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THE EFFECTS OF BANK EROSION ON SALMON SPAWNING HABITAT IN AN UPLAND GRAVEL-BED RIVER

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by

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Abstract

Two main problems of channel widening and fine sediment infiltration were identified as major causes of the degradation of salmon spawning gravels in upland rivers in Scotland. They are both commonly attributed to the process of bank erosion. The supply of fine sediment for infiltration into gravel beds is considered by many to be controlled by rates of bank erosion. This study attempts to identify the effects of bank erosion on the condition of gravel-beds and to evaluate its contribution to the fine sediment load of the river. It is also aimed at evaluating the effectiveness of bank protection in reducing fine sediment infiltration.

This was done by recording rates of fine sediment infiltration into gravel-beds at various locations through a reach of the river. The redistribution of bank eroded sediment was monitored by tagging fine bank sediment with fluorescent paint and tracing its removal from the bank and its dispersal and deposition both across the channel cross-section and in the downstream direction. Image analysis techniques were developed using computer software that allows quantitative analysis of sediment sample composition to establish likely source areas for the material. Also the morphological and hydraulic conditions were monitored in a reach of the river before and after the bank protection installation to record process changes that may affect sedimentation rates.

It was found that there are several physical factors which control the infiltration of fines into gravel-beds. The interaction of these dictates a complex pattern of sediment infilling and matrix development. But infiltration rates were shown to be largely dominated by sediment supply, both within and outwith the channel, although the actual process of infiltration is conditioned by the flow regime and the frequency and magnitude of floods, irrespective of the availability of fine sediment. Bank eroded sediment was found to have a considerable influence on levels of infilling, both locally and further downstream. Finally, although bank protection works have prevented further channel widening it has shown that reducing gravel-bed infilling cannot be achieved isolated stretches of bank protection alone.

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CHAPTER 1 - INTRODUCTION

1.1 - Background

The plight of the Atlantic salmon (*Salmo salar*) is a highly topical issue at present. There is much debate about the decline in annual catches and the numbers of salmon returning to their native rivers to spawn and who, or what is to blame for this trend. Many factors have been suggested as being responsible for this decline. These range from over-exploitation on the open seas, changes in marine conditions (sea temperature, salinity, food availability and predation) and changes in the quality and quantity of spawning and rearing habitat in rivers. Emphasis is at present being put on increasing the numbers of adult salmon returning to rivers. Shearer (1996) states that there is evidence which suggest that most rivers are presently producing the maximum number of smolts for the existing area of good habitat. Therefore, increasing the number of returning salmon will not necessarily result in an increase in the juvenile recruitment to adult population, as the river is producing the optimum for its present condition. If fisheries managers want to increase production, the first priority should be to increase the quantity and/or quality of nursery and spawning habitat or their quality.

1.2 - The Problem

The freshwater phase is the most critical period in the life history of a salmon. Populations are most vulnerable during this stage and are subject to many detrimental factors such as the vagaries of climate and the interference of man. Fisheries organisations, landowners and riparian owners are beginning to address the problem of habitat degradation with a range of restoration and enhancement projects. In order to successfully enhance salmonid habitats it is essential to understand how nature controls the flow characteristics and morphology of alluvial channels. The ecological requirements of salmon are dependant on basin and channel morphology, sedimentology, sedimentation processes and the hydrological regime (Bellamy et al. 1992). When in equilibrium, sediment supply from upstream balances the river's ability to transport it.

Any imbalance between these two results in erosion or deposition and a change in channel morphology which affects the distribution of salmonid habitats. The prevailing view is that bank erosion is reducing habitat quality and quantity. Consequently, it is of prime importance to identify the controls on natural erosion and deposition and the channel's response to this activity. This study aims to do this by considering the interaction between channel form, flow regime and sediment transport and how they affect the quality of salmon spawning habitat. The main body of this work will revolve around a central theme being :

to ascertain and evaluate the direct consequences of river bank erosion on the quantity and quality of salmon spawning beds in an upland gravel bed river.

1.3 - The Aims of this Research

This central theme will be investigated by undertaking several specific objectives:

1 to monitor the rates and types of fine sediment infiltration in the Water of Mark over a 12 month period;

2 to identify the downstream and cross-stream spatial and temporal variations in rates of sediment infiltration within a reach of 800 metres in length;

3 to assess the significance of channel hydraulics, bed characteristics and natural channel and bank processes on the rate of sediment infiltration;

4 to determine the importance of bank erosion as a primary source of fine sediment by identifying the pattern of downstream redistribution of tagged fine sediment after release from an eroding bank;

5 to record natural and engineered channel and bank modification, and their effects on channel hydraulics; and,

6 to evaluate the efficacy of river bank protection works and their effects on the sediment load of the river, and on rates of fine infiltration.

By monitoring changes in the rates of infiltration and the supply of fine sediment, observing the effects of natural and engineered changes to the river channel and banks, coupled with establishing how the sediment released from an eroding bank redistributes downstream, it should be possible to provide an estimation of how significant bank erosion is in the process of salmonid habitat loss, compared with other detrimental factors and processes.

1.4 - Thesis Structure

The thesis begins with an introduction to the field of salmon habitat requirements for the freshwater phase of its life, by giving a background overview of the major habitat components in Chapter 2. The lack of the 'complete' habitat for salmonids is assessed and the reasons for its degradation are discussed, both in terms of quantity and quality. Fine sediment infiltration of gravel-beds is introduced and the problems associated with it are outlined. The latter part of the chapter concentrates on a review of existing literature in the field of fine sediment infiltration and retention and provides some theoretical background to the problem. Finally, it refers to the specific aims and objectives set out earlier and gives an indication of how this study fits into the contemporary literature.

Chapter 3 introduces the field site in detail discussing its physical characteristics in terms of its geology, geomorphology and landuse. Details are also provided on a habitat improvement scheme that was implemented at the research site during the study period. This chapter also outlines individual methods of data collection, their importance in the study is put into context and explanations as to why each method was chosen are also provided.

Chapter 4 is devoted to the presentation of the data in various formats and analysing the spatial and temporal variations that are found within the data. An attempt is made to relate each of the findings to some of the theoretical concepts that are outlined in Chapter 2. Chapter 5 provides an interpretation of the results by giving a summary of what they show, compare the findings with those of the contemporary literature and to establish what the implications are for fisheries management in the Water of Mark. The wider implications of bank erosion, its associated problems and its management are also discussed. Finally, the last section of the chapter discusses the methods used in this study and the research design and how appropriate and effective they were in addressing the specific objectives set out at the beginning of the work. The preparation and presentation of the data is also assessed as to its suitability and suggestions are made on areas for work to be undertaken in this field in the future.

Finally, the conclusions are presented in chapter 6 which ties all aims and objectives of the study together, and summarises the results and discussion sections in terms of their relevance to the continuing debate on upland salmonid habitat degradation.

CHAPTER 2 - SALMON HABITAT AND THE PROBLEM OF FINE SEDIMENT INFILTRATION

2.1 HABITATS FOR SALMON AT DIFFERENT LIFE-CYCLE STAGES

2.1.1 The fundamental habitat components

Before attempting to assess salmonid habitat degradation in upland gravel-bed rivers, it is important to look at the life-cycle, behavioural pattern and habitat needs of salmonids when they return to their native rivers and proceed upstream to spawn in the upland headwaters. Wesche (1985) identified four fundamental habitat components for salmon in spawning tributaries to which a fifth is added:

1. acceptable water quality and adequate water supply
2. food production areas
3. spawning and egg incubation areas
4. adult holding pools and cover
5. juvenile and nursery habitat.

The extent to which each of these components are present in a river is dependant on the river's physical, chemical, hydraulic and biological characteristics. In order to provide the 'complete' salmon habitat, the river must exhibit each of these components in its upland reaches

2.1.2 Water quality and quantity

Water must be of acceptable quality in terms of pH, turbidity, nutrient levels, phosphate levels, temperature, oxygen levels and other industrial or agricultural pollutants. If these are not at favourable levels fish will not ascend the river system to its upper reaches, as they will not pass through a barrier of contaminated water. This then renders all parts of the productive river system upstream useless. Similarly, the stability of flow of the river is important, as a river with a slowly rising and falling discharge is ideal for salmon spawning and nursery requirements. Also there must be a sufficient water supply in low flow periods to maintain a juvenile population and to allow adult salmon to ascend the river at spawning time in October to January.

2.1.3 Food production areas

The abundance of food producing areas are vital for the survival and growth of the juvenile salmon during its first two or three years in the river before migrating to sea. Owen (1971) indicates that riverside trees are important, in that they deliver about 90% of the diet of the salmon when invertebrates fall from the trees into the river. He also comments that trees enhance food supply when the leaves fall into the river providing food for aquatic micro-organisms and plant-eating invertebrates.

It was suggested by Odum (1959) that riffles are the primary in-river food producing areas, due to their relatively high velocity, substrate composition and shallow water depths. According to Scott (1958) and Allen (1959), velocity is the most significant parameter in determining distributional patterns of aquatic invertebrates (benthos or bottom dwelling insects). The velocity is fundamental to the benthic invertebrates by governing the rate of oxygen renewal to the insect living in the gravel substrate. The faster the water current, the more efficient the renewal rate i.e. increased velocity leads to greater substrate throughflow and the enhancing of the exchange rate between the organism and the water supply, thereby promoting respiration and food acquisition (Giger 1973). For instance, Kennedy (1967) discovered that the greatest number of organisms were where velocities are of 0.3 - 0.4 ms^{-1}, with few invertebrates present in lower velocities.

Directly related to water velocity is substrate size, with larger clasts associated with faster currents and smaller clasts (silt and sand) with slower currents. Benthic invertebrates decrease in population as substrate size becomes smaller. Similarly, the depth of water effects benthic population, as the depth regulates the light intensity, so influencing the photosynthetic production of food. As depth increases, light penetration subsides and invertebrate numbers retract, but light penetration also varies with fluctuations in turbidity.

The three parameters of faster velocities, large substrate and shallower water depths tend to combine effectively in riffle reaches in most rivers. Thus riffles provide the optimal conditions for the majority of invertebrate species survival and are therefore much more productive than pools (Wesche 1985).

2.1.4 Spawning and egg incubation areas

The desired spawning and egg incubation habitat for salmonids has usually been defined by measuring the chemical, physical and hydraulic parameters existing in the sections of river utilised by actively spawning salmon. Similar to food production areas, the general characteristics that influence these areas include water velocity, water depth and substrate size. However, fish size also determines if an area is acceptable for spawning, with larger fish being able to dislodge bulkier substrate and endure higher velocities than smaller fish. There is a consensus of opinion (Mih 1978; Wesche 1985; Crisp & Carling 1988; Mills 1989; Kondolf & Wolman 1993), that salmon spawning sites exhibit a general water velocity of between $0.15ms^{-1}$ to $0.9ms^{-1}$ with a substrate size range of 6mm to 76mm (average of 22mm with 50% falling between 15mm and 35mm) and a water depth of no less than 0.15m.

Bellamy et al. (1992) produced a preferred particle size curve for a salmon spawning bed from work carried out on the Credit River in Ontario, Canada (Fig.2.1 (a) below). This shows a range of particle sizes with 50% being more than 8mm in size, which has been shown to be good for spawning purposes. Figure 2.1 (b) shows a bed material configuration that is too coarse for spawning, as the eggs would be entrained by the fluid flow through the gravel. This substrate is consistent with good feeding and resting habitat, as the larger particles and resultant cavities provide shelter from the flow for juvenile fish.

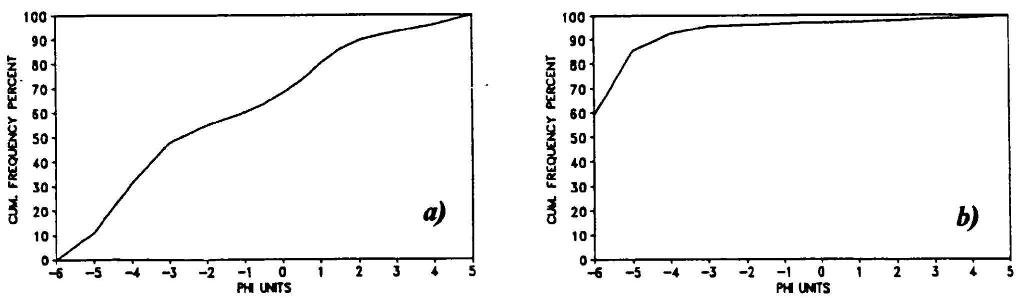
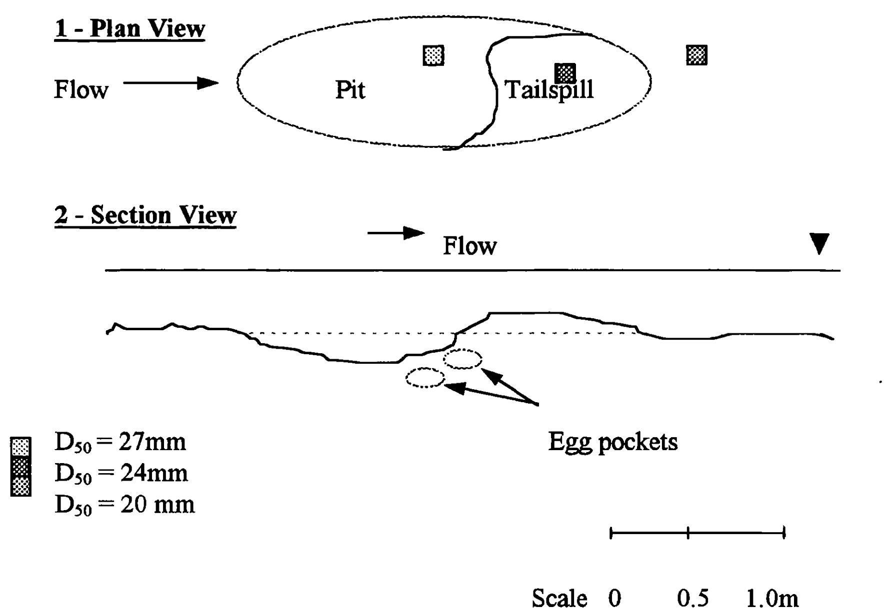


Figure 2.1 a) and b) - Particle size curves for spawning and non-spawning beds *(Bellamy et al.1983)*

The process of redd (or nest) construction, the laying of the eggs in the redd and the subsequent covering up of the eggs is a well documented phenomena (Gustafson-Marjanen & Moring 1984; Crisp & Carling 1989; Kondolf et al. 1993), but in order to understand the processes that occur after redd construction, it is necessary to describe briefly how redds are formed. The female salmon, after finding a site with suitable substrate, velocity and water depth creates a depression or pit in the gravel-bed. This is done by turning on her side and using abrupt repeated flextures of her tail within a few centimetres of the gravel, usually with a male in attendance. Her movement creates a suction effect which throws the bed material up into the current. Once exposed to the force of the flow, gravel particles are carried up to one metre downstream to form a growing tailspill, with the finer interstitial fractions of sediment carried much further downstream in suspension. On the emergence of a suitable pit, the female begins oviposition (release of 2,000-15,000 eggs) and the attendant male fertilises the eggs immediately. After egg deposition the female rapidly resumes digging upstream to bury the eggs. The sequence of oviposition and covering may be repeated several times in one redd. The morphology of the resultant redd, with an upstream pit and a gravel tailspill is distinctive.

Figure 2.2 - Redd Morphology (after Kondolf et al 1990)



The depth of the egg deposition is an important characteristic which is inclined to vary. Salmon tend to bury their eggs within the stream-bed gravels to a depth of typically 80mm to 300mm (av. 152mm) below the bed surface (Milner et al. 1981). Several authors, summarised by Milner et al., have observed that the depth of egg burial increases with the size of the female fish, although burial depth is also known to be dependant upon gravel composition and water velocity, as well as fish length. Crisp & Carling (1989) found that eggs of larger fish will generally be buried deeper than those of smaller fish and will, therefore, be better protected from flood flows capable of re-working the gravel-bed which can destroy eggs. The incubating eggs need constant darkness and must be immobile, so movement of the gravel substrate during a flood event will have a devastating effect. In Carl Beck, Ottaway (1984) buried artificial colour coded fish eggs at various depths up to 130mm below the surface in the gravel-bed. After a season of spates, eggs were relocated by digging the gravel over. Recovery of eggs buried at 120mm and over was close to 100%, whilst recovery of eggs buried at 60mm depth was 2%. This highlights the importance of burying the eggs at a specific depth. Too shallow and they will be moved by flood flows or exposed in periods of low flow, too deep and there will be too little throughflow for survival.

It has also been established that there needs to be a significant substrate throughflow (Table 2.1), to enable the delivery of oxygen to the incubating eggs necessary for their growth and survival (Milhous 1982 and Kondolf et al. 1993). The development of salmonid eggs is directly related to dissolved oxygen levels, with demand increasing as the eggs develop, and reaching a maximum just prior to hatching. The throughflow rate influences the length of incubation and the relative sizes of emerging fry, and thus the pore spaces within the gravel need to be silt free allowing this percolation (MacNeil 1964). This throughflow also removes toxic metabolic waste material discharged by the developing fish embryos. This necessity for throughflow has led to spawning sites tending to be at the downstream end of pools where the bed gradually assumes a convex appearance causing a downward movement of water into the gravel, or at the tail-end of riffles where there is an upward flow of water (Mills 1989) (Figure 2.3).

Figure 2.3 - Spawning location at downstream-end of pools and tail-ends of riffles

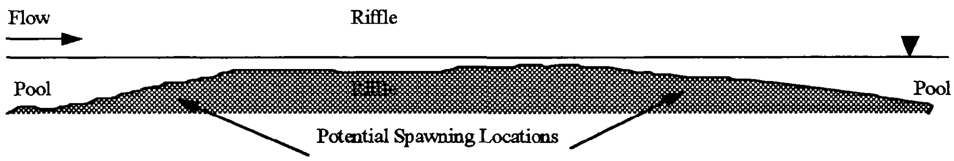


Table 2.1 - Relationship between egg survival and apparent velocity through spawning sediments (Milhous 1982).

Apparent velocity (m s^{-1})	Egg survival (per cent)
0.00034	89
0.00011	78
0.000054	68
0.000026	59
0.000014	36
0.0000094	26
0.0000067	16
0.0000039	2

2.1.5 Juvenile and nursery habitat

The next life-cycle stage that needs to be provided for is that of the juvenile fish after emerging from incubation. After about five months incubation period, the eggs hatch and the young fish, called fry, wriggle upward through the gravel to emerge into the water column. Hence the gravel substrate must be relatively silt-free and have a certain porosity to allow them to emerge. When the fry surface, they require a range of depths, velocities and substrate sizes for their growth and development from fry to the next life-cycle stage called parr, and eventually becoming young adult fish when they are termed smolts. On emergence, the fry start to feed on nymphs and larvae of aquatic insects (Mills & Graesser 1992). The recently emerged fry are inclined to hide under stones and quickly establish a territory. This has the effect of spreading the population through the stream system, leading to a more efficient utilisation of the food supply. It is within this micro-habitat that the fish will spend the majority of its time feeding and resting, so the availability of juvenile habitat has to be plentiful and thus is a determinant of fish population. For example, juvenile salmon prefer fast flowing water (ie. riffles) from spring to autumn, but in winter they change their behaviour completely : they spend their day hiding in crevices between stones in the stream bed, and emerge at night to feed, when they prefer slow flowing water (ie.pools) (Heggenes et al. 1993). Since crevices under stones tend to become silted up in pools but not in riffles, the fish must commute between the two habitats in winter, so both pools and riffles must be available. It must also be noted that the river flow levels vary seasonally and even diurnally with the distribution of juvenile fish varying accordingly dependant on river conditions O'Grady et al.(1990) found that the most productive areas which support juvenile salmon populations are shallow (0.7m) relatively fast flowing (0.3 to 1.0ms^{-1}.) areas with a rubble or broken bedrock substrate.

2.1.6 Adult holding pools

The final habitat component that is fundamental to the most productive use of a river system is an adequate supply of adult salmon holding pools and cover. Adult salmon ascend the river making for the headwaters in search of a suitable spawning site. On reaching the spawning tributaries they require holding pools so that they can rest before they are ready to spawn. In summer, in times of drought or low flow, the salmon are able to sink into the depths of these pools to avoid the sun's rays. Cover is also required in the streams and is provided by overhanging or submerged vegetation, submerged objects (stumps, logs and rocks) and is utilised by salmon due to them exhibiting thigmotaxis (a desire to be in close contact with an object) (Wesche 1985). In periods of low flow when there are few pools and shallower water courses, entry into spawning reaches may be delayed or physically impossible and hence for spawning purposes that part of the river may be rendered useless (Shearer 1992).

2.1.7 The 'complete' habitat

It is evident form the description of the habitat components required, that the key characteristic of any productive in-stream habitat is diversity. The velocity, depth and substrate of any river are interrelated and are combined in different ways to produce the required diversity. Generally, the size of the bed material increases with water velocity because the force of the current winnows out the finer particles. Jowett (1992) found that velocity, and often substrate size, decreases as depth increases in rivers with well-defined pool-riffle sequences. However, in more uniform rivers he found that the reverse tends to occur; with the main current in the deeper section of the river and shallow slow-flowing water at the margins. In biological studies these interrelationships make it difficult to separate the different effects of velocity, depth and substrate on biota.

It is imperative that the combination of water depths, water velocities and substrate types exist together to form the 'complete' habitat. For example, provision of suitable depths and velocities for spawning is fine, but if they are not present over the correct substrate size, the habitat value is diminished. Likewise, a stream reach consisting entirely of riffles and runs may have an abundance of food production and spawning capacity, but it is not good for juvenile development and may not be capable of holding mature fish due to the absence of pools. Thus, on a microscopic level, the diversity of depths, velocities and substrate must be present to adequately provide for each habitat component; while on a macroscopic level, the diversity of habitat components (ie.riffle and pool sequence) must be available to form the complete habitat for all the in-river life-cycle stages of the salmon (Wesche 1985).

There are various methods of quantifying the habitat suitability of any particular reach of a river. Habitat Suitability Curves can be produced that can estimate the 'usable area' of a river for a particular habitat, with weightings from one (optimum) to zero (unsuitable) (Waters 1976). At various points in a stream reach, the suitability of the velocity, depth and substrate is evaluated on the scale of zero to one from the curves. The results from the habitat suitability curves can be combined with habitat survey data to calculate the amount of suitable habitat in a stream reach. This is called the instream flow incremental methodology (IFIM) and was developed by Bovee (1982) and Jowett (1982). This process allows the diversity of a particular stretch of river and its suitability as a habitat or range of habitats to be quantified. This means that the habitat value of a reach for different species can be assessed and aids in the determination of the quantity and quality of habitat available.

2.2 THE LOSS OF QUANTITY AND QUALITY OF SALMONID HABITATS

As indicated by the voluminous body of research at present, the presence of the 'complete' habitat for salmonids is being degraded by several processes. Two of the most well documented of these are that of the widening of watercourses by bank erosion with the subsequent infilling of adult holding pools, and fine sediment infiltration of spawning gravels. This amounts to the loss of the diversity of the natural pool/riffle sequence that is so vital to the development of salmonids. The first of these problems is relatively well understood, but it is the problem of fine infiltration into gravel spawning beds that will be the main focus of this research and therefore be discussed in greater detail.

2.2.1 Channel widening

As banks erode progressively, the channel widens and the gravel and sediment released into the river is believed by many to relocate in the pools. This leads to an overall shallowing of water depth and the loss of vital resting habitat for adult spawners (Shearer 1992). It has been suggested that the geomorphological evidence for this is not very good. It is more likely that bank erosion gives wider channels, which have lower shear stresses, meaning that pools are not maintained by erosive processes and that the bank eroded sediment may not be involved with pool infilling. But it is accepted that in periods of low flow, the resultant shallower watercourse may deny access to the spawning grounds upstream by the adult salmon, so reducing the production capacity of the river.

2.2.2 Fine sediment infiltration

The problem of infiltration of fine sediment into the interstices in the gravel substrate is a well known process (Harrison 1923; Milhous 1982;Carling 1983; Frostick et al. 1984; Bellamy 1992; Diplas &Parker 1992 and Kondolf et al. 1993). The introduction of fine material (< 2mm) into the interstices of spawning gravel has been shown to reduce the hydraulic conductivity (throughflow) of the gravel, thus preventing the flow of dissolved oxygen to the incubating eggs and the removal of toxic metabolic waste (Milhous 1982; Chapman 1988). Chapman also showed that high levels of interstitial coarse sand and very fine gravel can also prevent fry from emerging to the surface by effectively cementing or sealing the bed, through which the fry cannot travel. The accumulation of fine sediment can also cause an ecological shift by reducing the population and diversity of the benthic invertebrate community, which is the main food source for the fish emerging from the inter-gravel environment. Figure 2.4 shows a bed material particle size curve with high levels of sand and fine gravel which is 'poor' habitat for salmonid and invertebrate production. Figure 2.1 shows a comparative curve representative of 'good' habitat.

