specific controls on the transport of given grainsizes, which probably relate to the roughness of the bed and the complex local hydraulics. The transport of particles finer than 32mm is restricted except for SMR and NR1 sites. Whilst this supports the movement of 22mm material at both these sites as determined by magnetic tracing and Helley-Smith bedload sampling, it suggests that the material sampled at TR2, TR1, and NR2 represented locally exposed sediment. The protection afforded by the hiding effect of a rough bed clearly operates preferentially for particles less than 32mm B-axis, whilst relative protrusion produces the same preferential transport of intermediate sized material as observed by Thorne and Milhous (1982) and Hey (1982).

The observations of coarse sediment transport at hydropower discharges are not constant through time. Table 12.6 shows the effects of time on the transport lengths and percentage entrainment of particles at TR1 and NR1 during periods of relatively constant discharge maxima.

Table 12.5 Comparative average values for tracer distances (m) in riffle and pool locations for a range of discharges up to bankfull.

Grainsize (Phi class)		Maximum discharge (cumecs) 20		30		105		151	
		R	P	R	P	R	P	R	P
22	$\bar{x}$	0.01	0.0	2.9	0.1	2.2	0.6	15.9	5.8
	max	1.2	0.0	16.0	0.7	5.3	0.8	36.0	35.0
32	$\bar{x}$	1.1	0.0	2.2	0.3	6.1	2.4	26.6	17.8
	max	7.5	0.0	17.8	2.1	37.0	10.0	169.0	96.0
45	$\bar{x}$	0.6	0.0	2.1	0.3	1.0	0.9	14.2	18.7
	max	6.8	0.0	16.2	3.0	3.3	1.8	98.0	112.0
64	$\bar{x}$	0.5	0.0	3.0	0.1	1.1	0.5	34.7	17.6
	max	5.4	0.0	23.4	1.4	3.9	0.8	164.0	99.0
90	$\bar{x}$	0.6	0.0	1.6	0.0	0.3	0.9	10.9	31.0
	max	8.0	0.0	8.2	0.0	0.6	1.8	40.0	170.0
125	$\bar{x}$	0.7	0.0	2.2	0.0	0.5	0.0	7.5	14.0
	max	1.2	0.0	6.6	0.0	0.5	0.0	20.0	29.0

Table 12.6: Reduction in Particle Transport lengths at two riffles during conditions of low-moderate discharge

Qmax	x distance	max distance	% moved	Days
Tarset Riffle 1				
13.0	0.6	1.5	77	2
16.5	0.3	1.0	23	77
16.4	0.0	0.0	0	152
23.1	0.2	1.0	13	223
Newton riffle 1				
51.0	3.7	23.4	85	11
17.2	0.8	6.8	47	35
18.3	0.1	1.0	16	123

The results are important, first because they indicate that subsequent transport lengths at higher discharges are not affected by the unrealistic over-exposure of tracer material, and secondly , because they suggest a time frame for the incorporation of freshly "deposited" sediment within the structure of riffles under hydropower flows.

Table 12.6 again shows the hiding effects on sediments < 32mm. However, it is also possible that the lack of movement reflects the rapid incorporation of finer sediment into structurally stable positions. The probability of a smaller particle finding a stable niche within a rough bed will (intuitively) be greater than that for a larger particle since the range of available niches will be greater. This is expressed in the data from TR1 and NR1 particularly, since it is the finest particles that cease to be transported so far, or in such quantity before those of intermediate size. The reduction in transport length and percentage entrainment of material > 64mm, possibly represents a progressive change in the balance between relative exposure and inertia, favouring inertia as the larger particles obtain a greater pivoting angle due to embedding (Carling et al 1992). The relative mobility of intermediate sized particles (those approximating the D_{50} of the bed material) is again reflected in the tracing results.

The rate at which freshly deposited sediments > 22mm are stabilised at riffle locations under hydropower discharges varies according to particle size and riffle. However, an approximate rate is indicated at 2.5 - 3 months to reduce particle transport lengths to 25% of their initial value at NR1 and TR1 respectively, and 6 months for a full reduction to zero. The proposed effect of bed structure development on the effectiveness of floods (Chapter 6) is illustrated by the reduced transport lengths and entrainment, associated with a 20 cumec event in November 1989 at TR1. Wolcott's (1989) assertion that fully developed structure would take 1 month to form under steady flow conditions is of the same order of magnitude as the results described here. Given that the time frame in this study is probably an over-estimate as a result of the assumptions of maximum discharge and the long periods between re-surveys Wolcott's figure of 1 month seems reasonable. If Harrison's (1951) observations of bed structure development are recalled, it is probable that the rate of structure development post-flood, depends on the particle size and rugosity of the bed. This in turn will depend upon the morpholo gy of the bed. More detailed research is required to investigate the conditions which create bed structure and bed strength, and which influence their rate of development.

Returning to Table 12.5 and Table 12b, (Appendix F), reveals the effect of regulation on the transport of tracers within the North Tyne. Upstream of the Tarset/Chirdon confluences, the discharge maximum is still only 20 cumecs and pool sediments remain stable, whilst downstream, the maximum discharge experienced for the period 19.04.89 - 13.01.90 is 30.2 cumecs and pool sediments exhibit some movement. The pattern of movement of pool sediment at 30 cumecs is characterised by preferential entrainment of the finer particles < 45 mm. However, like the riffle sediments, average transport lengths are longest for the intermediate sized particles. In the Pool-head (NP6) maximum particle size moved was 67mm in contrast to 47mm in the pool-tail. However, this masks a greater percentage entrainment and longer transport length for material < 45mm in the pool-tail. This is explained by the lack of movement of all particles within the deep, rough region of the pool-head. Transport lengths of all particles are greater on riffles at 30 cumecs.

Table 12.5 and Table 12c (Appendix F), depict the data for tracer transport at flows up to bankfull. The effect of regulation is again apparent upstream of the Tarset/Chirdon confluences, with discharge maxima of 105 cumecs, versus a maxima of 151 cumecs downstream of the confluence. Correspondingly, the transport in the pools is again significantly different between the Newton site and the TP1 and SMP sites. Although the increase in discharge is 43%, the difference in average transport lengths in both pools and riffles is in the order of 300-2000%.

As hypothesized, the mean transport lengths in both pool-head and pool-tail are longer on average (of those particles moved) than on the riffles, although the percentage entrainment is significantly lower (Table 12c, Appendix F). This latter point results from the immobility of particles nestled in between the large roughness elements in the pool deeps which enabled them to withstand shear stresses of up to 258 N/m^2. The immobility of particles in the pool-tail is associated with the extreme margins of the channel, where side-wall reduction in energy dominates grain resistance, (Williams, 1970). Correspondingly, the values in Table 12.5, which records the average distance of all particles, results in greater transport lengths for riffle sediments.

The data for TP1 is unique in withstanding sediment transport across the total stream width, despite a discharge of 105 cumecs. This scenario must result from the ponding back of North Tyne water by the influx of the Tarset Burn the effect of which is to drastically reduce the shear stress in the backwater region upstream of the confluence. This latter observation solves the question of the contribution of sediment from the North Tyne in the construction of the Tarset, (or other) tributary confluence bars (Brierley 1983; Petts and Thoms 1987; Carling 1988). All the material > 22mm within the bar is derived from the Tarset Burn itself despite the highest post-regulation flow down the North Tyne since Kielder reservoir was constructed. The effectiveness of such floods will clearly be dependent upon the timing of the arrival of the North Tyne flood wave with respect to that passing down the Tarset Burn. Nevertheless, the evidence from SMP also suggests that little pool movement is effected at 105 cumecs regardless of ponding at tributaries. Reference to Best (1987) suggests that sediment mobilised from upstream of tributary confluences, will be routed around the tributary bar. Correspondingly, the pool downstream of the Tarset Burn conlfuence will be supply limited resulting in scour during floods.

Scour at the YR1 riffle, closest to the dam site, exhibits preferential removal of intermediate sized particles (45-64mm), whilst SMR experiences the preferential removal of fine particles (< 64mm). Transport lengths at the YR1 site are also slightly greater than the SMR site for finer particles.

The average percentage movement of individual size ranges for riffles and pools over the discharge ranges studied, are depicted in Figure 12.2. Fewer pool sediments are entrained at all discharges and for all size categories shown. This is largely the result of the immobility of pool-head sediments discussd above, in relation to large roughness elements, but also reflects the reduced spatial extent of the active zone of the pool bed.. The size selectivity of pool sediments is clearly evident with no movement at discharges less than 30 cumecs and no movement of 125 mm material at discharges up to 105 cumecs. Riffles and pools show an increase in the percentage of particles moved with discharge, which indicates that progressively larger areas of the bed become mobile.

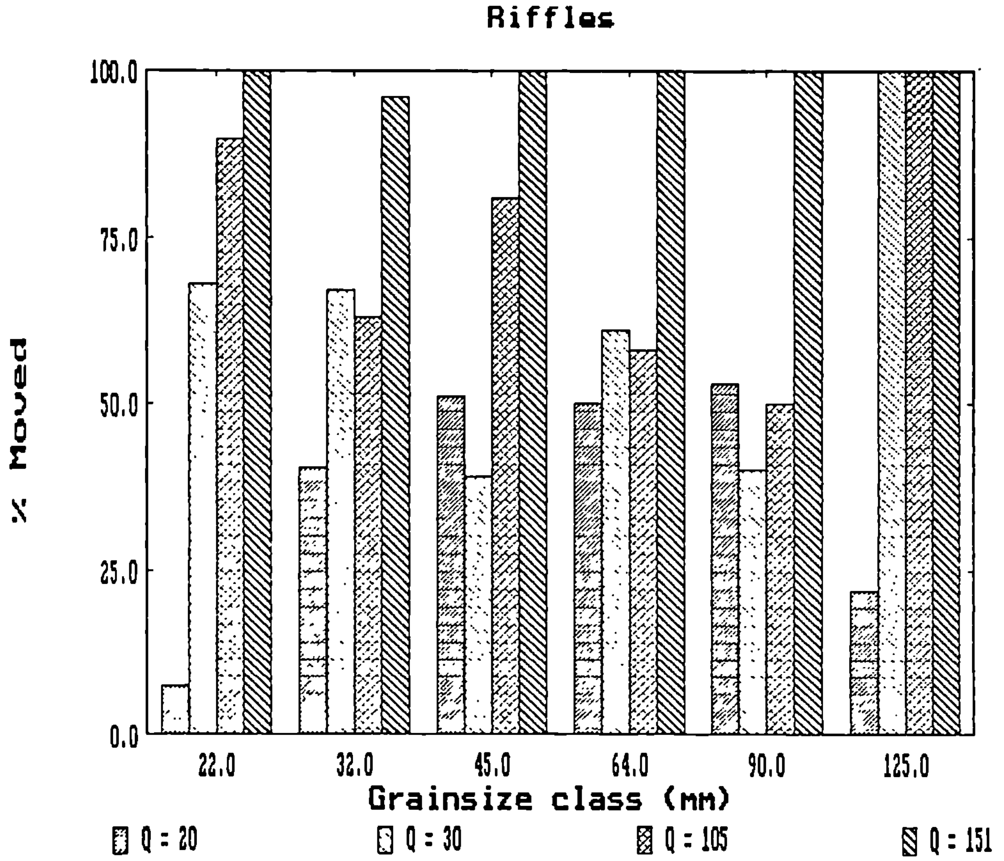
As the discharge rises in the riffles the intermediate particle sizes are initially entrained more frequently than than the finer particles but this reverses at 32 cumecs with the exception of the 125 mm particles. At bankfull discharges the percentage movement of all size ranges is approximately equal, though some 32 mm particles remain immobile.

In the pools as the discharge rises the percentage of finer particles moved is greatest for 22 and 32 mm particles and declines with increasing size. At 105 cumecs a higher percetage of intermediate sized particles (45 mm) are entrained and at bankfull discharge the percentage movement increases with particle size.

Site specificity characterises the transport of coarse sediment in pools and riffles at discharges approaching bankfull. However, a broad pattern of preferential transport of intermediate sized sediments is apparent in both pools and riffles. During discharges up to 105 cumecs, the sediment transport system is discontinuous through riffle-pool-riffle sequences, with preferential transport rates experienced on riffles for all sediment sizes.

The result of the processes discussed above are summed up in Figure 12.3 which illustrates the effect of river regulation in the North Tyne on the cumulative mean distance of transport of sediment > 20mm moved. The effect of river regulation is expressed as the percentage of the catchment area unaffected by the Kielder reservoir impoundment. As this latter figure rises, so the connectivity between riffles and pools increases. If expressed in terms of a sediment budget, then the dominantly regulated reach of the North Tyne is characterised by a net removal of sediment off the riffles, into the pools, and a local re-distribution of this material within the pools. In contrast, the

Fig 12.2: The variation in the percentage of particles entrained by grainsize, in relation to increasing discharge in riffles and pools.



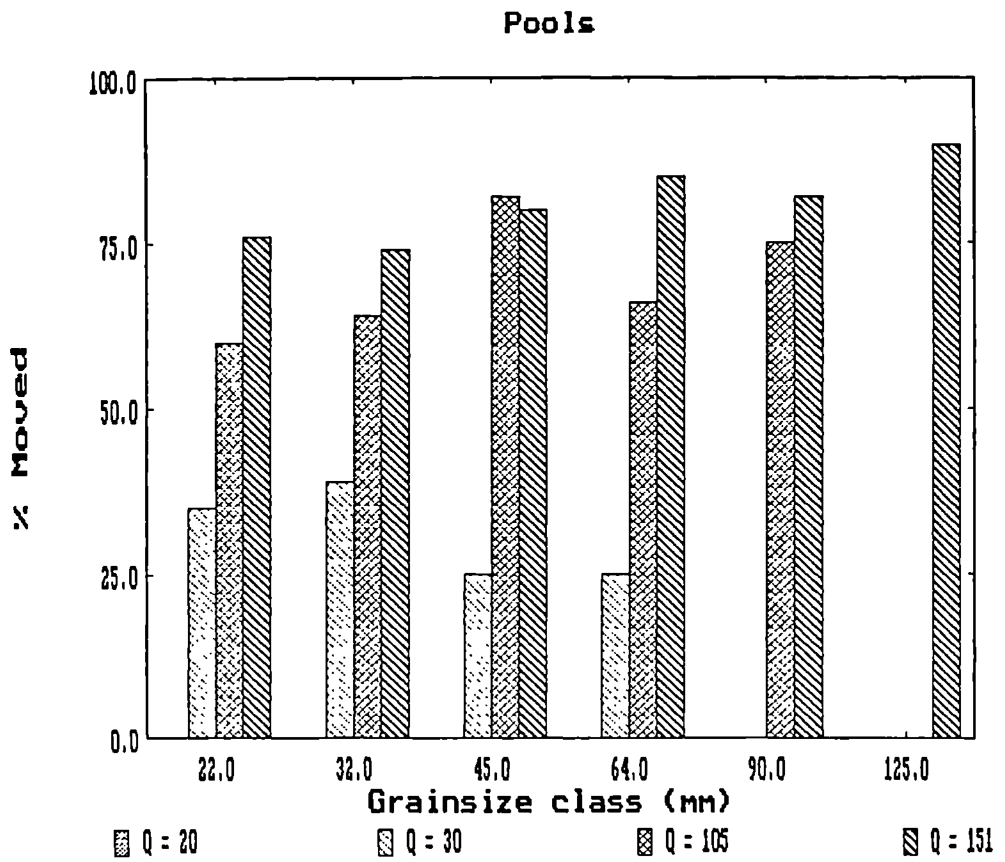
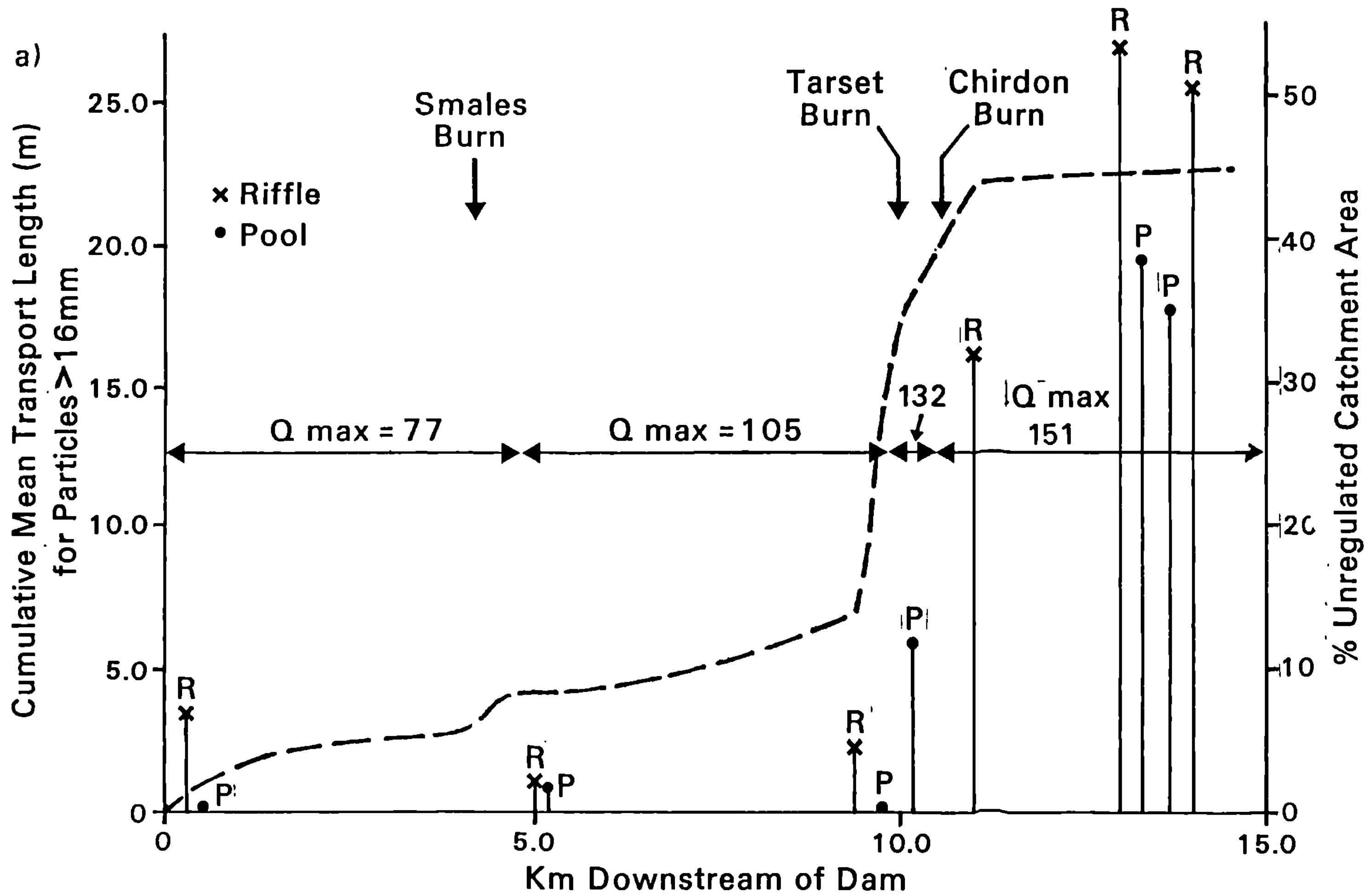


Fig 12.3: The influence of river regulation as expressed in the cumulative mean distances moved by tracers > 16mm in riffles and pools downstream of Kielder reservoir.



effect of a single bankfull flood is to redress the net input of material from riffles by the scouring of the pools; although cumulatively the riffles still experience a net export of sediment into the pools long term.

12.6: The role of intrinsic factors on the transport of sediment in riffle-pool sequences.

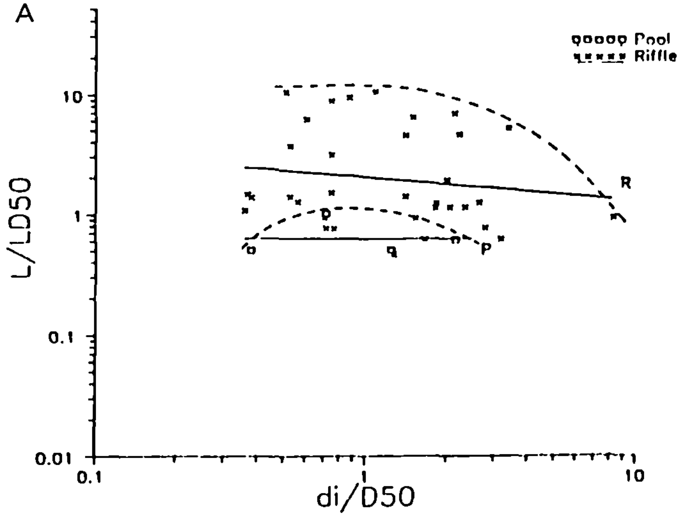
Intrinsic factors include particle characteristics and local hydraulics.

The discussion above illustrated the importance of the size of the individual particle in the transport process. However, this effect is not simply a question of proportionality between particle size and distance moved (Hassan and Church 1992; Reid et al 1992; Tacconi et al 1992). Hassan and Church (1992) investigated the role of relative particle size on the transport length of coarse sediment by using the dimensionless D_i/D_{50} versus the dimensionless transport distance L/LD_{50}, which is the transport length of a given tracer divided by the transport length of the median particle size. Figures 12.4a - d illustrate the role of relative roughness on the dimensionless transport length of particles.

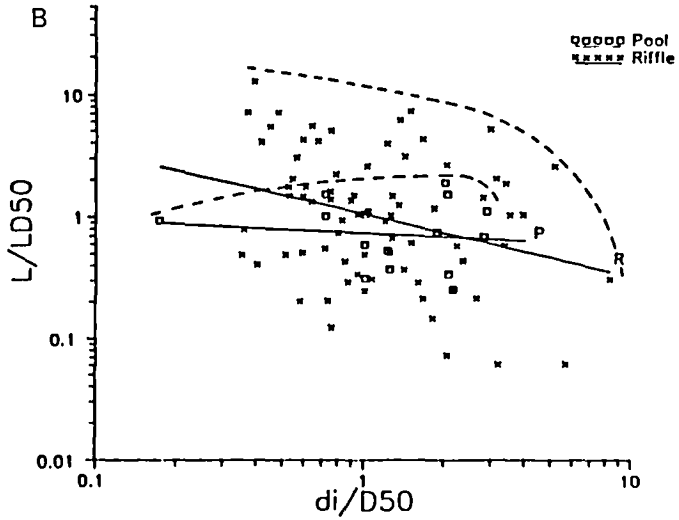
The data for the pools consistently plots closest to the log-log regression lines which are depicted as a guide to the trend within the data along with the envelope curves. This is intuitively correct, given the loose pool sediments, and size selectivity of the entrainment process. The riffle sediments, contain considerable scatter, which reflects the stochastic nature of coarse sediment transport associated with the breakup of structural elements. Hassan and Church (1992) identified considerable scatter in their relationship between dimensionless transport length and d_i/D_{50}, as well as a sharp decline in transport length once particle size was much greater than the surface sediment D_{50}. The data used by Hassan and Church (1992) represented relatively short distance transport analogous to the data collected in this study at discharges up to 105 cumecs.

The data in Figure 12.4a - c exhibit a general trend of decreasing transport length with increasing particle exposure. This scenario is particularly evident on the riffles, where the slope of the trend initially increases with discharge as the transport length of material finer than the surface D_{50} increases faster than coarser particles. The same pattern is followed in the pools, although the trend is not so obvious. This pattern is expressed in

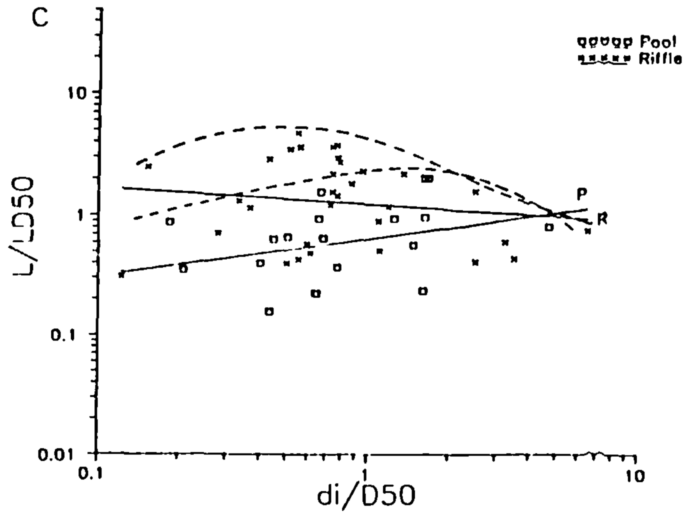
12.4 The relationship between di/D50 and dimensionless transport distance for riffle and pool tracers at Q = 20 cumecs.



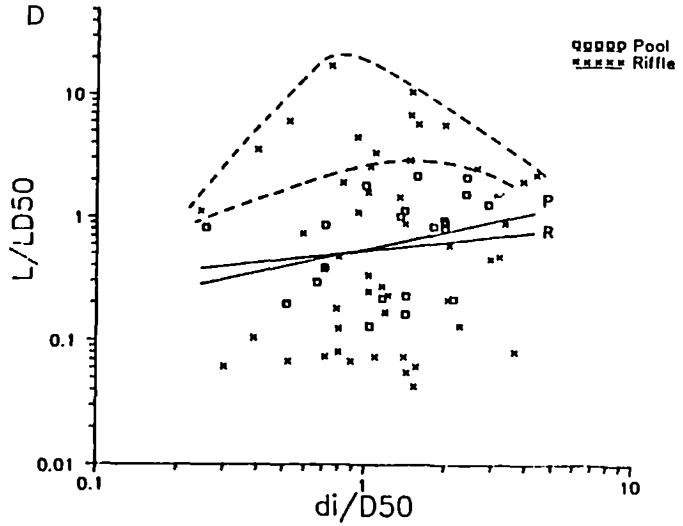
The relationship between di/D50 and dimensionless transport distance for riffle and pool tracers at Q = 30 cumecs.



The relationship between di/D50 and dimensionless transport distance for riffle and pool tracers at Q = 105 cumecs.



The relationship between di/D50 and dimensionless transport distance for riffle and pool tracers at Q = 151 cumecs.



the envelope curves, which show a sharp decrease in the transport length after a D_i/D_{50} of 1, which is consistent with the observation of Hassan and Church (1992). At a discharge of 105 cumecs, riffle sediments coarser than the surface D_{50} are still associated with shorter transport lengths, whereas in the pools the situation has reversed. However, the envelope curve still exhibits a decline which implies that the transport of larger particles is still dominated by inertial effects as opposed to relative exposure.

Figure 12.4d, shows that at bankfull discharge, the transport process at the riffles operates significantly differently than at lower discharges, whilst the pool sediments respond in a similar manner to lower discharge transport. The envelope curve for riffle data shows peak transport lengths associated with sediment of the same size as the surface D_{50}, whilst a decline is apparent in the transport lengths of finer and coarser particles. In terms of the sorting of riffle sediments, it is clear that at lower discharges fine sediments move furthest off the riffles, leaving the coarser material behind, whilst at bankfull discharges, the median sized sediment is lost, leaving both coarse and fine sediments behind. In the pools, sediment that is coarser than the surface D_{50} is preferentially transported longer distances, leaving behind finer sediments. The apparent ineffectiveness of increasing relative exposure to result in longer transport lengths on riffles is assumed here to reflect the high proportion of larger particles that are in stable structures. Clearly, the effect of particle size, expressed as D_i/D_{50}, varies between riffles and pools and with increasing discharge.

The effects of the weight of a particle were analysed to ascertain the degree of influence this factor had upon the transport lengths of particles. No significant correlations were found, although three patterns were observed:

1. Increasing particle weight does reduce the distance travelled by a given sized particle, but it is not a significant factor.

2. Weight effects are less apparent as a factor in reducing transport lengths within pools.

3. Increasing discharge reduces the effects of weight in the transport of sediments of all sizes.

Figure 12.5 illustrates the influence of local shear stress at the point of entrainment upon the transport length of a given particle. The scatter that is present in both riffle and pool environments reflects the dominance of other factors in the transport of sediment > 22mm. However, the envelope curves clearly show that the transport lengths of sediment increases with the strength of the force on the bed at entrainment. Furthermore, the rate of increase in transport length is greater for particles starting in pools than in riffles.

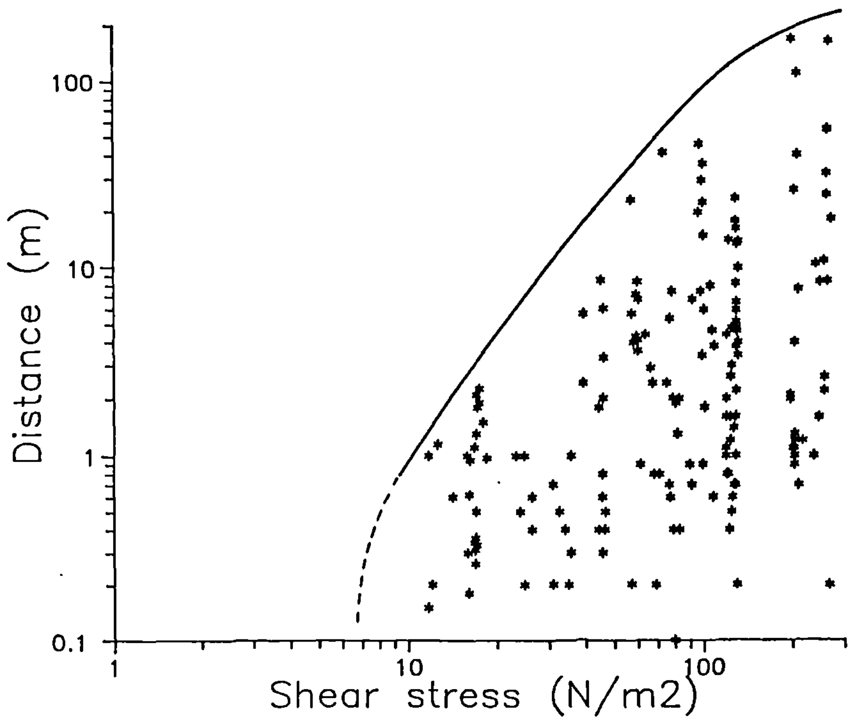
The differential effect of shear stress in riffles and pools is apparent for all particle sizes, although the rate of increase varies per size range. In pools, the trend in the data, as revealed by least squares regression, presents a picture of increasing rate of increase in transport length as particle size increases. No such pattern is evident on the riffles, which reflects the dominance of other factors in the determination of transport length.

As shear stress increases above 100 N/m^2, in both riffles and pools, the rate of increase in the distance travelled appears to decrease. This is due to the change in the shear field associated with the movement from pool-head to pool-tail, and from riffle into pool. The rate of decrease is correspondingly higher in the pools than the riffles, since a movement from a riffle into a pool-head does not involve such a reduction in shear stress.

Following the discussions in Chapter 7, regarding the relationship between shear stress distribution and secondary flows, it was considered necessary to investigate the possibility that their presence might affect the trajectories of particles in motion. Recent models of sediment transport in meander bends suggest that finer particles can be deflected inwards towards the centre of curvature by the cross stream component of secondary flow (Dietrich 1987; Markham and Thorne 1992). Although curvature effects are considered minimal at the sites in this study, the evidence of secondary flows reported in Chapter 7 warrants an investigation of dispersal trajectories.

Table 12.7 presents the mean values for angle of deflection from direct downstream trajectory, for the range of grainsizes involved in the tracer surveys. Analysis of variance indicates that there is a significant difference between riffles and pools at discharges of 30, 105 and 151 cumecs. In terms of actual deflection, the pools clearly exhibit preferential deflection of the finer grainsizes at 30 and 105 cumecs, but not at 151 cumecs. There is some tendency for finer riffle sediments to be deflected across stream, Fig 12.5: Distance moved by tracers in riffles and pools in relation to maximum shear stress experienced at emplacement site.

Distance moved by tracers (> 22mm) located at riffles, in relation to shear stress experienced at point of motion; envelope curve is shown.