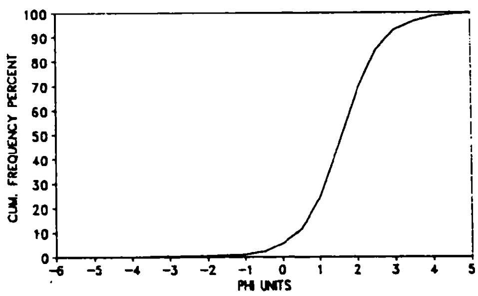


***Figure 2.4 - Particle size curve for poor salmonid habitat** (Bellamy et al. 1983).*

2.2.3 Mechanics of fine sediment infiltration and retention

Suspended sediment transport in gravel-bed rivers is an important process in determining fluvial processes and is well described by Walling and Webb (1987). During high flow in gravel-bed rivers there are variable amounts of fine particles in suspension. In response to interaction between the turbulence of the water flow affecting the trajectories of fine grains, and the settling properties of the suspended particles, a certain amount of the particles intrude into the interstices in the river bed. Different depositional processes determine whether these fines are deposited on the bed surface or are incorporated into its top layer so that the pore space is reduced ie. the river bed is progressively clogged. Schälchi (1992) stated that the general substrate characteristics of clogged river beds are:

1 a dense positioning and compact texture (low porosity)

2 comparatively high resistance against increasing discharges due to armouring ie. 1

3 reduced hydraulic conductivity

All three characteristics are detrimental to the survival and development of incubating salmon eggs and populations of benthic invertebrates. Carling (1992) suggests that heavy clogging of more than 20% of 2mm sediments or finer will reduce the recruitment of fish to the population. Adams & Beschta (1980) found that the average fine content of gravel-bed rivers is 17.4%. The average polymodal size distribution of a gravel-bed river deposit was suggested by Carling & Reader (1981) showing the finer matrix material and the coarser framework (Figure 2.5)

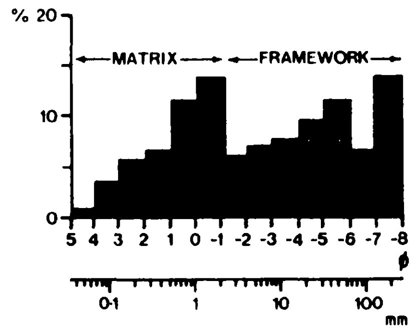


***Figure 2.5 - Example of polymodal gravel deposit** (after Carling & Reader 1982).*

2.2.4 Redd construction and its effect on sediment infiltration

During the excavation of redds by spawning female salmon, intersticial fine material is winnowed from the streambed gravels (Kondolf et al.1993). The gravels and fine sediment excavated during this process are exposed to currents and are differentially transported: gravels move a short distance, while the fine sediments are swept further downstream. These differential removal rates may cause the redd gravels to have different size distributions from adjacent undisturbed gravels. The larger particles that remain in the pit as a coarse lag create open interstices that make good sites for egg lodgement. Therefore the egg pocket may consist of gravel coarser than the rest of the redd (Chapman 1988). This reduction in the fine sediment content has left the fine sediment reservoir in the redd empty, but the sediment reservoir in adjacent gravels should still be full. Any fine sediment will now tend to accumulate in the redds and will decrease their permeability (Milhous 1982). Carling & McCahon (1987) observed that redds are likely to be fully silted in a matter of a few days after construction, assuming normal loads of suspended sediment for gravel-bed rivers.

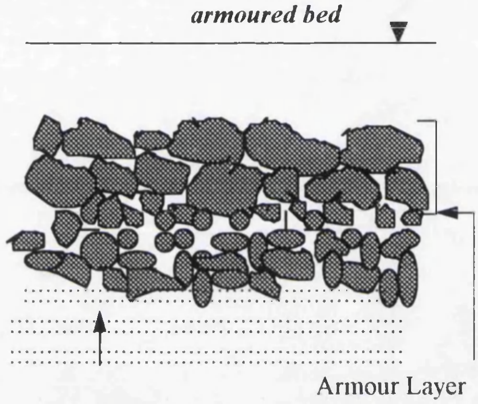
It has also been found (Rosato et al. 1986) that the dilatant process and jiggling of gravel involved in redd cutting, results in finer sediment sinking deeper into the redd by the process of kinematic sieving, so that eggs at the bottom of the redd may be heavily silted. The principal effect of cutting is, therefore, to loosen the gravels, and thus to increase the porosity and the potential intra-gravel flow rate. As a secondary effect, some fine particles are moved down towards the base of the redd.

Once a redd is constructed, its topography disrupts the near-bed flow field. Everest et al. (1987) suggest that the topographic features should discourage fine sediment deposition in the egg pocket. The pit should serve as a settling basin upstream of the egg pocket, and the acceleration of flow over the tailspill should prevent deposition. However, redds may be more susceptible to fine deposition than other sites on the streambed because their topographic form promotes downwelling and hence the transport of suspended sediment into the gravel. But, no studies have examined gravels to determine whether rates of intersticial fine sediment deposition are greater with downwelling water than from gravitational settling alone.

2.2.5 Research into fine infiltration in gravel-bed rivers

The actual mechanics of fine infiltration have been the subject of various studies. Adams & Beschta (1980) noted that the percentage of fines (<2 mm) within the streambed varied spatially and temporally. The spatial variation across the channel is more pronounced than along the channel, and fine content was vertically stratified, increasing with depth. The temporal variability of fines is dependant on high flows setting the bed in motion. Carling & Reader (1982) observed that at the earliest stage in the rise of a hydrograph, the first bedload to be mobilised is fine sediment stored as Ostler (or shadow) lenses. The matrix material around surface framework particles or armour layer (Figure 2.6) is then entrained with the resultant coarse surface gravels being termed a 'censored layer' instead of a tightly packed armour layer. The censored layer affords a degree of protection to fine matrix at depth until high flows move the framework population. When this occurs, the sediment reservoir is emptied rapidly (flushing phase), delivering a 'pulse' of sediment for transportation, the consequence being the suspended sediment load of the stream becomes erratic. The basic concept is that the armour layer controls the form of sediment transport in gravel-bed streams. Almost all gravel-bedded streams have a coarse surface layer to a greater or lesser extent, with the stability of the bed being dependant on the size of the armour material. When an armouring particle is disturbed, the material covered by the particle is then subject to hydraulic forces greater than those required to move it, with the result being that fine particles are 'plucked' from the opening. Milhous (1973) also noted the importance of a mobile armour layer on the deposition and retention of fines. Therefore, it is thought that the best management procedure would be to control flow conditions so that they flush fines from the surface and the interstices, without disrupting the gravel substrate. This would provide the textural and structural characteristics that are evident in quality spawning sites.

Figure 2.6 - Schematic Diagram of an armoured bed



The fines that have been entrained are then deposited and tend to infiltrate gravel-beds in two different modes (Diplas & Parker 1992). The first mode is characterised by unobstructed settling through the voids of the framework material. In the second mode the fines are inhibited from settling freely ; instead they bridge the gaps among particles of the gravel-bed, thus creating a seal that limits any deeper penetration of fines. This is also the process identified by Einstein (1968), Lisle (1989) and Frostick et al (1984).

Einstein (1968) discovered that the depth to which the fines will settle depends upon their size relative to the size of the bed material and its vertical grading. This is due to the particle size of the bed material mediating the size of the intervening pores. Gravel porosity should decrease as the standard deviation of the gravel mix increases (Parker 1995). However, scour and fill will alter the active bed surface level so that sand lenses may be deposited at depth (Lisle 1989). Some of the coarser particles infiltrating will inevitably be larger than the pore spaces. Consequently, lodgement occurs, hindering the passage of other particles, and as a result a sand seal may develop (Carling 1984). Beschta & Jackson (1979) and Lisle (1989) observed that scour of streambeds during floods, and subsequent fill, may deposit at least as much fine sediment and as deeply in clear gravel-beds as infiltration. With parts of the streambed being scoured during individual storms to depths of 0.1m, incubating eggs could be crushed. Therefore, scour and fill could be equally crucial to the survival of eggs and embryo as is the infiltration of fines.

Frostick et al.(1984) aimed to identify spatial variations in the vertical and horizontal infiltration of matrix material with the use of strategically located sediment traps. They highlighted differences in infiltration rates brought about by the influences of channel plan-form and cross-section on the stream thalweg.

Their results indicate the coarse surface layer super-imposed on a finer substrate, which is typical of gravel-bed rivers, was found to encourage the clogging of the near surface pores with matrix fines. Flow events that caused bed activation resulted in higher amounts and larger size of ingressed fines. These intruding fines were found in greater quantities in pools compared to bars, whilst for the same cross-section the area of highest fines content coincided with the area of highest velocity. Investigations on the river Langeten in Switzerland by Schälchli (1992) have shown that a variable and irregular bed geometry reduces the development of this clogged layer. This is important, given that river beds are variable and irregular, but flume beds (usually) are not.

Overall, infiltration of fine sediment into alluvial framework gravels is highly variable temporally and spatially, and is controlled by many physical factors. They include the rate of supply and the size characteristics of potential matrix sediment, the size and shape of the framework gravels and the resultant pores, the flow regime of the river, the cross-sectional morphology of the channel and its effect on stream flow. The interaction of these variables dictates a complex pattern of matrix development and causes the diversity of temporal and spatial distributions.

2.3 THE EXTENT OF THE FINE INFILTRATION PROBLEM TODAY

The problems of fine sediment infiltration have been realised for many years with the main body of research into the processes of infiltration being undertaken in the last two decades. But the overall amount of infiltration in some rivers is thought to have increased over the same period and is believed to be one of the most important factors in the decline of quality and quantity of salmon spawning areas (Mills 1989; Diplas & Parker 1992; Mills & Graesser 1992 and Shearer 1993). The amount of infiltration is directly proportional to the amount of fine sediment being transported in the river. The reasons put forward for the increase in fines are varied and are discussed in the following section. The importance of fines and their infiltration of gravel-beds is underlined in the fact that of all factors deleterious to spawning likely to be exacerbated by mankind, it is one of the most prevalent (Diplas & Parker 1989).

2.3.1 Increased sediment load within rivers

The source of the fine sediment which causes the clogging of gravel-bed rivers is thought to be provided by several different processes that contribute to the overall sediment load. The increase in afforested catchments with the resultant ploughing and drainage systems may have led to greater sediment yields to the river by surface erosion (Meehan et al. 1969, Anderson et al. 1976 and Mills 1989). Mills & Graesser (1992) also suggest that this is enhanced by the overgrazing of upland areas by sheep and deer and the loss of the thick protective vegetation cover, thus promoting larger sediment discharge rates. The sheep also contribute to the instability of the hill ground and river banks by creating innumerable tracks and narrow paths and by using small knolls and irregularities in the ground and river banks as 'scratching posts' and for protection from weather.

Muirburn has been put forward by Mills & Graesser (1992) as another factor which may also contribute to erosion and landslides in certain types of terrain. Repeated burning of the heather at close intervals to promote new growth may result in the disappearance of herbaceous species, which in turn has an adverse effect on the soil, destroying the organic horizon, whereupon erosion is inevitable and becomes accelerated, flushing sediment into the watercourse. This tends to be a problem only if muirburn is not carried out properly and the temperatures become too high. There is also the problem of stream regulation by damming. Dams tend to eliminate any annual peak discharges that may occur in a river. In rivers that have peak flows, these higher flows are important as they are capable of activating the bed and thus releasing the fines that accumulate during low flows (Diplas & Parker 1992).

2.3.2 Bank erosion as a sediment source

The erosion of river banks has been assumed to be a primary contributor to larger sediment concentrations in rivers. The majority of upland rivers are active laterally and this promotes the erosion and deposition of bank materials. Some degree of lateral activity is vital to a river if it is to retain the natural geomorphic and ecological attributes which make it such a valuable and diverse habitat provider (Thorne et al. 1995). But it has been suggested (Smith & Bennett 1994) that due to changes in the rainfall intensity there have been alterations to the flood hydrograph of many rivers over the last three decades. Flood frequency has increased which may have caused rates of bank erosion to increase. Britain as a whole had the wettest decade on record in the 1980's (Marsh & Monkhouse 1990). Investigations using a composite rainfall series for Great Britain by Gregory et al. (1991), showed that Scotland was 5% wetter in the 1980's than in any decade since the 1930's. The River Dee (at Woodend Recording Station) showed an upward trend in mean flow rates from 1970 to 1989 with a rise from 30 to 42 cumecs. This is an increase of 40%, with an overall increase in variability of mean flows (Smith & Bennett 1994). The flood hydrograph changes are due to rivers having these 'flashier' regimes that have higher peak discharges as a result of altered land management/use techniques in upland catchment areas. Together, changes in rainfall intensity and alterations to the flood hydrograph can be combined and suggested as an explanation of the statistically significant trend to increased flows in Scottish rivers that has been demonstrated by Smith & Bennett (1994). Increased and more variable flows in Scottish rivers would seem to point to a higher frequency of floods and high flows capable of eroding sections of river bank.

The processes and consequences of bank erosion have been well covered by the literature especially Thorne (1982) and Charlton (1982). They effectively conclude that bank erosion can be attributed to :

1 abrasion due to high velocity flow adjacent to the bank

2 abrasion due to flow over and down the face of the bank
3 abrasion due to animals and humans on the bank
4 scour at the toe of the bank followed by collapse
5 bank collapse due to increased inter-granular pressure caused by seepage of water
6 bank collapse due to loss of soil strength caused by an increase in moisture content
7 bank collapse due to loss of strength by drying followed by shrinkage and cracking

But the nature of the bank material is also relevant by its existence as a non-cohesive, cohesive or composite mass and by its size and geometry. Gravel bed streams generally have non-cohesive, coarse sediment banks, which may be overlain by cohesive, fine, overbank sediment deposits. This general configuration results in bank undercutting as the coarse bank material is fluvially entrained and the occasional collapse of the upper fine layer, injecting a pulse of fine sediment into the river for downstream transportation by suspension (Hassan 1995). There are two other methods of fine transfer into the channel from an eroding bank (Thorne 1982): weathering of fine sediment resulting in the subsequent sheetwash transport of fine particles to the base of the bank; also the fine sediment may be fluvially entrained when stream stage is high, especially if the sediment layer has been weakened by weathering.

2.4 OVERVIEW OF EXISTING RESEARCH

It is evident that two significant processes have been identified as the primary contributors to the degradation and loss of salmonid habitat in upland gravel-bed rivers.

- Bank erosion is responsible for the widening and subsequent shallowing of spawning tributaries,

- Fine sediment infiltration causes clogging of spawning substrates and juvenile habitats

The processes of bank erosion are understood and have been well documented. There is still a continuing debate about whether or not the actual rate of bank erosion has increased over the last 30 to 40 years leading to a faster rate of bank retreat. Section 2.3 dealt with some of the issues connected with bank erosion and discussed some of the reasons for the belief that the overall bank erosion rate has increased. The problems of bank erosion are being addressed in various forms and on various scales and methods of mitigating the situation are being evaluated at present.

The process and effects of fine infiltration have also been well researched. The process of river sedimentation has been identified as a serious source of stream pollution and habitat degradation, but there is a comparatively limited amount of research been conducted into the mechanisms of fine infiltration, and the sources of the fine sediment (often assumed to be local bank erosion). The effects of fine infiltration are quite varied and it is known to reduce the hydraulic conductivity of the gravel, prevent the emergence of salmon fry after incubation and reduce the population and diversity of the benthic invertebrate community. There seems to have been little work done to investigate the actual source of this fine sediment that is found in the gravel-beds. There have been varied localities suggested as likely sources of this fine sediment, but few conclusive studies have been undertaken to actually determine the source. Bank erosion is commonly assumed as the primary supplier of fine sediment to gravel-beds, but there appears to be limited quantitative data available to allow an estimation to be undertaken of its significance towards the clogging of gravel spawning beds.

2.5 - RESEARCH AIM AND OBJECTIVES

2.5.1 Overall Aim

To ascertain and evaluate the direct consequences of river bank erosion on the quantity and quality of salmon spawning and rearing habitat in an upland gravel-bed river

2.5.2 Specific Objectives

1 to monitor the rates and types of fine sediment infiltration in the Water of Mark over a 12 month period;

2 to identify the downstream and cross-stream spatial and temporal variations in rates of sediment infiltration within a reach of 800 metres in length;

3 to assess the significance of channel hydraulics, bed characteristics and any natural channel and bank processess on the rate of sediment infiltration;

4 to determine the importance of bank erosion as a primary source of fine sediment by identifying the pattern of downstream redistribution of tagged fine sediment after release from an eroding bank;

5 to record natural and engineered channel and bank modification and thier effects on channel hydraulics; and,

6 to evaluate the efficacy of river bank protection works and their effects on the sediment load of the river, and on rates of fine infiltration.

By monitoring changes in the rates of infiltration and the supply of fine sediment, observing the effects of natural and engineered changes to the river channel and banks, coupled with establishing how the sediment released from an eroding bank redistributes downstream, it should be possible to provide an estimation of how significant bank erosion is in the process of salmonid habitat loss, compared with other detrimental factors and processes.

CHAPTER 3 - METHODS

3.1 - FIELD SITE LOCATION

3.1.1. - The Water of Mark

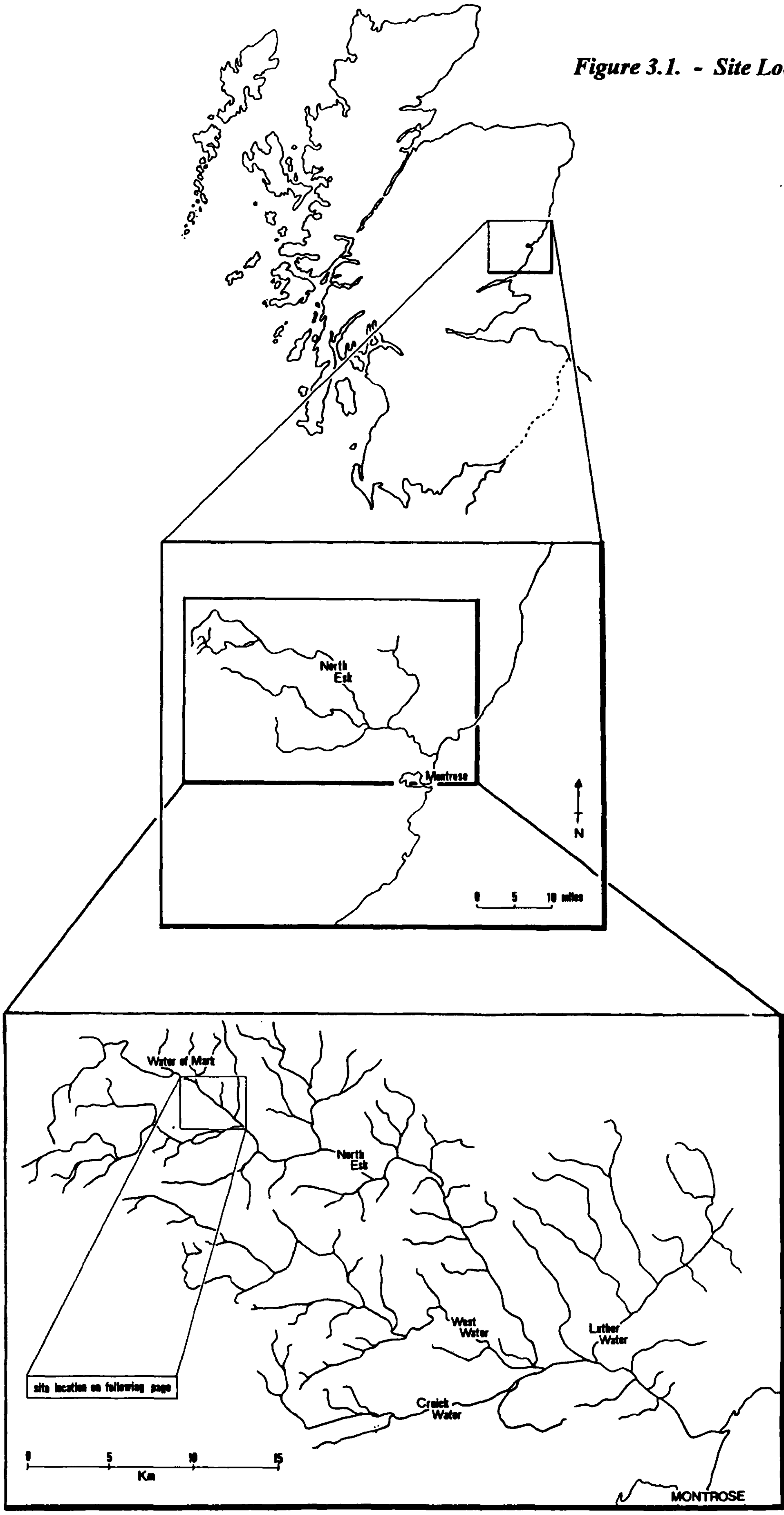
The Water of Mark is a well known spawning tributary in the upper reaches of the North Esk in north east Angus. Several reasons suggested the choice of this as a suitable location. Contacts had been established between the relevant landowners and the Fishery Board through previous work undertaken on the river. Additionally, there was to be a pilot river habitat restoration project implemented in the spring of 1995, that would give rise to the opportunity to employ a comparative study of river processes before, during and after the scheme. The Water of Mark is one of the largest of the North Esk's 75 tributaries and the large areas of good spawning gravel which the Mark and other streams provide, probably accounts for the position of the North Esk as the major east coast salmon producing river, measured on the basis of catch per kilometre (Little 1990).

The North Esk is a relatively small river system having a drainage area of about 732 km^2 (Figure 3.1). Its highest tributary rises 72 km from the sea at a height of c.740 m. Discharge ranges between 2 and 280 m^3s^{-1}, with an average daily flow of 13 m^3s^{-1} (Shearer 1992). Mean annual precipitation is of the order 1250mm. There are two recognised main tributaries to the North Esk, the Waters of Mark and Lee. The Lee flows into Loch Lee, which has been dammed to provide a water supply to Stonehaven, South Kincardine and North Tayside. The Mark and the Lee join at Invermark to form the North Esk.

3.1.2. - Geology, Geomorphology and Land Use.

The Water of Mark can be termed as a typical upland "wandering" gravel-bed river located in a 'U'-shaped, glaciated valley. Evidence from aerial photographs and historical maps (Appendix A) suggest that this is a moderately dynamic river, susceptible to channel migration across the valley

Figure 3.1. - Site Location Map



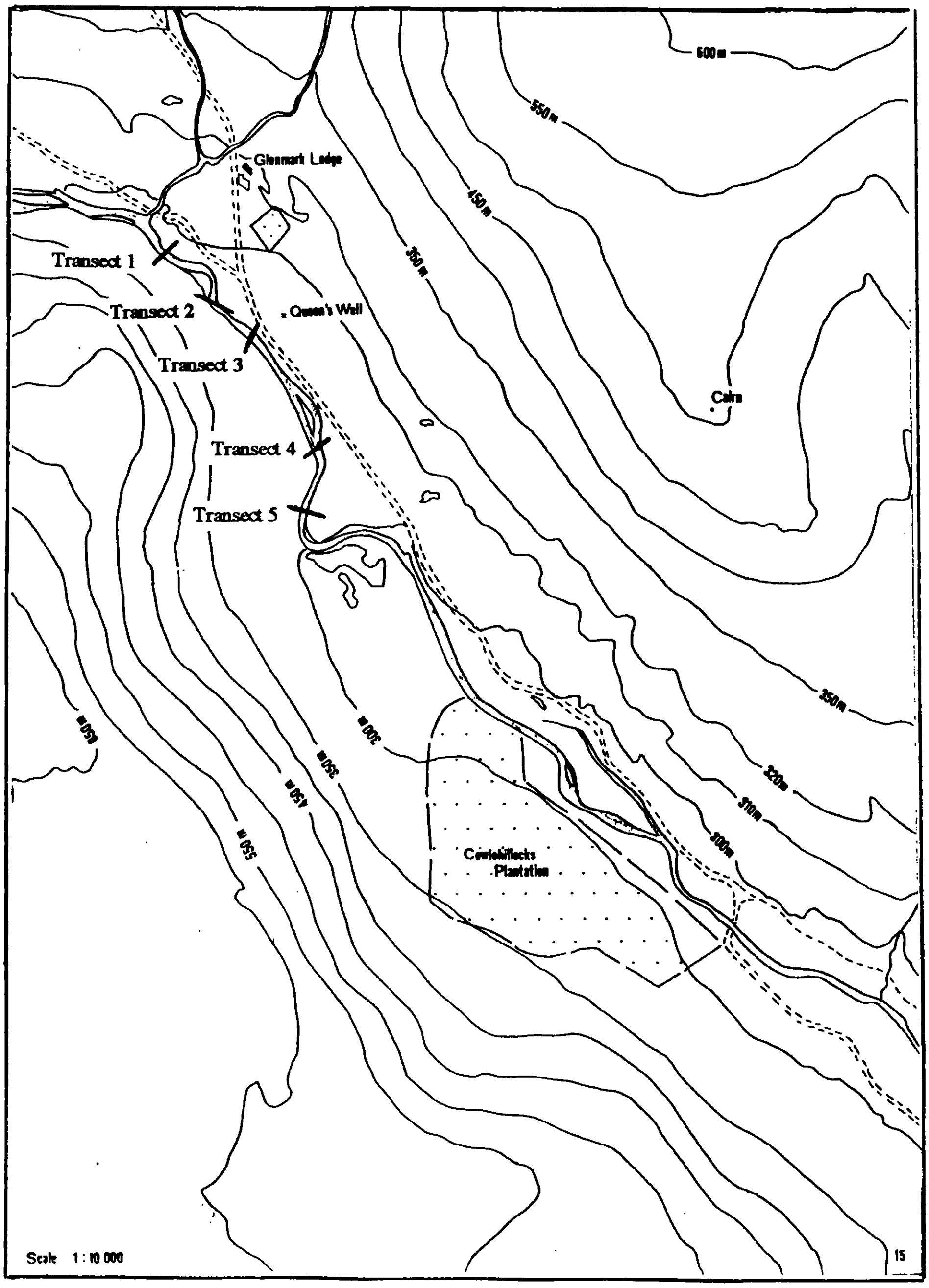
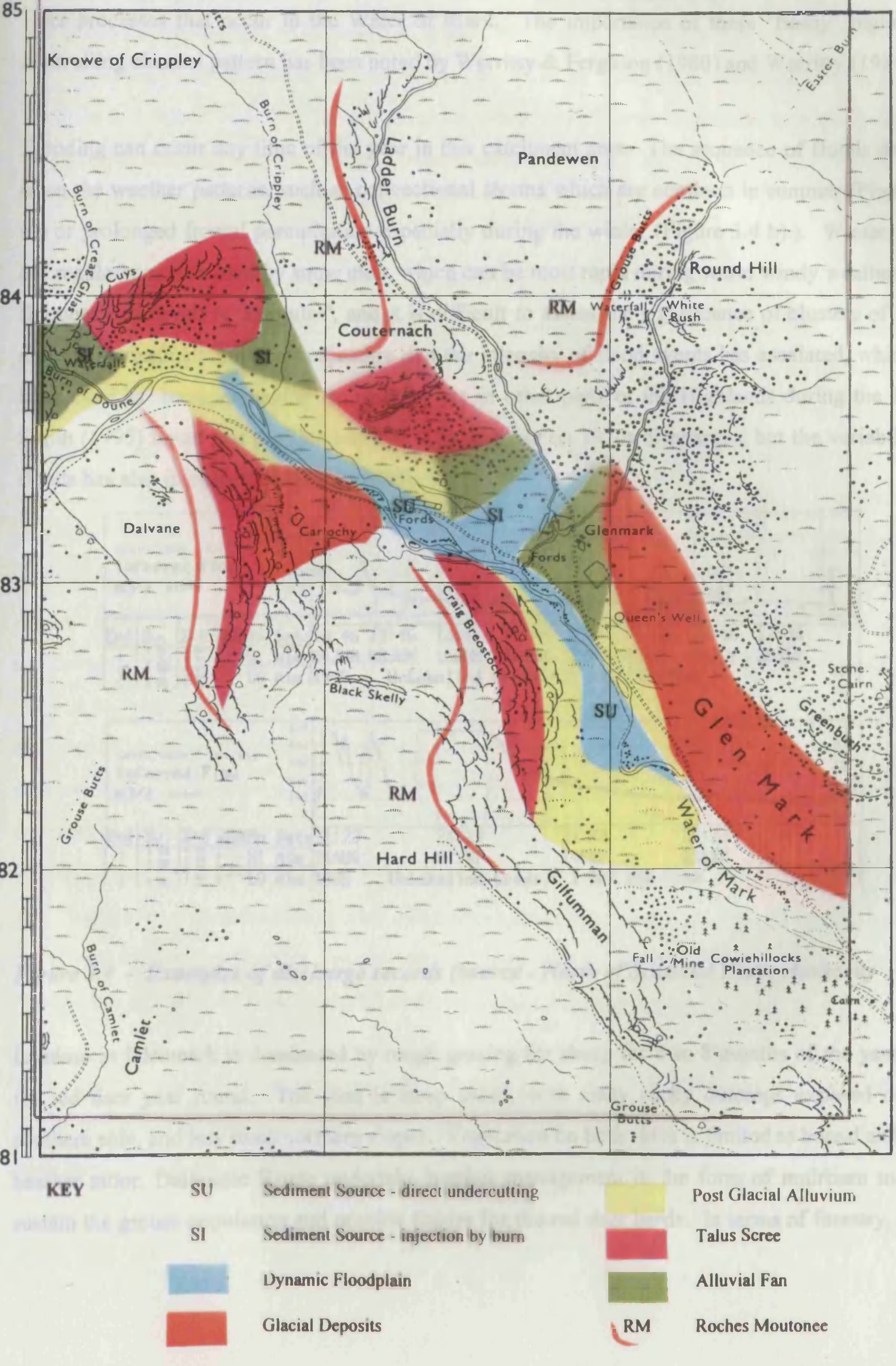


Figure 3.2 - OS map of Glenmark (1972) Angus sheet NO 48 SW

floor. The river periodically transports coarse gravel and cobble sized sediment that is stored temporarily in mid-channel and lateral bars. These gravel bar systems and associated riffles and pools change their relative position within the channel over time. This tendency of having an intermittently mobile gravel-bed (during high stage flows) explains the ephemeral nature of major channel features and is the reason that the Mark experiences channel dynamism. The head waters of this tributary flow over Quartzite and Quartz Schist lithologies, eventually flowing onto stretches of Gneiss in the glacially eroded trough of Glenmark. In this valley section, channel migration is unhindered across the valley floor. The stream bed consists of pebble and cobble sized clasts providing an intermittently mobile gravel framework. Small patches of glacial outwash gravels remain on the upper slopes of the glen (Figure 3.3 on the following page) which is one of the sources of the coarse grained bed material. Other sediment sources that the river readily exploits are along undercut banks and the steep tributary burns that have sediment built up as alluvial fans which can be fed into the main river. Most of the fine sediment load of the river is thought to be derived from eroding banks or is reworked material from in-river sediment 'sinks' due to the lack of visible sources outwith the channel.. An estimate of average sediment yield for upland peat/moor terrain such as Glenmark, was suggested by McManus (1993) to be about 120-213 $t/km^2/yr$. This is relatively insignificant in terms of global fluvial sediment yield, but is relatively high for UK catchments.

The channel itself has a dynamic "wandering" planform. It is generally wide and shallow, with alternating deeper sections where scour dominates and shallow reaches where gravel accumulates. Historical sources over the past 130 years have documented distinct areas of channel migration and lateral and mid-channel bar development (Appendix A). Paleochannels and river terrace remnants also indicate past channel dynamism. The present channel formation signifies a moderately high energy environment that allows intermittent bed mobility. The steep catchment and abundant stores of sediment found in deposits such as river terraces and alluvial fans are vital in influencing the type of river system in the glen. During flood conditions the flow is capable of eroding and transporting its coarse bed sediment, which has an average D_{50} of 64mm. Under normal flow conditions it is only the very fine grained silts and sands, winnowed out from between the coarser

Figure 3.3. - Water of Mark : Geomorphological Map, showing principle sediment stores and sources. (Source - Own mapping 1995.)



channel deposits, that are transported regularly by the river. However, the frequency and magnitude of flood events is the most important environmental control over the nature and rate of river processes that occur in the Water of Mark. The importance of these 'flashy' regimes on controlling channel pattern has been noted by Werritty & Ferguson (1980) and Werritty (1984).

Flooding can occur any time of the year in this catchment area. The sequence of floods depends upon the weather patterns, such as convectional storms which are common in summer (Figure 3.4 a)) or prolonged frontal precipitation especially during the winter (Figure 3.4 b).). Winter floods are regularly exacerbated by snow melt, which can be most rapid during warm windy weather. The frequency of floods is 'irregular', and it is difficult to assess the significance of clusters of floods and the increasingly popular conjecture that the intensity of flood events has escalated, which has been cited as being damaging to many rivers in other parts of the Highlands during the 1990s. Smith (1995) noted that the Dee has had 40% increase on 1970s discharges, but the variability of floods has also increased during the 1980s.

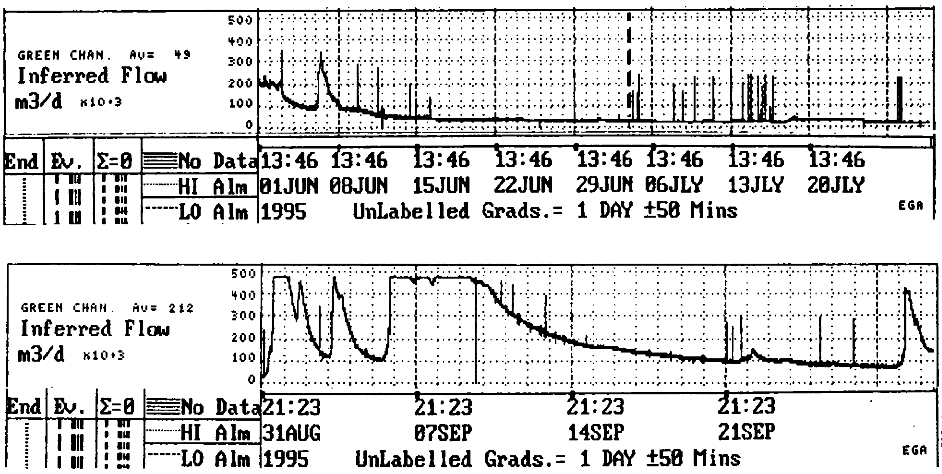


Figure 3.4 - Examples of discharge records (source - North of Scotland Water Authority

Landuse in Glenmark is dominated by rough grazing for sheep for 6 to 8 months of the year, and for red deer year round. The glen is steep sided, with many rocky outcrops exposed on the southern side, and less steep northern slopes. Vegetation on both sides is limited to boreal and bog heather moor. Dalhousie Estate undertake heather management in the form of muirburn to help sustain the grouse population and provide fodder for the red deer herds. In terms of forestry, there is well established conifer plantation of about 4 hectares with an adjacent 5 year old plantation of 2 hectares, and a plantation of similar size half a kilometre upstream. The floor of the glen has a track in it running parallel with the river for estate vehicles to gain access to grouse moors and deer stalking areas beyond. The nature of landuse and management undertaken by the estate (the lack of intensive afforestation for example), has aided in maintaining Glenmark in a stable condition in terms of vegetation cover and subsequently the resistance of the land to erosion. Thus, the potential sediment supplies external to the channel are limited and the most likely sources are the channel boundaries and in-river 'sinks'

3.1.4. - The Water of Mark Habitat Improvement Scheme

The Water of Mark has been identified as a major spawning tributary of the North Esk. from data stretching back to the 1960's, indicating that it contributes the bulk of the smolts which return to the North Esk as spring running adult salmon (Shearer 1993). Over the last 30 years, both the quantity and quality of the spawning and nursery habitat in the Water of Mark are believed to have significantly declined. Shearer (1993) noted that there are less adult holding pools in the tributary and the major holding pool at the Queen's Well (OS 420828) has been filled in with gravel and is no longer part of the water course. At this active meander bend there is an area of significant bank erosion, thought to be the primary source of fine sediment that infills the gravel interstices in spawning beds downstream. The other problem is that where the banks have disintegrated, the water is no longer confined to a narrow channel, and the pool/riffle sequence has been replaced by stretches of unstable gravel and a wandering water course (Shearer 1993). These areas have very shallow depths in low flow as there is insufficient flow to cover the increased bed width. A pilot restoration project aimed at rectifying these problems was to be implemented by a tripartite group including Scottish Natural Heritage (SNH), Esk District Fishery Board and Dalhousie Estate. This was planned for implementation in May 1995 and is described in section 3.1.4. This gave rise to the opportunity to combine this research with an investigation into the effects on river processes, both during and after engineering works on this stretch of the river.

A programme aimed at improving the quality and quantity of salmonid habitat in a reach of the Water of Mark was commenced in the early part of summer 1995. The project aims comprised of three elements and were stated in the proposal (Shearer 1993) as being:

1 A fenced 'buffer'zone stretching 2km to exclude sheep and deer. This was to protect the vegetation from the grazing stock and allow natural regeneration of bankside and marginal plants. Also judicious planting of trees and shrubs in strategic clumps was proposed throughout the fenced corridor.

2 Bank recovery to be aided by modest engineering of eroded banks. To be done by reducing bank gradient and installation of local rock as revetment to reduce the worst erosion.

3 To harness the water to create preferred habitat by strategically placed croys/deflectors to grade the gravel and to recreate the riffle/pool sequence. In addition, the braided stretches were to be restored to a single channel of sufficient width to contain the predicted flows.

The first two stages were implemented as described, whilst the third element of the programme regarding instream works were advised against by Scottish Natural Heritage. They suggested delaying any instream engineering until the effects of the first two stages of the project have been assessed and until more is known about the physical impacts of such instream works. The programme is on-going and the success of the initial work is being monitored and evaluated at present. Section 3.4 investigates the effects of the bank engineering on the channel hydraulics and the patterns of sedimentation.

3.2 - SITE MORPHOLOGY

3.2.1.- Spawning site identification

The main objective of this research is to assess the extent of fine sediment infiltration in areas of salmon spawning gravel and to determine the significance of bank erosion as a contributor to this process. Potential salmon spawning sites were identified within a reach of the Water of Mark that is thought to be affected by the large section of eroding bank (Figure 3.2). Five sites (Plates 3.1 - 3.5), were located over an 800 metre reach that exhibited the velocity, water depths and substrate size characteristics of spawning beds as identified in section 2.1.4. The uppermost site was located about 60 metres upstream of the eroding bank and was chosen as a control location. The site furthest downstream was about 700 metres from the erosion area (Figure 3.2).

Plates 3.1 - 3.5 - Transects 1 to 5 identified as potential spawning sites

3.2.2. - Channel and bed stability

Distinct areas of channel migration and lateral and mid-bar channel development in this reach over the last 130 years have been documented in various historical sources. On a shorter timescale, the river is moderately dynamic and is subjected to intermittent bed movement and bank erosion, resulting in channel modification. A series of 10 channel cross-sections were surveyed by SNH over a reach of 1.5km of the Water of Mark in May 1994 and are due to be re-surveyed in the summer of 1996. This is an attempt to monitor the rate of channel migration in order to give an estimation of the degree of dynamism of the Water of Mark to aid in the long term projection of channel change. In an attempt to investigate smaller scale channel change in this study, a series of 15 detailed cross-sections were surveyed over a smaller reach of about 150m which encompassed the severly eroding section at the Queen's Well (Figure 3.5).

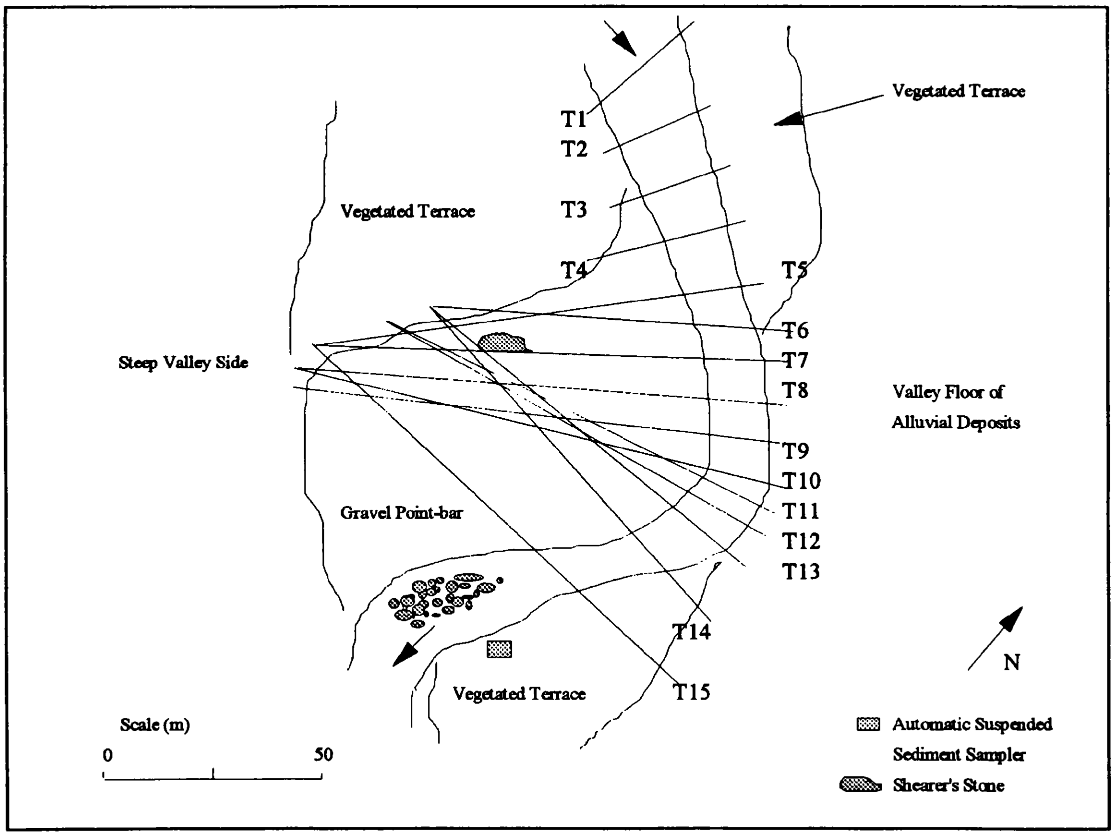


Figure 3.5 - Study Reach Map showing the cross-sectional survey locations T1 to T15

Aggradation and degradation processes were monitored by repeating surveys of the 15 uniformly spaced cross-sections spanning the meander bend. The surveying was continued beyond the edges of the active channel to permanent marker pegs on stable ground beyond the bankfull level. The transects were re-surveyed at six month intervals to monitor the rate of channel and bank alterations. The second survey was undertaken after six months of natural conditions, but the third survey was after extensive engineering had been implemented in the reach. This allowed the channel and bank modifications by engineered methods to be monitored and compared with the previous natural channel characteristics.

3.2.3 - Bank retreat rate measurement

The outer bank of the study reach at the Queens Well is affected by severe erosion caused by undercutting and subsequent bank collapse due to its composite nature (Plate 3.6 and Figure 3.6). The natural rate of erosion was monitored in a previous study by using pegs on the bank surface. This did not account for undercutting of the bank, so bank erosion pins were used in this study. These were steel rods, 5mm in diameter and 600mm in length, which were inserted horizontally into the streambank on the outer edge of the bend, leaving only a fraction of the rod exposed.

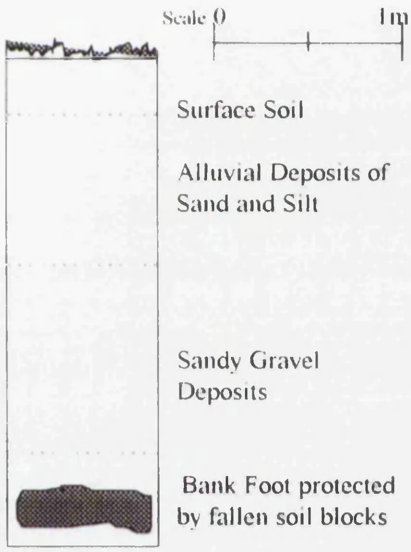


Figure 3.6 - Sedimentological log of the eroding bank

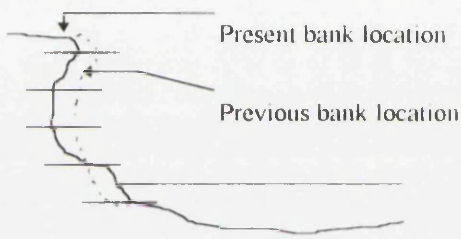


Figure 3.7 - Erosion Pins

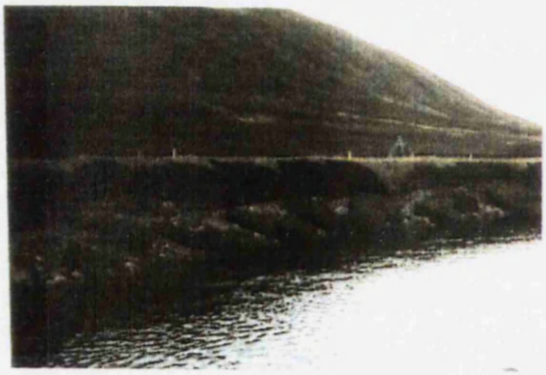


Plate 3.6 - Eroded bank at Queens Well

The pins were aligned in a vertical profile (Figure 3.7), with a spacing of 10 metres between each vertical array. Bank retreat was measured from the progressive amounts of pin exposure. These rates of retreat can be compared with changes in the bank data extrapolated from the cross-sectional surveys. Only six months data was accumulated due to installation of 'hard' bank engineering that prevented bank erosion from progressing any further.

3.3 - MEASUREMENT OF FINE SEDIMENT INFILTRATION

3.3.1. - Sediment trap construction and installation

At each of the five potential spawning sites, sediment traps were installed across the cross-sectional profile of the spawning bed, similar to the method of Frostick et al. (1984). Each transect had five traps across it, except the fifth site which had two traps, due to a constriction in the channel at this location. The location of each of these traps can be seen on cross-sectional plots in Section 4.2 Figure 4.11. The channel widths varied at each transect with T1,2,3,4 and 5 being 22,17,46,32 and 9 metres wide respectively. The five traps on each transect were evenly spaced across the profile.

Sediment trap designs used in a previous study on the Water of Mark were modified to assist in relocation and the regular removal of trapped sediment in a quick and simple manner. The traps consisted of cylindrical fired clay rebated flue liners (300mm height x 185mm diameter) which acted as a protective outer casing. Within the flue liner, a plastic flower pot (180mm diameter) was inserted which sat flush with the rim of the flue liner (Plate 3.7). The inner base of the flower pot which had drainage holes, was covered with Nybolt™ PA-5-250/XX mesh which is only water permeable to ensure that no fine sediment escaped. The traps were then dug/inserted into the gravel beds at each site to a depth that left the top of the flue liner level with the bed surface (Plate 3.8 and Figure 3.8).

Plate 3.7 and 3.8 - Sediment trap and trap installed in river bed

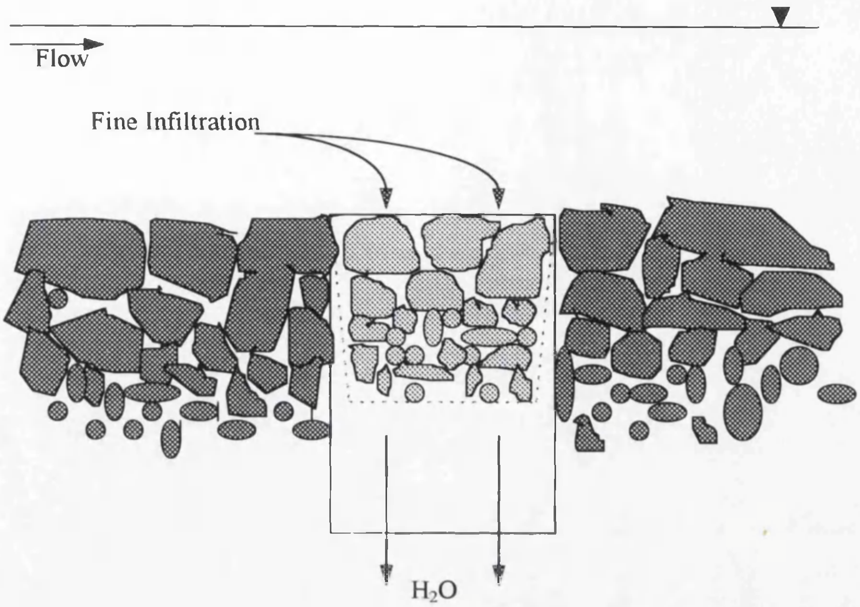


Figure 3.8 - Schematic Diagram of Sediment Trap Installed in the River bed.

The traps were linked via a chain which was secured by steel pins to the bank. This enabled the traps to remain firmly in situ throughout the study period, and facilitated relocation after high flows. The inner trap was filled with bed/framework material of a size greater than 4 mm to act as natural bed substrate. A minimum grain size of 4mm was chosen because it has been suggested that it is sediment under 4mm that infiltrates spawning beds (Milhous 1982; Chapman 1988).

3.3.2. - Long profile and discharge variability

The 5 trap transects were located over a reach of about 800m, which allowed the distribution of infiltration rates along the long profile to be assessed. The reach has a channel slope of 6.89m/km or 0.7% (Welsh, M. 1994 SNH pers. comm). The reach has a median surface grain size of 48mm and a mean discharge of $3.77m^3s^{-1}$. Each trap was emptied every two months over the 12 month study period, and then re-filled with gravel substrate of >4mm. The material removed from the trap was separated, with material >4mm being discarded and material <4mm retained for analysis. The retained material was weighed and recorded as a measure of the mass of infiltrated sediment in each trap for the two month period.

The infiltration rates also display temporal variation. By monitoring the amounts of sediment entrapped at each location at regular intervals over the twelve month period, the variations can be plotted over a time sequence. These variations in infiltration rates can be combined with discharge data for the Water of Mark, and any relationships that occur between high and low flow periods and infiltration rates can be identified. Discharge data was obtained from Tayside Regional Council Water Services Department (TRCWSD now North of Scotland Water Authority) via their water treatment plant near Invermark. A monthly Teletrend output was obtained for the study period from January 1995 to January 1996, indicating the flow for the Water of Mark on a daily basis, with the monthly average and monthly maximum and minimum flow recordings.

3.3.3. - Cross-sectional variability

The spatial pattern of infiltration is expected to vary, not only in a downstream direction, but across the channel cross-section. The five trap sites were chosen primarily because they exhibited the habitat characteristics (combination of substrate type, velocity and water depth) that is preferred for salmon spawning. They provided different characteristics which produced slightly contrasting profiles, but were all still suitable for spawning. This diversity of cross-sectional profile allowed the variability in fine sediment infiltration to be determined in a spatial context.

Each sediment trap transect was surveyed at the start of the study. Velocity readings were also taken in normal discharge (av.3.77m^3/s), as close to the surface of each trap as possible, to highlight the velocity variations across a cross-section which is a controlling factor on the rate of infiltration. A sample of 100 river bed clasts were randomly chosen across each of the five trap transects. The b-axis of each framework clast was measured and recorded using a template. This allows an estimate of average substrate size at each transect to be attained. This is an important characteristic to record as differences in framework grain size, and therefore pore size, exercise a strong controlling factor on the infiltration process and rate (Frostick et al. 1984).

3.3.4. - Measurement of void space infiltration

Percentages of intragravel pore space that were infilled by the fine matrix material were estimated using a method similar to Frostick et al. (1984). This will determine whether or not the fines occupy a significant proportion of the intragravel pore space. Wolman counts were taken across the 5 transects giving the median particle diameters of the gravel substrate. The percentage void space could then be calculated for each transect using Komura's (1961) least-squares relationship. By measuring the volume of the trap it is then possible to calculate the volume of void space once the trap is filled with gravel substrate. The void volume can then be correlated with the volume of fines infilled and a percentage of void infilling can be obtained.

The traps located across each transect permitted vertical ingress of material and a vertical throughflow of water via the Nybolt™ mesh fixed in the trap base. What the traps did not allow was any horizontal movement of fine particles subsequent to penetration of the stream bed in response to weak currents in the interstices. This is an experimental difficulty that has to be borne in mind when interpreting the results.

3.3.5 - Sediment trap infiltration and quantification

As mentioned in section 3.3.2., each trap was emptied after periods of 2 months. The retained fraction <4mm was then sieved using a sieve range from 2.8mm to 0.063mm. This provided an accurate picture of the distribution of grain sizes over each sample, and an indication of the similarity of samples. Particle size analysis permitted comparisons to be made between the trap samples and 0.5kg samples obtained from the face of the eroded section of bank. This and other methods of analysis will allow the potential of the bank as a likely sediment source to be assessed.

3.4 - CHANNEL HYDRAULICS AND SEDIMENTS

Any channel modification may alter channel hydraulics, channel competence and bed characteristics, which will affect the sedimentation process in the reach. By recording the hydraulic conditions (such as velocity flow patterns and shear stress) in the reach over the 12 month period, the effects both of natural and artificial channel alteration on channel hydraulics can be recorded, and their influence on sedimentation processes can be evaluated.