Distance moved by tracers (> 22mm) located at pools, in relation to shear stress experienced at point of motion; envelope curve is shown.

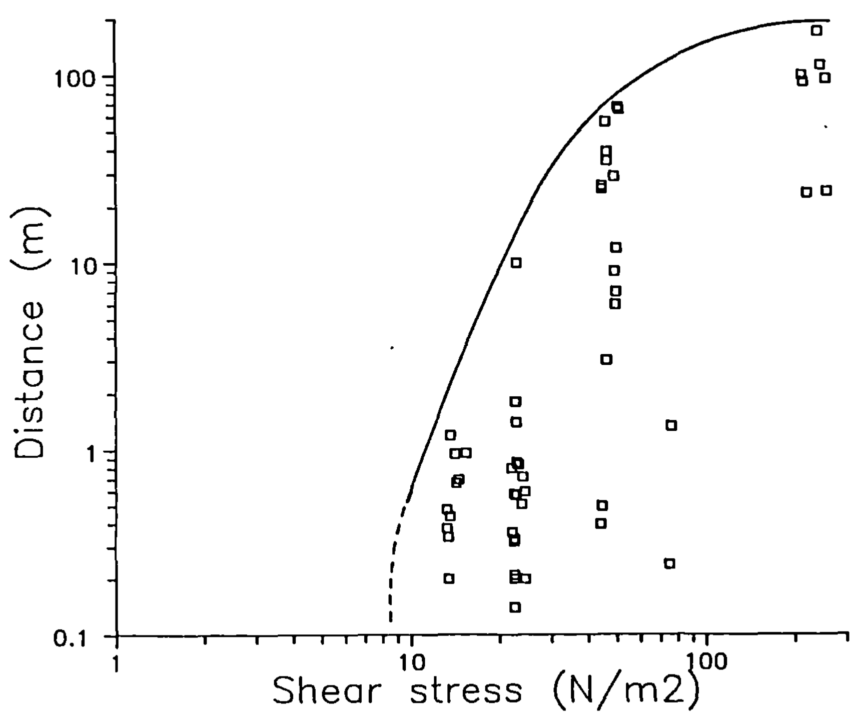


Table 12.7 Mean values of particle trajectory deflection from direct downstream displacement. (Degrees)

Grainsize (Phi class)	Maximum discharge (cumecs) 20		30		105		151	
	R	P	R	P	R	P	R	P
22	11	--	9	7	3	23	16	--
32	11	--	12	11	17	22	26	8
45	17	--	16	5	11	8	10	6
64	13	--	14	2	18	8	9	7
90	17	--	8	--	3	--	12	7
125	24	--	9	--	--	--	14	8

particularly at higher discharges. Bathurst et al (1979), have described the decay of secondary current strength above moderate discharges which may be evident from the pool deflection measurements. Further research would be needed to elucidate these patterns more effectively, but a lateral sorting of fine sediment is hinted at, particularly in pools at intermediate discharges, but also on the riffles at discharges approaching bankfull. Reference to Chapters 4 and 5 indicate that asymmetry, both of cross-section morphology and sediment size, is a characteristic of all the pools monitored in this study. From the tracing results, it appears that much of this takes place at discharges below bankfull.

12.7: The influence of flood hydrograph shape on the transport of coarse particles

The differential distribution of the rate of shear stress increase through riffle-pool sequences has important implications for the effectiveness of individual floods. From the evidence of the shear stress values calculated in Chapter 7, and the documented downstream variations recorded in Ashworth (1987), Petit (1986) and lately Clifford and Richards (in press), it is clear that different parts of a stream bed are mobilised at different discharges. Correspondingly the particle transport lengths that are recorded for different morphologies should be re-assessed in terms of the duration of transport. For this purpose it is necessary to reconstruct the flood hydrograph for a given tranporting event and to assign a critical discharge for initiation and cessation of transport for each morphology. In this study, the initiation of transport for 50 mm particles (approximate D_{50} of the North Tyne) is obtained from Table 12.3. The values for cessation of tranport were estimated using the mean values for pools and riffles calculated in Chapter 11. The values for critical discharges for initiation of transport and cessation are represented in Table 12.8.

Table 12.8: Critical discharges for the initiation and cessation of transport of 50 mm particles.			
Site:	Qci (cumecs)	Qcc (cumecs)	% Reduction
SMR	67	2	97
SMP	97	56	42
TR2	35	23	34
NR1	15	2	87
NPH	38	18	53
NMP	54	23	57
NPT	105	36	66
NR2	19	2	90

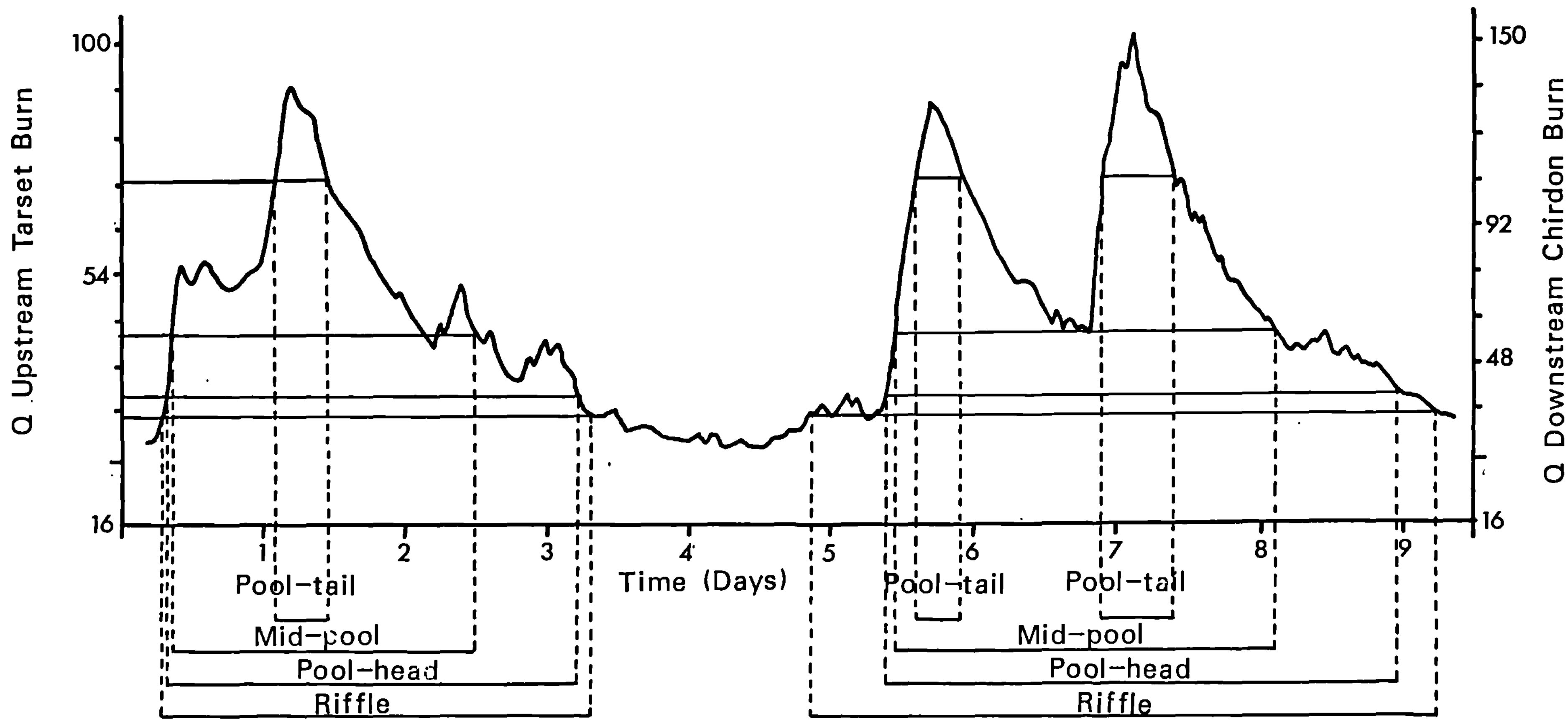
These are subject to the limitations of the hydraulic calculations, and in the case of all riffles, with the exception of TR2, present extremely low values for the critical discharge for cessation of 50 mm particles. These are considered to be spurious and so for the purposes of the comparative analysis of particle velocities the critical discharge for cessation of transport is considered to be equal to initiation. The affect of this assumption does not alter the morphological hierarchy for duration of bed mobility, although the effect is to extend the duration for each component of the riffle-pool sequence. This is illustrated for the multi-peak flood event of February 1990 (Figure 12.6).

Figure 12.6 reveals that the duration at which a bed is competent to transport sediment of the median bed material size, varies through the riffle-pool sequence in the order:

riffle 1 > pool-head > mid-pool > pool-tail < riffle 2

This is maintained even if the cessation of transport varies by the values determined for riffles and pools in Chapter 11. The duration of discharge above critical, will clearly be influenced by the duration and magnitude of a given flood hydrograph. This observation is particularly important for regulated rivers where the reservoir function includes flood protection storage and where where the surface area of the reservoir is large relative to the catchment area. For Kielder reservoir the flood magnitudes have been reduced by 60 % whilst Brierley (1983) has modelled reservoir attenuation at 75-80%. The corresponding effect on the hydrograph is to reduce flood peak and extend the times to

12.6 The variation of critical discharge duration for different morphologies of the riffle-pool sequence according to hydrograph shape. (Qcrit is for D50 particles)



peak and recession. Returning to Figure 12.7 indicates that this will have profound effects on the movement of sediment through the riffle-pool sequence. Riffles and pool-heads will experience enhanced durations of bed mobility during flood events, whilst pool-tails will be less frequently mobilised. The corrollary of this scenario is for a long term aggradation of pool-tails and the scouring of riffles and pool-heads. The evidence for this is examinined in the following Chapter 13.

The differential durations of bed mobility through the riffle-pool sequence affect the interpretation of particle transport lengths. Particle velocities are calculated by dividing the mean transport length of 45-64mm particles by the duration they are predicted to be mobile. Table 12.9 summarises the effects of the unequal duration of bed mobility in terms of particle velocities.

Table 12.9: Average particle velocities for 45-64mm particles through riffles and pools during flooding on the North Tyne.

Site:	Particle velocity (m/s)
SMR	0.000007
SMP	0.000130
TR2	0.000020
NR1	0.000060
NPH	0.000140
NPT	0.000240
NR2	0.000070
$\bar{x}$ Riffles	0.000040
$\bar{x}$ Pools	0.000170

On this basis particles of the median bed material size travel on average 4.4 times faster though pools than through riffles. Clearly there are limitations to the assumptions made in this discussion, for example, the assumption that motion was continuous during the duartion above critical transport threshold, and indeed that the critical transport threshold is realistic. However, the notion that particle velocities over riffles are much slower than through pools is supported by observations of the effects of relative roughness on sediment transport rates, and the effects of high structural densities on transport lengths and transport rates (Ferguson and Ashworth 1989; Hassan and Reid 1990). Further supporting evidence is derived from the observations of Langbein and Leopold (1968), who reported lower particle velocities in regions of high sediment concentrations. The presence of bed structure, and tightening of particle interlock are effectively expressions of higher particle concentrations. This is supplemented by the effects of relative roughness, which is enhanced on riffles by the presence of bed structure and the winnowing of fine particles (Robert 1989). Furthermore, evidence for the hierarchy of bed structure decomposition suggests that as a flood passes, stoss and wake particles are entrained before obstacle clasts (Brayshaw et al 1992; Naden and Brayshaw 1987). Consequently as discharge rises so the entrapment opportunities increase for particles entering a riffle. The progress of particles is therefore retarded by high cluster densities and average particle velocities drop.

The differentiation of particle velocities is consistent with the theories of kinematic waves, discussed by Langbein and Leopold (1968) in terms of riffle and bar development. This is discussed in more detail in Chapter 14.

The following Chapter identifies the morphological expression of the sediment and hydraulic patterns revealed in the preceeding Chapters and explores the corrobarative evidence for the effects of hydrograph modification as a result of river regulation for hydropower.

Chapter 13.0
Scour and fill within riffle-pool sequences.

13.1 Introduction

Scour and fill in riffle pool sequences has been conceptualised from empirical observations into a characteristic phenomenon whereby riffles scour at low-moderate flows, and pools fill, with a reversal of this trend during major bed mobilising floods (Lane and Borland 1953; Andrews 1983; Campbell and Sidle 1985; Clifford and Richards 1992).

The reasons for this behaviour has been attributed to the pattern of shear stress experienced through a reach, and characterised by higher values on riffles at low-moderate flows, and a reversal in this position at higher (bankfull) discharges (Andrews 1983; Lisle 1979). Quite often the data for individual riffles and pools has been collected at time intervals of several days, months, or even years. The corresponding patterns of scour and fill then represent at best the gross balance between sediment supply and transport for an individual flood as a whole (Andrews 1983; Campbell and Sidle 1985), or the long term response of a channel reach to extrinsic sediment supply conditions (Lisle 1982). When data on scour and fill is available for time periods more consistent with fluctuations in sediment transport rates of individual sections then the picture becomes more complex. Jackson and Beschta (1982) document the bed level changes in a riffle-pool-riffle sequence at time intervals of hours during a snowmelt flood of several days. Two important observations were made:

1. Scour and fill is temporally and spatially varied during the passage of a single flood event, both at a section and within a reach.

2. Bedload transport rates at riffles were closely correlated with bed dynamics, but the dynamics of the pool bed were not correlated with the bedload of the upstream riffle, or with the output of sediment at the downstream riffle.

Hassan (1990) documents similar spatial variability in scour and fill, as inferred by the burial depths and movement of magnetic tracers. On average, the data on scour and fill, inferred from scour chains did not fully represent the magnitude and variability of scour and fill that occurred during a single flood. Scour was not restricted to riffles, pools or bars, but locally attained values that indicated the presence of discrete scour holes. Ergenzinger (1992) explains the lack of correlation between scour and fill and the sediment transport at a section as resulting from inputs from upstream. Clearly this is not the overriding factor explaining the bed dynamics in pools (above).

Clifford (1990) describes the scour and fill at a riffle-pool sequence during a single flood event and concludes that the relative elevations between components of a sequence tend to equalise at bankfull discharges. However, the relative elevations returned to their post flood levels upon recession. This contrasts with all other observations, which suggest riffles fill and pools scour at bankfull discharge.

Whilst this may be the inevitable conclusion from a single riffle-pool sequence during a single flood event, it could have resulted as easily from an upstream sediment source as from local hydraulics or differential patterns of bed structure. Further examination of Clifford's data shows that the pool scoured and filled at bankfull discharge and that the same was true for the riffle (Clifford and Richards 1992). What is important is the discharge at which the change in bed elevation occurred and from their Diagram 12 (Clifford and Richards 1992) it can be seen that significant motion of the mid-pool bed occurred at a discharge 20% lower than that at which the riffle scoured. This is consistent with the observations from this study that pool sediments are less structured and therefore have lower critical entrainment thresholds. Subsequent filling would result from upstream pool-head scour, riffle scour or a lateral supply from the same section.

13.2 Scour and Fill: Results.

Scour and fill at riffles and pools has been determined from three databases: the re-surveyed NWA cross sections (Chapter 4); the re-surveyed FBA cross sections (Chapter 4); and the re-surveying of cross sections within the period of this study (Appendix A). The morphological changes identified from these databases have been described in Chapter 4 and showed that, in general, the channel capacities of riffle and pool cross-sections have reduced by up to 5.4%, though some sites increased in capacity by up to 4.4%. This data represented the total bankfull cross-section changes and included aggradation of vegetated islands that are now largely out of the active regulated channel. Figure 13.1 represents the net scour and fill experienced at individual sections of the active regulated channel, drawn from all three databases covering the period 1978-1990. The NWA cross-sections were allocated to riffle or pool from identification from aerial photographs (1:7000 scale), and the FBA sections were allocated to riffle or pool from site visits. The results from the contemporary surveys of riffles and pools do not include the effects of the bankfull flood of February 1990.

The results shown in Figure 13.1 indicate that 70% of the riffles surveyed have experienced a net scour since the dam was constructed and 85% of pools surveyed have experienced net filling.

Within this pattern, it can be seen that scour is particularly associated with riffles closest to the dam site and around the Falstone bridge at 2.4 km downstream from the dam. This is in accordance with other studies of degradation below dams that have identified a particularly susceptible region within 69 widths distance from the dam site (Wolman 1967; and Chapter 1.3). Between 5 and 10km downstream of the dam site, the majority of riffles and pools have experienced a net filling of their cross-sections, which includes the aggradational site at Ridley Stokoe (Appendix A ; Chapter 4). This is a region characterised by post-regulation fining of sediments, and is possibly the current position of the fine sediments eroded from the upstream reach closer to the dam (Chapter 5). The presence of aggradation would support the view that the reach is also fining, since degradation is largely associated with sediment coarsening through armouring by selective erosion of finer particles (Dietrich et al 1989; Chapter 1.3).

The sites from 10.5 - 14km downstream of the dam are the Tarset and Newton sites respectively. The values for net scour and fill are generally lower than those for the period 1978-1988, but nevertheless show the characteristic scouring of riffles and filling of pools. Consideration of the time averaged rates of scour and fill show that although of the same order of magnitude, the rates associated with the short term surveys are accentuated on the riffles whilst remaining similar for the pools (Table 13.1). The values for the contemporary surveys do not include the effects of the February 1990 bankfull flood.

13.1 Variations in the net scour and fill experienced at riffles and pools downstream of Kielder Reservoir for the period 1978 – 1990.

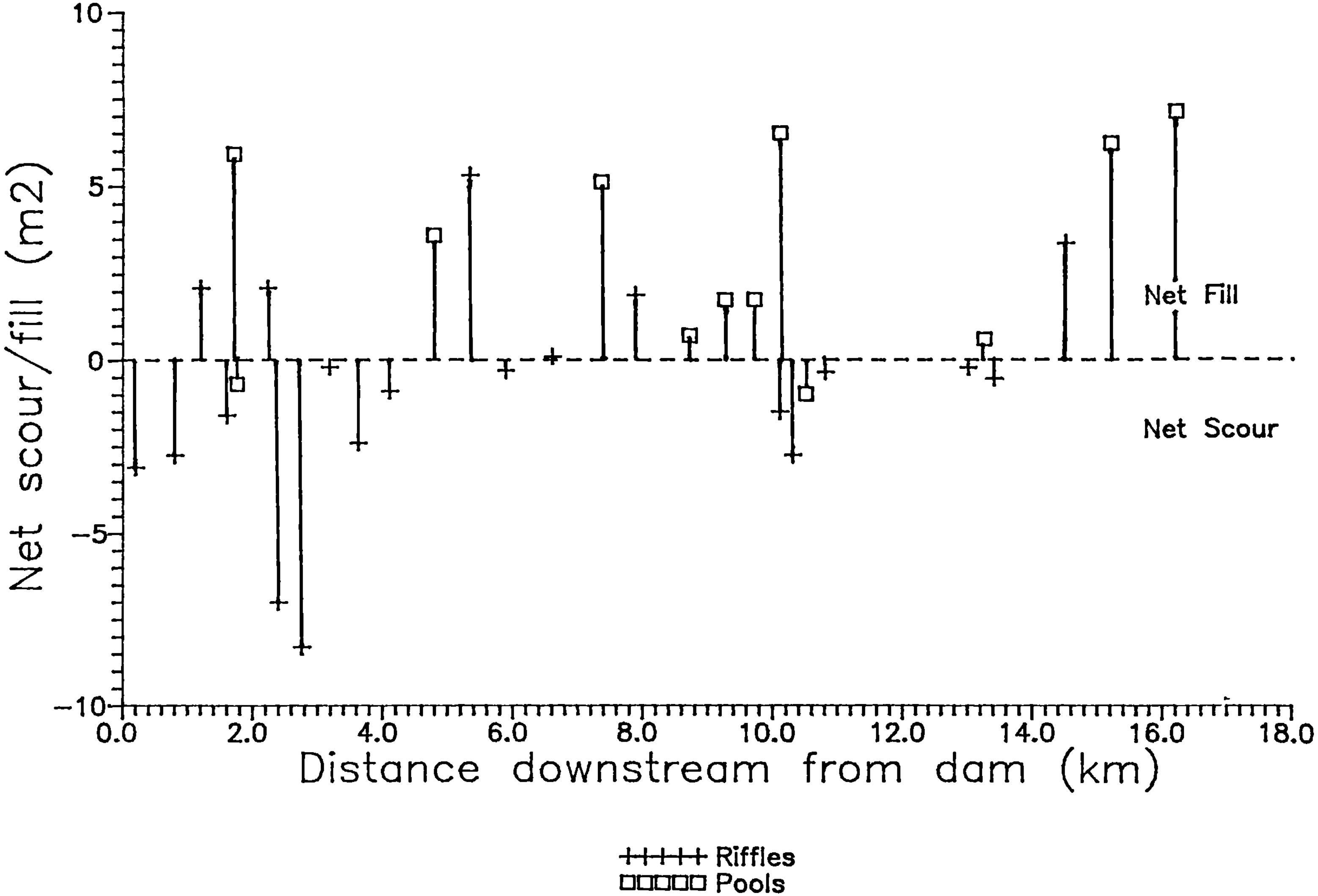


Table 13.1: Comparison between rates of scour and fill derived over differing time periods

Time period (years)	Morphology	Rate of scour (m^2/yr)	Rate of fill (m^2/yr)
9-11	Riffle	-0.17	0.15
9-11	Pool	-0.05	0.43
2	Riffle	-0.83	0.35
2	Pool	-0.04	0.41

The increase in the rate of scour at riffles may be explained by the operation procedure for the Kielder Reservoir for the period of the study 1988-1990. Although hydropower generation occurred in the period 1978-1988, the increase in Q_{50} was from 3.4-7.1 cumecs, whereas for the period 1988-1990 the Q_{50} increased from 7.1-15.7 cumecs (see Chapter 3). From the discussion in Chapters 7 and 10, it can be shown that these discharges promote high shear stresses on the riffles which can locally entrain sediment up to 137 mm. The equivalence of pool aggradation rates is a reflection of where in the pool the cross sections were taken. Since material eroded from riffles is preferentially deposited in pool-tails, the survey may not be picking up the eroded sediments.

The last three sites have all experienced a net filling which must result from an input of sediment from either unsurveyed riffle scou r or the cumulative deposition of material brought in by unregulated tributary floods from the Tarset and Chirdon burns over the period since 1978.

The sediment balance in terms of the average scour and fill for riffles and pools indicates that whilst 0.93m^2 of sediment has been lost from riffles, 3.26m^2 of sediment has been deposited in pool sections. An imbalance therefore exists between supply from degrading riffles and inputs to aggrading pools. The additional material in the pools may be derived from the large fine sediment input that occurred during the construction of the dam and which is described by Cave (1985). Alternatively, the material may be derived from tributary floods that locally scour pools of fine sediments and which, once in the pools, is stored due to the reduced frequency of pool scouring discharges (see Chapter 12). This latter point is supported by the observations of scour and fill during the bankfull flood, as well as the results from the infiltration data. Bank erosion sources have been effectively eradicated since regulation.

Table 13.2 depicts the scour and fill associated with the surveyed sections monitored during the course of this study. The net change in cross-sections is given, together with peak discharge for the period between surveys. In all cases the surveys cover the period 1987-1989 and 1989-1990. The sections together with survey years are all contained in Appendix A.

Yarrow riffle 1, the riffle closest to the dam (0.25km), experiences a consistent net scour throughout the period of study. The fill associated with this site is minimal in comparison with other riffles, despite a flood peak of 77 cumecs in February 1990. This is due to the lack of sediment supply available from the short scour pool between this riffle and the dam which fails to replace the scoured material. This is supported by the movement of tracers at this site with a high recovery rate (80%), which indicates a lack of burial. In contrast, TR1 experiences an equivalent net scour to YR1, but fills by almost an equal amount following the February flood. This is largely attributable to the reworking of the right bank island and the supply of sediment from the aggrading upstream reach. The direct sampling of bedload at this site, and the high infiltration rates recorded during a range of discharges, confirm the accentuated sediment transport and supply at TR1.

A net filling of the riffle sections following the bankfull flood of February is associated with NR1 and NR2 downstream of the Tarset/Chirdon Burns, but not with the TR2 riffle. The anomaly at the TR2 riffle may largely result from the interaction of tributary flows which trapped most of the sediment within confluence bars at both the Tarset and Chirdon Burns. The relative dynamism of tributary junctions is evident from the Tarset Scour re-surveys, which exhibit the largest changes in cross-sectional area. The scour pool is scoured to a depth of 2.8m below compensation flow levels during 1987-1988, and filled by some 0.55m during 1988-89. In contrast, maximum scour at pools and riffles, even during the 1990 flood, reach only 0.30m and that at YR1.

The Tarset pools exhibit a net filling during the period 1987-88 and 1988-89. The filling within the Tarset pool downstream of the Tarset Burn confluence effectively covers the

Table 13.2

Scour & Fill at riffles and pools in relation to peak discharge

	YR1		SMR	SMP	TR1		TR2	
Discharge	32	77	105	105	22+	105+	58	151
Scour (m^2)	2.20	1.00	0.41	0.30	2.75	0.20	0.00	1.10
Fill (m^2)	0.00	0.15	0.11	0.54	0.00	2.75	0.30	0.45
Scour max (m)	0.30	0.20	0.15	0.11	0.30	0.07	0.08	0.15
Fill max (m)	0.05	0.10	0.05	0.08	0.00	0.28	0.10	0.08
Net Change (m^2)								
Scour	2.25	0.85	0.30		2.75			0.65
Fill				0.24		2.55	0.30	

	TP1		TScour		TP2	NR1		
Discharge	22	32	39	42	42	58	51	151
Scour (m^2)	0.30	0.1	5.30	0.14	0.00	0.63	0.41	0.16
Fill (m^2)	0.75	0.20	0.57	3.90	1.28	0.72	0.28	1.89
Scour Max (m)	0.21	0.35	0.75	0.15	0.00	0.15	0.15	0.13
Fill Max (m)	0.15	0.30	0.27	0.55	0.22	0.38	0.13	0.28
Net Change (m^2)								
Scour	--	--	4.73				0.13	
Fill	0.45	0.10		3.76	1.28	0.09		1.73

	N3	N5		N7		N9		N11	
Discharge	151	51	151	51	151	51	151	51	151
Scour (m^2)	1.33	0.00	0.02	0.15	0.19	0.18	0.02	0.08	0.10
Fill (m^2)	0.25	0.04	0.35	0.27	0.57	0.49	0.39	0.26	0.45
Scour max (m)	0.18	0.21	0.04	0.12	0.14	0.04	0.14	0.05	0.04
Fill max (m)	0.05	0.06	0.14	0.14	0.08	0.08	0.12	0.08	0.22
Net Change (m^2)									
Scour	1.08								
Fill		0.04	0.33	0.12	0.38	0.31	0.21	0.18	0.35

	N13		N15		NR2	
Discharge	51	151	151	58	51	151
Scour (m^2)	0.00	0.60	0.05	0.49	0.26	0.00
Fill (m^2)	1.00	0.23	1.00	0.10	0.11	2.74
Scour max (m)	0.05	0.09	0.01	0.15	0.13	0.18
Fill max (m)	0.14	0.08	0.08	0.18	0.10	0.40
Net Change (m^2)						
Scour		0.37		0.39	0.15	
Fill	1.00		0.95			2.74

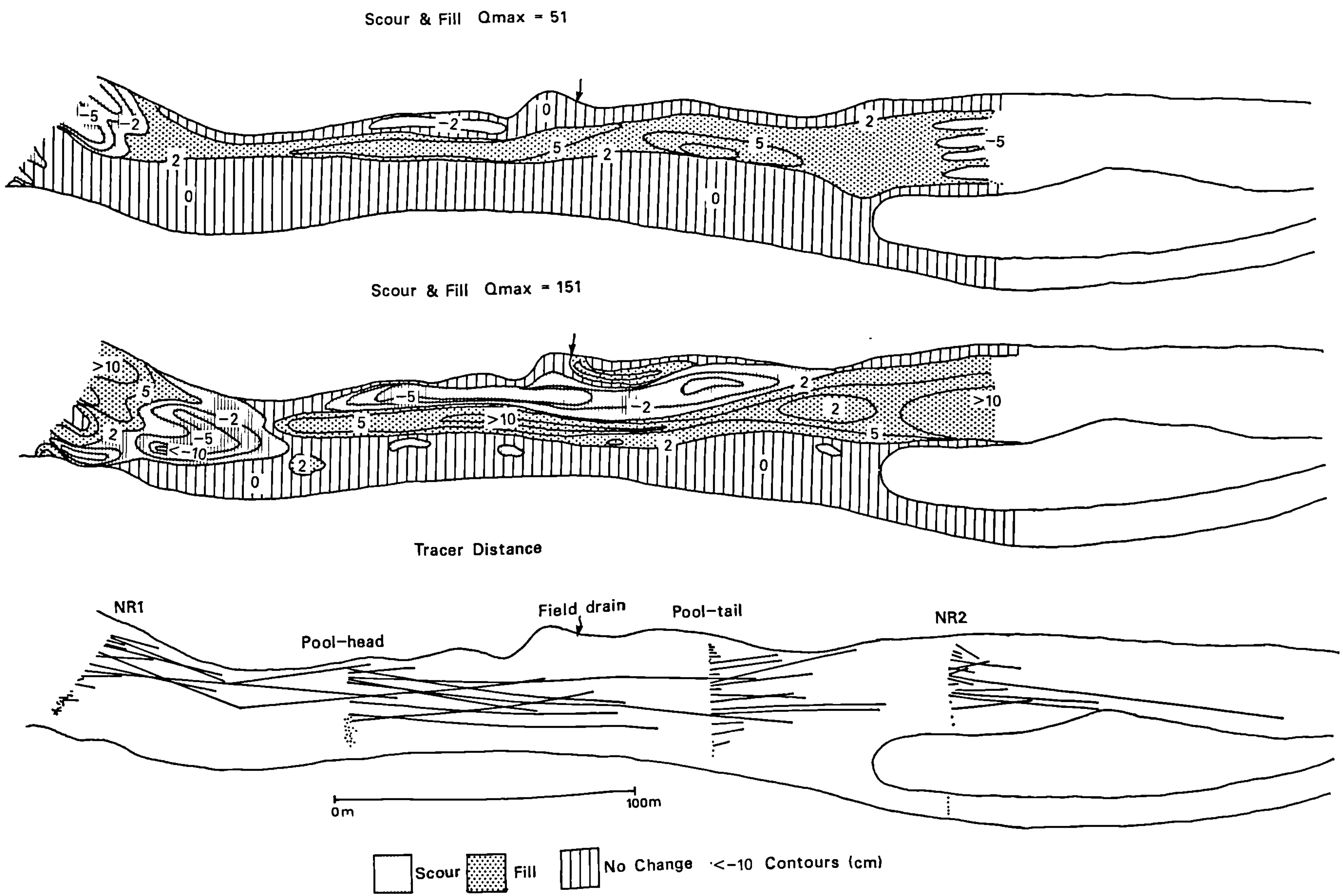
large roughness elements of the bed. The smoother profile presented in 1989 supports the hydraulic observations described in Chapter 7. Unfortunately, no repeat pool soundings were made in 1990, but the tracer surveys indicate that no change occurred at the TP1 site, whilst the Tarset pool (TP2) experienced a net filling of the left hand bank as a result of the redevelopment of the Tarset confluence bar (Chapter 4).

The Newton site was surveyed in detail throughout the pool. Figure 13.2 presents maps of scour and fill at the Newton site as determined from detailed resurveys using echo-sounding equipment (Chapter 4). In addition, a map of the trajectories and distances moved by tracers during the February 1990 bankfull flood are shown. The data from the echo-sounded cross sections was compared between successive surveys and the net change in bed depth below the reach Arbitary Datum was calculated. This information, together with the information from surveyed riffle sections, was mapped and the contours interpolated using Unimap 2000 software.