3.4.1. - Velocity measurement

Eleven of the survey cross-sections were selected as sites for velocity measurement at approximately 10 metre intervals around the bend of the study reach. The channel cross-sections were divided into one metre intervals with velocity readings taken at each interval using a velocity meter. At each vertical interval the horizontal distance, the water depth and meter readings were noted. For each interval, readings were recorded at 0.05m from the bed and 0.05m from the surface, with the number of intervening readings being proportional to the depth of flow. The meter readings were then plotted as vertical velocity profiles for each interval (Figure 3.9).

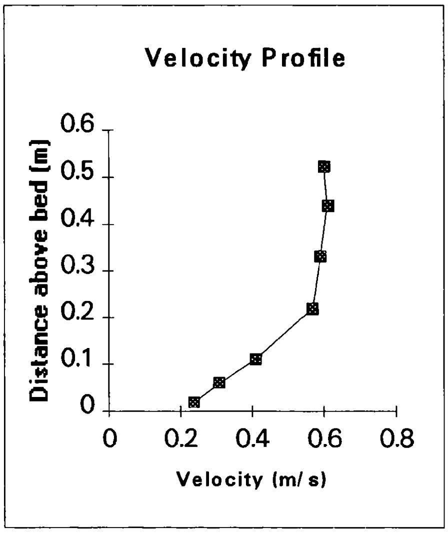


Figure 3.9 - Example of a typical velocity profile

Channel slope, bed roughness and intensity of turbulence are all known to influence velocity profiles and thus there are velocity variations across each section of the study reach. From each of the velocity profiles, the mean vertical velocities can be calculated, and both surface and bed velocity plots can be constructed for the 10 velocity cross-sections. Water velocity in fully turbulent flow increases semi-logarithmically, with the mean velocity occurring at 0.36 of the depth from the streambed (Gordon et al. 1993). The more rapid the increase in velocity away from the bed (in the lowest 25% of the flow), implies greater shear stresses than do slower increases. The nature of the velocity profile is thus an important determinant of flow intensity strength. In this study, the surface and bed velocity plots were arranged in sequence through the reach, which gives an indication of flow conditions or how flow negotiates the study reach. By recording velocity data before and after bank engineering, the effects of the works on the hydraulic characteristics of the reach can be identified and evaluated by comparing the velocity plots.

3.4.2. - Discharge calculation

Discharge was calculated for the study reach for the days when velocity readings were taken using the continuity equation :

$$Q = w.h.v$$

Q = discharge (m^3/s)

w = width (m)

h = average depth (m)

v = average velocity (m^3/s)

The average velocities were measured, the average depth is calculated from measurements taken at the time of the velocity readings, and the width of the channel is directly measured by surveying . Because of the variation in velocity within a stream, the accuracy of discharge measurement depends largely on the number of points at which velocity and depth readings are taken. Turbulence will also create "noise" in the readings, although it is assumed that the error is random and will not cause bias with the amount of measurements taken. Most gauging is cited as accurate to plus or minus 5 - 10 %.

3.4.3. - Shear stress calculations

As water flows by a solid surface it can generate lift and drag forces that move sediment particles. The distribution of these is influential in sediment transport and the sedimentation process within a stream reach. The frictional force causing flow resistance along the channel boundary can be expressed per unit area as shear stress. Shear stress can be determined as the measure of shearing (lift and drag) forces exerted on individual particles on the stream bed (Gordon et al. 1993). Shear stress can be calculated directly from velocity profiles by using von Karman-Prandtl's 'law of the wall'.

For fully turbulent flow, the von Karman-Prandtl 'law of the wall' states that:

$$\tau = \rho \left(\frac{\kappa . u}{\rho n [z / z_o]} \right)^2$$

where τ = Bed shear stress (Nm^{-2})

κ = Von Karman's Constant ($\cong 0.4$)

u = Velocity at height z (ms^{-1})

ρ = Density of Water ($1000 kg/m^3$)

z = height above the bed

z_0 = roughness height ($0.1D_{84} = 0.0096$m)

The roughness height was calculated using 0.1 $D_{84,}$ which is suggested by Bray (1980) and Ferguson et al. (1989) to be a value that gives an accurate representation of the actual roughness height in gravel-bed rivers. Bed characteristics affect the velocity profiles and shear stresses that are calculated and the importance of these can be determined in terms of streambed roughness. A random surface sample of the bed was collected as previously described. The D_{84} of these samples was calculated and used in the relative roughness calculation to determine whether the bed can be described as hydraulically smooth or rough and an overall degree of roughness can be established.

Relative roughness is defined as:

$$\frac{h}{D_{84}} \quad \text{where} \quad D = \text{particle size (cm)}, \quad h = \text{depth of water (cm)}$$

Shear stress typically increases with discharge, but as with velocity, it is unevenly distributed within a channel. By calculating the shear stress before and after engineering works and plotting them against each other the modifications to shear stress levels around the study reach and how it is likely to effect the sedimentation process can be assessed.

3.5 - FINE SEDIMENT TRACING

3.5.1 - Sediment tracing

As mentioned in section 3.1.4 it has been suggested that the principal source of fine sediment in the gravel beds on the main spawning stretch of the Water of Mark, is the eroding bank (OS 418829) near the Queen's Well. In order to validate this assumption, tracer particles were introduced at the eroding bank, and their dispersion downstream once entrained from that location was monitored. Sediment traps were already installed in potential gravel spawning sites throughout the 800 metre study reach. The proportion of tracer sediment entrapped in each sediment trap was recorded. The resultant calculation of tracer particle concentration can be used to estimate the contribution to sediment contained in the gravel bed framework from the eroding bank. This assists in determining the significance of this bank as a source of the fine material that is detrimental to salmon spawning habitat in this reach.

3.5.2. - Tracer sediment production

Eighty kilograms of bank material under 4mm in size was excavated and taken to the laboratory. A magnetic tracing technique based on the enhancement of the background magnetic susceptibility of the natural bank sediment was considered (Oldfield et al. 1981; Arkell et al. 1983; Stott 1986; Leeks et al. 1988; Parsons et al. 1993 and Caitcheon 1993). By heating natural sediment at 900 °C, paramagnetic or imperfect antiferromagnetic iron minerals in the sediment are often converted into ferromagnetic oxides such as magnetite or maghemite (Oldfield et al. 1981). This process of superparamagnetic enhancement gives the material a differing background magnetic susceptibility than the natural material and allows it to be traced using a magnetic susceptibility meter. Problems were encountered in that unless exotic enhanced material is introduced and used for tracing, the method is limited to areas of relatively uniform, iron-rich (but non-ferromagnetic) material. After carrying out a background X-ray defraction (XRD) analysis on a sample of bank material it was found that it was Quartz/Mica rich, but iron-poor.

It was decided to use a fluorescent tracer instead. The techniques for labelling particles with a fluorescent dye are well established and are documented by Teleki (1966), Yasso (1966) and Kirk et al (1974). The fine bank sediment under 4mm in size is added to a paste of fluorescent pigment (colouring agent), acrylic lacquer (colour fixer and binding media) and toluene (thinner). These are mixed in proportions of approximately 1:8:13 parts by weight respectively, to 120 parts of sediment. The resulting compound is then spread out to dry. Kirk et al. (1974) developed a fluorescent dyeing machine that kept the drying sediment constantly in motion to prevent aggregation. In this instance it was deemed suitable to use a manual cement mixing vessel to mix the sediment and dry it to an extent to prevent aggregation. Once suitably mixed the sediment was left to finish drying naturally. The resultant material, when dry, was then crushed and sieved to reproduce the natural bank material grain size (Figure 3.10 (a) and (b)).

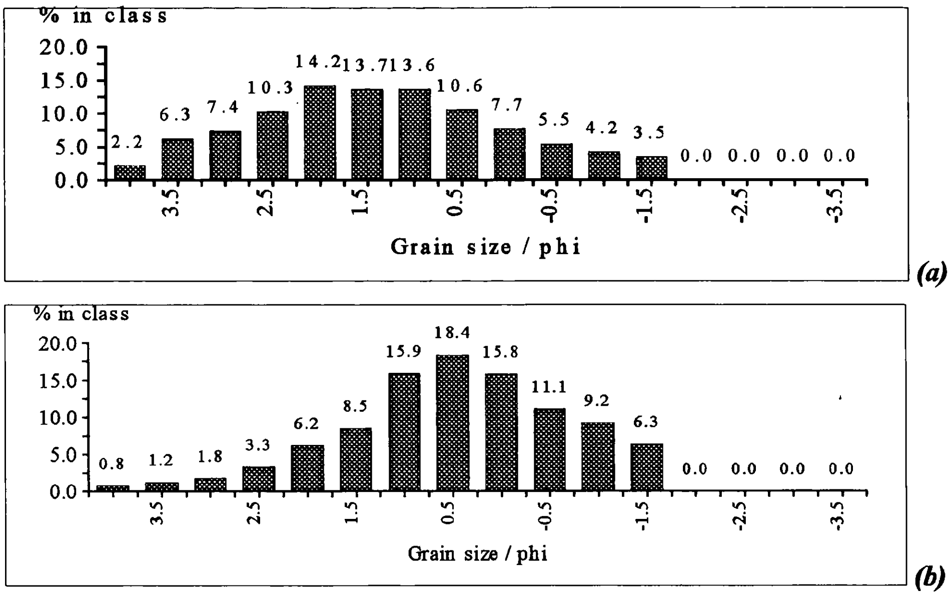


Figure 3.11 - Grain size curves for bank material (a) and tracer material (b).

3.5.3 Incorporation of magnetite as a secondary trace element

In the event that either the dye was worn off the particles by abrasion or there were no particles located in the traps, there would be no means to specify whether the material had been entrained from the bank, or whether it had by-passed the traps. For this reason a magnetic tracer was amalgamated with the fluorescently dyed material, to allow magnetic tracing to be carried out as a back up procedure. A sample of 10kg of crushed magnetite (Fe_3O_4) was incorporated into the fluorescent bank sample as a secondary trace element. By carrying out magnetic separation analysis of the trap samples it should be apparent if any of the tracer material at all has entered the trap or if it has been by-passed.

The use of magnetite, however, introduces the problem of using a material of a higher density (4.758 g/cm^3) than the natural bank material (2.338 g/cm^3). This difference in density might be expected to be reflected in differences in entrainment from the bank and subsequent transport through the study reach. The main advantage of this method is that the presence of any magnetite in the trap samples will indicate the efficiency of the traps and give an indication of when the tracer material has been transported.

3.5.4. - Tracer injection and subsequent analysis

The fluorescent and magnetite enhanced tracer material was replaced on the eroding outer bank on 25/10/95. It was placed at a level that meant that it would only be entrained during a significant discharge that would be capable of eroding the unstable bank. The sediment traps were emptied after the first flood flow of sufficient size to transport the tracer sediment, which was after 15 days. Each trap sample was disaggregated into each constituent particle size range. The resultant sub-samples of each particle size range, at 0.5⌀ intervals, were individually examined by a quantitative Image Analysis Software Package to determine a percentage of tracer material within the total trap sample for each particle size range. A public domain Image Processing and Analysis programme for the Macintosh called NIH Image was chosen. This freeware package was developed by the United States Institute of Health and available from the Internet by anonymous FTP (Appendix B for web site). The package was used on a PC by reading the software through EXECUTOR, a Mac Emulator package for PC's.

To obtain an image of the sediment for processing and analysis, an Ultra-Violet light source was required to highlight the fluorescently dyed particles within each sample. A dark viewing cabinet with Ultra-Violet light sources was constructed with access for a high quality ccd video camera lens to take an image of the samples (Plate 3.9). Four slides were prepared for each sediment sample. Adhesive slides were assembled to ensure that each slide had a uniform layer of one particle thick covering of sediment. This allowed four images to be processed and averaged to provide an indication of the percentage of fluorescing to non-fluorescing particles. Each live image from the ccd camera was relayed to the computer via a video card and captured using a frame grabbing or capture facility. The still image (Plate 3.10), was imported via EXECUTOR to NIH Image for colour manipulation to enhance the fluorescing particles (Plate 3.11), and then quantification by using colour spectrum threshold analysis. The colour thresholds of fluorescing and non-fluorescing particles were established and the number of pixels in each image within these thresholds was calculated. Once this data was obtained, simple calculations produced percentages of fluorescing to non-fluorescing particles in each sample. This image processing and analysis stage allows an estimate to be made of fluorescing particles present in a sample. By calculating a percentage of the sample that is tracer sediment, it can be established how much inter-gravel fine sediment is bank derived and how much is provided by other sources. By splitting the samples into individual particle sizes, it is possible to determine where different size ranges are deposited across a cross-section and also which are transported the furthest in a downstream direction..

Plate 3.9 - Image analysis operation

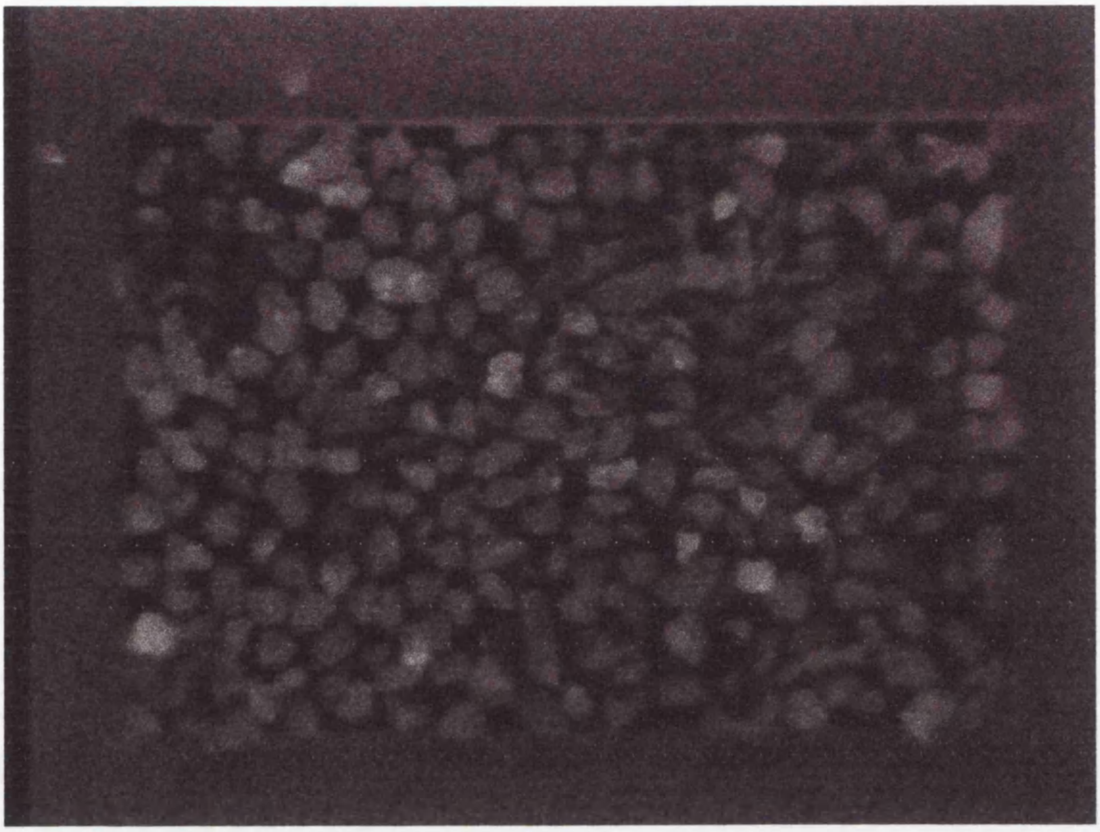


Plate 3.10 - Video image of sample

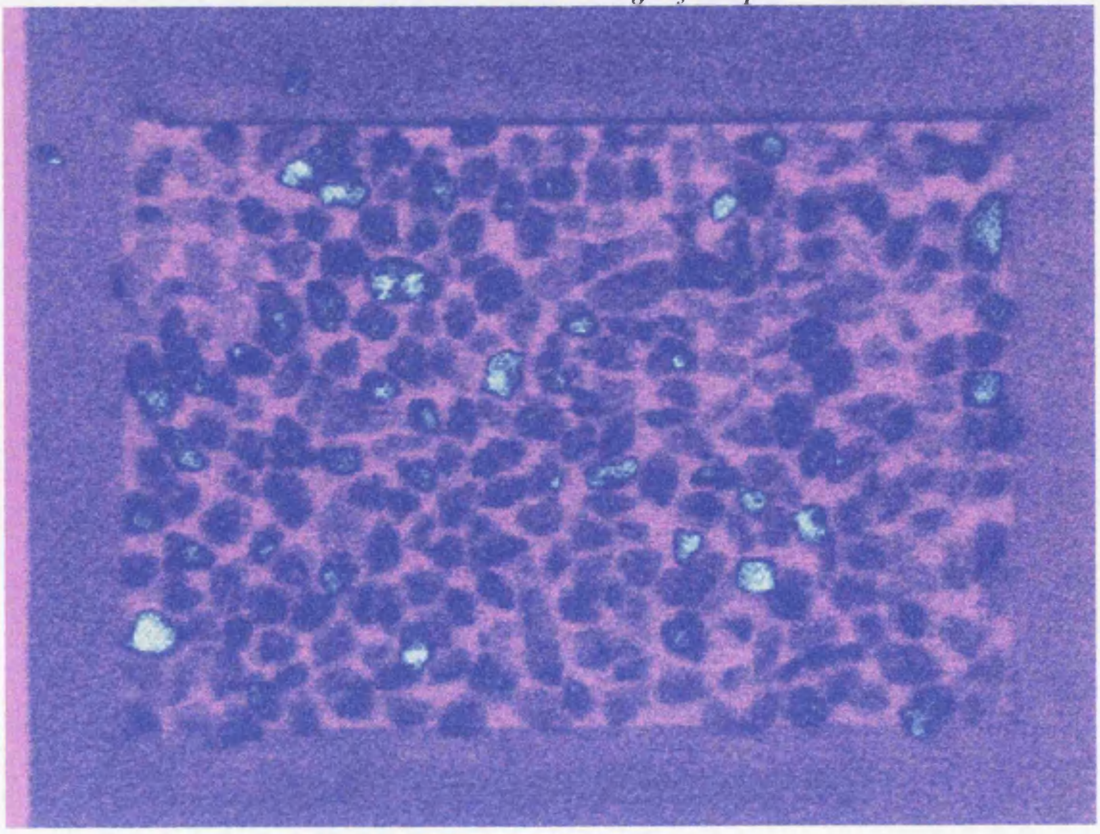


Plate 3.11 - Image after colour manipulation

It was also hoped to monitor the suspended sediment load of the river to establish if it was altered by the engineering works. This was to be done by installing an automatic suspended sediment sampler at a point 50 metres downstream of the eroding bank and taking water samples at hourly intervals throughout flood events. The sampling head was attempted to be fixed 5cm above the bed in the hope of obtaining a record of suspended sediment likely to be presented to the bed at the matrix traps. By comparing the data recorded before engineering, with suspended sediment concentration data taken after the completion of bank restoration work, the effects of bank revetment on suspended load should be highlighted. Problems occurred in locating the sampler intake probe in a fixed position just above the streambed, where the suspended sediment concentration should peak. Different methods of locating the probe were attempted, but difficulties prevailed throughout, and therefore the samples that were obtained, when analysed in the laboratory, were deemed unrepresentative of the suspended sediment load of the river.

CHAPTER 4 - RESULTS AND ANALYSIS

4.1. - SITE MORPHOLOGY

4.1.1. - Channel Stability

The eroding bend at Queen's Well has experienced significant changes in channel morphology which have been documented over the last 130 years. Intermittent channel changes have been followed during the past 30 years by accelerated channel migration as the outer bank of alluvial material is progressively eroded. It is estimated (Dunkley 1993) that the channel migrated by about 15m in the period 1978 to 1993, an average of 1m per year. This is expected to continue as the unconsolidated bank material is continually being eroded under present conditions.

The rate of natural bed and bank modification at the eroding bend was monitored over the first six months of the study period by 15 cross-sectional surveys (Appendix F). The rate of change was found to be relatively low during a period containing 26 flood discharges. In general, cross-sectional changes consisted of small scale alterations to the channel geometry, such as to the left outer bank profile by localised slumps and minor amounts of point bar aggradation. Profiles at transects T1 to T4 cover the straight section of the reach, located at the tail-end of a riffle. This section stretches to about 40 metres upstream of the main section of eroding bank (Figure 3.6). The channel at T1 is 16 metres wide and narrows to 12 metres at T4. Only minor fluctuations at T1 to T4 were recorded during the first six months, and these are within the range of uncertainty in the surveys. T5 is situated immediately upstream of the eroding section, as the flow enters the bend where the channel is reduced to 11 metres wide. There was between 0.15 and 0.2m bed scour at the base of the outer bank, towards which the flow is directed.

T6-T10 all show very little change. The only noticeable change is at T6 where the channel is only 8.7 metres across and the shallower inner channel on the right and the bar face aggraded by about 0.1m. Outwith the channel, the left bank of these profiles are between 1 and 2 metres in height and composite in nature. This coupled with the main flow being concentrated on the outside of the bend has precipitated varying amounts of bank slumping. At T6 there was toe scour, whilst T7 to T10 all exhibit a build up of material at the base of the bank in the channel margin and a retreat of the upper section and bank face, which would seem to indicate slumps at these transects. Bank retreat rates are considered in section 4.1.2.

The final five transects (T11 to T15) cover the channel as it exits the bend and extend onto the head of the downstream riffle. Again minimal amounts of channel activity were recorded across these profiles, except for the lowering of part of the right section of the channel which is associated with the riffle head that is located just downstream of this final transect. Overall, the channel bed and banks remained stable during these 6 months. The only significant modifications were on the eroding section of the outer bank around the bend. Most of the fine sediment that was released as this erosion occurred was removed from this location, but some material accumulated at the toe of the bank. Field observations show that these accumulations are consolidated blocks of slumped bank material.

During the second period of monitoring (13/5/95 to 15/11/95), the remedial bank protection work was implemented throughout this reach and this is detailed by the surveys. Considerable alteration to both banks and bed are recorded, with the size and shape of the channel being modified in a way which has considerable effects on the flow patterns through the reach. These are described individually in later sections.

The engineering consisted only of bank work, with no bed modification being permitted until the effects of the first phase had been evaluated. Therefore, any change in channel shape is probably as a result of machinery working within the channel and the moving of large boulders (weighing up to 3 tonnes) into position as bank protection (Plate 4.1), not as a concerted effort to remodel the channel profile. It could also be as a result of channel narrowing, either by natural processes which may have occurred without the bank protection or as bed modification as a consequence of the bank work which has increased velocities and depths, leading to increased bed shear stress and promoting bed scour since the bank has been modified. This is investigated in section 4.3.

Plate 4.1 - Bank work at Queens Well

The first transect underwent little alteration during this second six month period, apart from an increase in the slope of the channel margin at the right bank. The channel at T2 to T6 reduced in width by about 2m as a result of the placing of large locally derived boulders on the left bank. There is also a slight deepening of the channel adjacent to the now reveted left bank. This concentrates the flow in the deeper, narrower part of the channel near to this bank.

Transects T7 to T14 exhibit varying degrees of channel width and bank slope/height reduction. T7 to T10 show increases of a few centimetres in depth adjacent to the restored left bank, whilst T11, T12, T13 and T15 have greater increases in depth in the outer left zone of the channel with a corresponding increase in slope and height of the point bar face. T14 has not increased in depth but the channel has been considerably narrowed by a reduction in left bank slope and an increase in the height of the point bar on the inner bank.

Although no instream modification was permitted as part of the restoration programme, the nature of the remedial bank work and the size of the material used as revetment, has considerably altered the morphology of the channel. In general, the channel has been narrowed and slightly deepened from T1 to T15 and this has affected how the flow negotiates the bend and will change the subsequent hydraulic processes throughout the reach. Cross-section shapes can be described by width:depth ratios, which are inversely proportional to the force exerted by the flow on the bed and thus the rate of sediment transport. Any modification to a channel which affects its width:depth ratio thus affects its capacity for sediment transport and the likelihood of future instability of the channel. This reach has had its width: depth ratio reduced by engineering which should have increased its sediment transport capacity. For example the bankfull ratio for T10 was reduced from 26.45 to 24.14 and at T12 from 25.72 to 23.65 (Appendix D) and these are both situated near the apex of the bend. Also hard revetment has halted the progression of lateral erosion, although the rate of vertical erosion may have increased. Further surveying at future dates is needed to establish how channel morphology is affected in the long term, as only six months had elapsed between engineering and the last channel measurement.

4.1.2. - Bank Retreat Rates

Bank erosion pins were aligned in vertical arrays of 5 in the eroding left bank at transects T6 - T13 inclusive (Figure 3.5). The change in the exposure of each pin during the period 7th January and 8th June 1995 was recorded (Table 4.1)

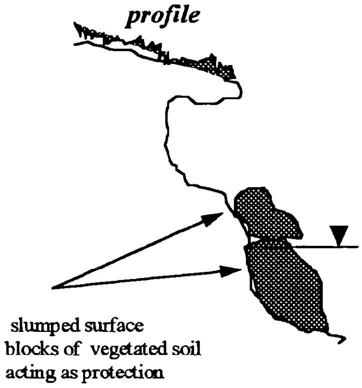
	T6	*T7*	*T8*	*T9*	*T10*	*T11*	*T12*	*T13*
Upper pin	*7.4*	*6.2*	*14.0*	*3.5*	*4.5*	*2.8*	*1.6*	*0*
	0.6	*8.8*	*8.1*	*4.4*	*5.8*	*11.4*	*1.9*	*10.4*
	0.9	*4.1*	*1.1*	*5.7*	*2.8*	*3.3*	*1.6*	*9.6*
↓	*2.2*	*0*	*-2.1*	*buried*	*buried*	*0.8*	*0*	*11.5*
Lower pin	*2.5*	*6.6*	*buried*	*buried*	*buried*	*30*	*0*	*7.1*

Table 4.1 - Bank erosion pin exposure rate (cm) over seven month period.

Due to its composite nature, the bank at this location has a concave profile (Figure 4.1). The lower non-cohesive sandy gravel deposits are formed from relic channel bars and the upper cohesive layer of sandy/silt and clay is an overbank deposit. The grain size distribution (truncated at -2ø) of the non-cohesive sandy layer shows that it is very slightly skewed to the fine end of the distribution and is poorly sorted with a D_{50} of 0.47mm (Figure 4.2 and Table 4.2). This layer is more easily eroded so that undercutting tends to occur. This is accentuated by the actions of sheep which use the bank as scratching posts, and the resultant overhang as protection from weather.

Bank erosion at this location is spatially variable, and some lower pins were covered completely by eroded bank material (such as at T8, T9 and T10). This is due to periodic collapse of large, overhanging surface blocks of consolidated material at these localities. These blocks are banktop overhangs which become gradually more unstable as the finer unconsolidated material below is eroded, as indicated by the gradual retreat rates of the uppermost pins. These blocks consist of clay/silt soils from the bank top, bound together by the roots of surface vegetation in blocks of 1.5m x 0.5m in size. These are too large to be transported and remain at the base of the bank providing a degree of protection to the bank foot. They are discontinuous around the eroding bend, so that some parts of the bank toe are more resistant to erosion than others at any one time. Eventually, these blocks are broken up in-situ, with larger portions falling into the channel and smaller sections transported downstream.

Figure 4.1 - Example of bank profile



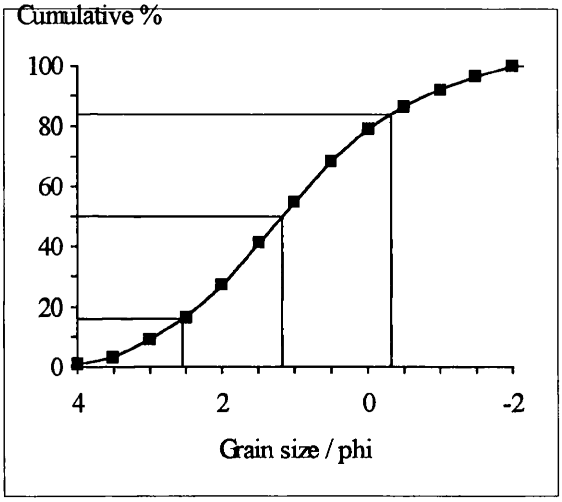


Figure. 4.2 - Cumulative frequency curve of bank material sample

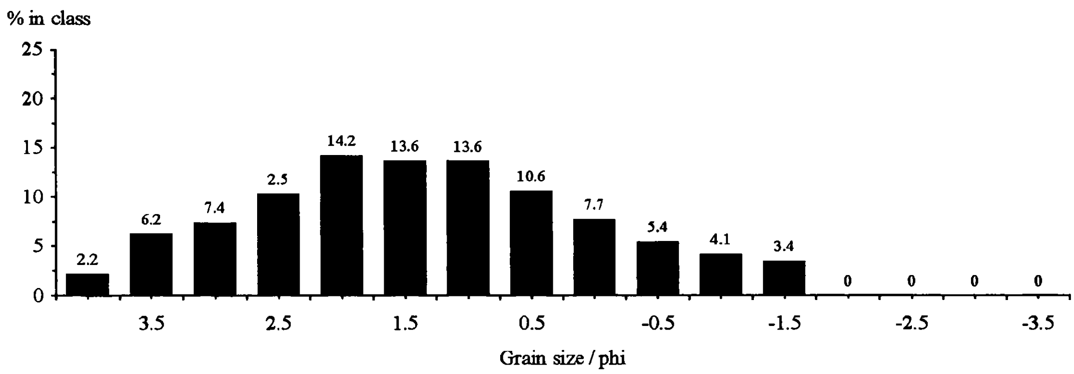


Figure 4.3 - Histogram of particle grain size distribution of bank material.

Parameter	mm	phi		
D_{16}	0.17	2.55	mean	1.14ø
D_{50}	0.44	1.18	sorting	1.42
D_{84}	1.24	-0.31	skewness	0.06
			$(D84/D16)^{0.5}$	2.70

Table 4.2 - Summary data for bank material sample

The large root bound blocks of soil can remain at the bank toe for long periods. Whilst in position they can act as large roughness elements which may protect the bank, but may also cause eddying and local scour exacerbating bank collapse at adjacent localities. This process can be termed basal end-point control (Thorne 1982), as the rate of basal accumulation or removal controls the subsequent bank failures to a large extent. The collapse of small parts of overhanging bank account for the sporadic nature of bank retreat recorded over the six month period, although the overall rate of bank retreat during this period was surprisingly low around this bend. An estimation of the volume of bank material lost is calculated (Table 4.3) using the prism formula (Ferguson & Ashworth 1992). The volume lost is calculated for each portion of the bank between each set of erosion pins, and is then aggregated to give a figure for total loss around the bend. An example of the calculation is given in Appendix D.

The Prism formula is :

$$V = \frac{hi \, . \, ri \, . \, L \, . \, (2 + a + b + 2ab)}{6}$$

where h_i = vertical distance between each pin at one end of the section (0.5m)

r_i = overall retreat rate of pin at same end of the section

h_j = vertical distance between each pin at the other end (0.5m)

r_j = overall retreat rate of pin at the other end

L = distance between each set of pins ie.length of section (10m)

$a = h_j / h_i = 1$

$b = r_j / r_i$

Height (m)	*T6 - T7*	*T7 - T8*	*T8 - T9*	*T9 - T10*	*T10 - T11*	*T11 - T12*	*T12 - T13*
2.0	523	777	674	309	281	169	62
1.5	362	650	481	391	660	512	473
1.0	192	200	238	327	235	188	431
0.5	85	0	0	0	0	31	0
0	350	0	0	0	0	1155	0
Total (kg)	1513	1627	1393	1027	1176	2055	966

Table 4.3 - Mass of material lost(kg) over a 70m stretch of eroding bank during Jan - May 1996

A previous study (Smart, 1994) recorded retreat rates at the same location of between 0.5 and 0.9m, and total eroded mass of 22 and 18 tonnes over a 12 month period (Figure 4.4). The differences found for the two studies may be due to the relatively short period of 5 months for monitoring retreat rates in this study, but could also be that the bend shape was slightly different and may have been eroding faster. Thus the reduced rate for the present study could represent an approach to a natural equilibrium bank shape.

	Retreat rate (m)	***Bank height (m)***	***Volume of material lost (tonnes)***
Peg number 1	0.5	1.74	between peg 1 - 2 (10m) 21.97
Peg number 2	0.93	1.92	between peg 2 - 3 (10m) 17.89
Peg number 3	0.64	1.41	

Table 4.4 - Bank erosion data from 1993 (Smart, 1994)

4.2 - MEASUREMENT OF FINE SEDIMENT INFILTRATION

4.2.1. - Spawning Site Identification

Five sites were chosen to record the rate of fine sediment infiltration into the gravel-bed. In choosing these infiltration transect sites, the three main characteristics measured were water velocity, water depth and surface grain size. The mean values for water velocity and depth across each transect were recorded in normal flow conditions.

	$v(ms^{-1})$	d(m)	Median surface grain size (m)
Transect 1	0.97	0.16	0.027
Transect 2	0.80	0.21	0.027
Transect 3	0.82	0.17	0.024
Transect 4	0.94	0.17	0.019
Transect 5	0.56	0.27	0.037

Table 4.5 - Mean values of hydraulic parameters at selected sites

All five transects had velocity, depth and substrate properties within the parameters required for them to be classed as potential spawning sites (Wesche, 1985). Although they all exhibited the necessary habitat requirements, there were varying combinations of each of the conditions at each transect, which may be able to be correlated with variations in sediment infiltration rates. It is important to note that when explaining overall patterns of infiltration in the following sections, averaged hydraulic parameters are used. Detailed hydraulic processes are looked at in section 4.3.

4.2.2. - Downstream and temporal variability in trap infiltration rates

Table 4.6 and Figure 4.4 illustrate the variations in total infiltration of sediment <4mm at each transect T1 to T5, along the long profile. The total sediment trapped at each transect over the study period is the sum of 6 separate measurements.

	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5
Total Sediment trapped (in grammes)	9026	8750	9998	12675	4827
Number of traps	5	5 then 4	5	5	2
Sediment/Trap (g)	1805	1750	2000	2535	2413

Table 4.6 - Downstream variation in total sediment infiltration

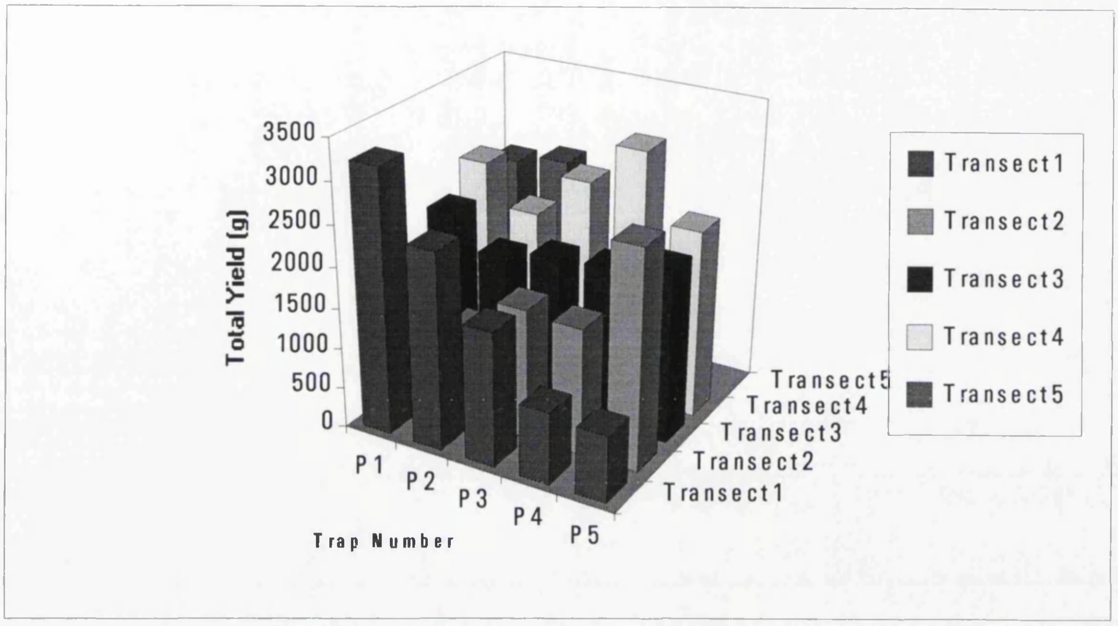


Figure 4.4 - Downstream and across stream spatial variability in infiltration rate

In Table 4.6 the lower total amount trapped at T2 compared with T1 and T3 is due to there being only three samples taken from trap 2 at this site, which was dislodged, broken-up and transported to a location about 75m downstream by flood flows between 1st and 10th September 1995. This has obscured the overall picture for T2 in terms of total sediment yield, as trap 2 had been a relatively high yielding trap. By referring to other sediment entrapment data for traps at T2 over the study period, and interpolating it for the missing samples, it is assumed that had the trap not been dislodged, the overall yield for trap 2 would have been approximately 9093g, which is similar to that of T1. This gives a more realistic figure for sediment per trap of 1819g at T2, compared to that of 1750g given in Table 4.6. This fits the general trend of increasing sediment per trap in a downstream direction (Figure 4.4).

The highest trapped volume was recorded at T4, which was about 30% higher than T1, T2 and T3. Transect 4 has comparable velocities and water depths to the other transects, but has a smaller surface D_{50} of 19mm compared with 27mm, 27mm, 24mm and 37mm at T1, T2, T3 and T5 respectively. This suggests that the smaller the gravel substrate size, the greater the tendency for fine sediment infiltration. This is consistent with Komura's (1961) relationship between void ratio and particle size which is investigated in section 4.2.4. But Figure 4.5 shows an increase in infiltration when the D_{50} is 37mm at T5, which does not follow the trend. This could indicate that other factors such as depth and velocity have a greater influence on infilling rates at this site (T5). Figure 4.8 shows how particle sorting (spread of particle sizes in a sample) changes as the amount of sediment infilling increases.

It can also be noted that smaller surface material is more mobile and during higher flows, capable of mobilising clasts of up to 19mm, there would be a high degree of bed activation at T4. This disturbance causes a flushing of fines from the substrate in high flows, leaving the sediment reservoir empty. As discharge recedes, fine material rapidly fills the empty voids in the 'clean' substrate, and consequently there are greater amounts of ingressed fines after flood flows. This compares with the findings of Frostick et al (1984). From similar experiments, they concluded that the presence of a coarse surface bed layer and bed-load motion are the dominant parameters influencing the amount and size of infiltrating fines and that bed agitation results in higher rates of sediment infiltration.

T5 had only two traps installed, hence a lower volume was trapped. If the mean volumes per trap are calculated, the total figure can be scaled up to give an estimation of the total volume had five traps been located here. This gives a total of 12067g for T5 which is similar to that of T4. Both traps were located in similar water depths (0.25, 0.30m) and velocities (0.55, 0.56ms^{-1}), with the median surface size being the largest of all sites (64mm). With reference to Komura (1964), this would indicate a smaller average porosity at T5 leading to less infiltration, but both traps recorded comparatively high levels of infiltration (Table 4.6 and Figure 4.4). This highlights the fact that other controlling factors influence infiltration rates. At this site, both traps are located in deeper water than traps at any other site and are subjected to lower velocities

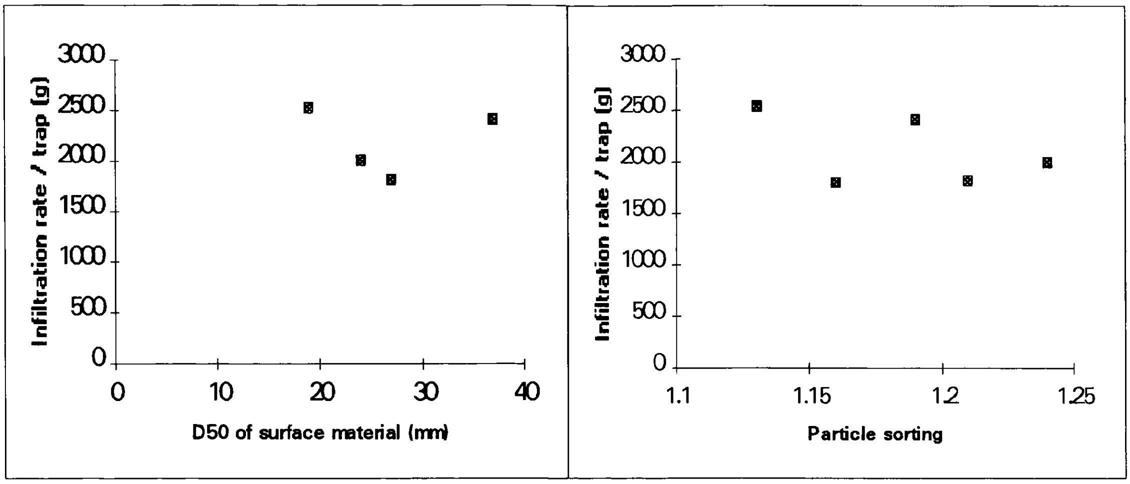


Figure 4.5 and 4.6 - The relationship between surface grain size, particle sorting and infiltration.

The infiltration rate also displayed temporal variability (Figure 4.7). The magnitude and number of flood events varied between each trap emptying date, and there are seasonal variations in sediment supply that will have an effect on the temporal trends encountered. Overall, the total yields, and those for each transect show a decline through the study period, except for the sample collected on 18/9/95, where each transect had an increased load of fine sediment (Figure 4.7). By correlating trap yield with duration of flood events it is possible to estimate trap yield per hour (Table 4.7). This gives a different picture of infiltration rates. Although total infiltration is reduced, the rate per hour of flood flow is increased showing an increased avaliability of sediment.

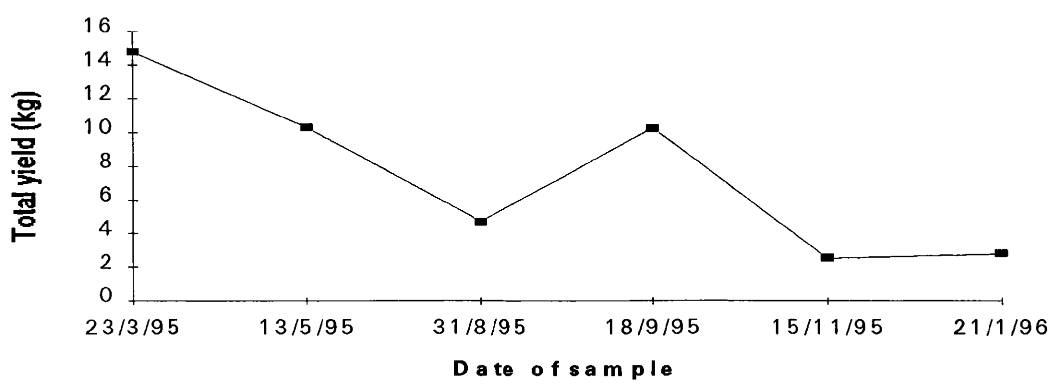


Figure 4.7 - Total Sediment trapped on each sample date

Mass in (g)	*23/3/95*	*13/5/95*	*31/8/95*	*18/9/95*	*15/11/95*	*21/1/96*
Transect 1	***3253***	***1989***	***1245***	***1303***	***647***	***588***
Transect 2	***2590***	***2573***	***886***	***1911***	***255***	***535***
Transect 3	***3792***	***1869***	***1004***	***2074***	***635***	***684***
Transect 4	***3788***	***3007***	***830***	***3864***	***611***	***574***
Transect 5	***1355***	***841***	***741***	***1083***	***397***	***410***
Total Yield	***14778***	***10281***	***4707***	***10235***	***2545***	***2792***
No. of Flood events	***12***	***14***	***4***	***4***	***14***	***15***
Total Duration	***253 hrs***	***133 hrs***	***50 hrs***	***176 hrs***	***242 hrs***	***528 hrs***
Total Yield per hour	***58g***	***77g***	***94g***	***58g***	***10g***	***5g***

Table 4.7 - Changes in sediment infiltration and flood characteristics during study period

The figures in table 4.7 are related to the discharge levels of the Water of Mark given by teletrend outputs from the gauging station at Invermark (examples in Appendix C). By counting the number of flood events that peak above a threshold level ($34.7m^3s^{-1}$) and estimating their duration (Table 4.7), the relationship between infiltration rates and the total duration of exposure to high flows can be explored. A threshold of $34.7m^3s^{-1}$ was chosen as it corresponds to $300 \times 10^3\ m^3\ day^{-1}$. This was arbitrarily selected as a threshold for sediment transport. It is calculated that 16% of the flow was above this threshold The traps were installed on 28th January 1995 and the first sample taken two months later. During this period there were major events from 2nd to 6th February, less prolonged peaks on 12, 13, 14 and 27th February and 9-12th March. These significant flood discharges may have caused extensive bed activation and will have mobilised various instream sediment 'sinks' and channel boundary sources. It may also be the case that bed disturbance during the installation of the traps may have increased the levels of fine sediment available for transport during this period. Both of these would have contributed to a high level of sediment load during these events and could explain the high levels of material infilling the traps.

During the second sample period, there were only 4 flood discharges over $34.7m^3s^{-1}$, in late March. No data was available for April due to a technical problem with recording equipment. By referring to data (Appendix C) recorded for April in the previous year (assuming normal conditions), this period is typified by a highly fluctuating discharge but a lack of large events. This pattern correlates with the reduced, but still considerable, level of sediment entrapment in sample 2. There was a decline in overall trap yield for this period, but by calculating yield per hour over the threshold discharge (Table 4.7), an increase in sediment infiltration rate during high flows is evident (Figure 4.8).

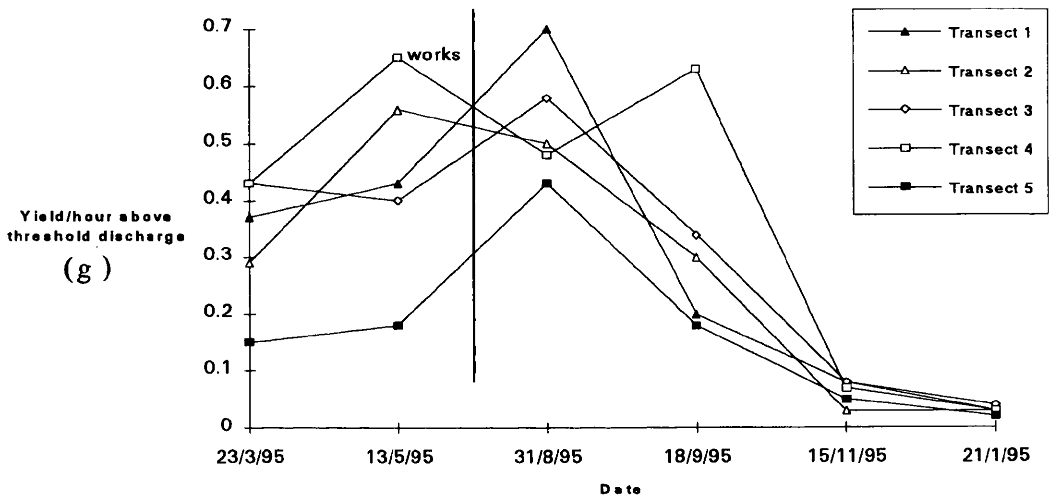


Figure 4.8 - Trap yield per hour during flood flows during the study period

During the third sample period, there were only four flood peaks, between 26th-31st May. These were short-lived and associated with a late snowfall and snowmelt. These flows may have caused brief periods of bed mobility, but not to the same degree as in previous sample periods. Following this cold spell, a protracted dry period ensued, leading to minimum base flows being experienced throughout the summer, and thus low sediment transport rates. This accounts for the relatively low trap yields on 31/8/95, although they may have been artificially distorted. Throughout late May and early June, there was considerable disruption to the gravel-bed throughout the reach due to the engineering works associated with the Habitat Improvement Scheme. Remedial bank work necessitated an excavator instream to implement the work. This caused severe bed agitation and resulted in high levels of sediment in suspension (Plate 4.2).

Plate 4.2 - Suspended sediment concentration during works

Due to the low flow conditions at the time, only the finest particles would have been transported any distance downstream, with the larger particles falling out of suspension rapidly to settle on the bed surface. This work may have increased the trap yields when sampled on 31/8/95 and introduced a higher proportion of finer particles. This is assessed in section 4.2.5.

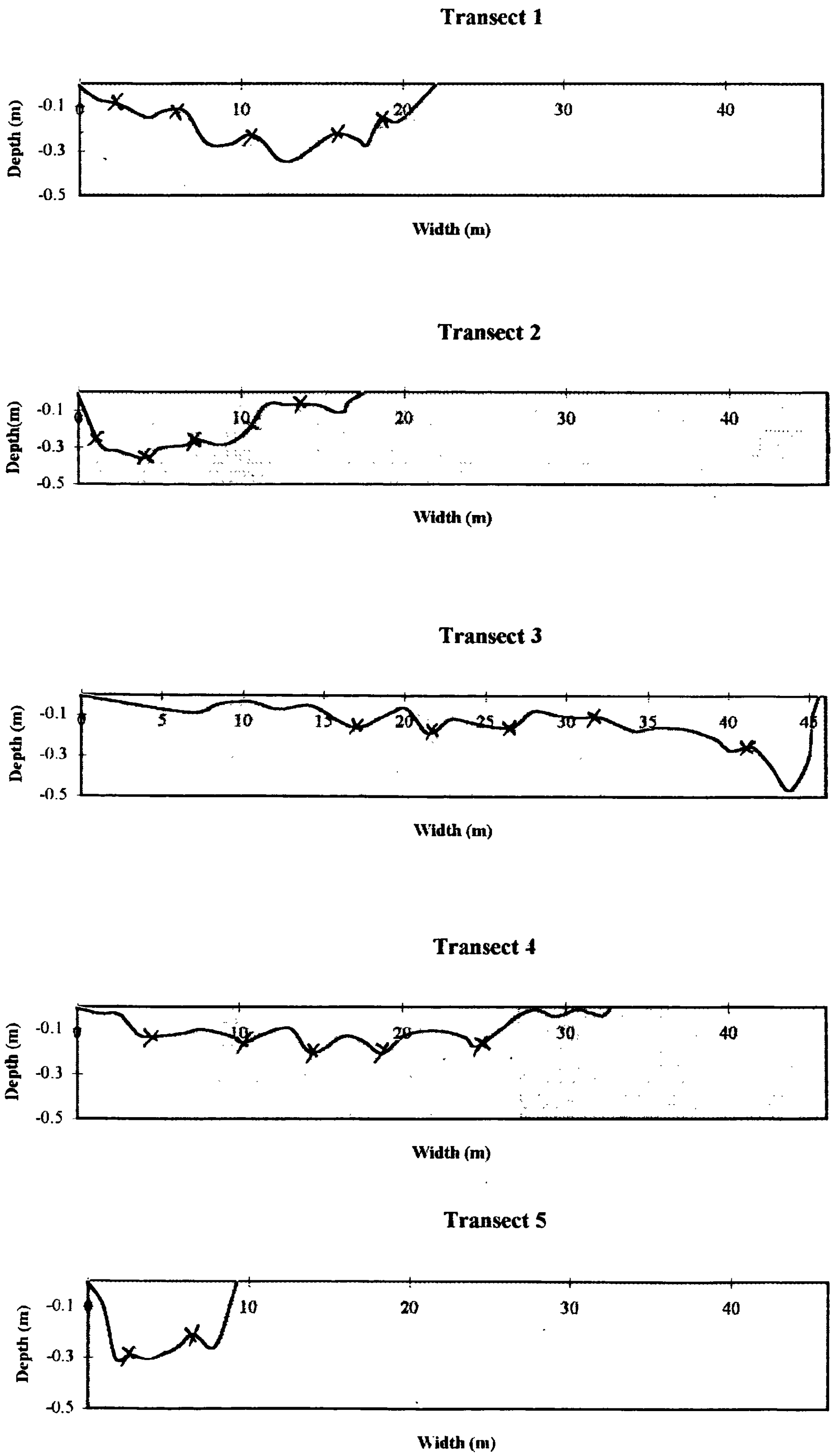
The subsequent sample (18/9/95), again had a higher overall trap yield and yield per hour, which was inconsistent with the overall trend of declining yields. This anomaly was recorded over all the sites so it was not a localised phenomena. However, when the total yield is related to the duration of high flows during this period (Table 4.7) it is comparable with the other sample periods. An explanation for the increase in sediment lies within the discharge data. Large flood events on 31st August and 3rd September, with a protracted event of high magnitude (> 57.9m^3s^{-1}) between 6-11th September could account for the higher than expected entrapment rates. After the sustained 3 month period of dry weather, the soil surface was dry and crusted so that the abnormally large quantity of precipitation experienced during the first 10 days of September could not infiltrate into the soil sufficiently. This facilitated the immediate run-off of rainwater into the main river channel and produced a rapid rise in discharge which was then maintained at high levels for 10 days. Considerable bed modification would be expected and it was during this period that Trap 2 at T2 was destroyed. Generally, there are three possible sources of 'extra' sediment during this sample period: a) the high levels of fine sediment on the bed surface, a legacy of the engineering work; b) in normal summer flows, fine material eroded from dessicated banks accumulates at the bed surface; c) erosion of sediment which accumulated elsewhere in the catchment during the dry period. This sediment is then readily available for resuspension by the first flood events after the summer, thus generating higher than normal concentrations of suspended solids. The high flows during early September would have been the first opportunity for this sediment to be transported, and the bed to be reworked and cleaned. This coupled with naturally higher sediment loads during high flows explains the high yields of 18/9/95.