Figure 13.2a represents the net scour and fill at the Newton site for the period 20/1/89 - 13/4/89 (90 days), during which time 30 cumecs was exceeded on 11 occasions, with a maximum discharge of 51 cumecs. The majority of the river bed does not exhibit any net change in elevation. This is particularly apparent at the channel margins and along the right side of the pool (looking downstream). This is an area of coarse colluvial material where fine bed material collects during hydropower discharges (Chapters 4 and 5). The relative roughness of this region of the bed can be seen in the sections 3-11 in Appendix . Determination of scour and fill in this region was complicated by the presence of large boulders, which recorded variable signatures, depending upon which part of them the transducer was passing over. However, evidence from the tracing experiments (Figure 13.2c) confirmed that little or no scour or fill of material >22mm had occurred.

Net scour in the Newton reach is evident at riffles, with some localised scour of the left bank within the pool-head. The scouring of riffles is well documented for discharges below bankfull (see discussion above) and is a feature of the majority of riffles surveyed in the North Tyne (Appendix A). The scour of riffles during moderate discharges is consistent with the results of the FBA site re-surveys (Chapter 4), and confirms the results of the bedload sampling and magnetic tracing experiments in terms of a morphological response to the accentuated sediment transport recorded on the riffles.

13.2 Scour & Fill in a riffle–pool–riffle sequence for floods upto bankfull. Tracer movement after Q = 151 cumecs are shown.



The tracing experiments illustrate that, although scour and fill may be evident within a section, the transport of coarse particles does not necessarily equate with the observed pattern. Therefore the transport of tracers at both Newton riffle 1 and 2 (Figure 13.2c) indicates scour was present, but the surveys indicate major aggradation. A similar picture is presented in the pool-head and pool-tail. Scour is indicated by the movement of tracers in the region that is shown to have aggraded. The inevitable conclusion is that, viewed individually, tracing experiments and re-surveyed sections only record part of the process at a site. Clearly, from the evidence of the tracing experiments, an initial scouring occurs throughout the riffle-pool sequence, with selected regions remaining stable. Scour occurs particularly in the pool-head, as evidenced by the long transport distances. This is a region of locally high shear stress at bankfull discharge (Chapter 7) in comparison with the pool-tail, which exhibits a shear stress maximum of only one fifth of that of the riffles or pool-head. Correspondingly, the transport distances are shorter than the pool-head and the region is characterised by aggradation. In contrast, the riffles experience maximum shear stresses of similar or greater magnitude to the pool-head and yet show shorter transport lengths and net aggradation. Sediment supply is controlling the scour and fill at these sites and effectively choking the riffles.

Following the scour, there is a net infill of sediment at the riffles and through a narrow section of the pool. This material buries some of the tracer particles which may remain in-situ at a section. The aggradation of NR2 results from the transport of sediment from the pool-tail immediately upstream, although this section itself is subsequently aggraded by sediment derived from as far upstream as the pool-head.

The re-surveys and tracer experiments confirm that the net changes observed before and after a flood event or over long periods of time often mask the complexity and magnitude of the scour and fill at a section. In addition, the observations from the Newton riffle-pool-riffle sequence confirm the observations of Clifford and Richards (1992), that sediment transport in pools is characterised by a narrow "active" region. The scouring of riffle and pool sediments prior to filling is also in accordance with the entrainment data discussed in Chapter 12, which indicates that, as the discharge rises, the riffles scour before the pools.

13.3 Scour and fill in relation to intrinsic controls on sediment transport

The controls on scour and fill at a cross-section are related to the net balance between sediment transport and sediment supply. Correspondingly, Ferguson et al (1992) have been able to correlate maximum sediment transport with scouring regions of a section, and vice-versa for aggrading regions. It was hypothesized from this that the factors controlling sediment transport, identified in this study as local shear stress and the strength of the river bed and size of the sediment at a site, should be capable of predicting the tendency of a particular part of a section to scour or not.

The data for scour and fill at five sites where full data-sets were available was combined with data on the shear stress bed strength and the local B-axis of the bed surface. The data was analysed for relationships between scour and fill and these variables using correlation and least squares regression. No relationships were statistically significant at even the 90% confidence level. Multiple regression of scour and fill depth against all three variables was also used for discharges < 51 cumecs and > 105 cumecs. Again, the combination of variables accounted for only 28% of the variance in scour and fill occurring at discharges < 51 cumecs, and only 7% for discharges > 105 cumecs. As a result, it is concluded that local hydraulics and bed status derived from individual events or from discrete periods of time in the discharge record cannot quantitatively account for the pattern of scour and fill observed over periods of time in excess of 1 month to several years. Consequently it is concluded that sediment supply at a given point in a section is more important a determinant of scour and fill over longer time periods at discharges < 51 cumecs and within individual flood events > 105 cumecs.

Despite the failure of local site conditions to account for the morphological changes observed in the riffle-pool sequences, the pattern of riffle scour and pool filling is supported by the gross differences in shear stress recorded for hydropower discharges and inferred from the movement of tracers at discharges up to 36 cumecs.

The results of the tracing experiments have indicated that river regulation for hydropower produces discharges that are locally competent to transport sediment up to 137mm B-axis 0.6m. However, the movement of surficial material is rapidly retarded by incorporation into the bed structure. The hiding effects of a rough heterogeneous bed dominate the entrainment of material smaller than the surface D_{50}, whilst at discharges up to 105 cumecs structural control and inertia govern the entrainment of coarser particles.

The structural and bed strength differences between riffles and pools is expressed in the entrainment thresholds for similar particle sizes, with pool sediments being consistently entrained at lower shear stresses than riffle particles. Nevertheless, riffle sediments are entrained at discharges lower than pool sediments as a result of the site specific relationships between shear stress and discharge. A reversal in shear stress is not required to explain the scouring of pool sediments.

The hierarchy of sediment transport at bankfull discharges reverses, with pool-head sediments travelling further than riffle sediments, and with an equivalent competence at least up to the 150mm B-axis tracer maximum. This is explained in the pool-head at Newton by a combination of the locally high shear stresses which are derived from the narrowing cross-section at this site and the relatively smooth surface of the bed. A correspondingly low shear stress is experienced in the pool-tail region, which is a region of diverging flow and sediment transport paths and consequently an area of net aggradation. The relative roughness of the riffle surfaces and the concentration of structural assemblages reduces the distance a particle travels before entrapment, despite entrainment early on in a flood. The rate of rise must also be a factor in the transport of sediment, since a rapid rise to bankfull will act to decrease the time at which riffles scour before pools. This latter point may explain why some studies record variable scour and fill at riffle-pool sections, since the scour at a riffle will be greater when a flood rises slowly to a peak prior to the evacuation of the upstream pool (Chapter 12). Sidle (1989) has described such a relationship, and Nouh (1990) has commented on the effect of flood duration on the armouring of a gravel bed. The models of sediment transport in riffle-pool sequences are clearly more complicated than at first conceived.

Chapter 14
Summary and Conclusions

Many of the conclusions of this dissertation have been included at the end of individual chapters. The main conclusions are summarised again here, and developed into a broader model of the development and perpetuation of the riffle-pool sequence. The development of the riffle-pool sequence under continued regulation for hydro-electric-power within the North Tyne is considered in the light of the findings of this study, and wider implications are discussed in the context of the riffle-pool model.

Historical Stability

* Historical analysis has shown the North Tyne to be have been laterally stable for the past 125 years. Sediment storage and transfer within the system formerly revolved around discrete sedimentation zones, wherein sediment supplied from tributary floods queued before dispersing through the intervening transfer reaches.

* Vegetation colonisation plays a significant role in locking up sediments, particularly during protracted periods of low flows. The distribution of a major sediment input in 1867-1898 took approximately 78 years. The evidence for a climatic cause to the historical pattern of sediment storage in the North Tyne is confirmed by similar observations from other rivers in the region.

* The riffle-pool sequence in the North Tyne is a relic of sediment transport and supply prior to regulation, and indeed many riffle sites are documented in the same position for at least 125 years. Sediment storage within a reach appears to be associated with riffle-pool instability rather than a change in channel width; this should be investigated/confirmed by future research.

Hydrological changes due to hydropower regulation

* River regulation affects the discharge regime of the North Tyne throughout its length to the Tyne (and beyond).

* The construction of Kielder Reservoir and the operation of hydropower generation has reduced the frequency of bankfull floods experienced in the North Tyne for at least 34 km downstream, the degree of reduction being related to the amount of unregulated catchment supply.

* Exceedence frequencies have been reduced for all flows above 25 cumecs, the degree of reduction being related to the magnitude of the flood; this confirms the calculations of Brierley (1983), who also reported an increase of flood duration by 75-82% for the reach upstream of the Tarset and Chirdon Burns. This requires confirmation.

* The operation of hydropower has increased the frequency of discharges in the range 2.0-16.0 cumecs by more than 100%, whilst compensation flow limits have increased the magnitude of flows associated with Q95 exceedence frequency for a gauging station 10 km downstream of the dam site.

* The North Tyne can usefully be divided into 3 sections on the basis of discharge regime; Section 1 (controlled by dam discharges), downstream from the dam to the junction of the Tarset and Chirdon burns; Section 2 (controlled by dam discharges but with infrequent sediment mobilising freshets), downstream of the Chirdon Burn to the junction of the River Rede; and Section 3 (controlled by dam discharges but experiencing relatively frequent sediment mobilising floods), downstream of the River Rede.

Changes in the sedimentology of the riffle-pool sequence

* Subtle sedimentological changes have occurred since river regulation, dominant of which is armouring of riffle sediments by selective erosion during hydropower releases. This has occurred at 64% of riffles sampled against a basin-wide trend of bar sediment fining, and is particularly evident in the first 2.5 km downstream of the dam site. Seventy-nine percent of riffles surveyed exhibited an increase in the size of D16 particles.

* Armouring occurs in riffles and pools within regulated and unregulated streams. Armouring is more accentuated on regulated riffles than unregulated riffles as defined by truncated armour ratios. The method of armouring is, however, different; riffles are

armoured by a process of fine sediment winnowing by selective erosion at low-moderate discharges, whilst pools exhibit preferential surface sediment coarsening indicative of equilibrium transport conditions during higher magnitude events.

* Pool and riffle sediments are best discriminated by surface sedimentology; pools are generally finer than riffles but by no statistically significant magnitude. This confirms the observations of Milne (1982a) and Ashmore (1979).

* Riffle and pool subsurface sediments are not statistically distinguishable on a particle size basis. However, there is a significant trend towards coarser D_{84} particles at riffles and poorer sorting of subsurface riffle sediments. The former point does not support Keller's (1971) observation of coarser riffle subsurface sediments.

* Bar surface sediments are significantly finer than riffle or pool surface sediments, which again confirms the observations of Milne (1982a).

* The most significant sedimentological processes are lateral fining in pools (from coarser pool-deeps to finer lateral berms) and downstream fining in pools (from coarser pool-head to finer pool-tail). In addition, pool-tails contain the highest percentages of fine (<22 mm) material, whilst the pool-head is often deficient in fines with respect to the upstream riffle.

* There is inconclusive evidence to suggest that riffles contain higher percentages of flatter particles than pools, although this is subject to the method of shape analysis used. This supports Clifford's (1990) observations that more research is needed to indentify the link between riffle-pool morphology and particle shape.

Bed structure and strength

* Riffles and pools are best discriminated by the percentage of particles in structured, stable positions. Riffles have up to 3 times more stable particles than associated pools. Riffles are also characterised by higher densities of pebble clusters than pools, independent of stream geology or environment. This independently confirms the same observations made by Clifford (1990).

* Bed structure in the North Tyne varies through the pool in the order riffle > pool-head > mid-pool > pool-tail. In the Store Blydal, cluster densities decrease from riffle to mid-pool but increase through the pool-tail. The size of structural particles also varies in the pool, with a general trend from coarser pool-head to finer pool-tail. This situtation is reversed during bankfull floods.

* Bed strength, a function of particle packing, sediment size and sediment structure, can be determined qualitatively by dynamic penetrometer. Riffles possess consistently stronger beds than pools. Within pools, bed strength declines from pool-head to pool-tail.

* Bed strength and stable structure are reduced on riffles by up to 57% after flood events that mobilise the surface sediments. Although pools exhibit an increase in stable structure (particularly in the pool-tail), the absolute values for stable structure remain lower than for riffles. However, the magnitude of discrimination between riffles and pools is generally reduced post-flood.

* Bed structure and bed strength readings on regulated riffles are on average 30% greater than those recorded from unregulated tributary streams. This is independent of particle size. The conclusion is, therefore, that hydropower regulation accentuates the development of bed structure and strengthens the surface compaction of the riffle spawning beds. This process results from the high shear stresses experienced on riffles during hydropower, which push finer particles into the bed, and which shake the surface particles into a more densely packed framework. The surface particles that are not able to find a structured position are moved off the riffles during hydropower releases.

* Tracing studies indicate that it takes around 1-3 months for particles on riffles to become incorporated into structurally stable positions, and that this occurs most rapidly for particles finer than the D_{50}. Post flood development of bed strength is a slower process and variable per site. A 6.6% increase in bed strength was monitored on a riffle after 76 days of continuous hydropower generation, whilst the next riffle downstream recorded a decrease in bed strength of 1.8%. Pools (particularly mid-pool and pool-tails) experience a 23% decrease in bed strength after 76 days.

* Bed structure is fully developed on riffles by the action of low-moderate flow winnowing. Bed structure in pools (particularly pool-tails) is developed during floods of near bankfull capacity.

Sediment transport

* A velocity or shear stress reversal is not required to transport sediment from pools. Lack of bed structure compensates for lower or equal shear stresses. Sediment transport is generally from pool to pool, with a period of dynamic queuing on the riffles (Figure 14.2)

* Sediment transport over riffles during hydropower releases is up to 500% greater than that experienced in associated pools

* Competence in the pools is 50% lower than riffles during hydropower events, and transport distances indicate that only fine coarse and fine sand can be moved through the riffle-pool sequence during hydropower discharges.

* Shear stress and stream power, determined from log-velocity profiles account for up to 42% of the sediment transport in pools and 32% at riffles. This relationship is improved when only locally entrained sediment is used. This latter point supports the observations of Meigh (1987).

* The critical shear stress for the transport of particles in pools is lower than that required for the same sized particles on riffles due to the presence of bed structure and compaction. As grainsize increases the difference in critical shear stress decreases. This latter point is, however, a function of the inherent uncertainties in the tracing technique used to evaluate critical conditions during flood events. It is therefore concluded that the lower transport thresholds recorded in pools for finer sediments also extend to larger particles as well. This is an area requiring further research for confirmation.

* Shear stress at the cessation of bedload transport in riffles and pools under conditions of supply sufficiency are lower than initiation of transport, which confirms the

observations of Reid et al (1985). The cessation of bedload transport in riffles occurs at a shear stress on average 3.1 times lower than for transport, whilst in pools the value is extended to 5.1 times lower than transport. This is may reflect the deficiency of sediment supply at riffles due to bed structure, or the relatively rapid incorporation of sediments into the structured riffle surface once shear stress begins to decrease. Further research is required to elucidate this point.

* Transport lengths and particle velocities of material > 22mm are lower over riffles than in pools. Particle velocities are highest in pool-tail and mid-pool locations, where the probability of becoming trapped in a structure is much less than on riffles. Particles in pool-heads experience the highest transport lengths during flood events, although particle velocities are generally lower than in other regions of the pools. Bed structures and a coarser bed surface over riffles delay sediment transport and reduce transport velocities. These observations are based on a limited set of observations, but an appraisal of complementary tracing experiments confirms the higher transport distances in pools.

* Sediment transport is confined to narrow sections of pools, associated with finer lateral gravel banks, rather than in the deepest coarser sections. This supports the observations of Leopold (1982) and Church (1982).

* The presence of bed structures and compaction of riffle surfaces tend to make the transport of particles appear equally mobile at low transport rates, since coarser particles are exposed to the flow whilst finer particles are hidden. In pools with little structure or strength, sediment transport is a size-selective process.

* During large bankfull floods, riffles import sediment and pools export sediment, so that riffle sections fill and pool sections scour. The sediments reaching riffles from pools during such floods are finer than the riffle surface which reduces the post-flood riffle surface grainsize. Coarse sediments are exported to riffles from pool-tail regions, not from the mid-pool or pool-head.

* The shape of the flood hydrograph is important for determining the duration at which different elements of the riffle-pool sequence are above critical transport thresholds. Low magnitude, high duration floods will favour riffle and pool-head transport. High

magnitude, low duration floods will route sediment through the whole riffle-pool sequence. The period of low flows between flood events is important for the development of stable riffle surfaces. Prolonged periods of low-moderate flows will stabilise the gravel-bed and subsequent transport will require a higher magnitude event. This confirms the observations of Reid et al (1985).

Summary discussion: Riffle-pool formation and dynamics

The conclusions of the experimental observations of this thesis have shed light on the sedimentology, morphology, hydraulics and sediment transport of the riffle-pool sequence. Individually these remain in isolation as descriptions; what remains to be effectively achieved is to integrate these observations into a physically robust model of the riffle-pool sequence. Figures 14.1 and 14.2 illustrate the model of riffle-pool dynamics and the application of structure induced kinematics to a wider conception of sediment transport in gravel-bed rivers.

Such a model is required to explain:

* why riffles possess higher bed surface structure and strength

* how riffles develop higher armour ratios than pools, and why subsurface riffle sediments possess coarser D_{84} particles while possessing poorer sorted sediments

* how the riffle-pool sequence is maintained in the same position over periods of 125 years, and during large flood events

* why the riffle-pool sequence is actively mobile in regions of sedimentation

* why, since river regulation, riffles and pool-heads have preferentially degraded (but not disappeared) and pool-tails have aggraded

To begin with, the structure and surface armour on riffles are formed during periods of low-moderate discharges (1-50% bankfull) by the action of hydraulic lateral and vertical winnowing of fines from between coarser particles. This process is accentuated by the spasmodic transport of larger particles under a widely varying shear field. Bed structure is developed as particles move into stable positions during small flood events. The higher shear stress on the riffles tightens the bed particles (not equivalent to packing by virtue of bulk density) by the force with which they are pushed together. The result is a stronger structured bed with a depleted surface fines content.

During small floods (or hydropower) pools export coarse sands. These are temporarily trapped in the subsurface of the riffles by vertical winnowing. The depth of penetration of these fines is dependent upon the velocity of flow within the gravels, with higher velocity flows pushing fines deeper into the bed, and removing fines from deeper in the bed. Local morphology will condition this process, together with the upstream pool fines content and sediment transporting capacity. The static riffle bed during moderate discharges acts as a fine sediment exchanger, storing fines during low flows at a given depth below the surface, and releasing them during higher discharge events. In this way, fines contents are variable between riffles and through time. The loss of higher scouring discharges will tend to increase the fines content of riffles at a depth conditioned by the dominant flushing flow and local morphology.

Pools do not experience the frequency of particle movement for long enough to produce bed structuring or tightening. This in itself suggests that during floods, pools experience a sharp transition from an immobile bed surface to a mobile one.

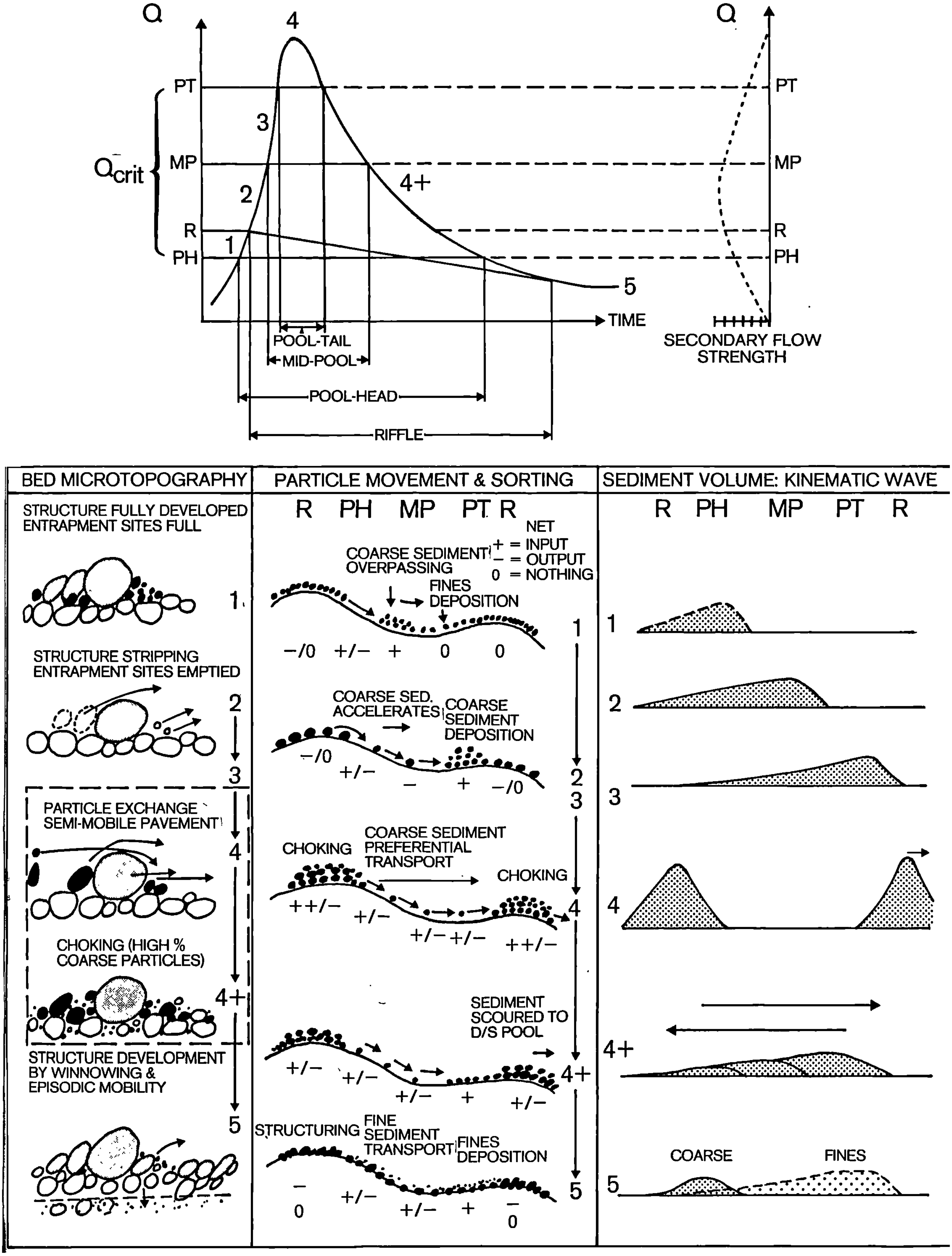
Bed structure, and particularly the presence of pebble clusters, together with an armoured surface of coarse particles, generates a higher boundary resistance, and a fluctuating shear field. A positive feedback is established whereby locally high shear stress develops a rougher bed and locally high shear stress. This loop is interrupted either by changes to the boundary caused by larger floods, or by structural resistance to motion which locks the bed surface at a roughness value dictated by the initial grainsize population. The locking of riffle beds by armouring, structure and tightening also prevents degradation, and maintains the position of the sequence during low to moderate flood events.

In pools, the shear field is characteristically variable, both downstream and laterally. This is largely a function of bed morphology, since pools widen and shallow downstream greater than increasing slope can accommodate. The regions of the pool defined as pool-head, mid-pool and pool-tail therefore respond quite differently to rising discharge. Correspondingly, competence and bed mobility is reached first in the order pool-head, mid-pool, pool-tail.

Bed structure and compaction increase the shear stress (and discharge) required to initiate sediment transport on riffles. The degree to which this affects the order of competence through the riffle-pool sequence depends on the size of sediment and, once moving the particle size (D_i/D_{50}) and bed rugosity control sediment transport lengths. Particles finer than the D_{50} of the bed are most affected by the structuring of riffle surfaces, and can be transported through the pool-head and mid-pool before they are moved from riffles. As particle size increases, the combination of size selectivity of motion, and rate of shear stress increase with discharge combine to render riffles and pool-heads competent before mid-pool and pool-tail. However, relative roughness effects and the presence of bed "stripped" structure (Figure 14.1) increase the probability of particle entrapment in these regions and so particle velocities are reduced. For riffles the particle velocities are 1000% lower than in pools, and particle velocity increases downstream to the pool-tail. The result of this should be the efficient routing of sediments through pools as an attenuating wave, which abrubtly steepens on approach to the downstream riffle. However, the particle transport lengths show that pool-head sediments catch up with pool-tail sediments, and mid-pool sediments probably equalise or exceed pool-tail particles. This is explained by the duration of time at which the different elements of the riffle-pool sequence are above the critical threshold for transport which is conditioned by the shape and magnitude of the flood hydrograph.

In the latest theory of riffle-pool maintenance, Clifford (1990; in press) explains the persistence of riffles by assuming that for most floods the riffle sediments remain locked in situ. The results from the North Tyne (and other studies) indicate that this is not the case. Consequently, the effects of bed structure and strength are partly to redress the entraining force inequality, but also to provide a bed of greater entrapment probability for duration of the flood hydrograph. Despite the evidence that bed structure is destroyed by bankfull flood events on riffles, the pattern of higher structure is preserved, though in reduced abundance on riffles post-flood. The operation of bed structure as an active exchange mechanism has been described by Reid et al (in press) and Billi (1988). Whilst sediment is queuing upstream in the pool-tail, sediment is removed from around the

14.1 SEDIMENT TRANSPORT IN RIFFLE-POOL SEQUENCES



obstacle clasts on the riffle (structure stripping in Figure 14.1), actually increasing the entrapment potential. The emptying of the pool-tail, as the threshold of motion is crossed, supplies new stoss and wake particles which are therefore slowed down over the riffle surface, enabling the particles behind to catch up. The increased concentration of particles reduces particle velocities (in accordance with kinematic wave theory), even though the particles are themselves in motion (Figure 14.1).

Sorting of sediments on a size basis (and probably shape too) occurs as a result of both low discharge conditions (most important on the riffles) and during high magnitude flood events of 80% + bankfull. The evidence, albeit from only two riffle-pool-(riffle) sequences, indicates that particles coarser than the surface D_{50} are preferentially transported through the pools once entrained. This is analogous to the observations of Ferguson et al (1989), who correlated higher gravel transport rates with lower bed rugosity. The confinement of coarse particle transport in pools to the finer gravel banks is in accordance with this observation. The operation of this process during floods will preferentially supply the downstream riffle (and pool-tail) with coarser particles during the period of initial riffle aggradation, and consequently may produce a higher coarse sediment composition in the riffle subarmour.

Figure 14.1 illustrates the process of sediment motion through the riffle-pool-riffle sequence during a single hydrograph. Incorporated into the linear considerations of transport downstream is the secondary component of lateral sediment motion. This is considered to be most significant at discharges between 20-70% bankfull on the basis of tracer trajectories and the observations of Thorne (1979) and Bathurst (1978). The consideration of secondary flow strength during the passage of a flood through the riffle-pool sequence coincides with the period of bed motion from riffle through pool-head to mid-pool, but declines in importance as the pool-tail is mobilised. The corollary of this is a tendency for material entering the pool-head to be deflected onto the finer gravel bank, and therefore into the region of maximum sediment throughput at the time when the pool bed is becoming mobile. This is particularly important for the finer sediment sizes and helps to explain the maintenance of asymmetric pool morphology.

The maintenance of the riffle-pool sequence is achieved through a process of kinematic wave motion, controlled by differential sediment entrapment potential on riffles, and enhanced particle velocities through the intervening pools. Figure 14.1 illustrates conceptually the passage of a wave of sediment through the riffle-pool sequence based on the differential timing of bed mobility within the riffle-pool sequence. Langbein and Leopold (1964) identified regions of low particle velocity with increasing particle concentration, which is analogous to the riffles. Intervening regions of low particle concentration are characterised by high particle velocities, the pools. The pool-tail is maintained as a region of sediment storage between floods by the higher frequency of bed mobilising events experienced in the pool-heads and mid-pools.

A disruption to this pattern, and hence the spacing of the riffle-pool sequence, will occur if the pattern of sediment concentration (kg/m) or throughput (kg/s) is altered (Langbein and Leopold, 1964). Clearly the longitudinal concentration of particles is altered by a net input of sediment. Kinematics dictate that an increased concentration of particles reduces particle velocites, therefore they do not travel so far in a given flood. This is compounded by structural development and bed strength. The spacing of kinematic waves is related to particle velocities, so that greater velocities lead to longer wavelengths (pools). Correspondingly, in areas of sedimentation one should expect shorter riffle-pool spacing, higher transport rates and lower particle velocities. In this way, the spacing of riffles is a function of the increase in linear concentration (sediment supply).

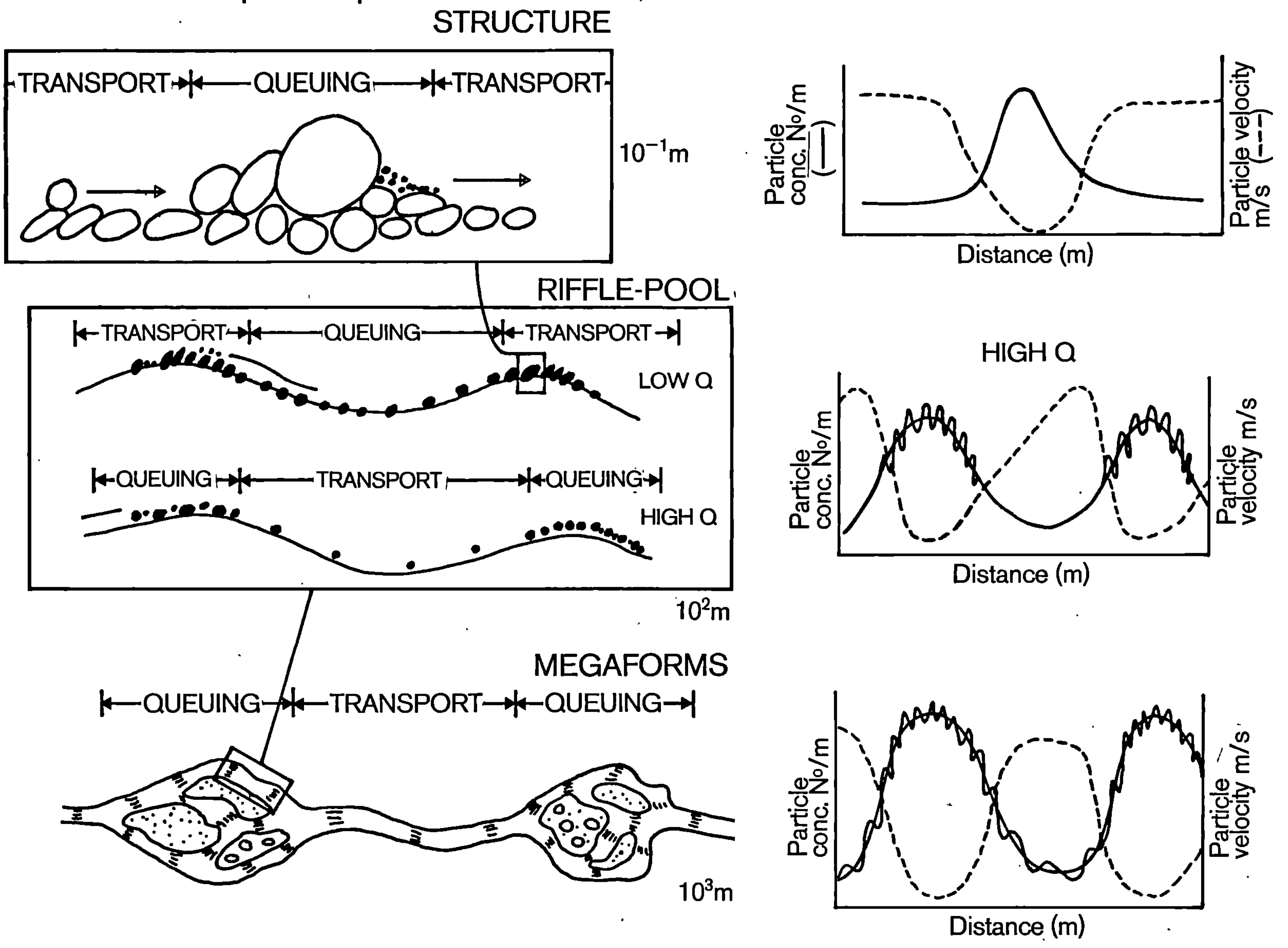
This process is exemplified by meander development models. With increasing stream length in a migrating (therefore eroding) meander bend, riffle spacing remains static until a threshold length is reached above which a new riffle is generated. Conceptually, an increase in channel length in an actively migrating bend equates with an increasing input of sediment to the pool. Simple queuing theory, driven by the discharge of sufficient magnitude to mobilise the pool bed, will eventually cause a new queue (riffle) to form once the linear concentration (length of eroding bank) reaches a critical length. An important consideration for future research is the distance required before kinematics translate the input of sediment into a morphological expression.