The final two sample dates both show significantly lower infiltration rates across all trap locations. T2 to T5 were expected to show this, due to the removal of the potential source of fine sediment upstream at the Queens Well by bank protection, which was directed at limiting fine sediment release from this location. The infiltration rate at T1 was expected to be lower than T2-T5 prior to any bank work and similar to them after restoration, but over the study period T1 was similar to T2 and T3. This could indicate that although the sediment contribution from the eroding bank has been 'removed', the sediment load of the river is maintained by sources upstream. The discharge readings for the final two samples show that for sample 5 there were two or three events of significance but no abnormally high flows. For sample 6, there was prolonged high flow for late November and late December/early January 1996. These can be related to periods of snow melt when linked to local weather data. Considering this sequence of discharge levels, especially in early January, the low sediment entrapment rates do not seem to correlate to the river conditions. This can also be seen by comparisons of the total yields and total duration of high flows for each period. Although the overall trend for infiltration rates and duration of high discharges show a similar increasing and decreasing pattern, the actual amounts of sediment do not correspond. The final two sample periods experienced long periods of high flow, but had low levels of sediment entrapment. This anomaly is investigated in the discussion chapter.

4.2.3. - Cross-sectional Variability

The variations in trapped sediment volumes have been investigated using cross-section averages in a temporal aspect and in a downstream spatial context. The volumes retained in individual traps can also be considered with reference to the water depth above each trap and the velocity at the surface of the trap for all traps (Table 4.8). The surveyed cross-sectional profiles of T1 to T5 (Figure 4.9) are shown on the following page to aid interpretation.

Figure 4.9 - Survey cross-sections of trap transects



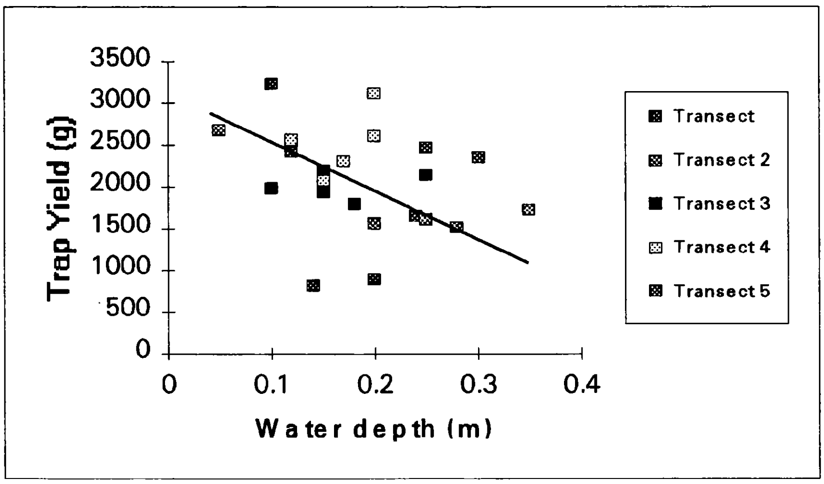
Trap Number	*Left bank* *P1*	*P2*	*P3*	*P4*	*Right bank* *P5*
Transect 1	***0.60 0.1*** ***3236***	***0.85 0.12*** ***2422***	***1.42 0.24*** ***1658***	***1.21 0.2*** ***889***	***0.76 0.14*** ***821***
Transect 2	***0.95 0.35*** ***1721***	***0.87 0.28*** ***1171***	***0.96 0.25*** ***1612***	***0.95 0.2*** ***1562***	***0.324 0.05*** ***2 684***
Transect 3	***0.82 0.15*** ***2191***	***0.91 0.18*** ***1785***	***1.08 0.15*** ***1923***	***0.73 0.1*** ***1969***	***0.59 0.25*** ***2130***
Transect 4	***0.85 0.12*** ***2568***	***0.93 0.15*** ***2070***	***0.77 0.2*** ***2606***	***1.14 0.20*** ***3119***	***1.05 0.17*** ***2312***
Transect 5	***0.56 0.30*** ***2355***	***0.55 0.25*** ***2472***			

Table 4.8 - Individual trap characteristics and infiltration totals

Layout of units for each figure velocity at trap surface (m s^{-1}) water depth (m) at normal flow

total fine infiltration (g)

Table 4.8 and the cross -sectional plots highlight the diversity of physical characteristics at each transect. When this data is correlated with the sediment yield of individual traps, spatial variations in infiltration can be appraised. The changes in infiltration rate with water depth and velocity changes are indicated in Figures 4.10 and 4.11.



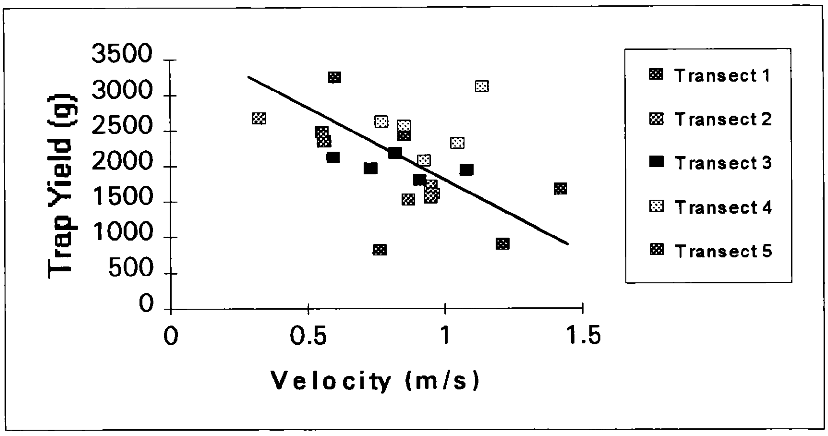


Figure 4.10 and 4.11 - Relationship between infiltration rate, water depth and velocity.

The best-fit lines in Figure 4.10 and 4.11 show that generally, infiltration is inversely correlated with both water depth and velocity, but there are departures from this relationship. This is similar to the findings of Einstein (1968) who found that increased water velocities and associated stronger turbulence limits the movement of sediment through surface pores and into a gravel bed. Table 4.8 shows that T1 recorded a reduction in entrapment from left to right (P1-P5) reflecting increased velocity from left to right. Shallow water with low velocity at T1P1 has enabled the deposition of fine sediment as the transport capacity is reduced. As the depth and velocity increase from T1P1 to T1P3 the yield declines as transport capacity rises. T1P4 has a low yield due to scour of both matrix and framework material as a consequence of a downward eddy produced by a boulder upstream which disrupted the flow patterns over the trap.

There is a slight decline in infiltration from T2P1-P4. There was an abnormally lower total yield at T2P2 due to their being no data for samples 4,5 and 6. As with T1P1, when velocity and depth are both reduced at T2P5 there is a marked increase in infiltration. T2P5 is also situated on the fringe of the inner point bar, which is the region where bedload transport processes move the finest sediments. Fine suspended sediments are delivered to this area in high flows, when concentrations are high. This coupled with this inner bar region being rarely subjected to extensive reworking, means that deposits tend to be higher and more persistent here.

The pattern at transect 3 is more inconsistent. T3P5 is in the deepest and slowest part of the channel so sediment deposition here is as expected. If the trends observed at T1 and T2 of yields increasing as depth and velocity decline were followed, T3P4 would have the highest yield. The data shows that, although T3P4 is relatively high, T3P1 has a higher yield and is slightly deeper. The next site (T4) shows a relatively constant entrapment rate from T4P1 to P5, with T4P4 being slightly larger. T4P4 is the area of highest velocity although depths are almost constant across this profile. Overall, the traps at T4 have higher yields than other sites throughout the 12 months and the highest total yield. This tendency could reflect the change in median substrate size at T4 leading to greater void ratios and subsequent infilling as discussed in section 4.2.2. Finally, T5 exhibited similar infiltration rates for both traps, which were located in relatively deep water with slow velocities, and this is reflected in their relatively high rates of entrapment.

4.2.4. - Void space measurement and percentage infilling

The percentages of intragravel pore space that were infilled by fine matrix material were calculated from the infiltration volume data. Komura's (1961) least-squares relationship between void ratio and particle size allowed Frostick et al.(1984) to estimate mean total porosities of 28%, 29% and 33% for gravel bed rivers where the substrate particles have median diameters of 48, 24 and 12mm respectively. The general pattern is that as median diameters of surface particles decline, the mean total porosities increase. Wolman sampling across the main transects T1 to T5, indicate median substrate sizes of 27, 27, 24, 19 and 37mm. These suggest void ratios of 29, 29, 29, 32 and 28%. Therefore with a smaller surface grain size at T4, it is expected that pore sizes are larger and consequently allow higher rates of infiltration. By calculating the volume of the empty trap and the volume of void space once the trap is filled with gravel substrate, the percentages of fines inhabiting the voids can be computed (see Appendix D for calculations). Carling (1992) estimates that fine contents of over 20% are detrimental to the survival of salmonid eggs incubating within the gravel beds. The graphs in Appendix D are examples of percentages of void space infilled over the six sample periods.

The time of year that peak void infilling occurs is important. By late May there ought to be no incubating eggs in the gravel as they should have hatched and fry emerged into the watercourse so infilling in this period does not affect incubating eggs. On the first sample date, 20 out of the 22 traps across T1 to T5, have levels of matrix material ingression (typically >30%) too large to allow the survival of incubating eggs. The highest recording is 49% at T1P2. On the second sample date (13/5/95), although showing generally lower void occupation, a number of traps (8 out of 22 sites) exhibited levels exceeding the acceptable threshold. By the third sample, all sites demonstrated favourable void space conditions except for T5P1 (21.4%). The fourth sample (18/9/95), saw a significant increase in void infilling resulting in 50% of sites having unsuitable levels of infiltrated fine sediment. The final two samples (15/11/95 and 21/1/96) saw all sites with percentages of infilling below the 20% threshold and it is during this time that the majority of salmon spawn in this tributary. There is an unexpectedly low infilling during these two sample periods, which is explored and discussed in the following chapter. Also discussed in the following chapter is the problem of emptying and re-setting the traps. This emptying is equivalent to a 'flushing' event and leaves the voids free of sediment. This will have an effect on the infiltration rate immediately after emptying. This can also be compared to the removal of fine sediment during salmon spawning and the subsequent rapid infilling of void spaces.

Variations in void infiltration across the channel are considerable and depend on variations in velocity, water depth and substrate size. It is difficult to identify a distinct trend of velocities and depths and relate them to percentages of void space inhabited by fines (Figure 4.12, 4.13 and 4.14). This is investigated in the discussion chapter.

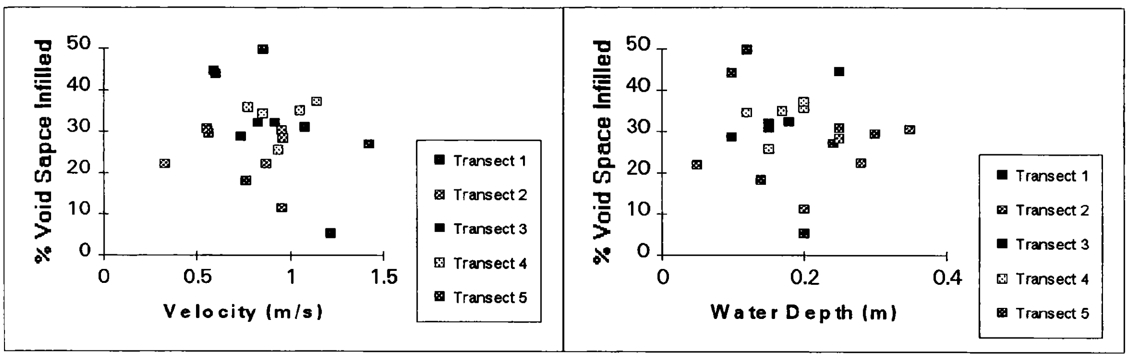


Figure 4.12 and 4.13 - Relationship between velocity, water depth and void space infilling

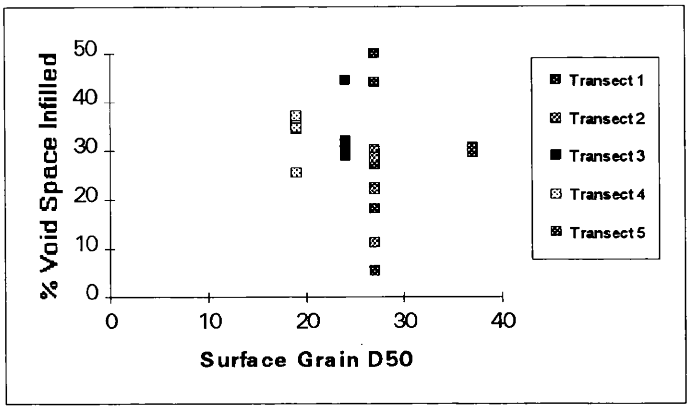


Figure 4.14 - Relationship between substrate size and void space infilling

4.2.5. - Grain size distribution of infiltrated sediment

Particle size analysis gives an indication of the degree of sorting of each trap sample. This is an important parameter to calculate as sorting affects the way the sediment is packed and how embedded it is, thus altering void space percentages. Skewness of the particle size distribution gives an indication of how coarse or fine the infilled sediment is. It can also indicate the proportions of bedload and suspended load and indicate source materials for the infiltrated sediments. A summary data chart is shown in Appendix E showing data for each of the trap samples.

From the summary data in Appendix E it can be seen that across T1 particle sorting decreases from left to right, with samples from the faster flowing sections of the channel (T1P3 and 4) having higher proportions of coarse particles. Samples from the final two sample dates (when the infiltration rate was low), exhibit a fine skew in all traps at T1, although there was greater percentages of fines at T1P4 and 5. At Transect 2 there was also better particle sorting in traps located in shallower sections, with the samples becoming finer in the shallower, slower localities (eg. T2P5). Again finer samples were recorded on sample dates 5 and 6 when the sediment yield was low, with higher proportions of coarse sediment in traps 4 and 5 in the shallower part of the channel. Thus it seems that as infiltration rates decline the percentage fine component increases, particularly in the samples in faster and deeper sections.

Downstream at T3, sorting again decreases with greater proportions of coarse sediment as depth and velocity increase. Higher percentages of fines are evident in the final two samples, especially at T3P5 in the faster deeper section of the channel. T4 has a similar sorting pattern across the whole transect which reflects its physical characteristics. The samples from T4P4 are consistently coarser and larger in volume than others at T4 which follows the general trend at the other transects where larger infiltration rates provide samples with a higher coarse element. Finally, T5 recorded coarser samples at P1 than at P2, which could be due to the slightly greater depth and velocity at this trap.

Figures 4.12, 4.13 and 4.14 show the sample variations with differing control factors. They show that depth, velocity and substrate controls are not so easily identifiable, which indicates that the generalisations seen in the summary data (Appendix E) are not so obvious, and that there are several controlling factors operating at any one locality and no single control is dominant. Figure 4.15 a) to e) show the relationships between sample characteristics and the infiltration rate. The best fit lines that are shown on the diagrams are an attempt to summarise the major trends and to indicate how the sample composition changes as the infiltration rate varies.

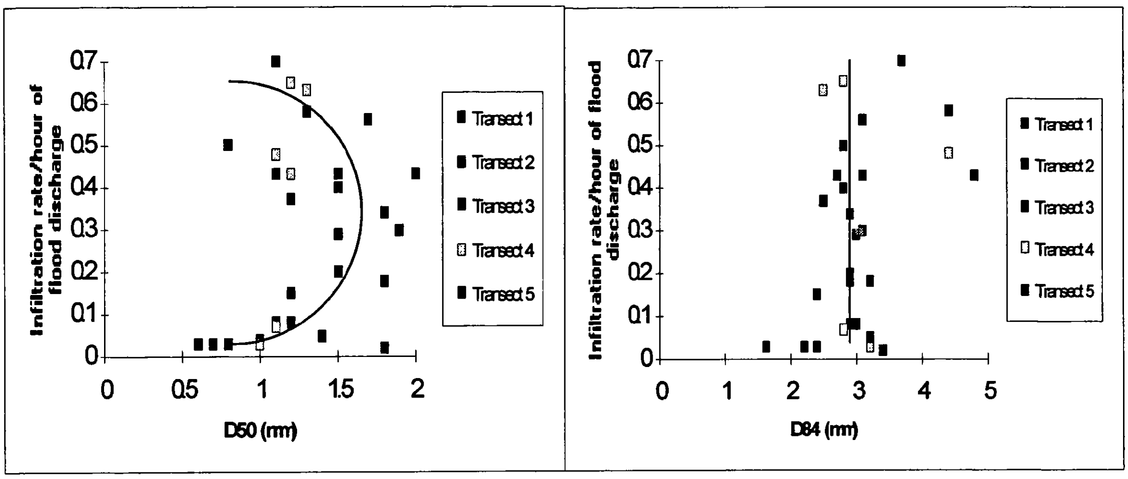


Figure 15 a) and b) – Relationship between infiltration rate and sample characteristics

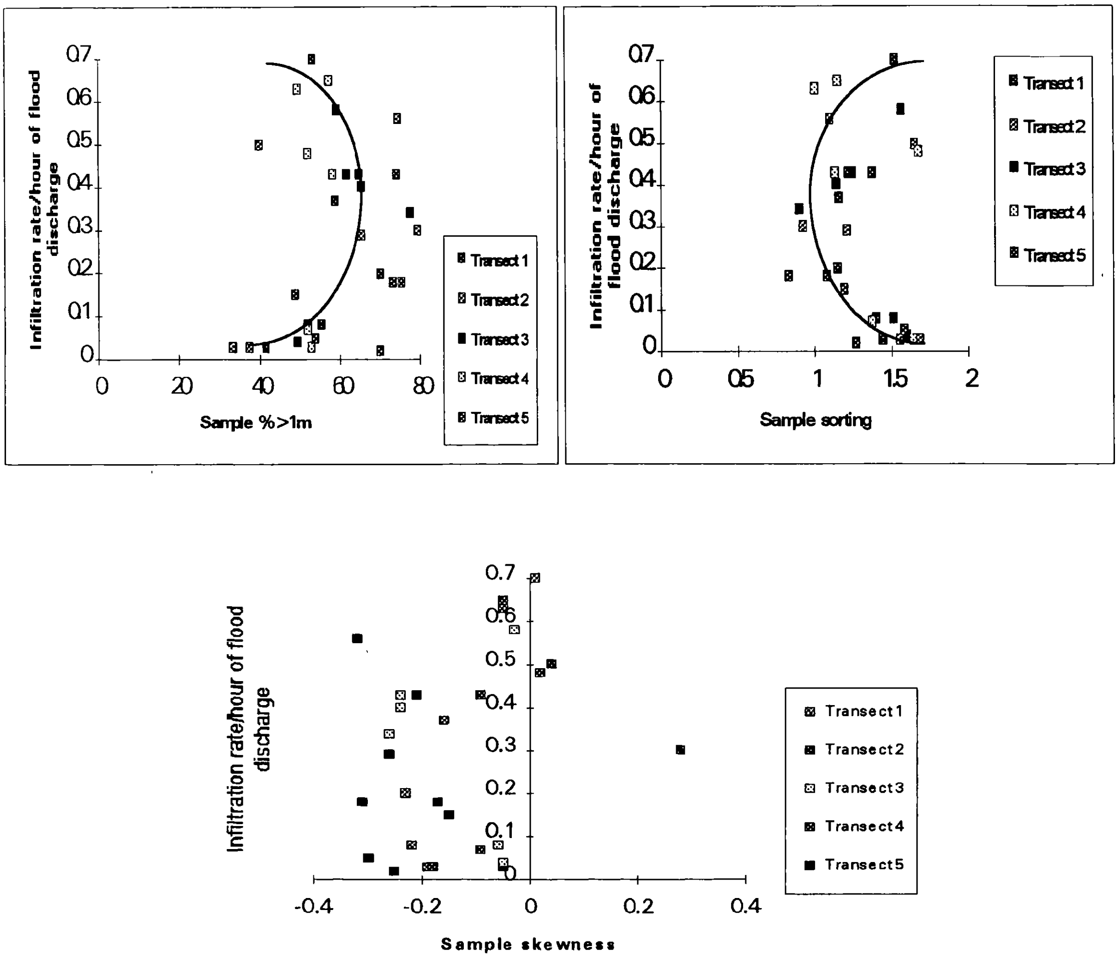


Figure 4.15 c), d) and e) - Relationship between sample characteristics and infiltration rate

Nearly all samples recorded poorer sorting in sample 3 after prolonged summer low flow and improved sorting in the subsequent sample on 18/9/95, after the high discharges of early September. Higher discharges lead to an increase in sediment transport rate, but sediment is deposited as the transport capacity is reduced, leading to higher levels of infiltration and better sorted matrix material with a higher proportion of coarse sand and gravel incorporated. Sorting improves with higher discharges because fine sediment remains in transport whilst the coarser elements are deposited, which leaves a reduced particle size range in the gravel-bed. But if there are few high discharges (such as during sample period 3), infiltration rates are reduced, with higher proportions of fine sediment in the more poorly sorted matrix material. This fine material accumulates on the bed surface and can generate high concentrations of suspended sediment at comparatively low discharges during infrequent summer floods, which results in a finer trap sample. On sample dates 5 and 6, each sample experienced lower levels of infiltration with the samples being more finely skewed. Also as the infiltration rate is lowered, there is a greater proportion of fines in the traps in deeper faster localities. This shows a reversal in the trend that was found for high infiltration rates, when coarse particles are more prevalent in these deeper sites.

Nearly all samples (91%) contained > 50% of sediment greater than 1mm. The highest level was 93.6% at T5P1, but most samples were in the 60-70% range. This coarse element was reduced by the time of samples 5 and 6 when only 52% of samples had >50 % of material > 1mm. These can be compared to samples taken from the eroding bank which were nearly symmetrical and poorly sorted with only 13.4% of material >1mm (Figure 4.3 and Table 4.2). The matrix sediment infilling the traps has a higher coarse particle concentration. It is not possible to determine from grain size characteristics alone whether this coarse element has been selectively deposited from relocated bank material, or is reworked matrix material or is from a supply of coarse material introduced further upstream.

It is possible to calculate the particle size (D) which is capable of being suspended at varying depths through the study reach by using suspension criteria. A typical suspension criteria (Bridge & Bennet, 1992) is;

$$u_s = b.u^*$$

where u_s = settling velocity of sediment

b = constant $\cong 0.8$

u^* = shear velocity = $\sqrt{ghS}$

The fall velocity can be obtained from Rubey's 'impact law' (Richards, 1982) as;

$$u_s^2 = \frac{2}{3} D.g \frac{(\rho s - \rho w)}{\rho w}$$

where ρw = water density = 1000kgm^{-3}

ρs = sediment density = 2650kgm^{-3}

g = 9.81ms^{-2}

D = grain size (m)

Combining the two equations below gives the particle sizes (D) capable of being suspended (Table 4.9);

$$D = 0.093\,(bu^*)^2 = 0.0936^2\,ghS$$

$$= 0.582\,hS$$

Reach Slope (%)	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Water Depth (m)	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Grain Size (m)	0.0004	0.0008	0.0012	0.0016	0.0020	0.0024	0.0028	0.0032	0.0036	0.0040

Table 4.9 Particle size suspension criteria.

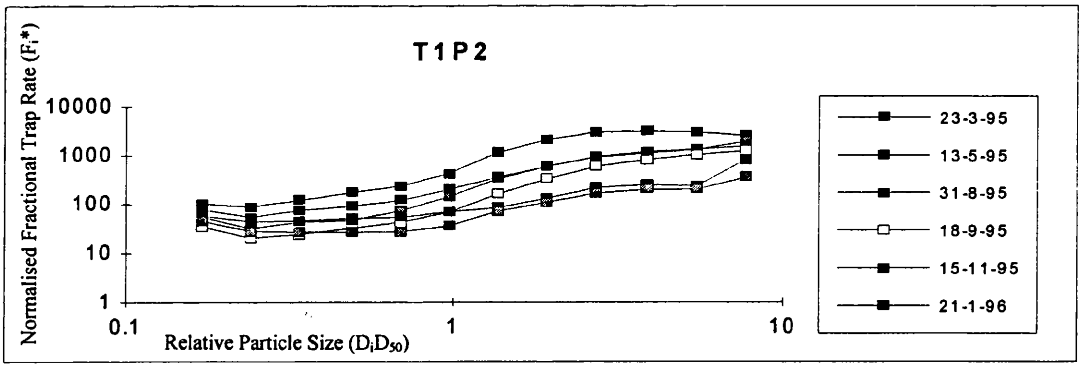
The suspension calculations show that at a water depth of 0.30m, particles as large as 1.2mm are transported in suspension, but at 0.10m only particles <0.4mm are suspended with grains >0.4mm being transported as bedload. This explains why there is a higher concentration of coarse sediment at deeper sites, as only the coarser elements remain as bedload and are in contact with the trap surfaces, with finer elements in suspension by-passing the traps. These calculations are a good indicator of bedload and suspended load characteristics in the reach. With depths ranging between 0.10 and 0.35m across T1 to T5, particle sizes <0.4mm are in suspension and >1.6mm are transported as bedload. The method of transport of the intervening size range is dependant on local water depths.

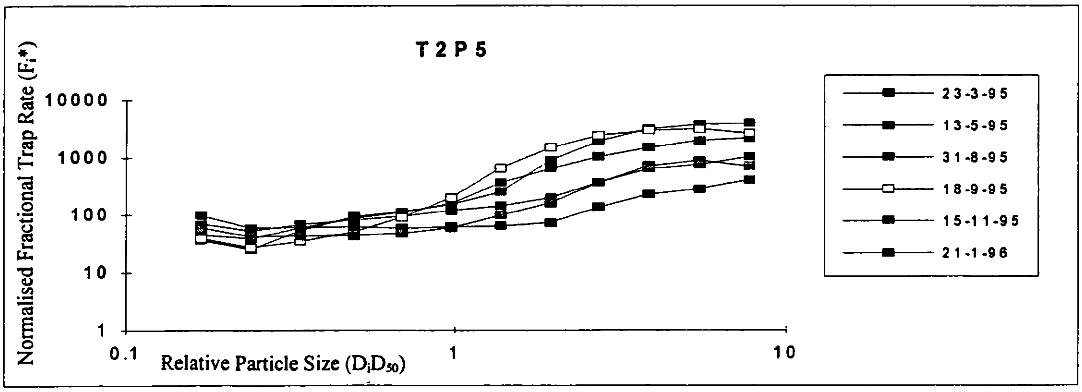
The changing grain size distributions can also be examined by calculating the normalised fractional trap rate (F_i*) as :

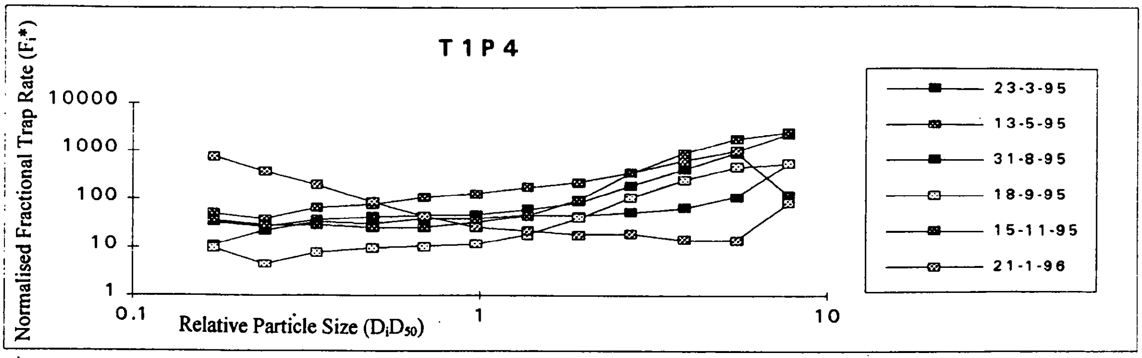
$$F_i^* = \frac{F_T \, . \, t_i}{b_i}$$

where t_i = proportion of sediment trap sample in the ith size class
b_i = proportion in source sample (bank)
F_t = trap infiltration rate/hour (grammes / hour)

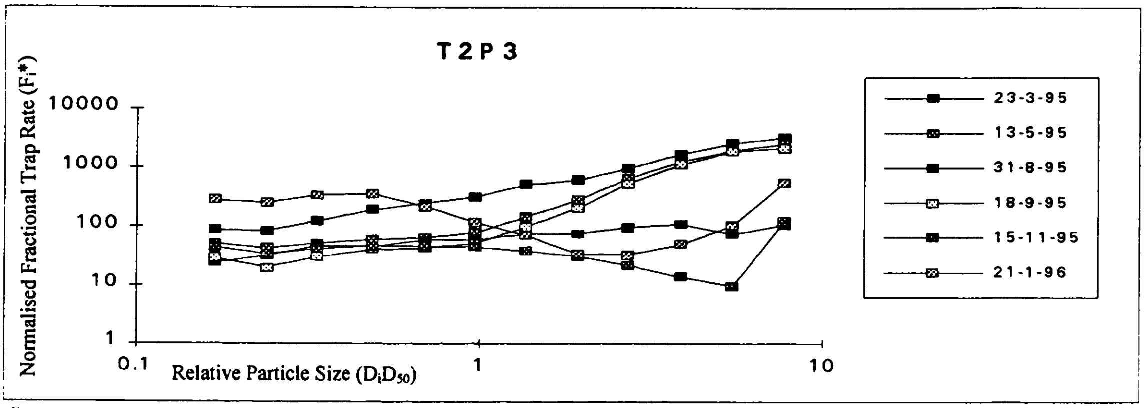
Normalisation allows the trap sample to be compared relative to the bank material. By plotting F_i* (y-axis) against the relative particle size (D_i / D_{50} on the x-axis), variations in sediment infiltration rate can be related to the composition of the matrix material. Also the similarity of the trap samples and bank samples can be evaluated to give an indication of the proportion of trap sample that may have been provided by the eroding bank. If the particle size distributions of the trap samples are similar to those of the bank sediment, they would plot as horizontal lines on Figure 4.16 a), b), c) and d). From the examples in Figure 4.16, it can be seen that most samples show a general positive slope, and so contain a larger coarse element than the bank material.







c)



d)

Figure 4.16 a), b), c) and d) - The normalised fractional trap rate showing the similarity of bank and trap samples

The plots from T1P2 and T2P5 show similar size distributions for each of the six samples, although the transport rate and thus the total mass of the sample declined through time. The plots for T1P4 and T2P3 both show that as the infiltration rate has decreased there is a greater proportion of fine sediment in these samples which is consistent with the pattern found previously. These two locations are in deeper fast flowing sections of the channel where the bulk of the flow is concentrated. This corroborates the previous findings that as the infiltration rate falls in these faster deeper sections of the channel, the matrix material increases its fine sediment component. Whilst in other parts of the profile, the composition of the matrix material does not change as much when infiltration rates change.

4.3 - CHANNEL HYDRAULICS AND SEDIMENTS

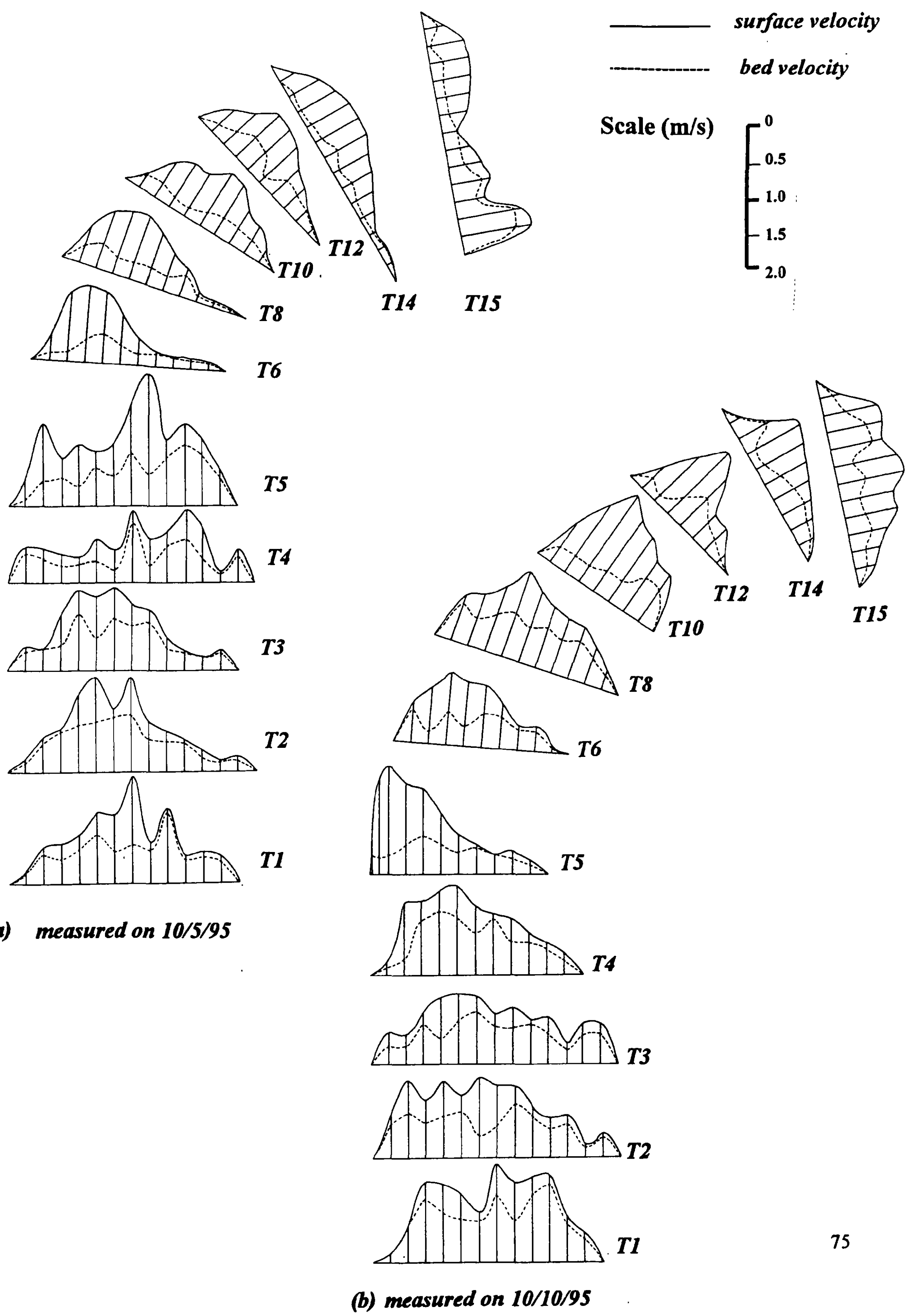
4.3.1. - Velocity measurement

Figure 4.17 shows the surface and bed velocity plots constructed from measured velocity profiles, for 11 cross-sections around the bend. Figure 4.17 a) is indicative of the natural conditions experienced in the reach, whilst Figure 4.17 b) is after engineering modification of the banks and bed. By comparing the plots, the channel narrowing, especially around the bend is clear, and the flow has been concentrated in the left channel adjacent to the outer bank. As water flows around a bend, centripetal acceleration forces it to the outside inducing cross stream currents which modify the direction of near bed flow and stress. The engineering has accentuated this process and has resulted in the surface and bed velocities generally being increased in the outer zone as highlighted in transects 4, 5, 10 and 12. In general, the position of the maximum velocity tends to move towards the outer bank at the apex and towards the inner bank as it exits the bend and crosses the downstream riffle. But as the water flows around the bend, super-elevation increases the water depth at the outside by a few centimetres due to centripetal acceleration. This changes the water surface slope, which in turn displaces shear stress from the deepest part of the channel. Also the point bar deflects the flow against the outer bank which is called topographic steering, and once again shifts the shear stress vector. As recorded by the cross-sectional surveys of the reach, the channel has been deepened slightly. These increased velocities towards the outer bend, and the deeper channel in the outer zone both increase the shear stress in this area. The reinforced bank should be resistant to this higher erosive force, but the bed may experience scour. Discharge was also calculated for the study reach on the days that velocity readings were recorded (Appendix C). The average discharges being 1.42 m^3s^{-1} for 10/5/95 and 1.27 m^3s^{-1} for 10/10/95. Both of these readings were taken in periods of low flow which registered as 5.1 and 5.0 on the stage recorder located at the flume/fishcounter at Invermark.

4.3.2. - Shear stress calculations

Bed shear stresses, calculated using von Karman-Prandtls 'law of the wall' (Section 3.4.2), are in Appendix C. They show bed stress levels before and after engineering modification, calculated from velocity readings taken in normal flow conditions. The shear stress calculations are

Figure 4.17 (a) and (b) - Surface and bed velocity plots around the eroding bend



averaged and do not account for any local turbulence that may occur across each cross-section. The presence of turbulence is dependant on the relative roughness of the bed. Bed roughness was also calculated for each transect Tl to T5, to determine whether the channel at these locations could be described as hydraulically rough or smooth. But data on channel roughness show a considerable amount of scatter due to the complexity of the relationships involved between several variables. Variations in roughness across the bed and between the bed and banks, can induce significant variation across the section such that the velocity structure of the channel is distorted. Thus the relative roughness of the channel at T1 to T5 (Table 4.10) will affect the infiltration rates found at each trap across the transect.

TABLE 4.10	***Relative roughness (D84/water depth)***
Transect 1	***0.60***
Transect 2	***0.45***
Transect 3	***0.77***
Transect 4	***0.38***
Transect 5	***0.46***

The larger relative roughness at T4 and T% correlate to the high levels of infilling at these two transects. The bigger roughness elements dissipate stream energy and reduce the transport capacity precipitating deposition and infiltration. The shallower and wider transects 1 to 5, show higher levels of bed shear stress than the transects that cover the deeper narrower section around the bend. This is comparable to the findings of Keller (1971) who noted that the non-uniform spatial and temporal distribution of bed shear stress in channels affects the flow conditions and bedload transport rate, but at normal flows shear stress tends to be greater in riffles than in pools.

As a general trend, there is an increase in shear stress levels on the channel boundary after engineering has taken place. It is also evident that at most transects there is a significant increase towards the outer left bank. This confirms the pattern exhibited by the velocity plots. As the flow follows the deeper section of the channel in normal flow, higher shear stresses are expected on the outer left bank where surface flows converge which causes downwelling. Carling (1992) reported that flow around a bend is complex, with fast flowing surface water directed towards the outer bank and slower near bed flows towards the inner point bar. The distorted flow gives upwelling and flows away from the bank at the apex resulting in low applied shear stress on the bank, but near the bed the flow is towards the bank and the stress on the bank foot may be high resulting in basal scour and bank recession.

The slightly deepened outer channel surveyed post-engineering, may be as a result of bed scour due to this enhanced shear stress, rather than any unintentional deepening during the works. The second survey of the cross sections was five months after the completion of the works. There had been sufficient flood flows during that period to have scoured and deepened the outer channel as it readjusts to the new hydraulic conditions imposed upon it by the engineering. This channel scour and the increased bed shear stress rates, should continue to deepen the outer left channel and create a deeper pool. This is important as an indicator of the effectiveness of the bank protection, as it has prevented lateral erosion causing channel widening, but precipitated vertical erosion.

4.4. - FINE SEDIMENT TRACING

4.4.1. - Quantitative analysis of trace element entrapment

The results of the image processing and analysis, to quantify relative percentages of fluorescing particles are given in Appendix E. The tracer material particle size distributions (T_i*) can be compared with those of the rest of the infill material using the same normalising function as used in section 4.2.5.

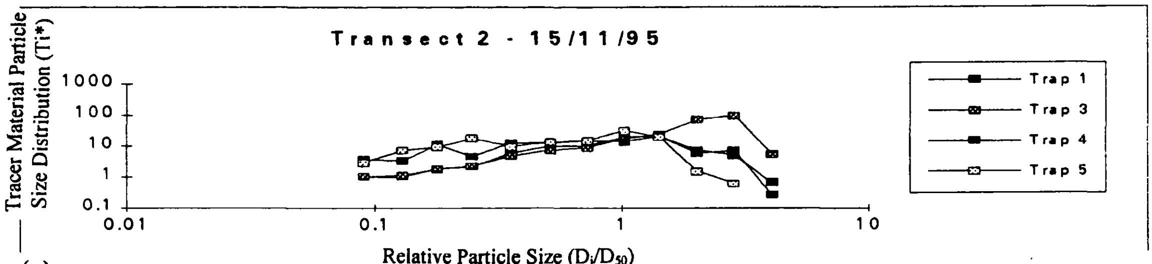
$$T_i^* = \frac{G_t \,.\, S_i}{t_i}$$

where G_t = total volume infiltrated (grammes / hour)

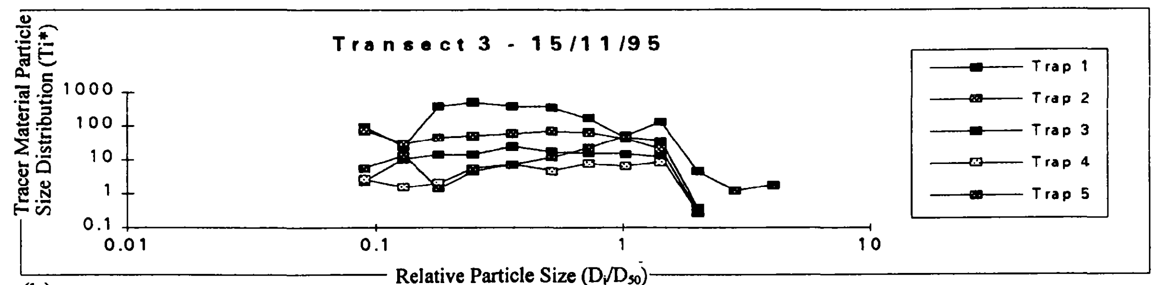
S_i = proportion of tracer in th $_i$th size class

t_i = proportion of infiltrated material in the $_i$th size class

Plotting T_i* (y-axis) against relative particle size (Di/D_{50} on x-axis) of the tracer material as implanted, aids the explanation of sediment sources and mixing of sediment from different sources (Figure 4.18). The control location (Transect 1) upstream of the source point, shows no fluorescing sediment. At T2 (Figure 4.18 a])there are traces of tagged sediment evident in all particle size ranges from 2.8mm to 0.063mm and in each trap sample. Fluorescing particles are most abundant in the size range 0.355mm to 1mm, with between 1% and 3.5% of the sample composed of trace sediment. As the particle size reduces to very fine sands and silts (<0.125mm), their abundance within the samples at T2 diminishes to levels that are almost undetectable eg. 0.003%. Across the transect, there is similarity in the particle sizes that have the greatest proportions of tracer (1mm to 0.355mm), but T2P3 has a greater amount of tagged sediment in the 2.8 to 1mm size range which is clearly seen in Figure 4.18 a). P3 is located in the portion of the channel that has the highest velocity and therefore transport of the larger tagged particles will be concentrated in this area. T2P5, although having the largest infiltration rate of the four traps, has the lowest proportion of tagged sediment in its composition. This would suggest that in higher flows, the tagged bank sediment is concentrated in the faster flowing section of the channel at T2 and has not dispersed evenly across the profile. This corresponds to the findings of Thorne & Lewin (1979) that material eroded from the outer bank does not tend to cross the channel and is deposited on the point bar face of the next bend downstream. Also T2P5 is on the edge of the inner point bar, where finer sediments from upstream are concentrated in high flows, thus a higher rate of deposition is expected in this trap. Figure 4.18 a) shows trap 5 to have a higher proportion of fine and less coarse tracer, which is consistant with previous trends.



(a)



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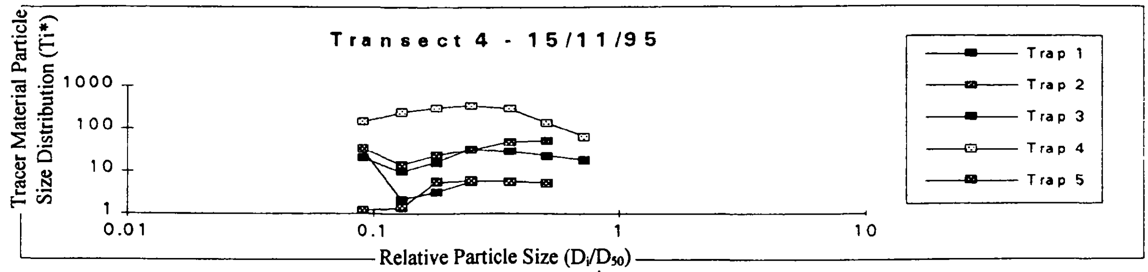

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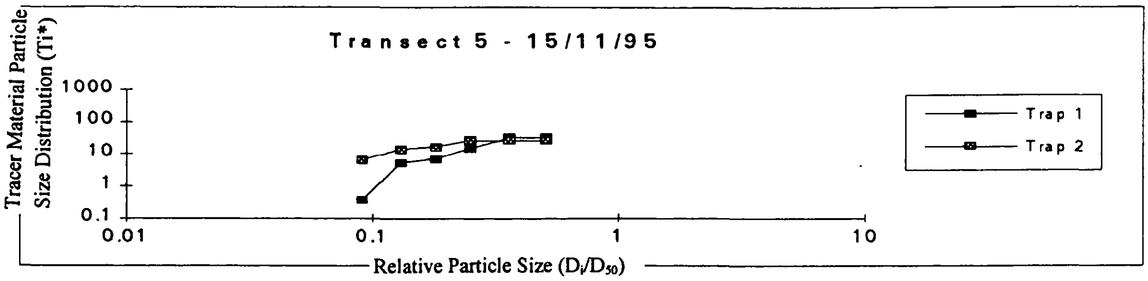

(d)

Figure 4.18 - The normalised fractional trap rate showing the particle size comparison between tagged and non-tagged infiltrated sediment

Transect 3, which is 243metres downstream from the trace sediment source, shows negligible levels of tagged sediment >1.4mm (Figure 4.18 b]). Particles of this size are likely to move as bedload and have been deposited further upstream. The bulk of the trace element in samples at T3 is in the 1mm to 0.180mm particle size range, with minimal levels in both the larger and smaller size ranges. At T3 there is a greater proportion of the sample that is tagged in this size range, than that at T2, especially at trap 5. This could be due to the bulk of the tracer sediment being entrained and transported to the tail of the next point bar downstream, and bypassing most traps at transect 2, as described by Thorne & Lewin (1979). In terms of cross-sectional variance in tracer concentration, there is a significantly larger proportion of particles >0.710mm evident at T3P5 (Figure 4.18 b])). This trap is located in deeper, slower flow and will have facilitated the deposition of these larger particles as the discharge level receded, whilst they would still have been transported at the other trap sites until flow levels subsided further.

The samples from T4 exhibited a further reduction in particle size of tagged sediment in each trap as shown by the truncated curves in Figure 4.18 c). There is also limited amounts of tagged sediment in the very fine size range. There is a notable increase in the particle size of the tracer elements from left to right across this transect as the velocity and depth generally increase in the same direction, which corresponds to the trend at other locations. Also, the curve for trap 4 shows a higher level of tracer infiltration which corresponds to the higher total yield for this trap. This indicates that as infiltration increases a significant proportion of the sediment is supplied by the eroding bank as there are higher levels of tracer in the sample. Finally T5, which is 675 metres downstream from the tracer input point, shows tracer elements only in the <0.355mm size range, with negligible levels <0.090mm (Figure 4.18 d]). No cross-sectional variation is evident here which ties in with the similar physical characteristics of the two trap localities.

Samples from the second sample date, which was 2 months after the first sample was taken and 10 weeks after the tagged sediment was implanted, still had significant levels of tracer incorporated within them. At T2 the size range of fluorescing particles was 1.4mm to 0.250mm, with a similar cross-sectional variation to that of the first sample. T2P3 recorded the largest percentages of fine sediment, with a reduction toward the shallower and slower flowing right bank. At T3, the size range is reduced to between 1.4mm and 0.5mm with no traces of fluorescing particles <0.5mm. Downstream at T4, there is only minimal evidence of tagged sediment in the 1mm to 0.710mm range and this is at T4P5. It was also this trap that received the greatest proportion of larger trace particles in the previous sample. There was no evidence of any tagged sediment of any particle size at transect 5 on this final sample.

The general trend is that fine sediment released from the eroding bank during a flood flow is transported downstream at different rates and the distance travelled is largely particle size dependant. This experiment allows estimation of the distance travelled by different particle sizes and where they are likely to be deposited in a cross-profile. As fine sediment is released from the eroding bank, it is dispersed in the flow but the majority of it remains concentrated in the deeper faster flowing portion of the channel as it negotiates T2. By T3 the particles >1.4mm seem to have been deposited. By T4 (528m), particles >0.500mm have dropped out of suspension and by T5 (675m) only sediment <0.355mm is being transported. The finer elements of tagged material (<0.125mm) tend to be deposited fairly uniformly, although in negligible amounts, throughout the 675metres. It can be said that in this study particles <0.355mm released from the eroding bank are transported at least 675 metres downstream after one flood event, and will infiltrate gravel-beds.

But no indication of the overall downstream extent of bank sediment redistribution can be deduced. It must also be noted that not all the sediment passes through the reach during this first event. It is possible that not all of the implanted sediment was entrained in this first flood event and some still remains at the bank. But it is also evident that some of the sediment (particularly the larger particles) are deposited in the reach and then re-mobilised during subsequent flood events.

CHAPTER 5 - DISCUSSION

By monitoring variations in fine sediment infiltration rates, the sedimentation process in salmon spawning gravels in the Water of Mark has been described, and its contribution to the decline in spawning potential of this tributary can be assessed. Tracing the release of tagged fine sediment from an eroding bank and mapping of its downstream redistribution, allows estimation of the contribution to infiltrating material provided by the eroding bank and provides an indication of its cross-sectional and downstream dispersion. Overall, the significance of bank erosion as a cause of spawning habitat loss in the Water of Mark can be evaluated.

The aim of this chapter is to summarise these results, to compare the findings with those in the literature, and to establish their implications for fisheries management in the Water of Mark. The wider implications of bank erosion, the problems produced by it and its management are also discussed. Finally, the last section of the chapter evaluates the methods used in this study, and suggests areas for future work in this field.

5.1 - CONTROLS OVER FINE SEDIMENT INFILTRATION

Variations in rates and grain size distributions of fines infilling gravel-beds are complex and at the reach scale are controlled by the supply of sediment, the transport mechanism, local hydraulics, flood magnitude and frequency, the dimensions of the interstices between the framework gravels, scour and fill sequences during floods and the reach morphology. This research tries to tie some of these controlling factors together and determine if there is a relationship between them and spatial and temporal patterns of infiltration found in a reach of the Water of Mark.