The pseudo-rhythmic spacing of riffles therefore becomes a function of the average transport lengths of particles, which in turn is a function of flood duration and magnitude. Once a wave or spatial concentration of particles is formed (these occur at a range of scales as pebble clusters, bars, riffles-pools and megaforms - see Figure 14.2), the hydraulics of the flood recession will be altered over the concentration, and subsequently bed structures will develop, along with bed tightening. The template for subsequent queuing will be created from which sediment transport is modified downstream and "fixed" by bed structure/strength.

The process of sediment kinematics is evident at a range of scales. Figure 14.2 illustrates this concept, and indicates that it is the operation of the process over a range of scales that explains the characteristic morphologies of gravel-bed rivers. In all cases, it is the interelationship between linear particle concentration and particle velocity that produces the storage of sediment. However, it is the stability of the microform queuing process, operating on the back of larger sediment flux divergences, that preserves the temporal stability of the feature. This process can be scaled up from microform to riffle and pool and to megaforms. The temporal stability of the features will depend upon sediment supply and flood shape and frequency and channel gradient.

In terms of the development of the North Tyne, the dual effects of flood attenuation (75-80%) and storage within the reservoir will produce lower magnitude, longer duration flood events in the North Tyne. In terms of the sediment transport in riffles and pools, this equates to a decrease in the sediment mobility of pool-tail regions, and an increase in the duration of sediment transport on riffles, pool-heads and mid-pools. Correspondingly, the expected morphological response will be the aggradation of pool-tails and the degradation of riffles and pool-heads. In addition, a reduced flood magnitude and increased duration will tend to increase the duration of strong secondary flow action in pool-head and mid-pools. Correspondingly, fine sediment will tend to collect as lateral channel berms. This model is confirmed to some extent by the results of cross section resurveys. The presence of accentuated bed structure and bed strength will retard the process of riffle degradation, whilst the infrequent bankfull floods experienced downstream of the Tarset and Chirdon Burns clearly reverses the process. The scenario for the reach closest to the dam site is one of continual riffle degradation until structure and compaction become sufficient to retard further removal. In addition, aggradation of pool-tails will lead to a reduction in depth and a possible increase in sediment mobility. This in turn may lead to structural development and an extension to riffle length. Channel width will also reduce, particularly in pool-tails, which will increase stream

14.2 QUEUING THEORY IN RIVER DYNAMICS:- Bed structure & the riffle-pool sequence in context



powers and sediment routing through the pool-tail. In this way, the riffle-pool sequence will be fossilised within a narrower channel. Any reduction in hydropower generation will increase the development of lateral channel berms through vegetation colonisation. The rates of capacity reduction will then increase.

The model of increasing riffle degradation and compaction, particularly in the first 10 km of the North Tyne downstream of the dam site, has significant ramifications for the successful recruitment of salmonids. Increased compaction of spawning gravels as a result of tightening and structure development will reduce the area available for redd cutting. With a policy of annual stocking of salmonids, together with the improvement of estuary water quality, the number of Atlantic salmon (Salmo salar) will increase as spawning grounds decrease. The result will be an increase in the number of overcut redds. This should be monitored for confirmation, together with bed strength and compaction values of selected riffles.

As linear sediment concentration and flood hydrograph morphology are important for determining channel morphology and sediment transport dynamics, then climate change and catchment processes that alter either of these can be expected to result in channel change. Land drainage, and arterial drainage in particular, increases the magnitude and reduces the duration of floods downstream. This will increase the throughput of sediment from pool-pool. Similarly, periods of increased flood frequency in association with accentuated sediment supply, as occurred in the late 19th century in the Tyne Basin (Rumsby 1991), will be expected to have a morphological effect on the riffle-pool sequence.

More research is required to effectively determine the rates of bed structure development at different morphological positions in the channel and the stream powers required to destroy structured beds. In addition, the effects of bed structure on entrainment, transport lengths and transport rates should be detailed for different particle sizes and geologies.

Further research should also be carried out to investigate the effects of varying flood hydrographs on the entrainment of path lengths of sediments from different morphologies. Additional measurements should also be made of sediment transport rates in riffles and pools, to confirm or reject the observations made in this study. A return to flume studies would be beneficial for determining the effects of meso-scale and macroscale morphologies on the transport velocities of individual particles. Time lapse photography of tracer particles may be effective in realising this goal.

Field studies should concentrate on sediment budgeting over reach scales, to account for morphological change. In addition, the use of high resolution echo-sounders during flood conditions may provide the answers to questions of the relative mobility of pool and riffle surfaces.

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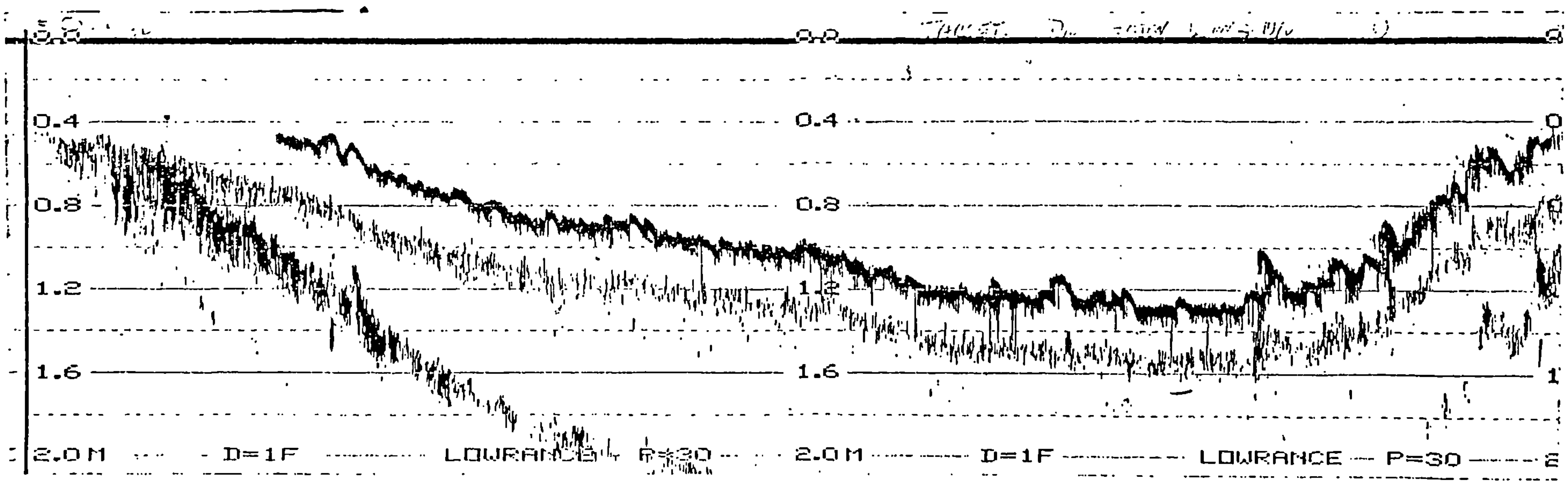
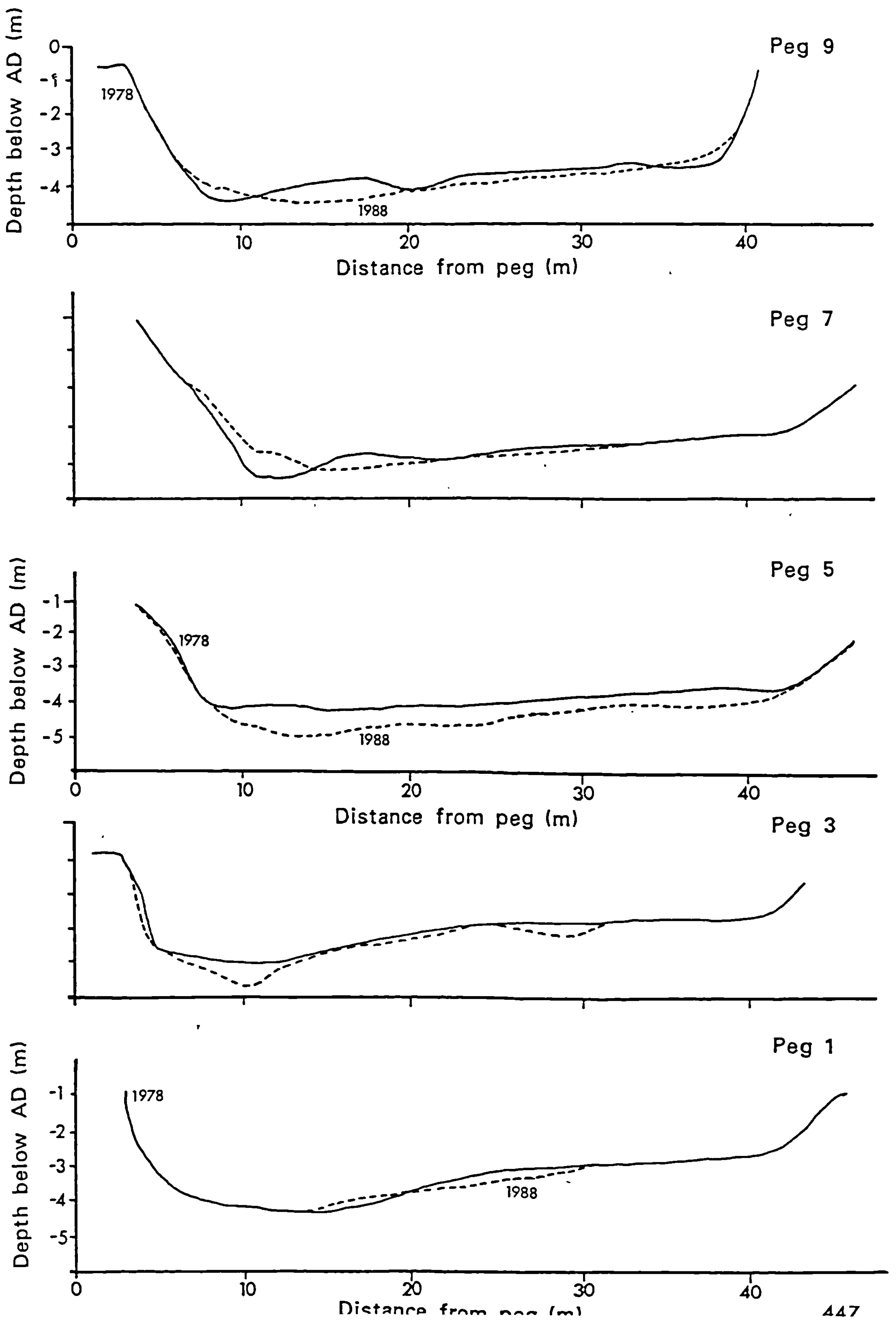
Appendix A

Cross sections used in the study

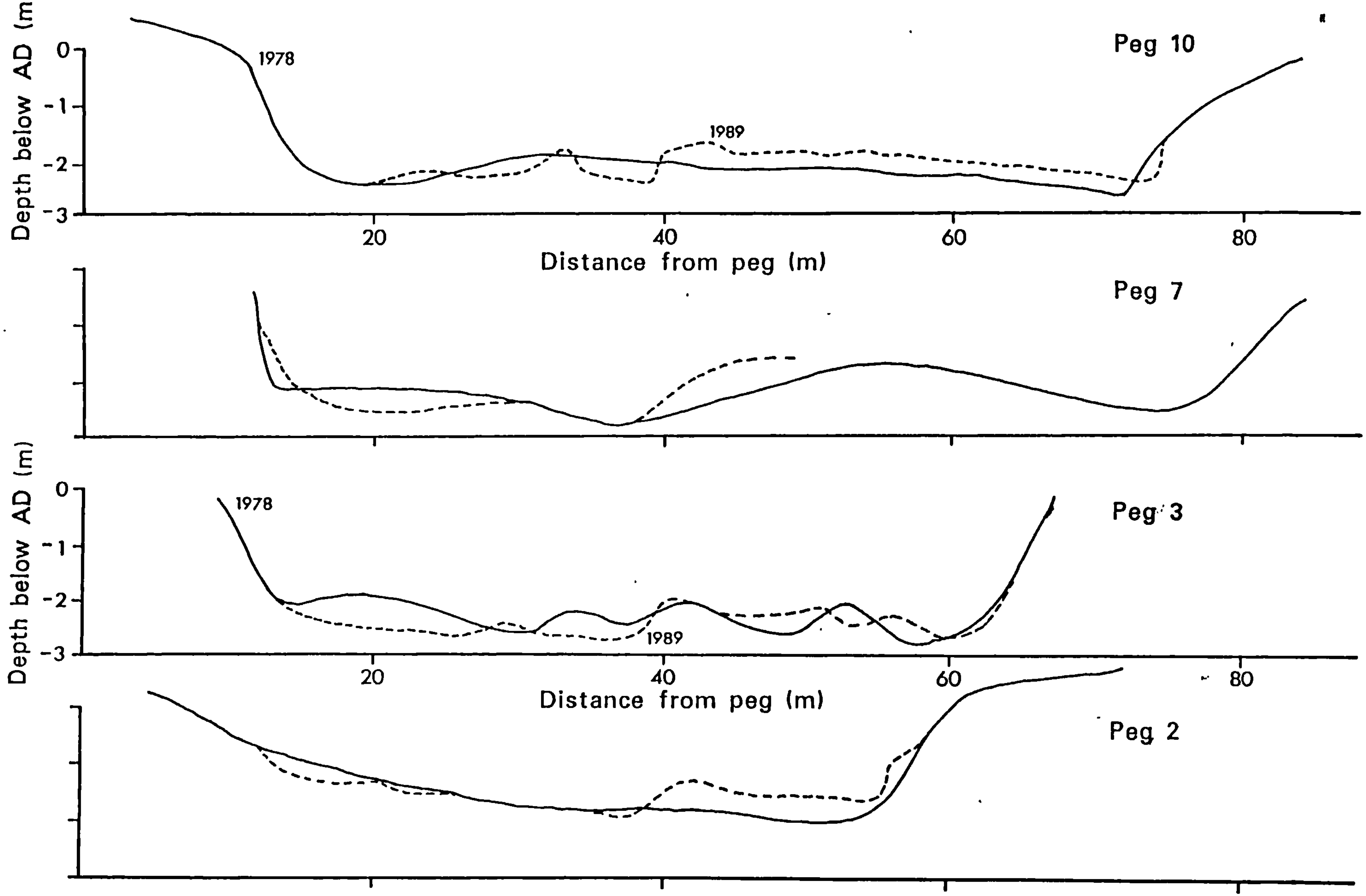
Figure A   Example of a "raw" echo-sound trace of a pool cross-section.



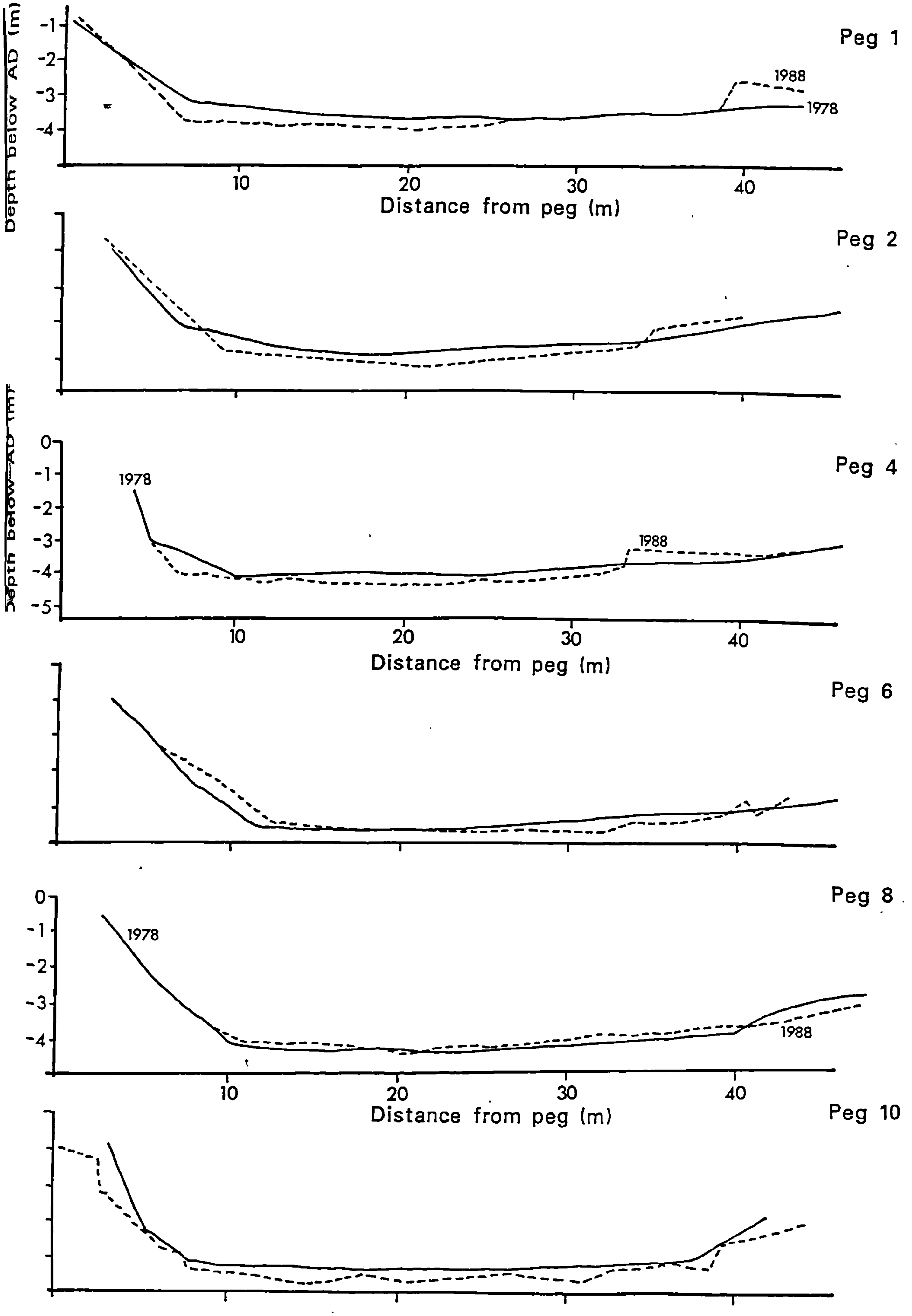
B FALSTONE SITE: Cross-section change over a 10 year period, (after Carling, 1979)



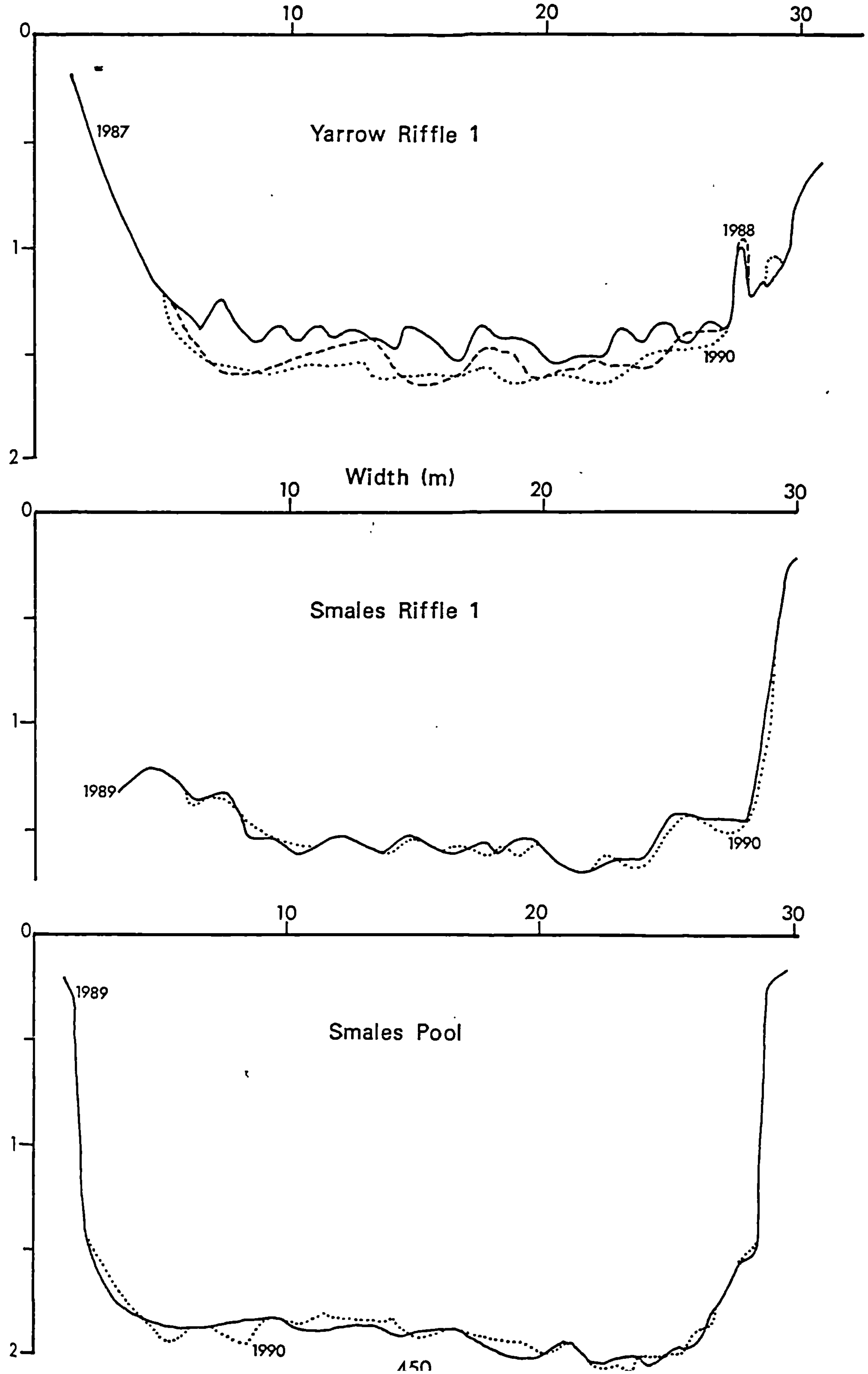
C RIDLEY STOKOE SITE: Cross-section change over a 10 year period, (after Carling, 1979)



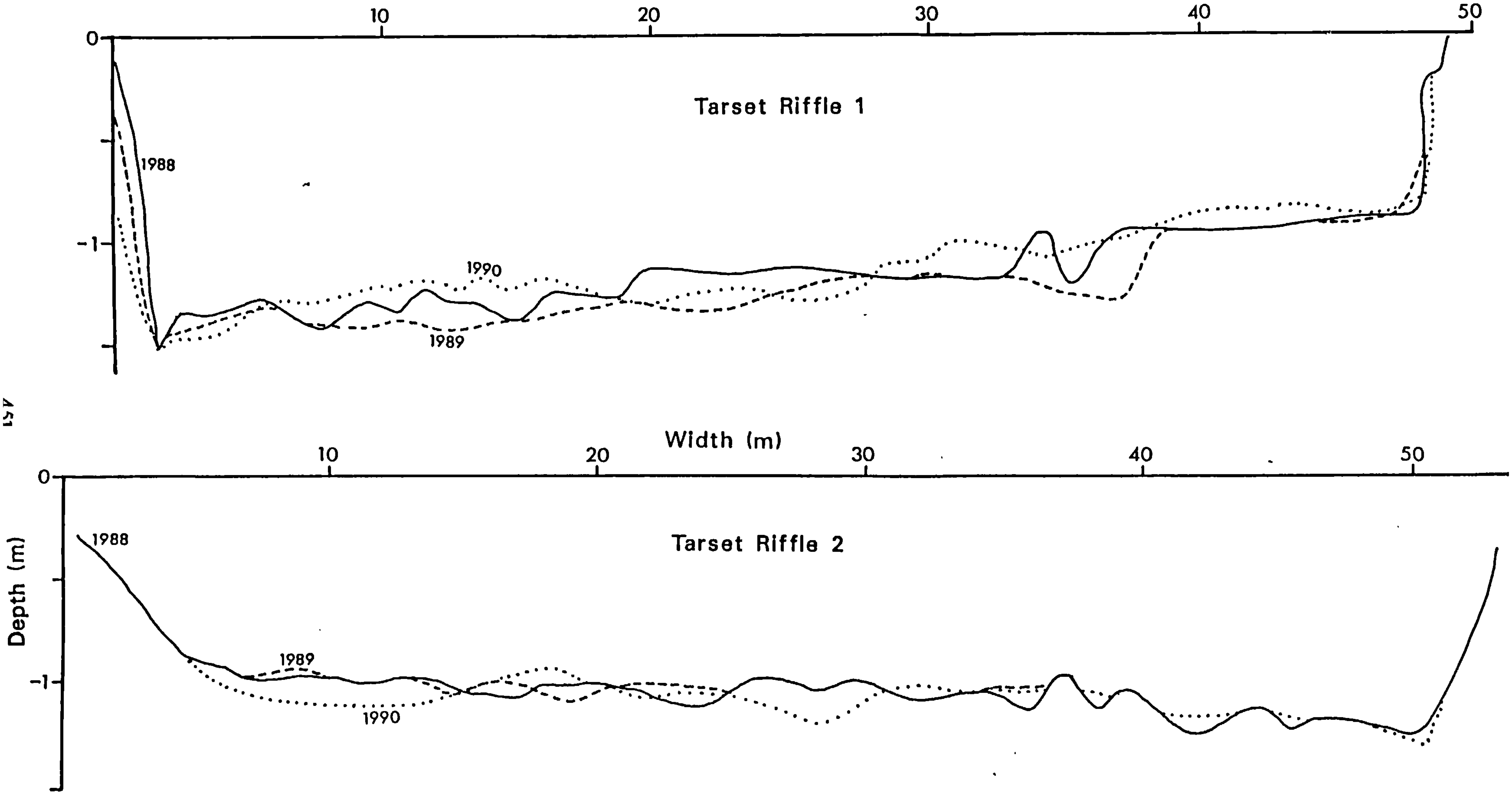
D NEWTON SITE: Cross-section change over 10 year period, (after Carling, 1979)



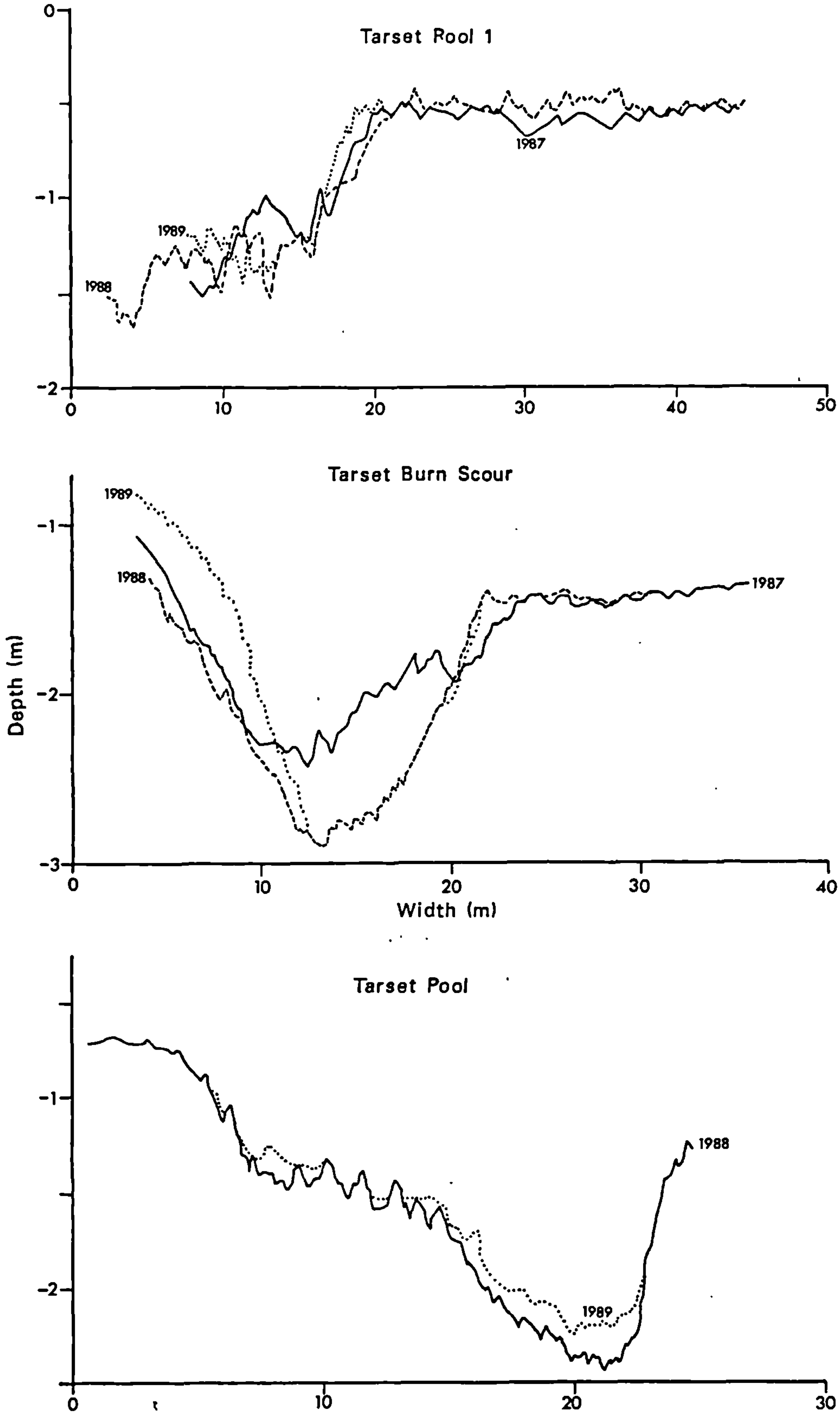
E All sections viewed as though looking upstream



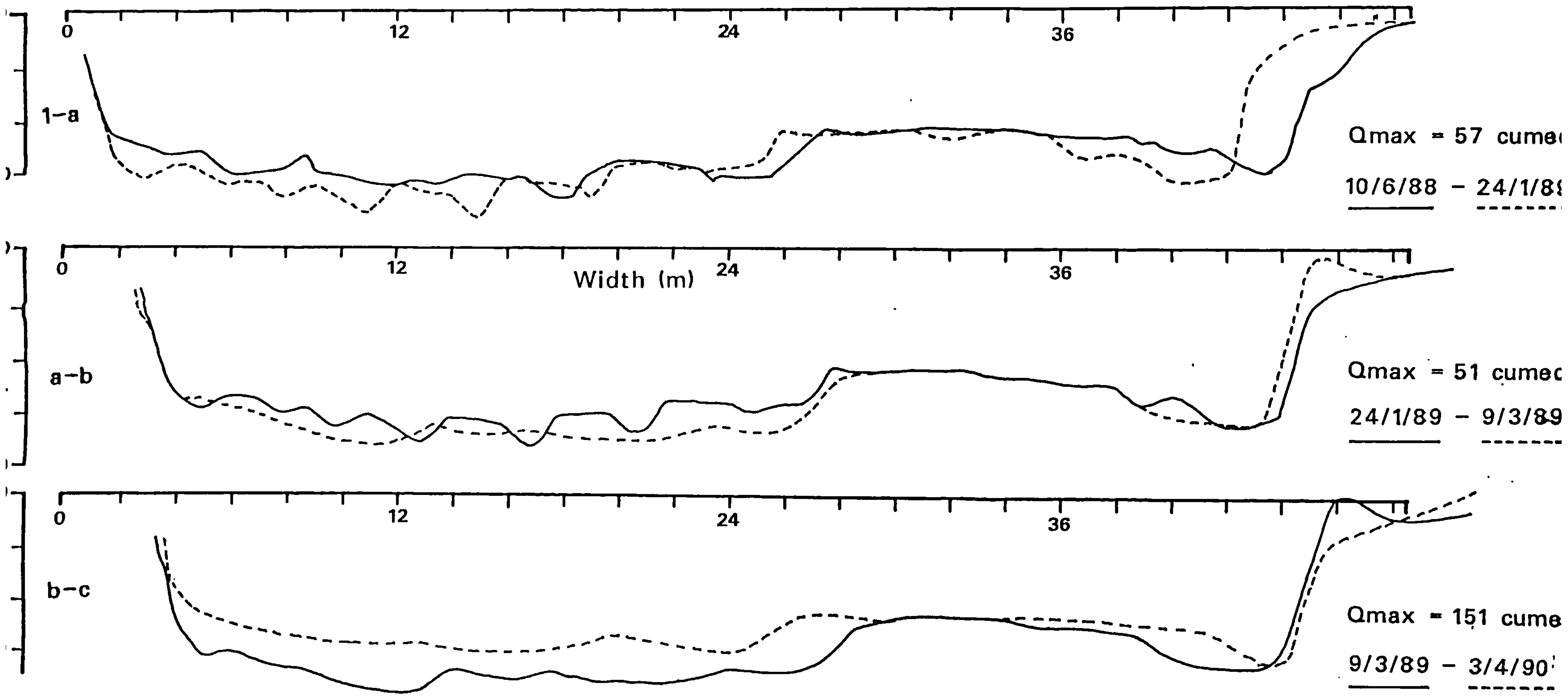
F All sections viewed as though looking downstream

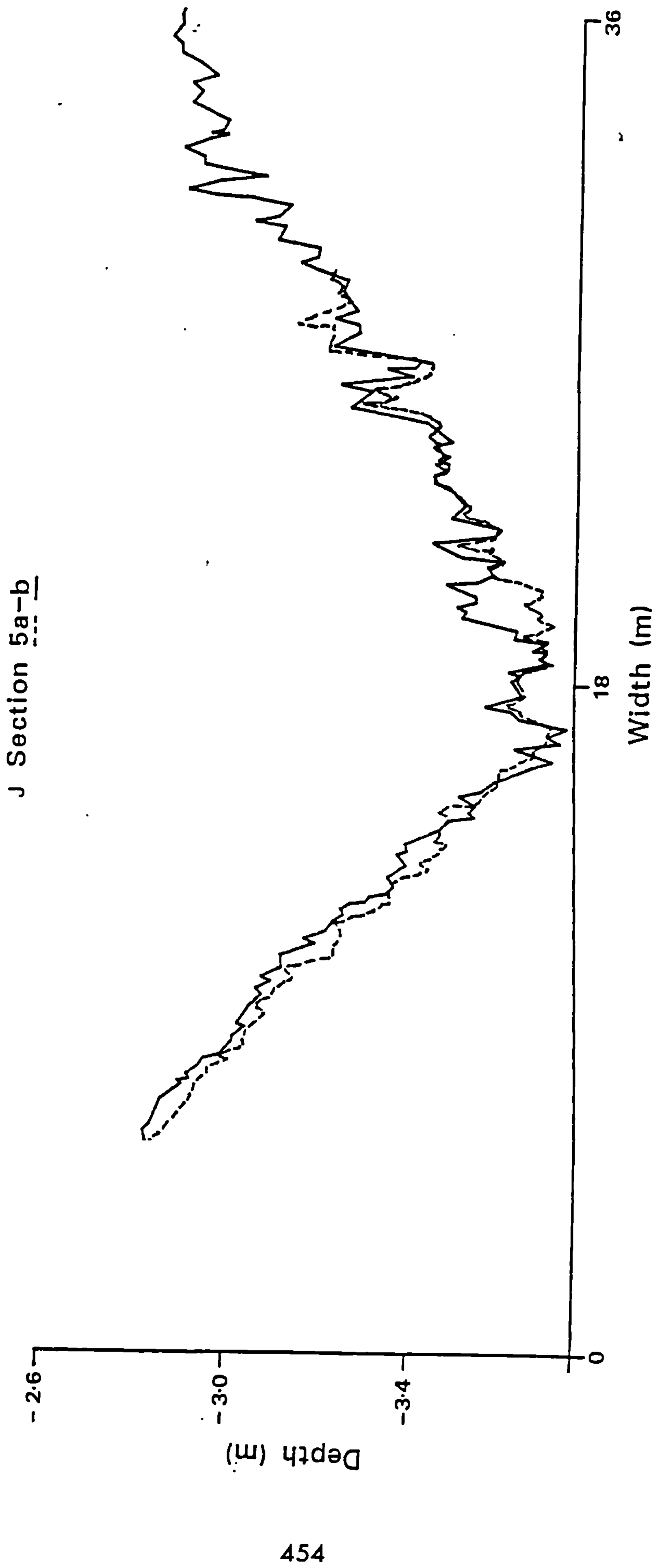


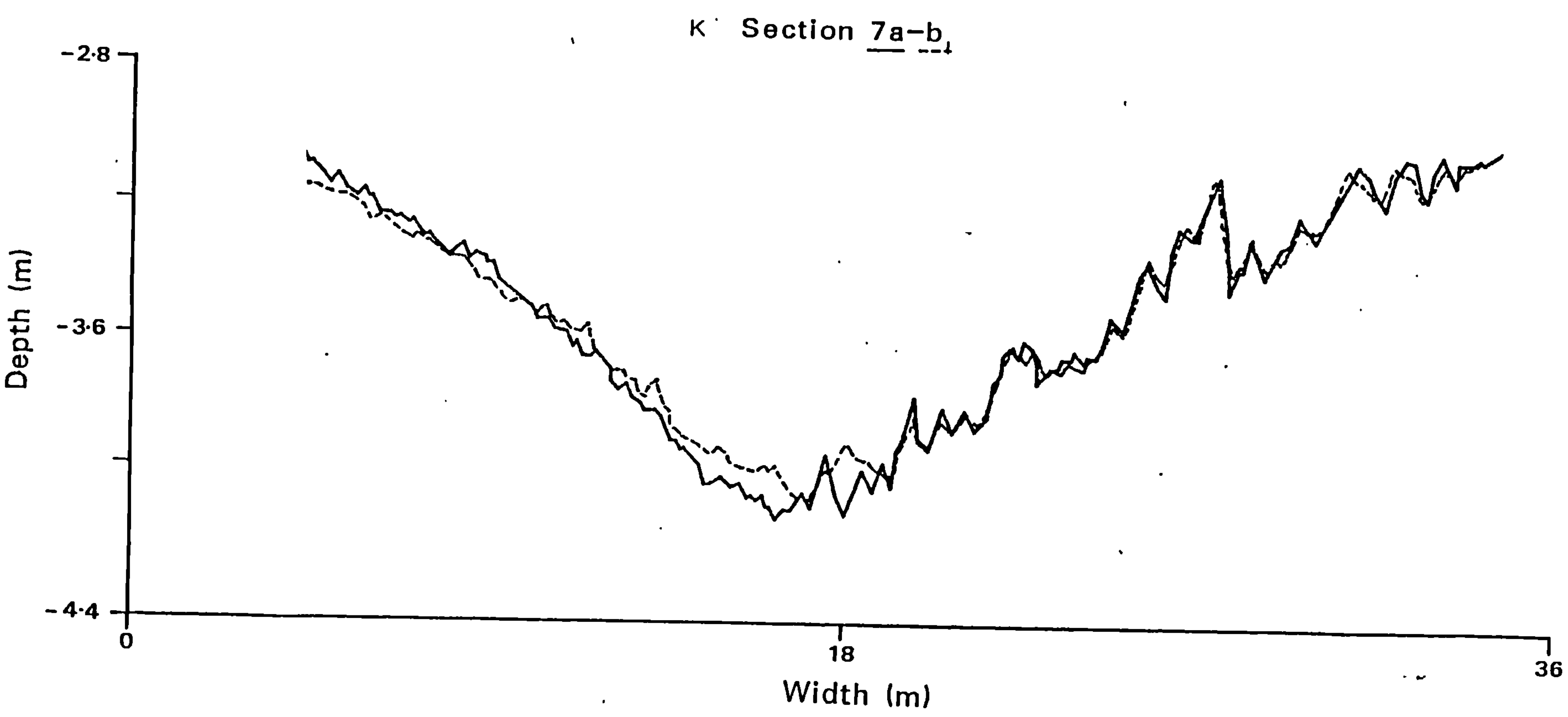
G All sections viewed as though looking downstream



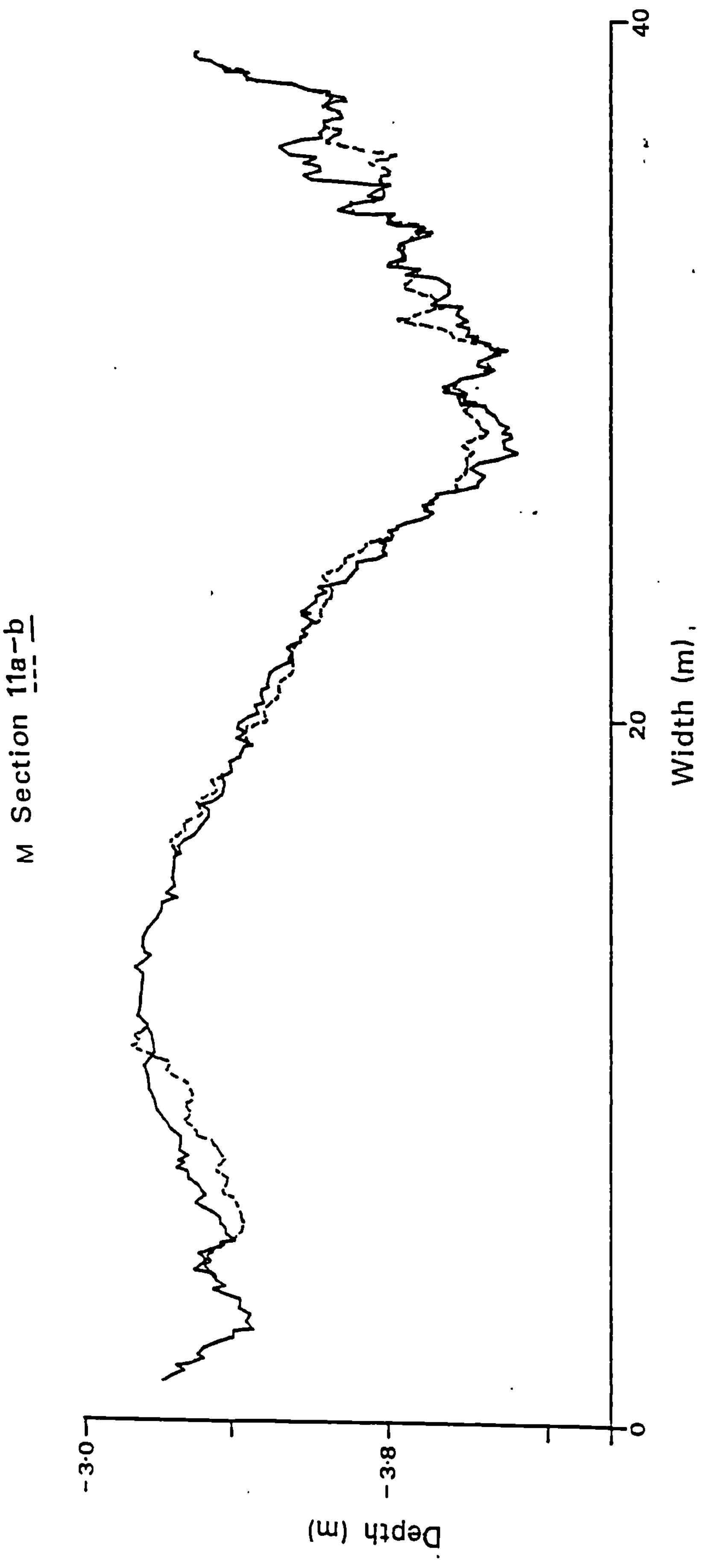
H Newton riffle 1

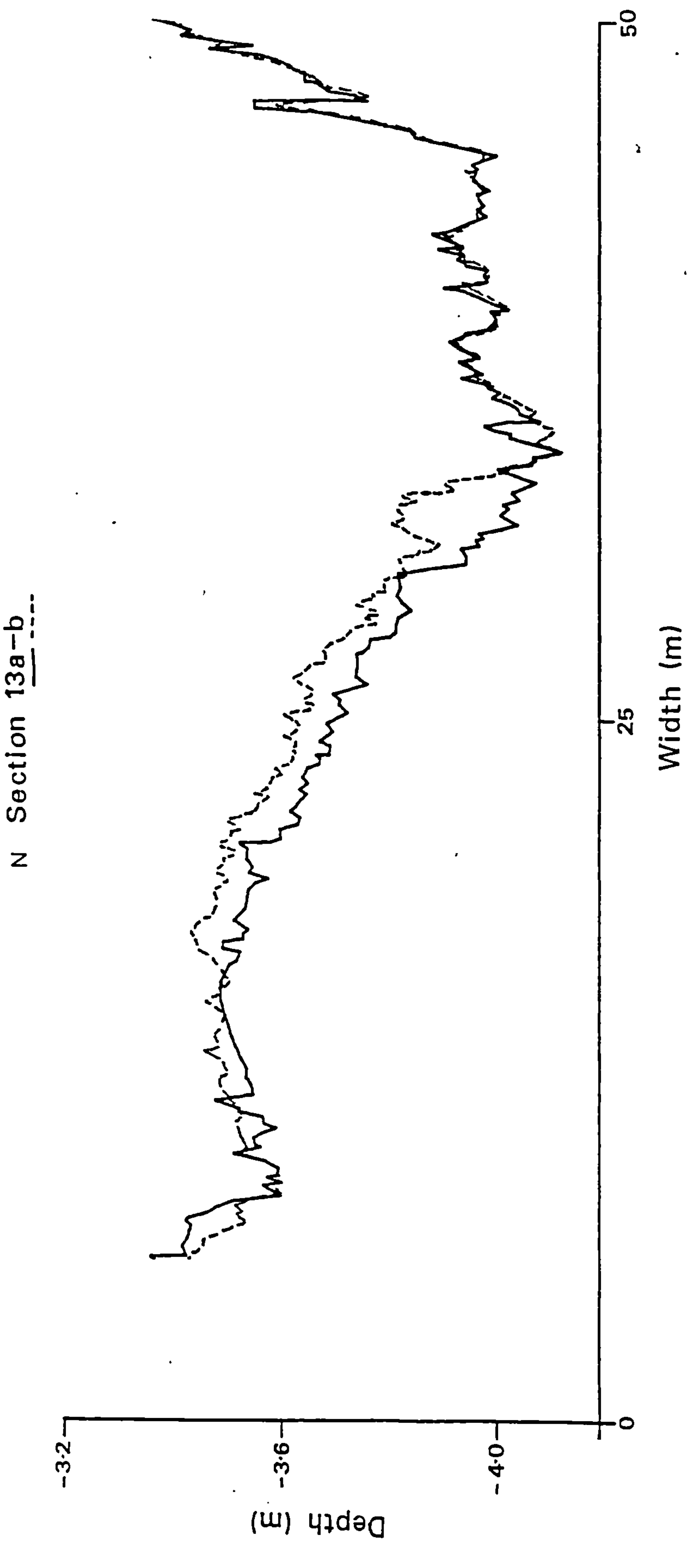



J Section 5a-b
Depth (m)
-2·6
-3·0
-3·4
Width (m)
0
18
36

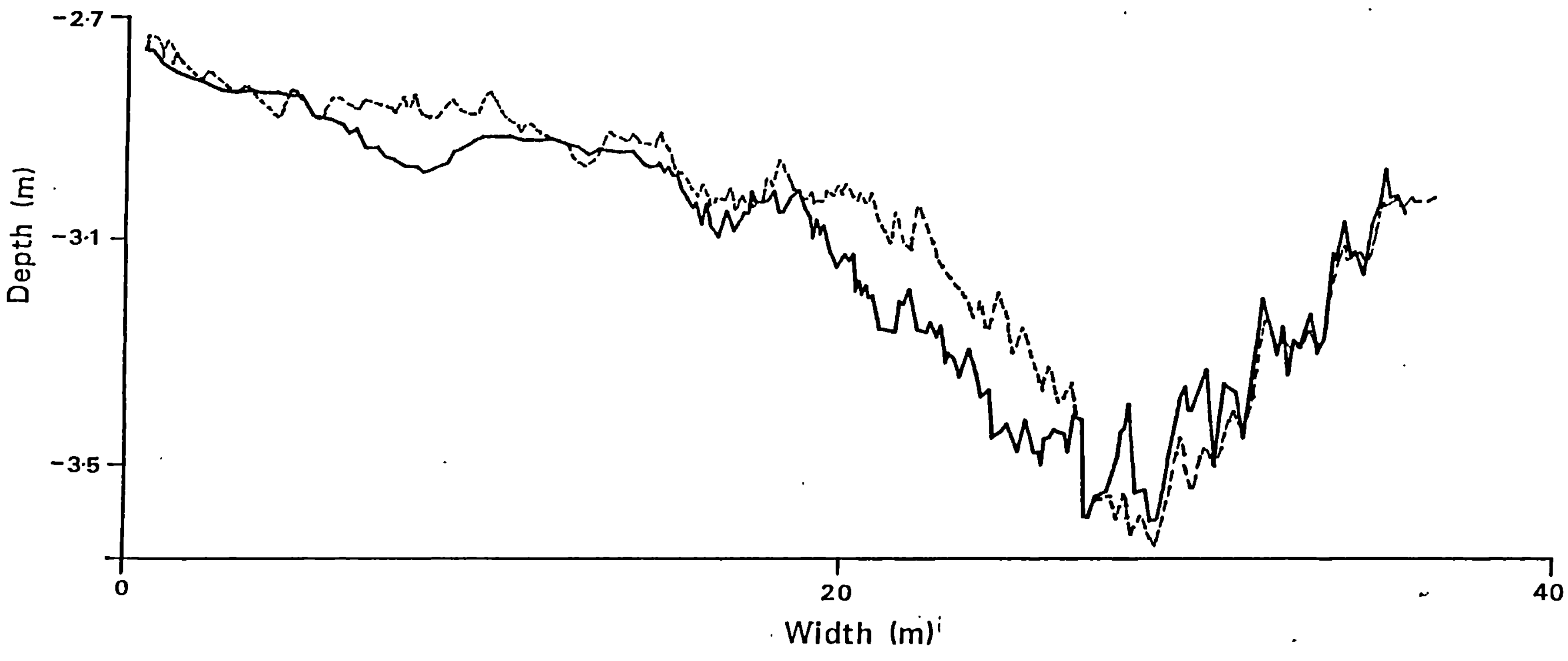


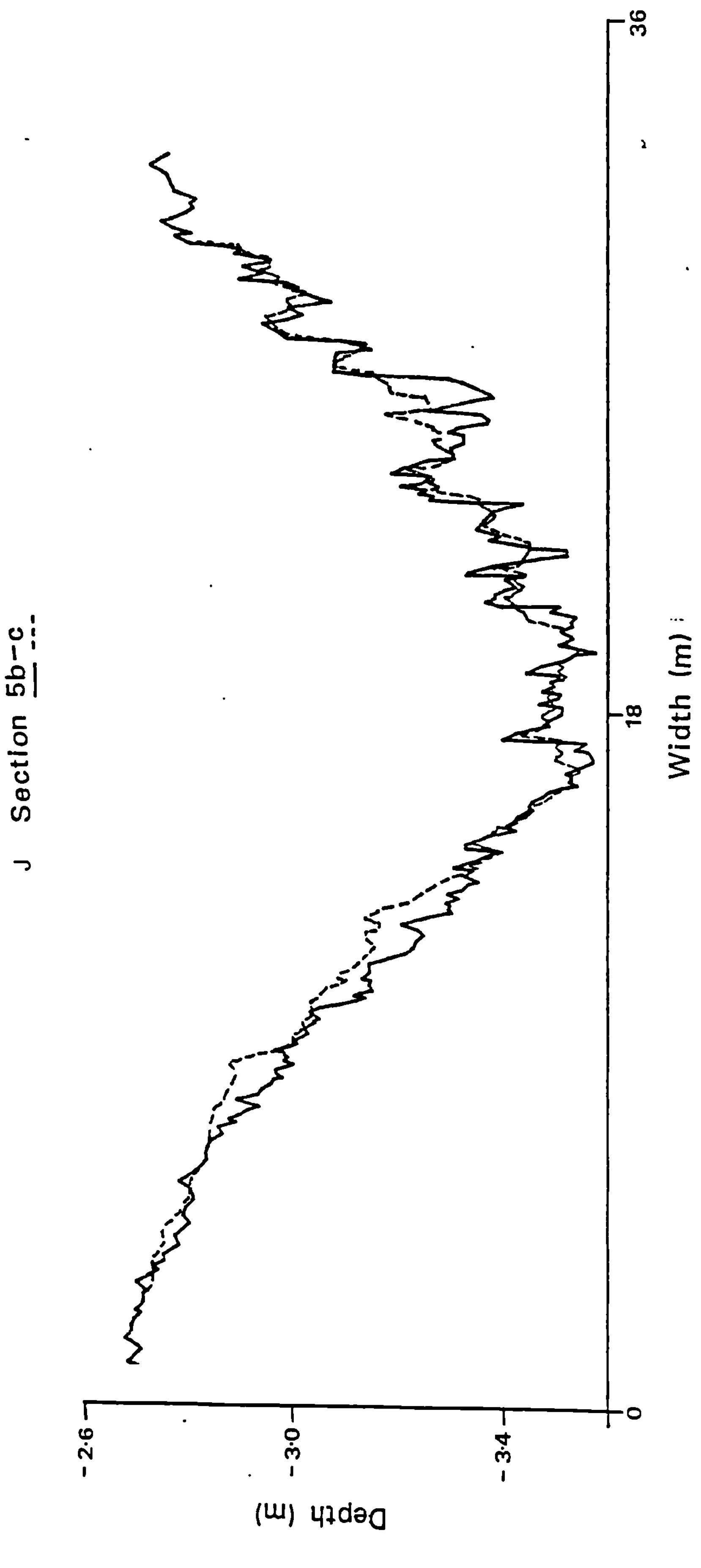
K Section 7a–b
Depth (m)
-2·8
-3·6
-4·4
0
18
36
Width (m)


M Section 11a-b
Depth (m)
-3·0
-3·8
Width (m)
0
20
40

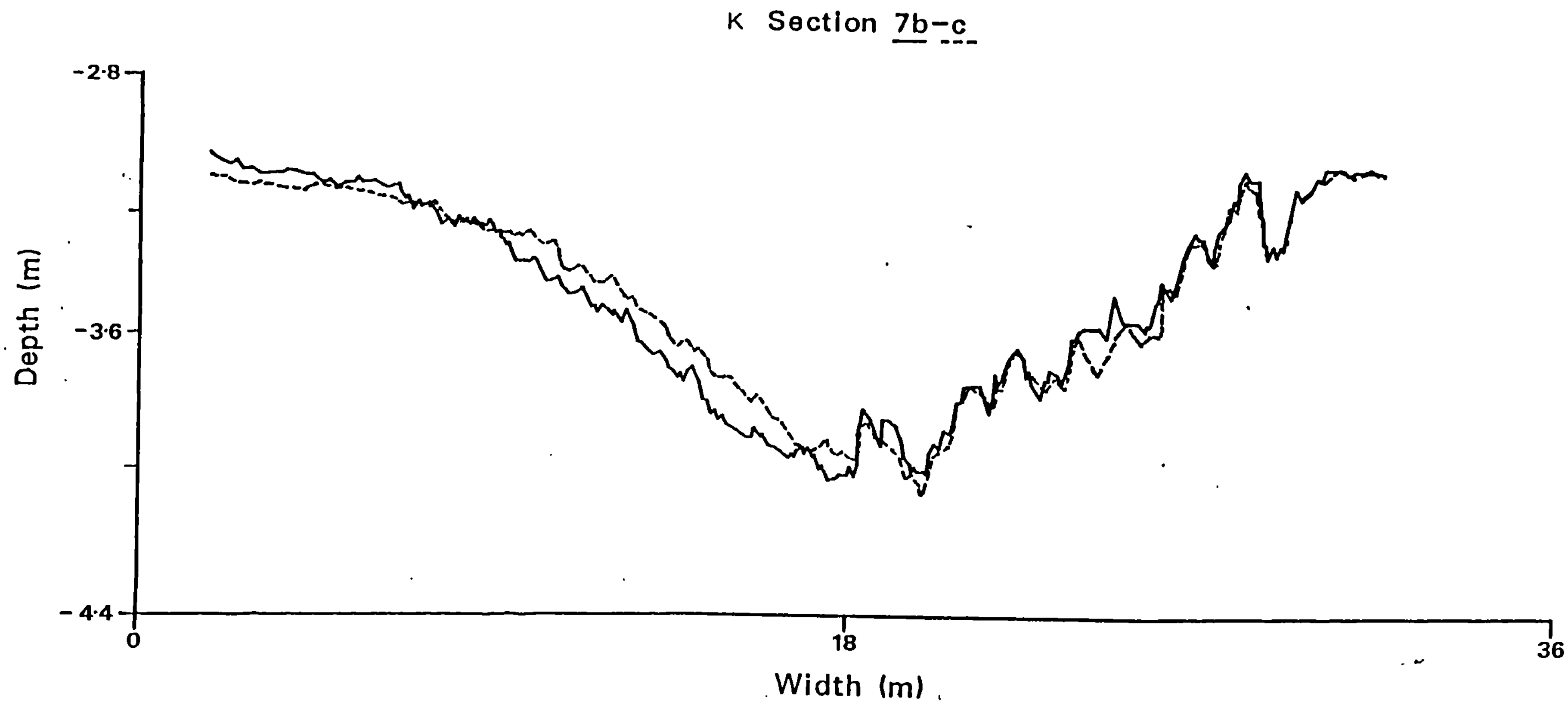

N Section 13a–b ----
Depth (m)
-3·2
-3·6
-4·0
0
25
50
Width (m)

Section 3c–b

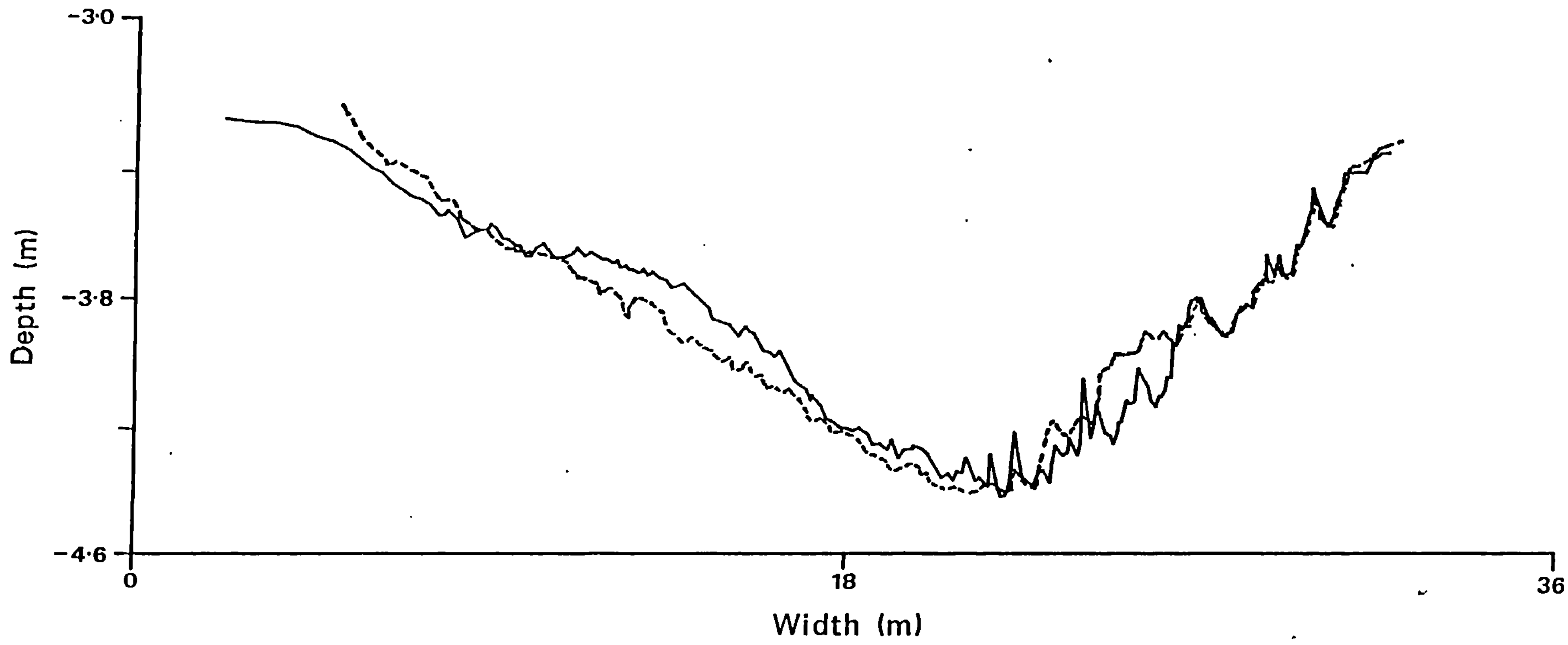


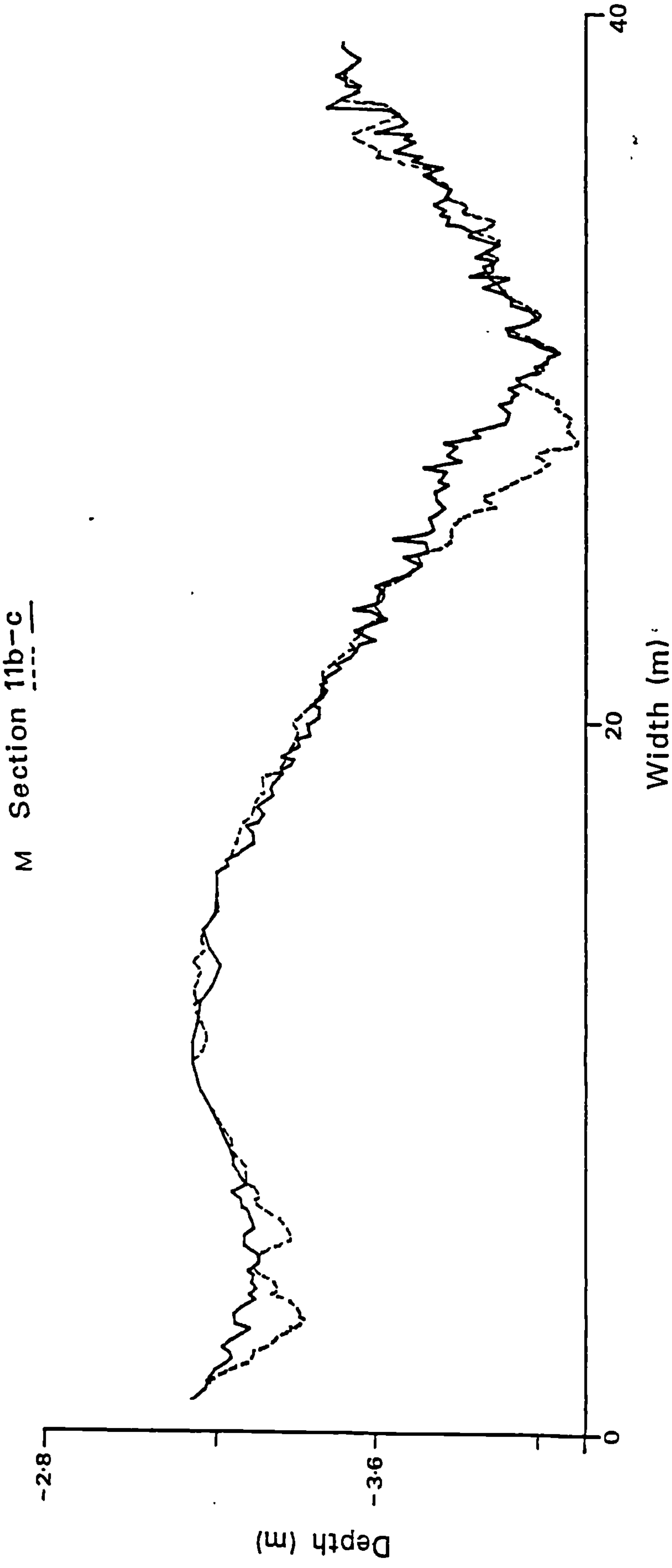


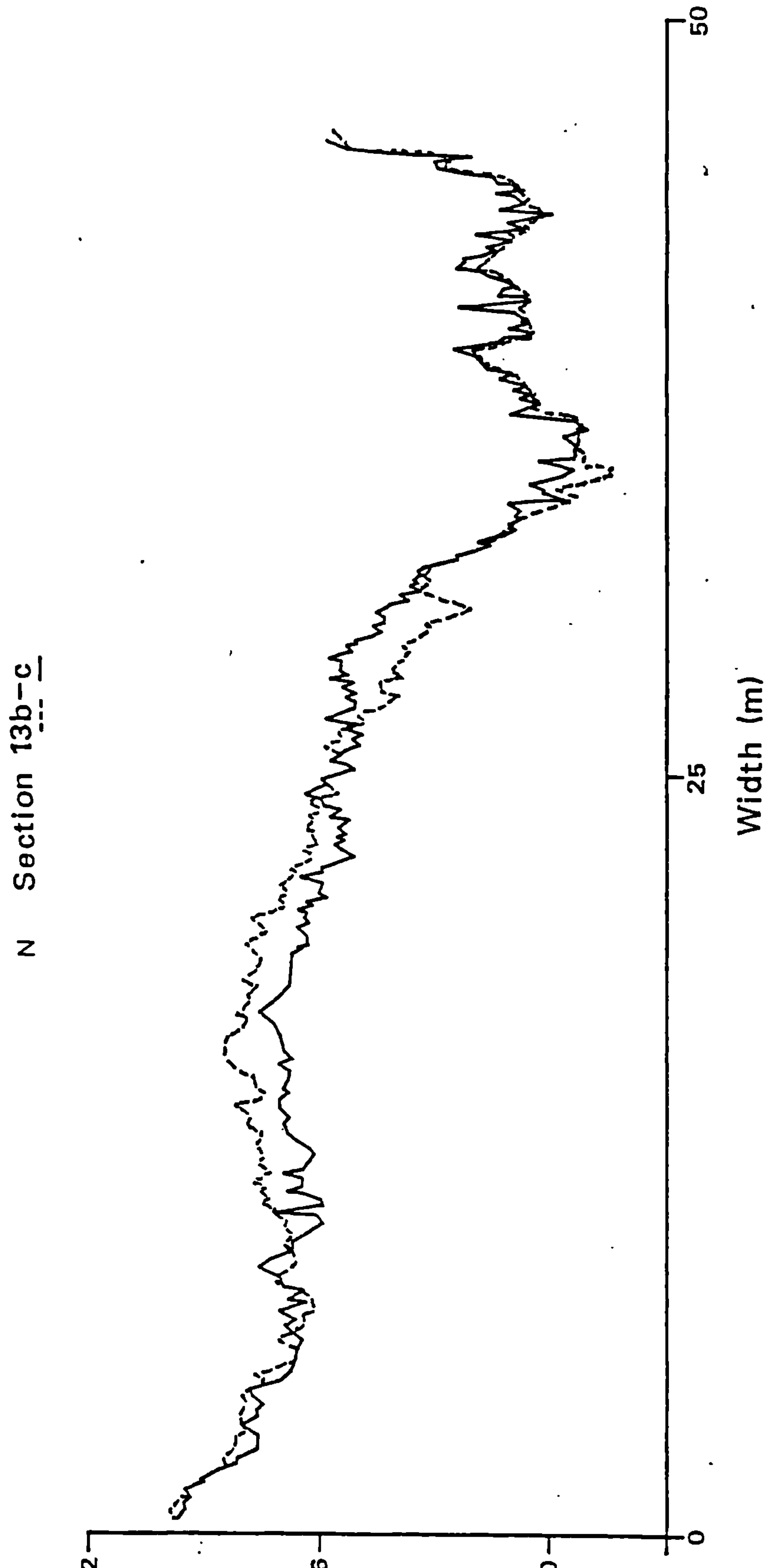
J Section 5b-c
Depth (m)
-2·6
-3·0
-3·4
0
18
36
Width (m)


K Section 7b–c
Depth (m)
-2·8
-3·6
-4·4
0
18
36
Width (m)

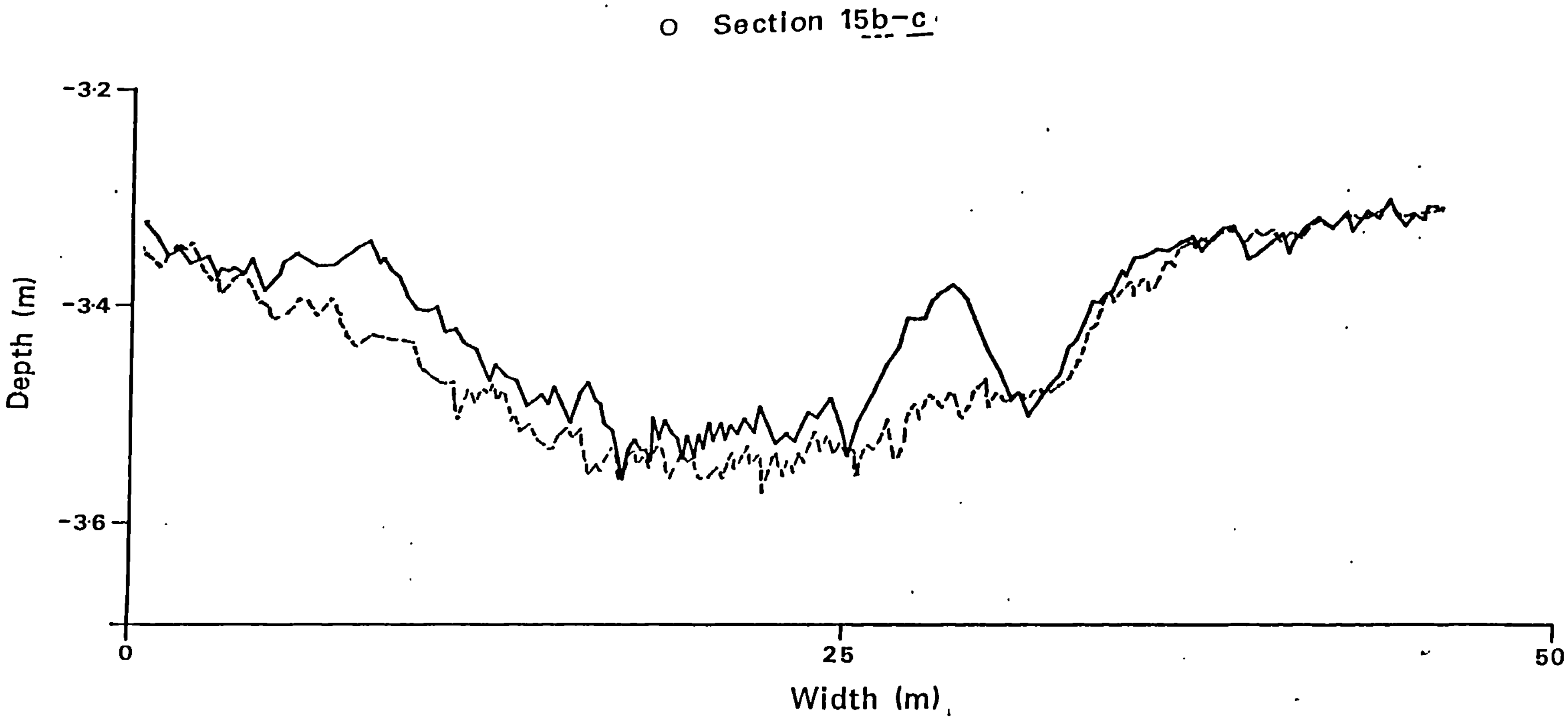
L Section 9c-b



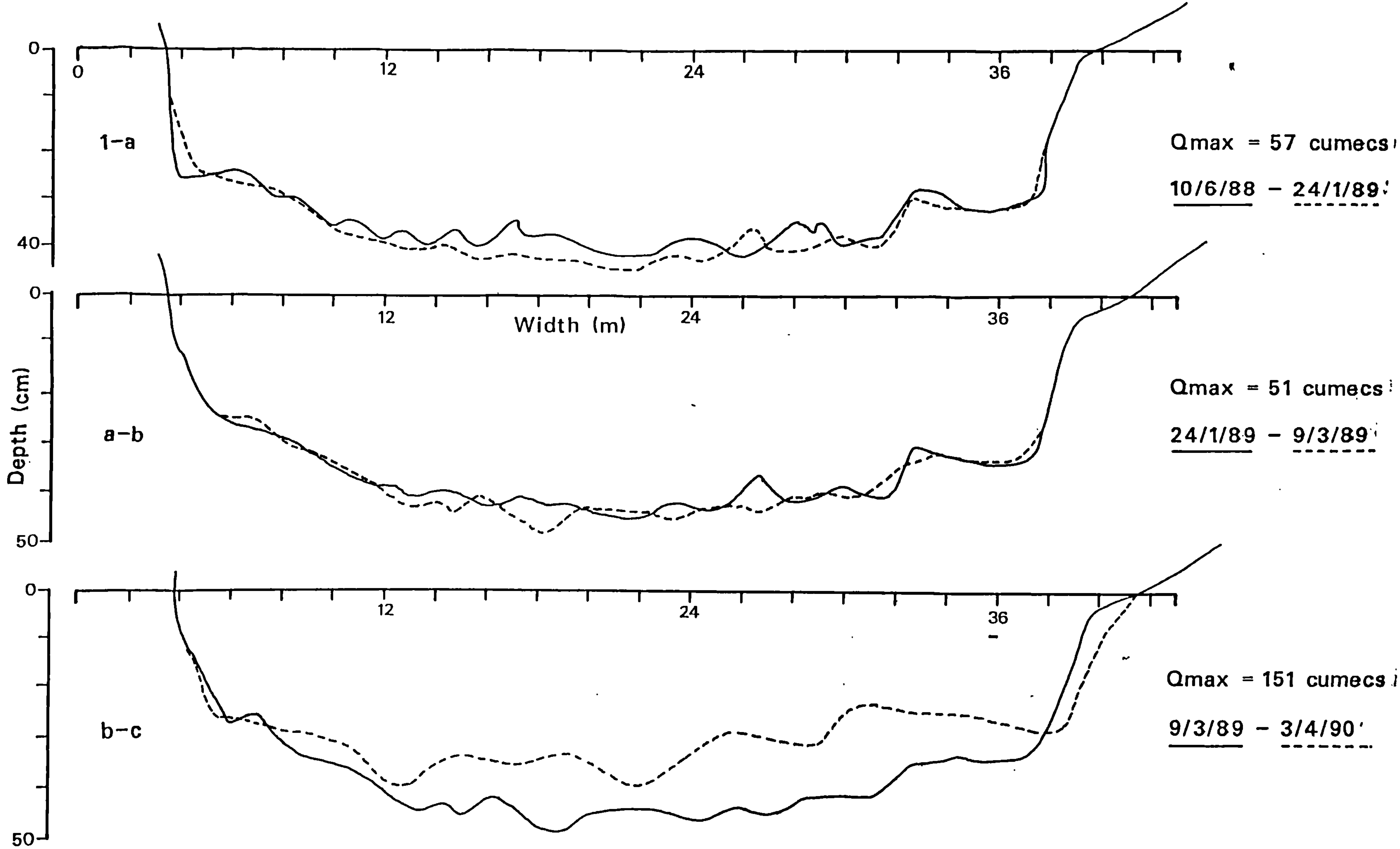

M Section 11b-c
Depth (m)
-2·8
-3·6
Width (m)
0
20
40



N Section 13b-c
Depth (m)
-3·2
-3·6
-4·0
Width (m)
0
25
50


O Section 15b-c
-3·2
-3·4
-3·6
Depth (m)
0
25
50
Width (m)

P Newton riffle 2



Appendix B

Bed strength and structure Tables

BED MORPHOLOGY/BED STRENGTH SURVEY

SITE: DATE:

FIELD SKETCH

FLOW CONDITIONS

	WINTER (OCT-MAR)	SUMMER (APR-SEP)
HIGH		
MODERATE		
LOW		

TRANSECT NO.	POSITION (ON SKETCH MAP) RIFFLE/POOL/BAR	

	TOT	%	D_{50}	256	180	125	90	64	45	32	22	16	11	8	6	4	≤2
OC																	
SP																	
WP																	
IM																	
LC																	
BS																	
OBI																	
OBN																	
IN																	
IU																	
			TOT%														

MORPHOLOGICAL CLASS

OBSTACLE CLAST	OC	BANK SHADOW	BS
WAKE POSITION	WP	INFILL (STABLE)	IN
STOSS POSITION	SP	OPEN BED INTERLOCK	OBI
LOOSE CLUSTER	LC	OPEN BED NO INTERLOCK	OBN
IMBRICATED	IM	ISOLATED/ UNPROTECTED	ISO

DIST. (m)																		$\bar{x}$
5cm																		
10cm																		

Table 6a: Frequency and mean grainsize of structural components.

Site	IM GS	IM Frq	OC GS	OC Frq	SP GS	SP Frq	WP GS	WP Frq	OBI GS	OBI Frq	LC GS	LC Frq	BS GS	BS Frq	OBN GS	OBN Frq	IN GS	IN Frq	IU GS	IU Frq
YR1	71	23	147	13	88	17	24	10	64	10	48	4	--	0	63	19	--	0	68	4
YP	--	0	161	5	70	2	11	5	60	4	52	1	--	0	66	37	18	17	71	29
FR1	88	18	112	16	64	13	22	5	68	18	52	11	--	0	50	8	17	7	60	4
FP	108	2	115	4	47	7	16	5	42	8	50	3	--	0	68	29	11	22	64	20
SMR	144	8	138	18	96	14	35	15	100	8	68	16	--	0	73	12	13	2	--	0
SMR*	58	8	200	18	67	10	3	8	67	14	40	4	<2	2	39	18	11	14	115	8
SMP	166	8	120	6	90	2	21	8	96	28	180	2	<2	2	64	38	11	6	--	0
SMP*	150	6	131	6	58	4	11	12	66	21	45	2	<2	3	47	34	8	9	2	3
RSR	94	10	99	22	80	12	35	6	58	16	59	8	--	0	62	10	12	6	75	12
RSP	--	0	125	5	62	8	8	6	40	9	47	8	2	3	58	26	8	12	62	23
TR1	64	4	122	8	69	16	30	10	63	24	55	4	--	0	57	26	22	10	--	0
TR1*	45	2	125	2	69	10	<2	2	84	18	66	8	--	0	44	26	8	16	63	14
TP1	--	0	96	10	22	2	15	6	58	10	22	2	2	2	42	20	16	26	53	11
TP2	--	0	114	9	45	4	4	10	40	6	22	3	<2	4	51	22	22	30	38	12
TR2	106	6	173	14	95	18	19	12	81	4	56	14	--	0	65	6	22	1	34	5
TR2*	64	4	181	12	125	4	18	8	53	6	64	4	--	0	57	42	22	10	41	10
NR1	86	16	108	16	71	12	8	4	64	8	47	8	--	0	44	28	12	8	64	4
NR1*	45	2	125	8	72	6	4	4	91	18	45	2	4	2	46	28	18	12	79	12
NPH	--	0	108	8	64	8	--	0	45	16	32	8	--	0	47	24	9	8	35	28
NPH*	--	0	131	3	58	8	11	8	40	5	55	10	--	0	40	16	11	18	64	33
NMP	--	0	180	4	45	4	--	0	23	8	45	8	3	12	41	32	2	8	57	28
NMP*	--	0	256	2	62	6	8	4	22	5	40	12	<2	14	28	16	4	13	60	28
NPT	--	0	--	0	61	4	--	0	63	4	68	8	2	4	38	20	8	24	47	36
NPT*	--	0	68	3	68	6	11	8	45	3	34	8	<2	2	24	11	4	36	57	23
NR2	90	2	41	12	58	12	25	16	77	16	45	2	--	0	43	12	27	8	51	16
NR2*	64	6	90	2	32	2	22	2	50	10	50	8	--	0	55	44	11	6	52	20

Unregulated systems

Site	IM GS	IM Frq	OC GS	OC Frq	SP GS	SP Frq	WP GS	WP Frq	OBI GS	OBI Frq	LC GS	LC Frq	BS GS	BS Frq	OBN GS	OBN Frq	IN GS	IN Frq	IU GS	IU Frq
BBR	97	11	215	6	104	12	40	12	117	11	83	9	--	0	77	25	51	3	66	11
CHBR	--	11	--	15	--	16	--	5	--	4	--	9	--	1	--	19	--	8	--	13
CHBP	--	6	--	9	--	4	--	6	--	4	--	6	--	0	--	27	--	12	--	26
KBR	154	4	347	9	168	10	27	7	169	10	102	14	11	1	76	31	29	13	128	3
LBR	183	21	186	10	108	10	46	11	71	6	97	10	34	4	65	14	19	10	71	4
WR1	90	2	162	10	90	2	12	4	75	29	63	14	--	0	43	18	8	18	56	4
WR2	--	0	203	11	125	2	8	6	105	20	108	17	--	0	104	28	12	9	26	7
FOR	90	2	174	11	108	4	11	14	92	16	52	9	--	0	28	18	7	19	44	9
WP	90	2	218	4	--	0	9	4	54	4	96	6	--	0	91	36	6	18	98	26
SMBR	71	7	169	13	83	17	22	1	63	23	73	11	--	0	52	14	22	7	66	6
SMBP	90	1	159	6	79	2	8	4	49	11	54	12	<2	4	34	26	13	13	36	21
TBR1	64	4	151	16	69	12	4	4	94	12	62	8	--	0	47	26	13	8	40	10
TBPH	125	2	218	4	115	7	7	4	88	12	115	10	<2	4	55	30	9	16	58	11
TBMP	--	0	214	7	107	4	7	8	64	11	46	7	<2	2	19	37	2	11	25	13
TBPT	--	0	157	5	59	5	2	2	107	13	49	11	--	0	28	27	6	18	38	20
TBR2	107	6	178	13	72	9	24	6	80	16	49	6	22	2	56	22	5	9	63	10
WR3	90	2	125	4	77	12	16	8	66	14	50	18	--	0	40	29	7	8	73	6
MHBR	22	2	51	6	25	6	4	2	24	14	25	8	--	0	23	40	8	6	17	17
MHBR	--	0	44	10	27	4	--	0	19	28	24	26	--	0	18	32	--	0	22	4
MHBR	--	0	58	6	19	4	--	0	25	22	20	18	--	0	23	34	7	8	26	10

* Post Flood values. **Bold values** refer to stable structural components

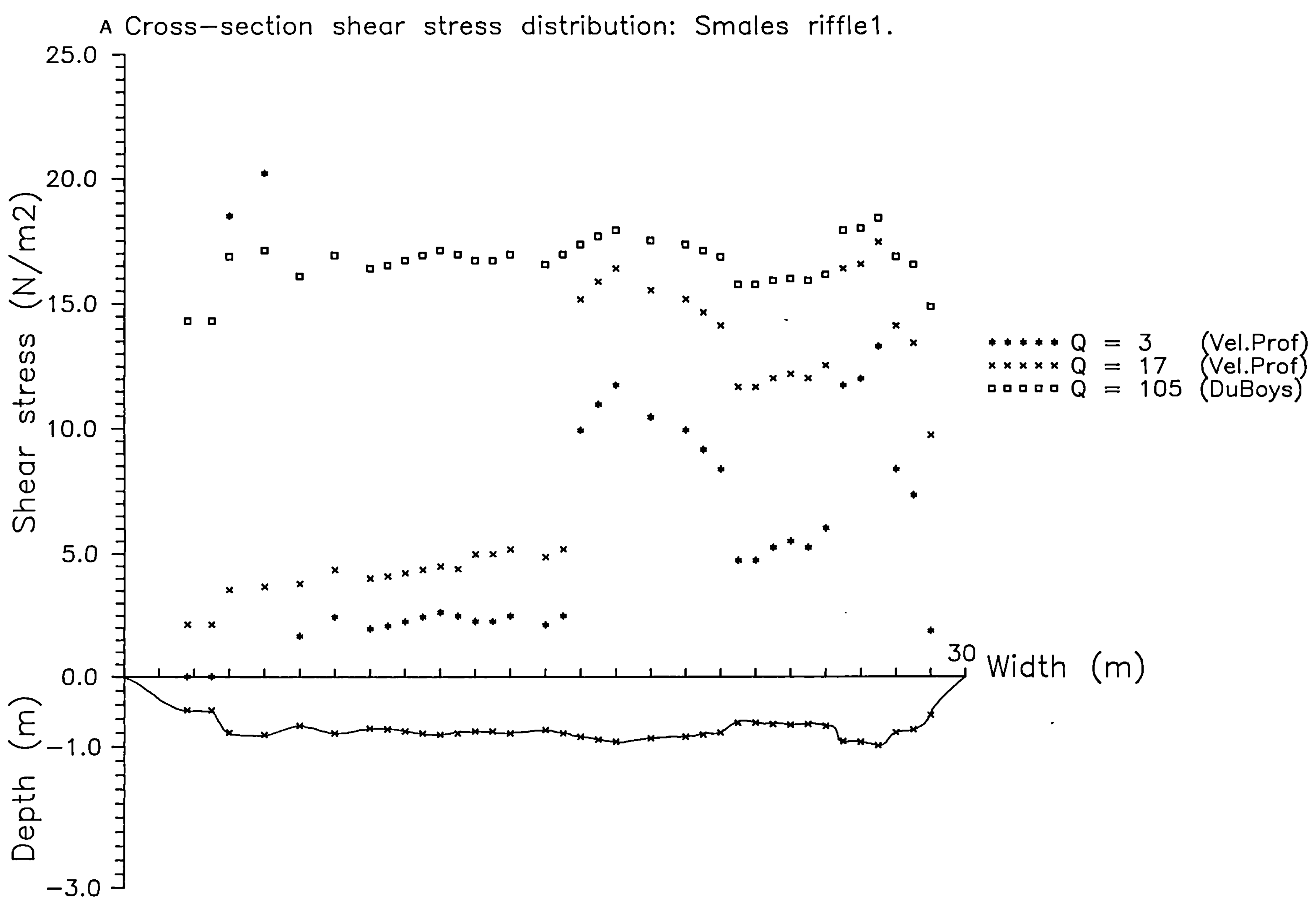
Table 6b: Mean and standard deviation of bed strength readings per site.

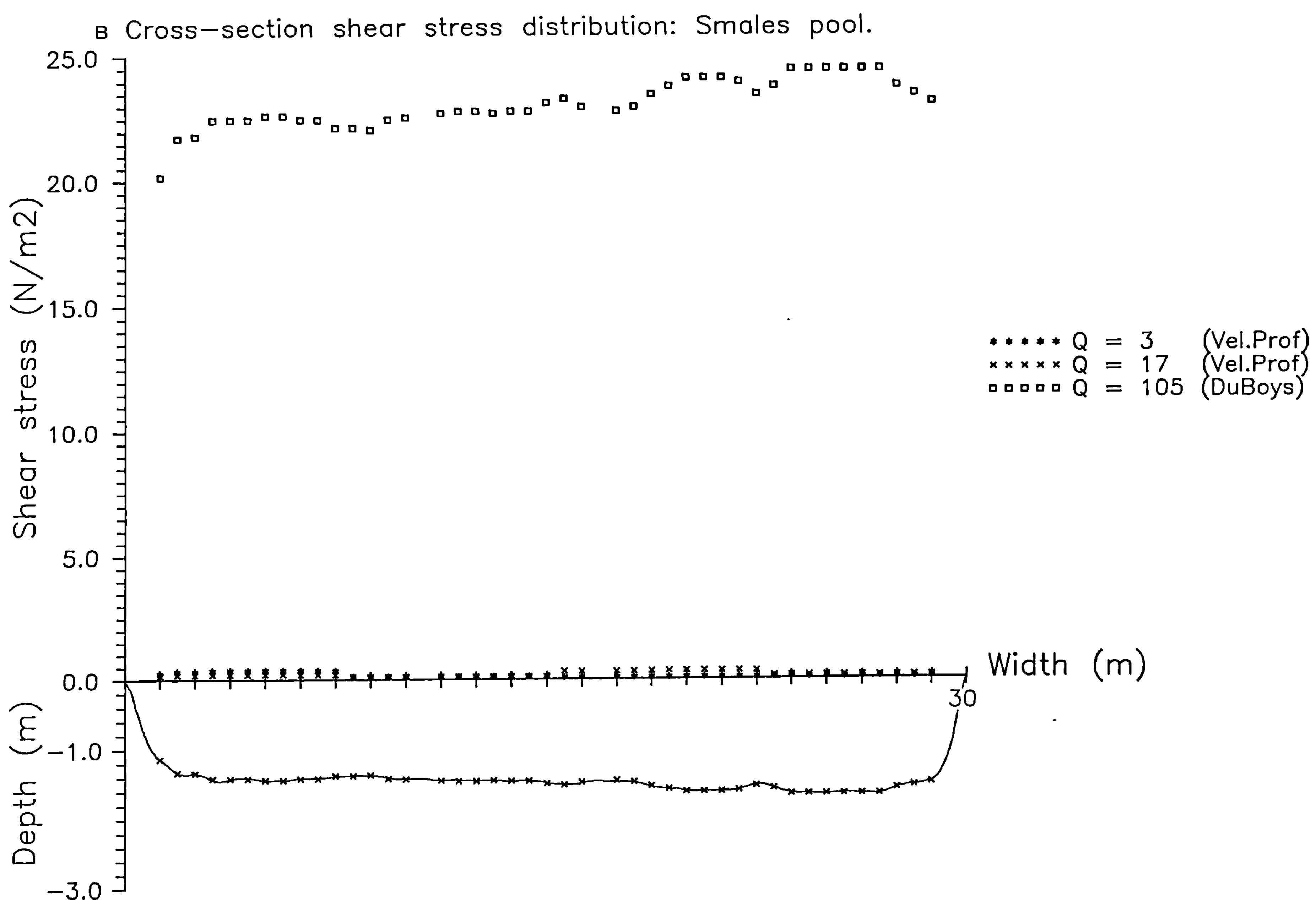
North Tyne (regulated)				Unregulated sites			
Site	x	sd	n	Site	x	sd	n
YR1	25.5	12.2	10	TBR	42.2	16.6	9
YP	16.1	5.5	10	CHBR	13.0	7.9	11
FR1	27.3	12.9	10	RRR	18.4	13.8	12
FP	18.8	11.7	9	SMBR	20.4	9.1	8
SMR	44.1	9.2	11	WR1	35.1	11.7	8
SMR*	33.0	16.7	11	WR2	23.1	6.8	9
SMP	28.9	6.7	11	WR3	38.4	13.6	8
SMP*	29.5	12.1	11	FNTR	30.4	14.7	8
RSR	31.8	6.9	12	WP1	24.8	11.9	8
RSP	22.8	7.3	8	WP2	29.8	14.5	8
HFMR	21.5	5.9	10	TBP	9.1	7.0	10
HFMP	16.1	4.1	9	CHBP	13.5	7.9	8
TR1	20.0	10.9	14	SMBP	12.1	5.7	9
TR1*	17.5	13.6	14				
TP1	16.6	7.2	10				
TP2	11.2	7.5	11				
TR2	39.4	14.4	16				
TR2*	20.2	12.3	14				
NR1	31.5	8.2	10				
NR1*	27.5	13.0	12				
NR1**	29.3	10.0	12				
NX3	20.5	6.9	13				
NX3*	21.3	7.6	13				
NPH	16.1	7.2	13				
NPH*	15.9	8.0	13				
NPH**	16.2	9.8	14				
NMP	23.7	17.3	13				
NMP*	31.9	13.9	13				
NMP**	24.3	11.4	11				
NPT	11.8	7.4	15				
NPT*	18.9	6.4	15				
NPT**	14.6	6.3	14				
NR2	15.3	6.7	13				
NR2*	26.6	8.0	14				
NR2**	26.1	8.1	14				

* = 6 days after bankfull flood ** = 76 days after bankfull flood

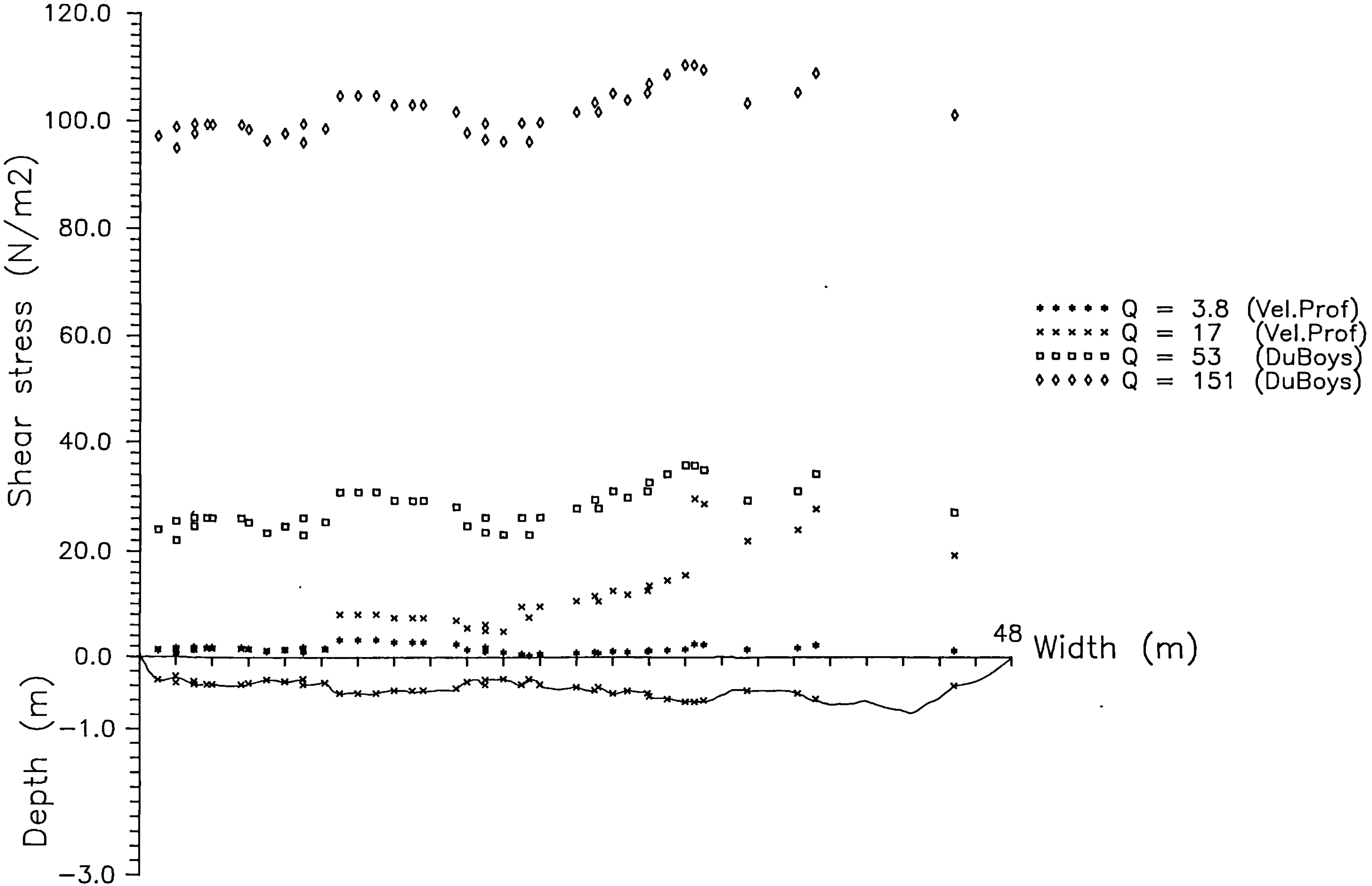
Appendix C

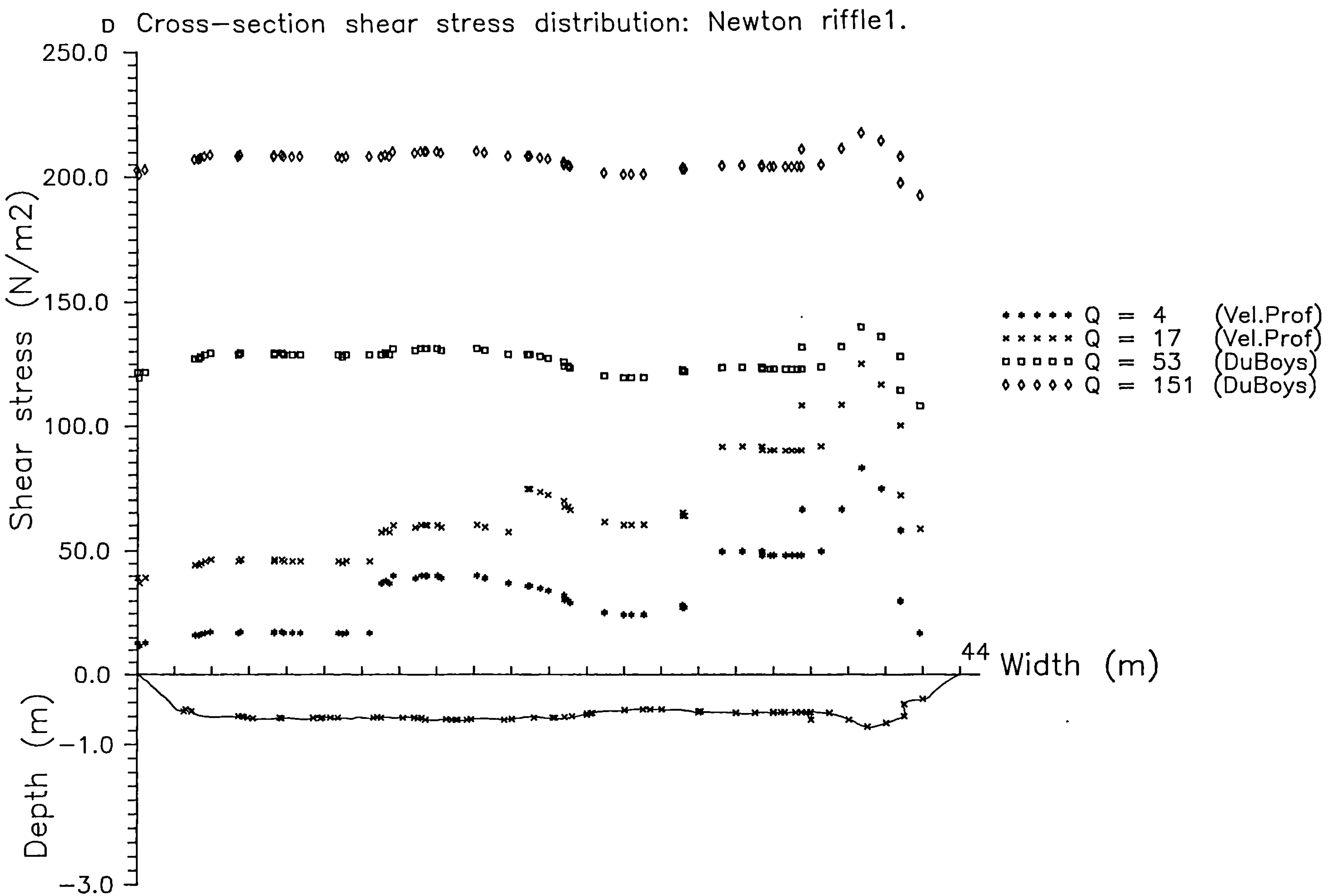
Cross section shear stress at tracing sites


A Cross-section shear stress distribution: Smales riffle1.
25.0
20.0
15.0
10.0
5.0
0.0
-1.0
-3.0
Shear stress (N/m2)
Depth (m)
30
Width (m)
Q = 3 (Vel.Prof)
Q = 17 (Vel.Prof)
Q = 105 (DuBoys)

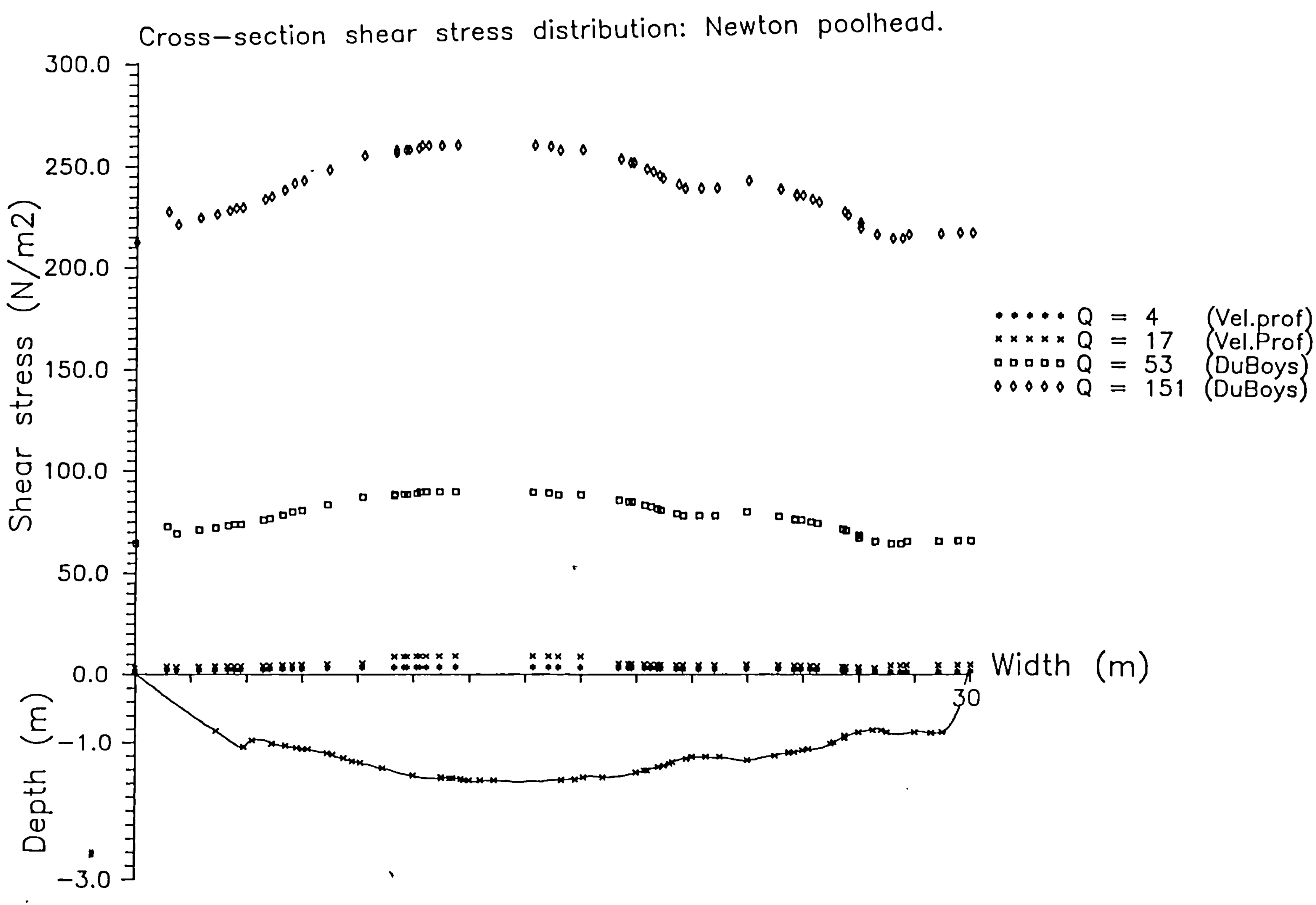

B Cross-section shear stress distribution: Smales pool.
25.0
20.0
15.0
10.0
5.0
0.0
-1.0
-3.0
Shear stress (N/m2)
Depth (m)
Width (m)
30
Q = 3 (Vel.Prof)
Q = 17 (Vel.Prof)
Q = 105 (DuBoys)

c Cross-section shear stress distribution: Tarset riffle2.

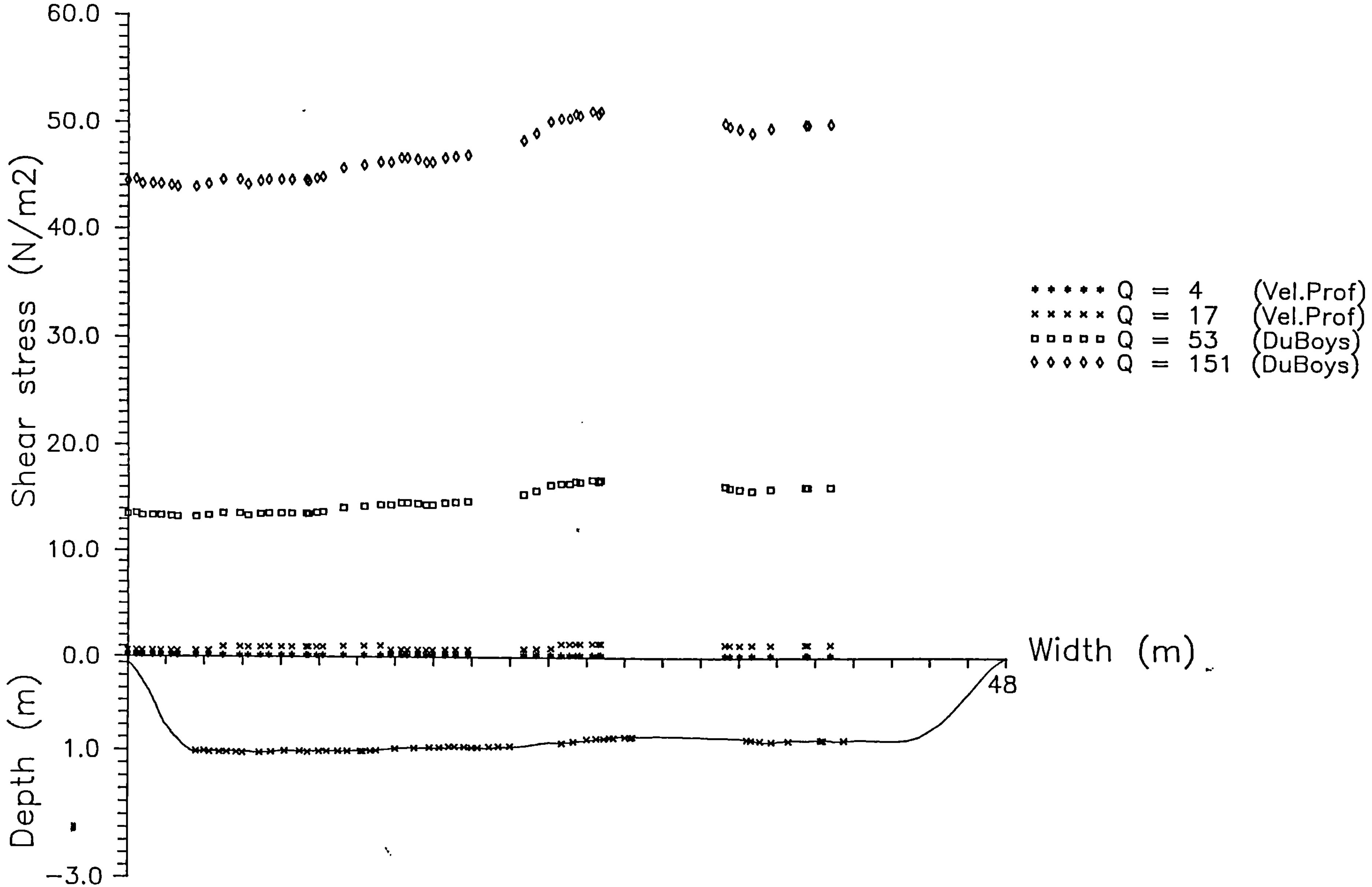


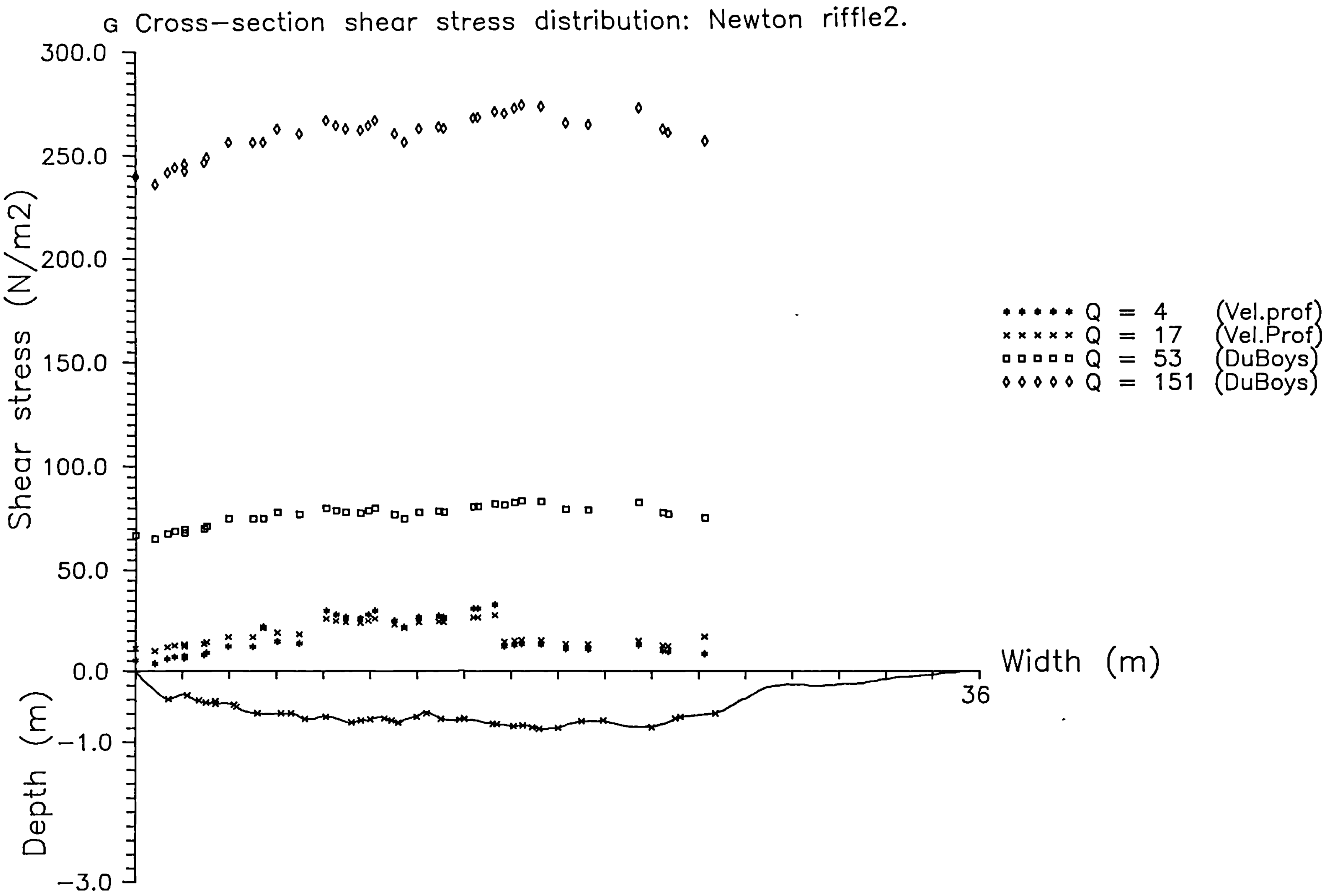


D Cross-section shear stress distribution: Newton riffle1.
250.0
200.0
150.0
100.0
50.0
0.0
-1.0
-3.0
Shear stress (N/m2)
Depth (m)
44
Width (m)
Q = 4 (Vel.Prof)
Q = 17 (Vel.Prof)
Q = 53 (DuBoys)
Q = 151 (DuBoys)


Cross-section shear stress distribution: Newton poolhead.
Shear stress (N/m2)
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Depth (m)
-1.0
-3.0
Width (m)
30
Q = 4 (Vel.prof)
Q = 17 (Vel.Prof)
Q = 53 (DuBoys)
Q = 151 (DuBoys)

F Cross-section shear stress distribution: Newton pooltail.




G Cross-section shear stress distribution: Newton riffle2.
300.0
250.0
200.0
150.0
100.0
50.0
0.0
-1.0
-3.0
Shear stress (N/m2)
Depth (m)
Width (m)
36
Q = 4 (Vel.prof)
Q = 17 (Vel.Prof)
Q = 53 (DuBoys)
Q = 151 (DuBoys)

Appendix D

Grainsize curves and Table of infiltrated sediments

Table A: Mean infiltration rates in relation to shear stress and bed velocity at each basket site.

Tarset Riffle 2

Basket	1	2	3	4
Compensation				
I_r (Kg/m^2/day)	0.0262	0.0228	0.0124	0.0278
$_p$ (N/m^2)	0.9	1.0	2.9	4.9
U_b (m/s)	0.02	0.2	0.04	0.37
Hydropower				
I_r (Kg/m^2/day)	0.0570	0.0303	0.0247	0.0279
$_p$ (N/m^2)	9.0	4.0	12.0	16.0
U_b (m/s)	0.36	0.38	0.38	0.26
Flood				
I_r (Kg/m^2/day)	1.0134	0.4030	0.3710	0.3887
$_p$ (N/m^2)	100	105	107	103
U_b (m/s)	---	---	---	---

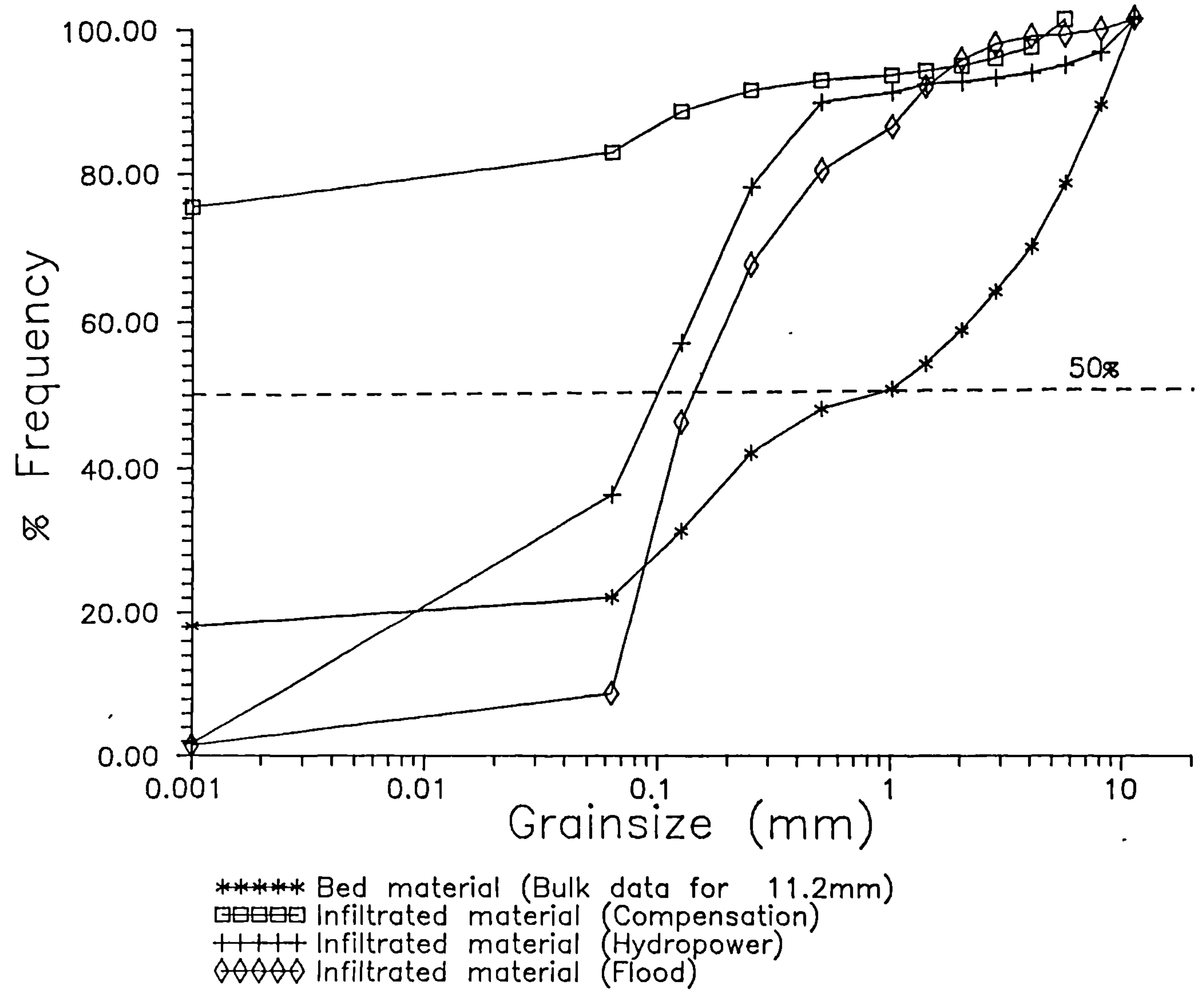
Newton Riffle 1

Basket	1	2	3	4
Compensation				
I_r (Kg/m^2/day)	0.0187	0.0110	0.0171	0.0106
$_p$ (N/m^2)	1.62	3.78	3.33	4.85
U_b (m/s)	0.46	0.31	0.42	0.22
Hydropower				
I_r (Kg/m^2/day)	0.0288	0.0125	0.0216	0.0272
$_p$ (N/m^2)	3.55	5.85	5.41	5.42
U_b (m/s)	0.56	0.59	0.62	0.48
Flood				
I_r (Kg/m^2/day)	1.5740	0.3130	0.4674	1.3451
$_p$ (N/m^2)	207	207	203	220
U_b (m/s)	---	---	---	---

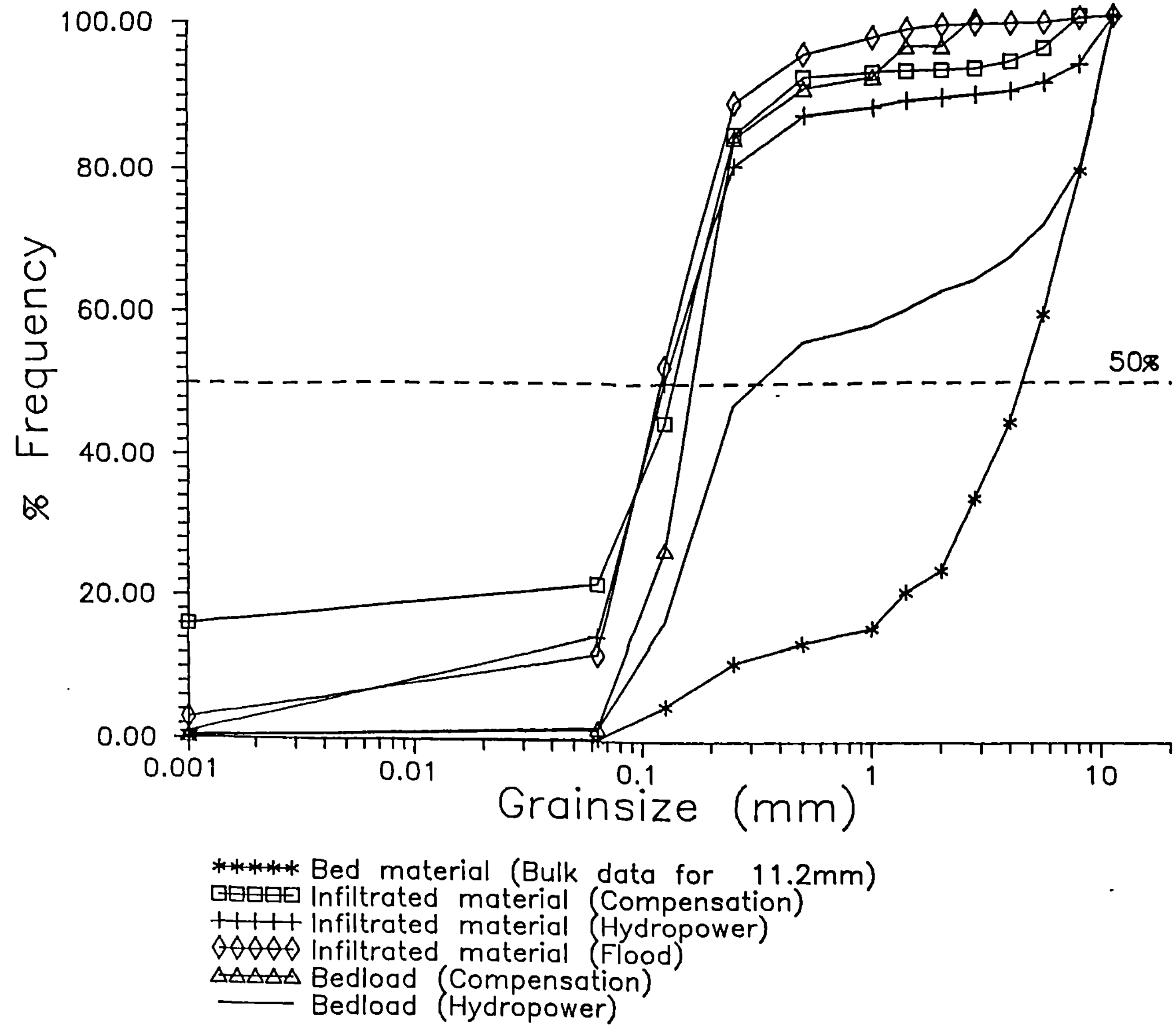
Newton Riffle 2

Basket	1	2	3	4
Compensation				
I_r (Kg/m^2/day)	0.0584	0.0100	0.0190	0.0180
$_p$ (N/m^2)	6.27	7.84	35.4	5.29
U_b (m/s)	0.50	0.47	0.42	0.55
Hydropower				
I_r (Kg/m^2/day)	0.0640	0.0071	0.0071	0.0230
$_p$ (N/m^2)	13.9	11.4	19.7	4.5
U_b (m/s)	0.62	0.64	0.66	0.68
Flood				
I_r (Kg/m^2/day)	0.9930	0.2790	0.0680	0.9500
$_p$ (N/m^2)	249	265	273	258
U_b (m/s)	---	---	---	---

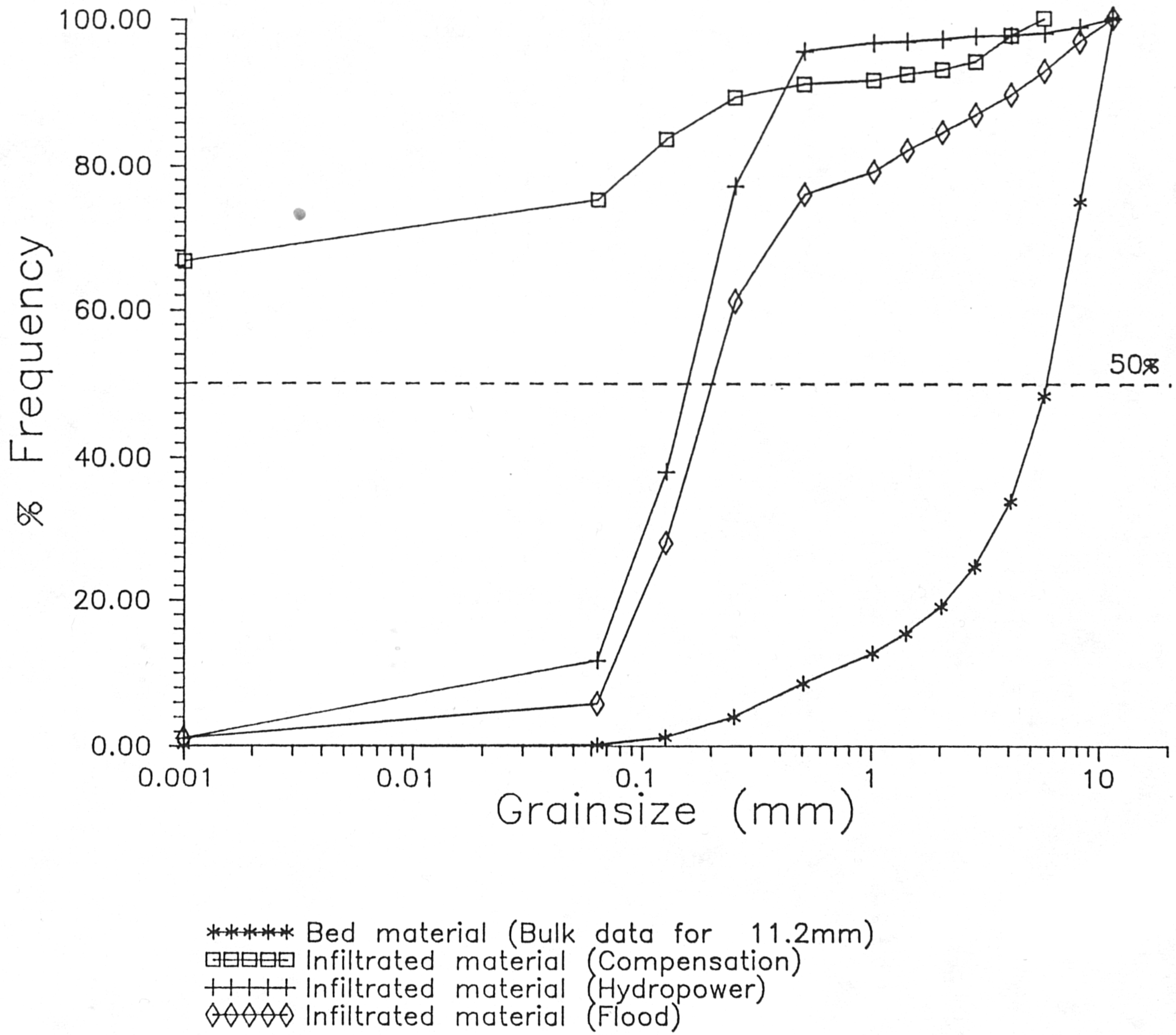
A Grainsize comparisons for Yarrow riffle 1.



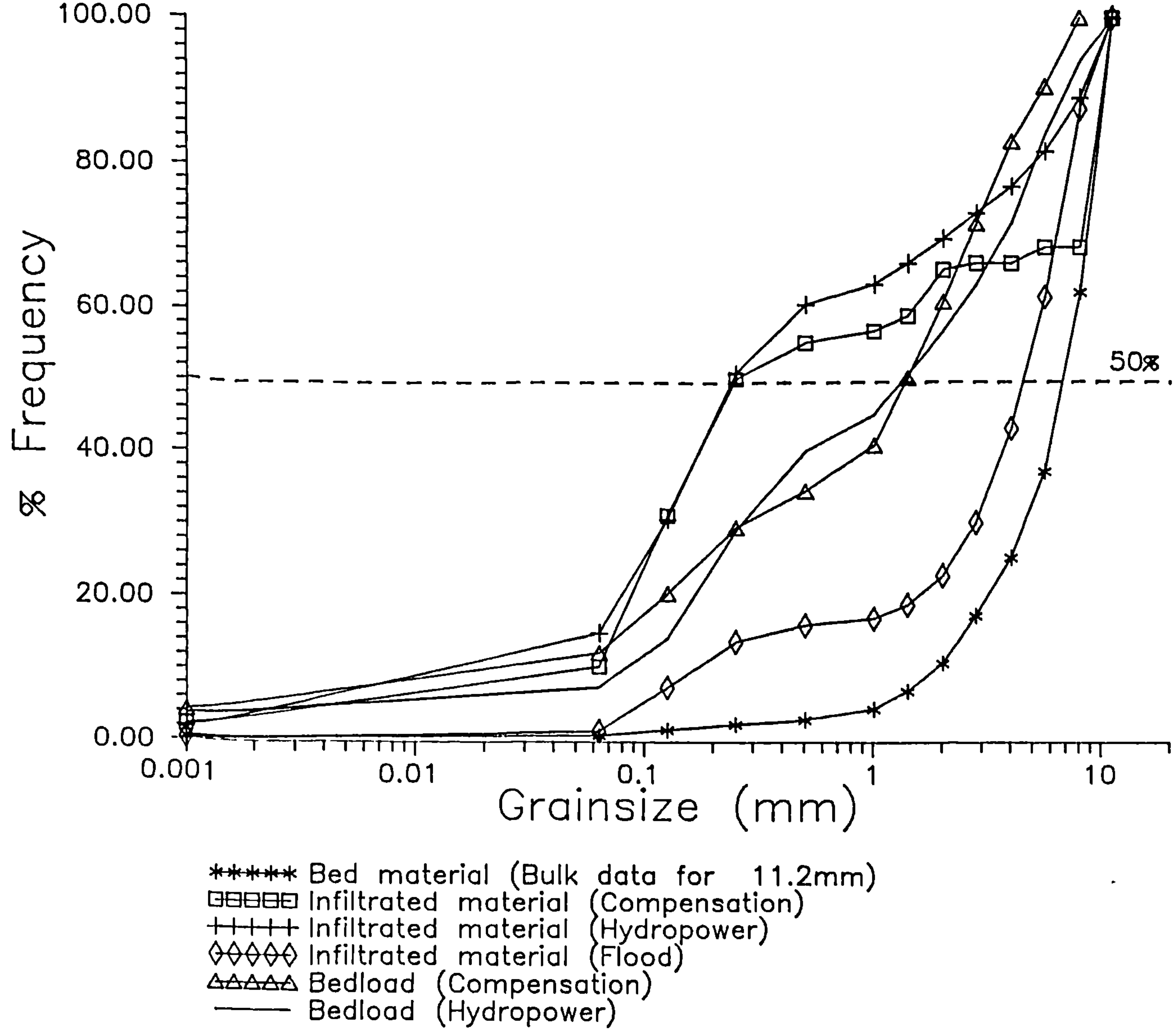
B Grainsize comparisons for Tarset riffle 1.



C Grainsize comparisons for Newton riffle 1.



D Grainsize comparisons for Newton riffle 2.



Appendix E

Experiments to determine the optimum magnetic enhancement recipe for North Tyne bed material < 22.4mm.

Appendix E

Experiments to determine the optimum enhancement recipe for North Tyne bed material < 22.4mm.

The enhancement of the magnetic susceptibility (X) of natural sediments by heating was applied to the tracing of fluvial sediments as a result of monitoring the effects of a forest fire on the magnetic signatures of shoal material in nearby streams (Arkell et al 1983). A series of experiments were conducted to accurately quantify the best practical means of enhancing the magnetic signature of sediments from the Plynlimon catchments. The results of these experiments are summarised in detail by Oldfield et al (1981) and Arkell (1985). These experiments concluded that the most rapidly-measurable magnetic parameter was specific susceptibility, which could be determined both in the laboratory and in the field using commercially-available equipment (Arkell 1985). Mineralogically the enhancement process involves the conversion, by heating, of the available iron minerals contained within the sediments into superparamagnetic magnetite. Prolonged heating converts the magnetite into haematite, which is disadvantageous since the susceptibility is much lower. The factors influencing the enhancement process were documented by Oldfield et al (1981), and include:

Peak temperature: At high temperatures partial melting may occur.

Rate of heating: Gradual leads to weak enhancement, rapid promotes enhancement.

Time at peak temp: Prolonged heating decreases enhanced X.

Rate of cooling: Slow decreases maximum X, rapid maintains X.

Atmosphere: A reducing atmosphere using flour or anthracite improves enhancement.

Particle size: Maximum uniform enhancement is achieved for finer size ranges.

Iron was known to be present within the North Tyne sediments due to visual observations of iron staining in the sandstone, as well as records of iron ore mining in the North Tyne

catchment since the 14th century, and commercially in the late 19th century (Charlton 1987).
Following the decision to try the enhancement process a sample of sediment was taken to Liverpool University and tested for enhancement suitability. Heat treatment was found to increase the specific susceptibilty of material < 8mm by up to one order of magnitude. As a result, a more detailed programme of tests was conducted at Newcastle University, to produce the optimum enhancement recipe. At this stage a local glassworks was contacted and arrangements were made to use their large glass furnace for "toasting" up to 300kg of sediment. The use of a reducing agent during the process was restricted, together with the rate of cooling which was set at slow. Both these procedures had been found by Oldfield et al (1981) to increase the conversion rate of iron minerals to SP magnetite (see above).

Under these constraints, a set of experiments was conducted using samples of sediment < 22.4mm collected from the emplacement site in the North Tyne. The experimental procedure is outlined below:

Size range: 22.4 - 5.7mm, 5.6 - 2.1mm, 2.0 - 0.5mm, < 0.5mm

Temperatures: 400, 500, 600, 700, 800 °C

Time at peak temperature: 5, 15, 30, 60, 120 minutes

Quantity of sediment: 20, 50, 100 gms.

The background specific susceptibility (X) was determined for a given sample from each size range using a Bartington MS2 enclosed loop susceptibility monitor. This sample was placed in a preheated oven and "toasted" for a given period of time. The sample was withdrawn from the furnace and allowed to cool slowly in its crucible, since this was the condition available at the glassworks. The X was then determined again and the value for enhancement ratio calculated according to:

$$X_e/X_b$$

where X_e is the enhanced specific susceptibility and X_b is the background value.

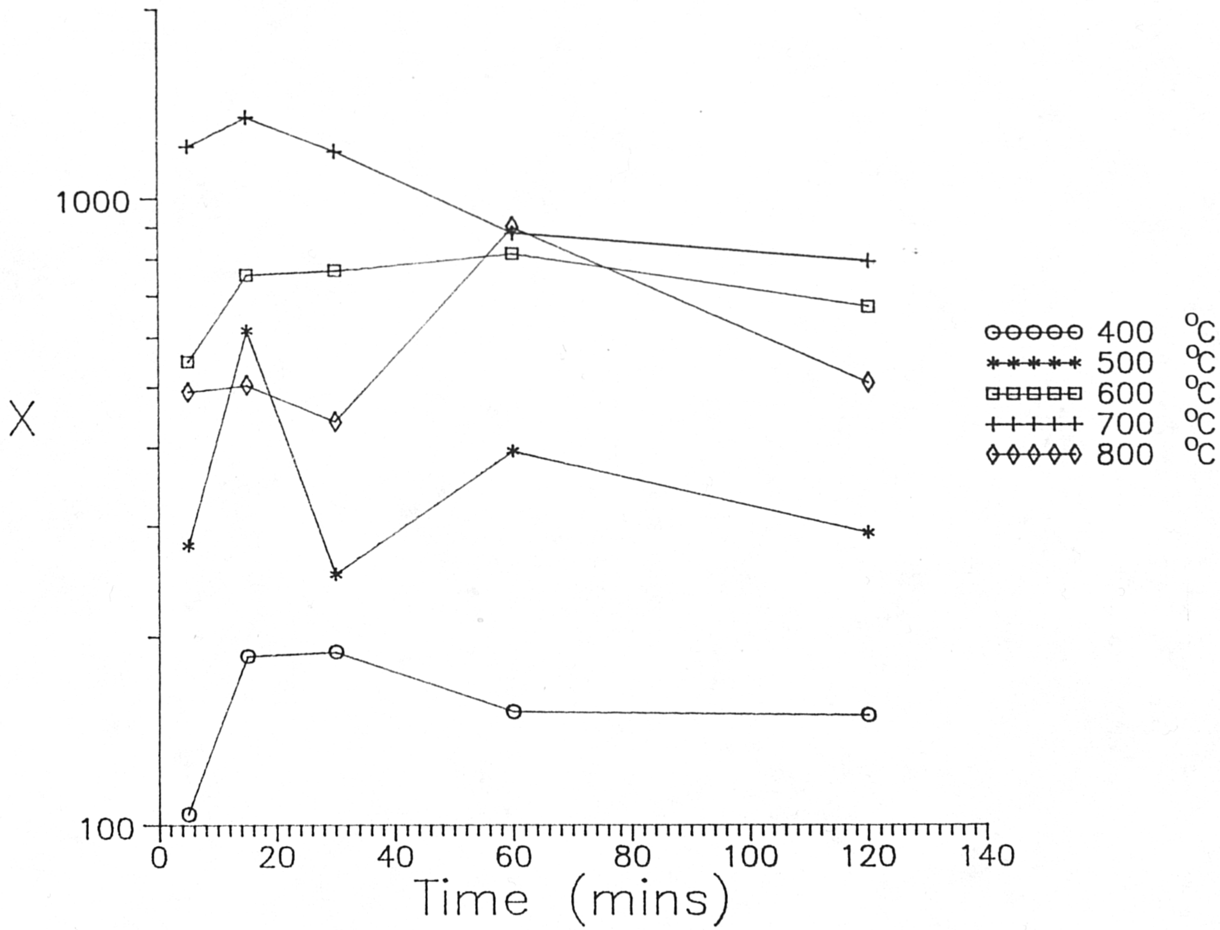
Table A E a below illustrates typical values for X_b X_e and enhancement ratio in comparison with sediments from other locations. The material from the Eggleshope Beck is similar to the Carboniferous sandstones of the North Tyne, although clearly the North Tyne material is richer in ferromagnetic iron, which tends to reduce the values of enhancement ratio.

Table A E a: Comparative values of enhanced magnetic susceptibility from different geologies and streams within the UK.

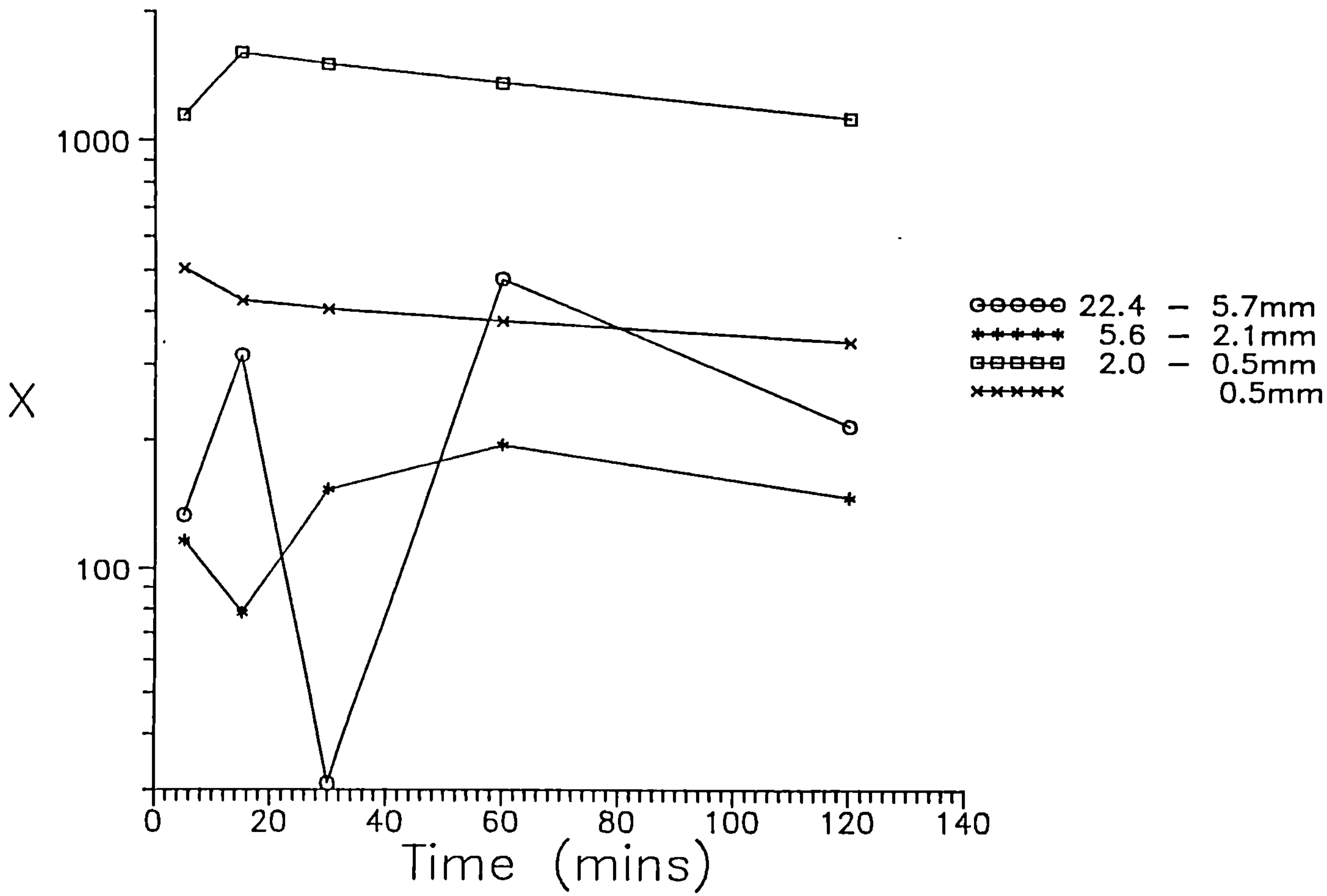
Sediment	Size (mm)	X_b	X_e	X_e/X_b
Silurian Shales & Mudstones (Plynlimon)	5	0.07	68	71
Carboniferous Sandstones & Limestones (Eggleshope)	2	0.05	44	880
Carboniferous Sandstones & Limestones (N. Tyne)	2	0.23	16	69

A series of graphs was constructed, from which optimum enhancement was deduced as the conditions which promoted the highest X value. Figure A E a depicts the variation in X with the time at a given peak enhancement temperature. On this basis the optimum temperature is clearly 700 ^{o}C, for a time of 15 minutes; however, this represents average conditions for a mix of particle sizes and a small weight (20g). Figure A E b shows the effect of sediment size, and duration at 700 ^{o}C, on X enhancement. It is clear that the time required at peak temperature increases for larger particle sizes. This trend was evident in the enhancement studies conducted on the Silurian Shales of the Plynlimon massif (Arkell 1985). The highest enhancement is associated with sediment in the size category 2 - 0.5mm, and < 0.5mm. This was also evident in the Silurian Shales of mid-Wales, which Arkell (1985) attributed to the enrichment of finer sediments in primary magnetic minerals such as magnetite. The reasoning for this was considered beyond the

AEa Superparamagnetic enhancement: X variations with temperature according to time at peak temperature.



AEb Superparamagnetic Enhancement: X variation according to time at peak temperature and particle size.



scope of this project, other than to take account of it in the optimisation procedure. The temperature of 700 °C is higher than that recorded for the Eggleshope bedload (600 °C), although Figure A E a shows that this is the next most optimum temperature for enhancement.

The data recorded for the experiments to determine the effects of sample size on X enhancement are shown in Table A b.

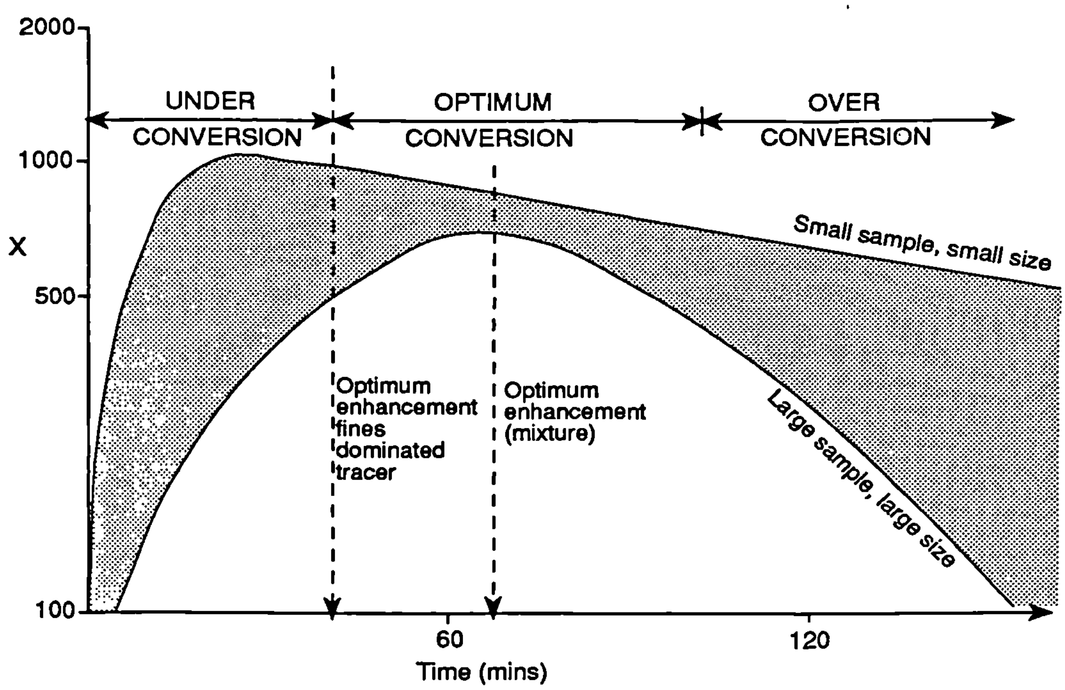
Table A E b: Experimental conditions and the results of magnetic enhancement for North Tyne bed material.

Weight (gms)		Temperature (°C) 400	500	600	700	800
	X_e	86	447	740	1364	444
50	X_b	49	34	34	62	80
	X_e/X_b	(1.8)	(13.2)	(22)	(22)	(6)
	X_e	137	1037	1213	2092	519
100	X_b	52	35	28	31	43
	X_e/X_b	(3)	(30)	(43)	(68)	(12)

The doubling of sample size, when treated for 60 minutes at a given temperature, consistently increases the X value and effectively doubles the enhancement ratio. Optimum temperature remains constant at 700 °C. The reasoning behind the increased X values in the larger sample probably relates to the thermal gradient within the sediment. Arkell (1985) describes this process in detail and concludes that three zones exist within a larger sample: an outer zone where material is heated rapidly and overconverts to haematite; an inner zone which does not experience such rapid heating or even the peak temperature, and which is subsequently underconverted; and a middle zone which experiences optimum conversion. In smaller samples, the zone of overconversion is possibly greater and the mixture requires less heating time to achieve optimum conditions Arkell (1985).

Using the criteria developed above it is possible to produce an optimum "toasting recipe" for large samples of North Tyne sediments. Figure A E c schematically depicts the

FIG. AEC: Schematic representation of optimum enhancing process for the North Tyne, Carboniferous sandstone



enhancement process. Optimum conditions for an equal mix of fine and coarser material is achieved at 700 ^{o}C for 60 minutes. Under these conditions the mix of over and under converted material is optimised to produce the highest X values. However, analysis of the tracer material shows that there is a dominance of fine sediments < 2mm which require less time at peak temperature to produce optimum enhancement. The optimum recipe decided upon for a total sample of 230Kg was rapid heating in a preheated furnace at 700 ^{o}C for a period of 40 minutes. Cooling was slow, with the heated sediment withdrawn from the furnace and allowed to cool at air temperature (which in fact took over 28 hours).

Table A E c shows the comparison between the laboratory enhanced sediments (100gms heated for 40 minutes at 700 ^{o}C), and the material treated in one 230 kg batch at the glassworks.

Table A E c: A comparison between laboratory and bulk (glassworks) enhanced bedload.

Size (mm)	X_b	X_e (lab)	X_e (gw)	X_e/X_b (lab)	X_e/X_b (gw)	n
22.4 - 11.2	0.02	02.43	01.80	122	90	5
11.2 - 5.6	0.05	01.39	37.96	28	759	5
< 5.6	0.23	10.79	19.10	47	83	5
Mixture	0.22	12.89	21.30	59	97	5

lab = laboratory enhanced gw = glassworks enhanced

It is clear from these results that the choice of optimum recipe was judicious, and succeeded in optimising the enhancement process beyond the tests in the laboratory. It is evident from this that the processes operating in the smaller laboratory samples were overconverting more material per sample resulting in lower X values. The tracer material is therefore more readily detectable both in the field and in the laboratory.

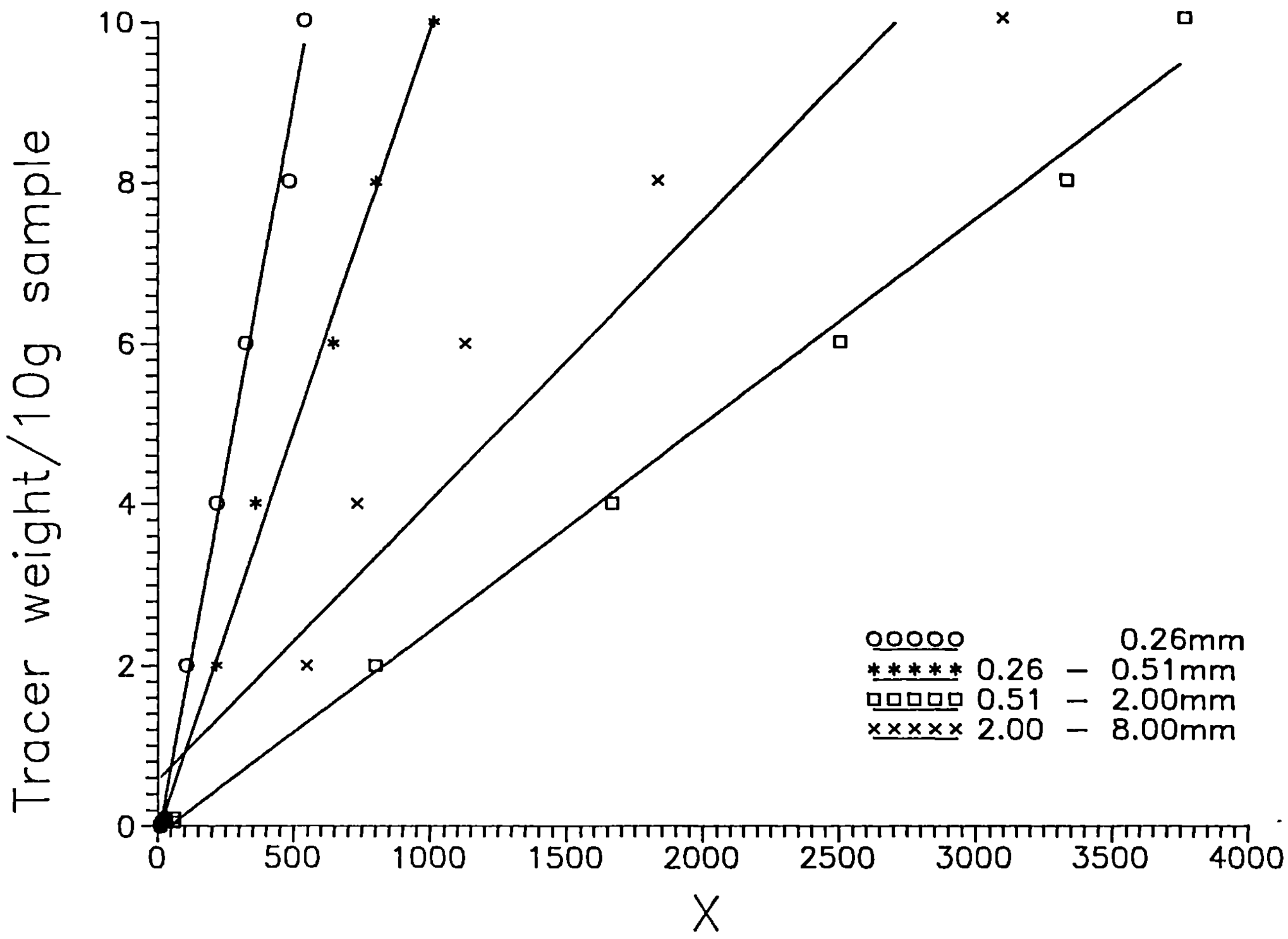
The identification of tracer material in the field was divided into two methodologies, according to those described by Arkell (1985). Large particles (> 8mm) were identified on the basis of colour the treatment process produced a charcoal colouration Munsell N40/30, as opposed to the natural colouration of 10YR73/56 similar to that described by

Arkell (1985) for the Welsh Silurian shales. In addition, samples of sediment were returned to the lab from points recording high field X values, and all particles larger than 8mm were passed through the enclosed loop susceptibility monitor. For the finer sediments, Arkell (1985) describes the production of calibration curves of laboratory values of specific susceptibility versus weight of tracer per sample. Although neither these calibration curves, nor their significance, are presented in Akell's thesis, they are clearly used to effect. A sequence of tests was carried out to develop equivalent curves for the tracer material in the North Tyne. Samples were taken and varying amounts of tracer added to them to make them up to 10gms. The samples were measured for specific susceptibility (units X 10^{-6} m^3 kg^{-1}) and curves calculated according to least squares regression. Figure A d depicts these curves whose equations and r^2 values are recorded in Table AEd below for the ranges of particle sizes shown. The samples returned from the field were sieved into the relevant size fractions, searched for traces of old fishing gear (some 15 fishing lures were recovered from the deeper pool regions in the course of the tracing period), or metal, and then passed through the susceptibility monitor in samples of 10gms. The results of this method proved effective, and are described in Chapter 10.

Table A E d: Equations for the determination of weight of tracer material in 20gm samples of North Tyne bed sediment.

Size range (mm)	Equation	r^2
8.0 - 2.0	0.018X - 0.196	0.99
2.0 - 0.5	0.010X - 0.104	0.99
0.5 - 0.25	0.003X - 0.111	0.93
< 0.25	0.004X - 0.560	0.98

AEd Relationships for weight of magnetic tracer and (X)



Appendix F

Tracer distances moved during period of study

Table 12a

Summary data for each site recording the mean and maximum distances moved by tracer particles (those moved), together with the percentage of tracers moved on a grainsize basis. Q = 20 (YR1, SMR, SMP, TP1, TP2, TR2, NR1, NP1, NP2, NR2).

Grainsize (Phi class)	YR1			SMR			SMP			TP1		
	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%
22	0.0	0.0	0	1.2	1.2.	22	0.0	0.0	0	0.0	0.0	0
32	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
45	0.0	0.0	0	0.6	1.0	20	0.0	0.0	0	0.0	0.0	0
64	0.0	0.0	0	0.2	0.2	22	0.0	0.0	0	0.0	0.0	0
90	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
125	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0

	TP2			TR2			NR1			NP1		
	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%
22	0.0	0.0	0	0.0	0.0	0	---	---	24	0.0	0.0	0
32	0.5	0.6	40	0.9	1.4	80	3.6	6.8	48	0.0	0.0	0
45	1.0	1.0	20	0.9	1.0	75	2.3	5.7	48	0.0	0.0	0
64	0.6	0.6	33	0.8	1.0	80	0.3	0.3	40	0.0	0.0	0
90	0.0	0.0	0	1.0	1.0	50	0.8	0.8	60	0.0	0.0	0
125	0.0	0.0	0	1.2	1.2	50	0.5	0.6	60	0.0	0.0	0

	NP2			NR2		
	$\bar{x}$	max	%	$\bar{x}$	max	%
22	0.0	0.0	0	0.0	0.0	0
32	0.0	0.0	0	---	---	33
45	0.0	0.0	0	0.2	0.3	50
64	0.0	0.0	0	0.6	1.2	100
90	0.0	0.0	0	4.2	8.0	100
125	0.0	0.0	0	0.0	0.0	0

Table 12b

Summary data for each site recording the mean and maximum distances moved by tracer particles (those moved), together with the percentage of tracers moved on a grainsize basis. Q = 20 (YR1, SMR, SMP, TP1), Q = 30 (TP2, TR2, NR1, NP1, NP2, NR2).

Grainsize (Phi class)	YR1 $\bar{x}$	YR1 max	YR1 %	SMR $\bar{x}$	SMR max	SMR %	SMP $\bar{x}$	SMP max	SMP %	TP1 $\bar{x}$	TP1 max	TP1 %
22	0.0	0.0	0	1.2	1.2.	22	0.0	0.0	0	0.0	0.0	0
32	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
45	0.0	0.0	0	0.6	1.0	20	0.0	0.0	0	0.0	0.0	0
64	0.0	0.0	0	0.2	0.2	22	0.0	0.0	0	0.0	0.0	0
90	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
125	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0

Grainsize (Phi class)	TP2 $\bar{x}$	TP2 max	TP2 %	TR2 $\bar{x}$	TR2 max	TR2 %	NR1 $\bar{x}$	NR1 max	NR1 %	NP1 $\bar{x}$	NP1 max	NP1 %
22	---	---	50	0.3	0.4	60	3.5	16.0	76	0.4	0.4	14
32	1.8	2.5	80	0.5	1.0	50	3.7	17.8	84	0.4.	0.5	13
45	3.0	3.0	60	0.1	1.0	10	3.3	16.2	68	0.3	0.3	8
64	0.8	0.8	66	0.5	0.6	22	8.2	23.4	100	1.3	1.4	8
90	1.0	1.0	100	0.0	0.0	0	3.1	8.2	80	0.0	0.0	0
125	---	---	100	1.0	1.0	100	2.5	6.6	100	0.0	0.0	0

Grainsize (Phi class)	NP2 $\bar{x}$	NP2 max	NP2 %	NR2 $\bar{x}$	NR2 max	NR2 %
22	0.6	0.7	40	0.0	0.0	0
32	0.7	1.2	24	2.3	7.5	50
45	0.7	1.0	42	1.4	2.0	30
64	0.0	0.0	0	2.0	5.4	56
90	0.0	0.0	0	0.5	0.8	66
125	0.0	0.0	0	0.0	0.0	0

Table 12c

Summary data for each site recording the mean and maximum distances moved by tracer particles (those moved), together with the percentage of tracers moved on a grainsize basis. Q = 77 (YR1), Q = 105 (SMR, SMP, TP1), Q = 151 (TP2, TR2, NR1, NP1, NP2, NR2).

Grainsize (Phi class)	YR1			SMR			SMP			TP1		
	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%
22	5.3	5.3	100	1.1	2.1	80	0.6	0.8	60	0	0	0
32	18.5	37.0	50	1.1	2.3	77	2.4	10.0	64	0	0	0
45	1.2	3.3	71	0.9	1.9	90	0.9	1.8	82	0	0	0
64	1.3	3.9	71	0.8	1.8	44	0.5	0.8	66	0	0	0
90	0.3	0.6	50	0.6	0.6	50	0.9	1.8	75	0	0	0
125	0.0	0.0	0	0.5	0.5	100	0.0	0.0	0	0	0	0

Grainsize (Phi class)	TP2			TR2			NR1			NP1		
	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%	$\bar{x}$	max	%
22	---	---	100	36.0	38.0	100	1.0	10.0	100	---	---	29
32	---	---	100	27.0	46.0	100	35.5	169	100	93.0	95.0	66
45	---	---	100	---	---	100	16.4	98.0	100	112	112	58
64	3.5	3.5	100	10.3	29.4	100	55.5	110	100	49.0	99.0	62
90	---	---	100	12.1	22.4	100	20.8	40.2	100	170	170	66
125	---	---	100	19.8	19.8	100	4.5	7.7	100	---	---	100

Grainsize (Phi class)	NP2			NR2		
	$\bar{x}$	max	%	$\bar{x}$	max	%
22	35.0	35.0	100	10.8	10.8	100
32	40.5	56.0	82	29.3	55.0	93
45	31.3	67.0	83	9.7	24.6	100
64	21.9	65.0	92	60.8	164	100
90	5.3	7.0	80	3.7	8.4	100
125	29.0	31.0	100	8.5	8.5	100