5.1.1 - Controls on the downstream and temporal variability of infiltration

There was no easily identifiable trend in the variability of downstream infiltration. This is confirmed by the absence of a marked increase in infiltration from T1 to T2, despite the potential source of fine sediment in the eroding bank at the Queen's Well between the two transects. It was anticipated that a distinct increase in infiltration would be recorded at sites downstream of this sediment source compared to the control site upstream. This was not borne out in the entrapment rates recorded across T1 to T5 in this study (Table 4.6).

T4 had an infiltration rate 30% greater than other transects. This is related to a smaller D_{50} than at other sites, which produces a higher void space availability promoting infilling. This is also consistent with the findings of Frostick et. al. (1984) as described previously. But downstream at T5, the D_{50} is almost twice as large but the infiltration rate is similar to T4. This indicates that surface substrate size is not the only controlling factor over infiltration rates. There is no overall downstream trend, but combinations of velocity, water depth and mean surface grain size account for site-specific variations in void space clogging. In this study a figure of 20% was used as a threshold above which void space infilling becomes deleterious, although Hobbs (1937) suggests that even a level of 4% in spawning redds is disadvantageous. Variations in infiltration rates and thus void space infilling along the long profile of this reach can be said to be related more to local variations in substrate size, flow velocity and water depth, than to a long profile trend, with no single parameter being dominant.

In a temporal aspect, the infiltration data (Table 4.7 and Figure 4.7) shows that the rate of infilling declined over the study period, except for an increase in sample 4 (18/9/95) thought to be due to the engineering works. However, by cross-correlating the infiltration data with discharge data for the same period, the pattern of infiltration is somewhat different (Figure 4.8). Sample 3 (31/8/95) had 70% less total infiltration than sample 1 (23/3/95), but the infiltration rate per hour of flood flow during the sample period was nearly 40% higher during sample 3. This shows an increase in infiltration rate per hour of flood flow during the summer months, which indicates that fine sediment is more readily available for infiltration which is similar to the findings of Hall (1967) (Figure 5.1). This could be due to natural processes of fine material eroding form desiccating banks accumulating at the bed surface or erosion of sediment which accumulated elsewhere in the catchment during the dry period. It could also be due to sediment 'sink' disruption due to bed movement during engineering works. Therefore it is difficult to ascertain from this study whether these increased infill rates are a unique event associated with the works, or if they represent normal sedimentation processes. What it does show is that during the summer months there is an increase in availability of fine sediment, which suggests that sediment availability within the river system dominates the downstream rate of infiltration irrespective of framework size and local hydraulics. The temporal variability of sediment infiltration is controlled by the magnitude and number of floods, and also by seasonal variations in sediment supply. Infiltration rates exhibit their highest rates during flood events when sediment transport fluxes are at a maximum.

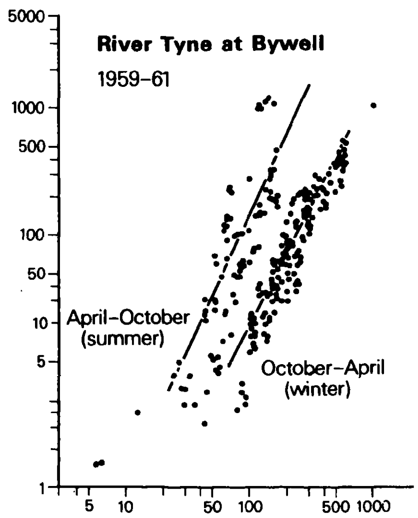

Figure 5.1 - Suspended sediment concentration-discharge rating relationship for River Tyne (source Hall 1967)

After the late summer floods, both the total infiltration rate and the rate per hour of flood flow drop considerably (Figure 4.8), indicating a reduction in sediment availability. Although the eroding bank has been protected thus preventing the release of sediment, this does not seem to be the main reason for this lack of sediment. T1 should have had an infiltration rate lower than the others prior to the works and similar to them after implementation if the eroding bank was the main fine sediment source, but this was not the case. This points to the fact that, although the sediment contribution from the eroding bank has been removed, the sediment load of the river is maintained by sources upstream. The reduced sediment availability during the final two samples can be related to two factors : Firstly, the magnitude of flood events during these final sample periods could have affected the infilling rate, but the evidence from the discharge data shows that there were considerable flood events of long duration which would be expected to facilitate infiltration. This suggests that the trend of infilling decline is primarily related to the second factor, sediment supply, which is controlled by sources upstream. Without investigating further, it is impossible to a give any further explanation for this supply reduction.

5.1.2 - Controls on cross-sectional variations in infiltration

In terms of cross-sectional variability of sediment infiltration, the results highlight the importance of site-specific controls. This study found that infiltration was greatest in shallow regions with low velocity. As depth and velocity increase the trap yield was found to decline which is due to the transport capacity increasing and more sediment bypassing the traps (Figures 4.10 and 4.11). This is in contrast to the findings of Frostick et al. (1984) as they recorded the highest infiltration rates in regions of high velocity (and greater sediment supply). But Carling and McCahon (1987) identified both slack water and high velocity areas as having high infiltration rates. The reason for this is that these processes differ; in slack water infiltration rates are high because the transport rate has declined and the opportunity for deposition is enhanced, whereas in high velocity regions the rate of sediment supply is accentuated. The infiltration rate was not particularly high in faster velocities in this study, which may have been because the size composition of the bank sediment meant that the bulk of the sediment was transported in suspension and did not come into contact with the trap surface in the faster localities or that local supply (from direct erosion from the bed) is reduced in this case.

Generally, infiltration rates are inversely correlated with velocity and water depth, which is similar to the findings of Frostick et al. (1984). They found spatial variation in that there were more fines in pools compared to bars and riffles, whilst for the same cross-section they found that flow concentrated in a narrow thalweg leads to accelerated water velocities and stronger turbulence, a factor shown by Einstein (1968) to limit the movement of sediment through surface pores. Adams & Beschta (1980) found that the percentage of fines within the streambed varied between streams, riffle areas in the same streams and within the same riffle. They also noted that the variation across the channel is typically more pronounced than it is along the channel.

There was also cross-sectional variation in the grain size composition of infiltrated material (Section 4.2.5). Samples were more finely skewed in shallower slower sites at the channel margins, for example T2P5 (Appendix E). This was associated with the fringe of point bars where fine sediment is concentrated in higher flows and it is the area that experiences the least bed reworking so that deposits are more persistent. In contrast, the samples in faster and deeper sites have significantly coarser composition. The infiltrated samples usually contained > 50% of particles > 1mm, although considerable inter-site variation was evident throughout the sample period, reflecting site-specific controls on sediment supply and infiltration rates. The abundance of particles >1mm in the samples can be attributed to the largest particles being transported in suspension through this reach being about 0.8mm. Particles larger than this are considered as bedload and are more available for infiltration than those in suspension. In deeper faster flowing sites high levels of local shear stress keep the suspended sediment clear of the stream bed, thus lower shear stress environments are required for suspended sediment infiltration. The importance of differential transport modes and rates were suggested by Kondolf et al. (1993) by estimating transport rates, suspension criteria and the settling velocities of quartz spheres using shear velocities and the Hjulstrom curve.

As discharge rises, bedload transport increases more in higher shear stress regions so that supply is most abundant in these areas. Consequently, the samples from the fastest flowing sections of the channel are more coarsely skewed. Additionally, as total infiltration declines there is a higher percentage of fines in each sample, especially in the faster, deeper sites ie. lower flows, so less sediment >0.8mm is transported, but some <0.8mm may well be moving as bedload. Lisle (1989) found that in higher discharges, only one fifth of trapped matrix material was suspended sediment, although it formed the bulk of total sediment transport. This was suggested as being due to the bedload being in constant contact with bed pores facilitating infiltration. This indicates that the trap samples do not provide a reliable indication of the particle sizes and general composition of the suspended sediment load of the river. Also, Sear (1993) found that during flood events where both bedload and suspended loads are not supply limited, the formation of surface seals or the turbulent resuspension of finer bedload particles reduces bedload infiltration in regions of higher shear stress. Seals may form when pore diameters decrease at the interface of surface and subsurface sediments due to increased proportions of finer sediments. Thus coarse particles that penetrate between the surface layers may be halted by seal formation. The formation of surface seals reducing infiltration rates is a mechanism identified by Lisle (1989).

As previously described, preferential deposition in normal flow causes finer sediment to be deposited in slacker water, whereas bedload is deposited in higher shear stress areas. But during flood discharges, when both coarse and fine sediment are available for infiltration, the rates are then dictated by the nature of flushing flows (greatest in high shear stress regions) and by the opportunity to deposit in slacker water. The increasing importance of bedload sized particles within infiltrated sediments during these higher discharges has been observed in other studies, and is generally related to the availability of different sediment populations as the flood rises (Frostick et al, 1984; Carling & McCahon, 1987). Post-flood discharges are only competent to transport the finer components, but fine sediment supplies will be exhausted after floods and thus as infiltration is reduced the sample D_{50} is increased as highlighted by the results in section 4.2.5.

To summarise, cross-sectional and downstream infiltration rates are controlled by the relationship between substrate grain size, porosity, local water depths and velocities, as well as external parameters such as sediment supply. However, these controls and the associated variations in infiltration rates that have been identified, operate at different scales (Table 5.1). For example, the variations can be identified at the scale of the whole study, at the event to event scale and also cross-sectional variations in any one event. This gives some indication of the importance of each of the controlling factors that were identified in Chapter 2, with sediment supply and flood magnitude and frequency being the most influential in the long term.

Controlling factor	Annual scale	Event to event scale	Within an event scale
Sediment supply	X	X	
Flood magnitude & frequency	X	X	
Surface grain size		X	X
Infiltrating sediment grain size		X	X
Water velocity			X
Water depth			X

Figure 5.2 - Controlling factors and their influence on infiltration rates at different scales

5.2 - CHANNEL HYDRAULICS AND SEDIMENT TRACING

5.2.1 - Velocity Measurement

Generally, the surface sediment in riffles is coarser than in pools. During low flow, riffles have faster currents over them than pools owing to reduced cross-sectional area. The flow diverges as it negotiates the wider riffles and converges as it approaches the narrower bend. This divergence and convergence induces secondary flow and complex shear stress patterns on the bed as identified by Dietrich (1987). As discharge increases, the relative difference in pool and riffle cross-section area will be reduced, so mean velocities and mean shear stresses become more alike in each section. But the complexity of flow around bends makes accurate measurement of velocities and the subsequent calculation of shear stress levels rather difficult. The surface and bed velocity plots constructed from mean velocity profiles recorded around the bend, allow the flow patterns to be illustrated in a simplified manner (Figure 4.17 a) and b)). When analysed in relation to the cross-sectional surveys, they highlight changes to the flow pattern that is as a result of the bank repair works and give an indication of how any change may affect channel processes around the bend. This aids the evaluation of the effectiveness of the bank revetment and pinpoints areas that receive the bulk of the flow and may be the source of any future revetment failure. Generally, the surveys and the velocity plots show channel narrowing due to the works, which has resulted in the velocity increasing both on the bed and the surface with more of the flow concentrated near the outer bank. The channel is also deeper which could be either natural or artificially induced, but has also aided in concentrating the flow which is shown to have increased bed shear stress levels. This increase in shear stress should cause channel deepening to continue around the outside of the bend, but further lateral erosion of the bank has been prevented by revetment. This confines the flow to a deeper and narrower section which is ideal for adult fish for resting purposes.

5.2.2 - Shear stress and channel roughness

The calculated shear stresses (Appendix D) do not account for any local conditions, such as turbulent fluctuations, due to the averaging process involved. They show an increase after engineering in the outer section of the channel, which is similar to the velocity plots. This is where the surface flow patterns converge causing downwelling, which induces basal toe scour aided by bed flows being directed at the bank. With the installation of 'hard' rip-rap horizontal erosion is subdued and vertical erosion should be accentuated causing deepening of the outer channel which is beginning to be visible on the cross-sectional surveys. This process needs further monitoring to calculate the rate of channel deepening to establish whether it is the channel morphology readjusting to the new bank or is it a natural process of the reach trying to reattain an equilibrium state. Also the bed particles act as frictional roughness elements, thereby affecting streamflow and also more importantly complicating patterns of shear stress. Roughness elements dissipate stream energy, thereby reducing bed shear stress, which in turn reduces the sediment transport capacity. Again, although bed roughness is an important controlling factor, it is shown not to be the sole criterion influencing levels of infilling.

5.3 - FINE SEDIMENT TRACING

5.3.1 - Tracing techniques

The techniques for tracing sediment used previously (Kirk et al 1974, Oldfield et al 1981, Arkell et al 1983 and Leeks et al. 1988) were developed and used in this study to aid in the identification of fine sediment sources, and to determine the routing of fine sediment on its release from an eroding bank by mapping its redistribution downstream. It is seen in the results (Section 4.4.1) that sediment tagged and implanted on the eroding bank is differentially transported and deposited downstream, with its distribution being both particle size dependant and influenced by channel hydraulics. The coarser sizes are concentrated in areas of larger depth and greater velocity although the infiltration rate is relatively low in these regions. At the same time, the sites in slacker shallower water had larger infill rates but reduced amounts of tagged sediment. This indicates that bank eroded sediment is concentrated in the deeper sections of the channel but does not disperse to any great extent as it progresses downstream. This fits the pattern observed by Thorne & Lewin (1979) that eroded sediment does not tend to cross the channel and is deposited on the face of the next point bar downstream, or as Sear (1993) noted, deposition is in pool tails where velocity is reduced. This is shown in the results by a marked increase in sediment in the middle size ranges (0.5 to 1.4mm) deposited at Transect 3 (Appendix D).

The downstream influence of the bank eroded sediment is shown to be at least 700 metres after 3 weeks and up until at least 13 weeks after release. This 700 metres covers a range of morphological features. The tagged sediment that reached T5 had encountered 4 riffles, 4 pools and 2 glides. This sediment routing through the reach depends largely on the discharge pattern at the time of entrainment. It is most probable that the sediment arrived at T5 after a series of mobilising events that allowed the sediment to be transported, temporarily stored and later remobilised, so transporting it through the various morphological features. Hassan (1995) states that bedload transport paths are discontinuous, travelling from riffle to riffle in discrete steps. Therefore when the eroded tracer sediment is entrained, it does not get transported through the reach immediately, but in discrete steps depending on the discharge pattern. This helps explain why there is tagged sediment in the second sample which was 13 weeks after impregnation, although in reduced quantities.

5.3.2 - Eroding bank as a sediment source

By correlating the percentages of tracer in each constituent size range at different locations, with the total amount of sediment labelled with the fluorescing dye, an estimation was made of the importance of the eroding bank as a sediment source. In this experiment 80kg of tagged sediment was implanted at the bank. This 80kg is a relatively small amount of bank material to monitor, when compared with a rough estimate from a previous study of the total amount of material lost from this section of eroding bank over a 9 month period, as being about 11 tonnes (Smart 1994). However, the relatively small amount of tracer sediment has contributed a significant proportion of the infiltrated material in the sediment traps, and its downstream redistribution is over a wide and dispersed area. This downstream depositional pattern is dependant on variations in transport rate at the time of entrainment and highly local flow conditions at each trap surface. This indicates that the release of large amounts of fine sediment from the eroding bank at Queen's Well, is a significant contributor to the level of fine infiltration of potential spawning beds and has a downstream influence of at least 675 metres. Nevertheless, there appear to be sources of fine sediment upstream of this eroding bank, as the total infiltration at the control site T1 shows a similar declining pattern throughout the study period, but rates of sedimentation are at the same level (Figure 4.10). This indicates that although a significant source of sediment has been removed by engineering, the sediment load of the river is still maintained by other sources upstream. In terms of the significance of the eroding bank as a source of fine sediment infilling gravel-beds downstream, it can be seen as a substantial provider of fines to the sediment load of the river at this location.

5.4 - IMPLICATIONS FOR FISHERIES MANAGEMENT

This research has addressed some of the problems that are being encountered on the Water of Mark which are known to be similar to those found on upland spawning tributaries in other river systems within Scotland. The problem of the loss of both the quality and quantity of salmonid spawning and rearing habitat is now being addressed by fisheries managers, although in a fairly ad hoc and piecemeal fashion in some systems. There are fisheries organisations that are tackling the problem as far as their limited staff and budget allow, but the extent of the problem in some systems will require years of restoration and improvement.

In the case of the Water of Mark, the District Fishery Board is trying to address the problems that have been identified as being detrimental to the recruitment of young salmon to the population of the river. These problems are loss of adult holding facilities for spawning fish due to channel widening and pool infilling and also the clogging of spawning gravels by fine sediment thought to be derived from several areas of eroding bank material. The Habitat Improvement Programme implemented in the summer of 1995 is aimed at addressing these two problems. Parts of this study provide some form of progress report on the efficacy of the project and can be used as part of the programme of post-implementation monitoring which is vital to the longevity of the habitat restoration.

The bulk of the project involved regrading the badly eroding banks and protecting them with large locally derived rock to prevent the progression of lateral erosion and subsequent channel widening and to preclude the eroding bank as a source of fine sediment. This study provides an initial indication on the success of the bank protection in preventing channel widening and monitors any changes, both expected and unexpected, in channel hydraulics, channel morphology and sediment transport. The problem that has been addressed in this work is that although the bank has been removed as a potential sediment source, there are likely to be other sources of considerable size, both within and outwith the confines of the channel, and thus the sediment load of the river may be maintained by these sources and the problem of clogging could prevail. The direct effects of the bank protection are : immediate prevention of further lateral erosion; the removal of a considerable source of fine sediment; the concentration of the bulk of the flow towards the outer bank which increases depths, velocities and shear stress; and the subsequent deepening of the channel in this outer section by vertical scour. This has increased the morphological diversity and therefore the habitat provision in this reach of the river, which is a major benefit for fisheries purposes.

The morphological and process changes to the channel over the 12 month study period have considerable implications for fisheries management. The rate of channel change over the first six months of the study under normal conditions was found to be relatively low. There were periodic and highly local slumping events that altered the bank profile at some transects around the bend with minor levels of aggradation on the opposing point bar face. The rate of bank retreat was found to be slower than that in a previous study and the calculated loss of mass from the bank was subsequently reduced for this second period. It can be seen from historical sources (Appendix A) that over the past 130 years this reach has been active and the channel has migrated across the valley floor. The rate of retreat was recorded as approximately 1m per year (Shearer 1993) between 1972 and 1990. It is difficult to establish whether the present reduced rates are due to one of the study periods experiencing abnormal conditions, due to the reduced length of the bank monitoring in this study or if the most recent figures are indicative of the onset of an equilibrium state within the reach. Only further surveying would have proven one of these presumptions. But the installation of bank revetment at this site 'should' have halted erosion, so no further assumptions can be made as to what was occurring naturally around this bend.

An estimation of the efficiency of the revetment can be made. Firstly, the rock revetment is aimed at preventing further fine sediment release from the eroding bank, which it has achieved. However, this study has shown how the sediment load of the river is maintained by other sources upstream, so the problem of fine sediment infiltration is unlikely to have been removed. This can only be addressed by further monitoring of sedimentation rates and investigation into other potential sources. This being said, the removal of this particular bank source can only be of benefit to the overall sediment regime of the reach downstream, and although not eradicating the problem it should have contributed to its amelioration.

Secondly, the revetment is designed to prevent the progression of lateral erosion which should reduce the channel width and provide deeper water capable of supporting spawning adults. Again, there is evidence to suggest that it has achieved this, supported by the cross-sectional survey data. Channel narrowing has concentrated the flow adjacent to the now protected outer bank which was illustrated by the velocity plots of the reach (Figure 4.22 (a) and (b)). This concentrated flow has also been shown to have increased bed shear stress levels, especially in this outer bank zone which has promoted bed scour and the deepening of the channel. This is an important indicator of the effectiveness of the bank protection, as it has prevented lateral erosion which causes channel widening, but has increased vertical erosion with the subsequent channel scour and pool deepening being a major advantage in the provision of adult salmonid habitat. However, excessive scour of the bed may eventually undermine the rock revetment protecting the bank causing them to alter their location. This slight movement of the rocks could allow the flow to penetrate between the rocks to the finer bank material behind, which may lead to the release of the fine material from behind the retaining rocks and the eventual collapse of the bank behind. This process is already evident at one or two locations in the bank work after only one season of winter discharges (Plate 5.1). As this progresses it may ultimately leave the large stone protection stranded in mid-channel as lateral erosion is re-commenced as shown in the Plate 5.2.

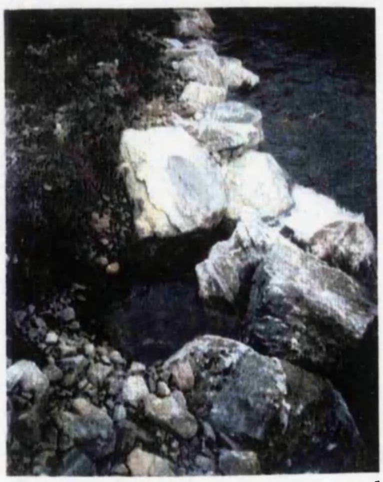

Plate 5.1 - Erosion behind revetment on the Water of Mark.

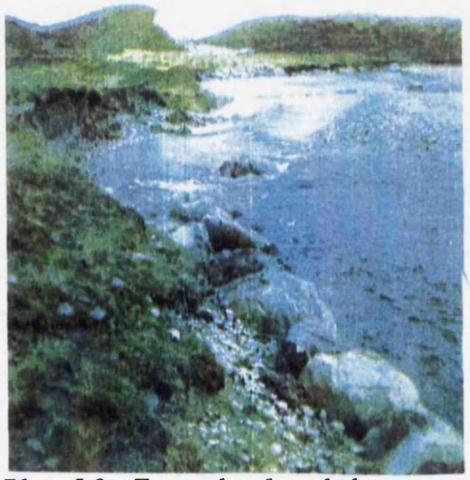

Plate 5.2 - Example of eroded revetment on the River Thrail.

This process of fine sediment release from behind the rock revetment could have been prevented by using a geotextile material such as Terram™ in the construction phase (Hoey et al, 1995). When placed under revetment, geotextile acts as a filter layer preventing loss of fine material and allowing plants to re-establish between the stones. The binding action of the roots consolidates the material behind the retaining stones and stabilises the bank. By not using a geotextile the bank is more vulnerable to flows penetrating the gaps between rocks and there is a chance that the backfill may be progressively removed over time, causing bank failure. In terms of the overall success of the bank revetment, it will be necessary to assess the effects of the work over a longer period of time than this study allowed. The 7 to 8 months that have elapsed since the work was finished, can be seen as a settlement period in which the river is re-adjusting to the new constraints imposed upon its natural processes. It is for this reason that it is difficult to establish whether the channel deepening that is evident at present is just a settling process or whether it is likely to be a long term process. The work has endured the first major flood events of its life and has only shown minor weaknesses at certain locations. With constant monitoring the repair of any damage , the stability of the work can be ensured so as the revetment survives its design life. Overall, it has addressed the problem of the lateral stability of the reach, but it has not prevented fine sediment infiltration.

The aims and objectives of this study were directed at providing a site-specific picture of sediment contributions, quantifying the significance of bank erosion in degrading spawning gravels and assessing the effectiveness of bank repair work in remedying the situation. This was the focus for this study as it was thought to address the most important problem being experienced in this tributary. It does not mean that by preventing bank erosion alone, salmonid habitat will be completely revitalised, as other enhancement methods such as re-vegetation of both the riparian and marginal zone, creation of fenced ungrazed corridors and instream control structures are all important parts of habitat improvement schemes that cater for the 'complete' habitat

5.5 - RESEARCH DESIGN AND METHODS

5.5.1 - Research design

The two most important factors in the degradation of salmon spawning habitat in upland gravel-bed rivers were identified in Chapter 2 as channel widening and fine sediment infiltration, which are both consequences of bank erosion. The processes and mechanisms of bank erosion are well documented and were only briefly mentioned and referenced in the review chapter. The resultant channel widening process is relatively straight forward and remedial measures have been identified previously. Similarly, the problems of infiltration have been realised for many years, but there is a perceived increase in infiltration rates in many rivers due to enhanced sediment supply from changes in factors such as land use, climate and rainfall intensity.

The review chapter identified a lack of work on the sources of fine sediment found in gravel-beds (often assumed to be derived from local bank erosion) and the controls on rates of infiltration at different localities. Bank erosion is commonly presumed to be the primary supplier of fine sediment, but there appeared to be little quantitative data available to allow an estimation of its contribution to the sediment load of the river and how the sediment eroded from a bank is redistributed downstream. Also, given the wide range of factors that have been identified as controls on infiltration rates and the site-specific nature of many of the results, the design of this study was found to have several in-built limitations. In future work it may be advantageous to modify the research design by reducing the controls to be investigated and to undertake experiments on several different reaches in different river systems.

5.5.2 - Methods

As often noted previously (Kirk et al. 1974, Arkell et al. 1983 and Leeks et al. 1988), there are problems involved with the trapping and tracing techniques presently used in fluvial environments, especially those of high energy and dynamic nature in upland regions. The main problem encountered in this study is the design limitations attached to sediment traps in unstable gravel-bed rivers. Firstly, (apart from digging them in by hand) there is the problem of them remaining in location for a 12 month period and being able to withstand considerable discharges. Although this was relatively successful in this study (95% recovery rate compared to only 26% in a previous study [Smart, 1994]), the loss of T2P2 reduced the accuracy of the data and introduced the need for estimation and averaging. Secondly, the traps only permitted vertical ingress of fine material. They did not allow any horizontal infiltration or movement of fine particles subsequent to penetration of the stream bed which is a response to weak intersticial currents. This must be borne in mind when interpreting the results as it may have distorted the infiltration rates. Carling (1984) found in a flume study that impermeable traps reduced trapping efficiency by up to 62%, whereas Lisle (1989) in a field study, found a 3% increase in the amount of infiltrated sediment in an impermeable trap. It is also known that intragravel sources of infiltrated sediments are particularly important for finer grain sizes, which may account for the coarse skew in most of the trap samples in this study. Sear (1993) recorded a 20-25% reduction in trapping efficiency for impermeable traps compared with permeable traps, which suggests that approximately one-quarter of infiltrated sediments are derived from intragravel motion. Thus intragravel sediment routing is an important process to acknowledge and if it had been accounted for in this study, the results may have been differed and thus altered the interpretation.

Another limitation of the traps are that they provide increased bed surface stability compared with the surrounding bed surface. They prevent any bed mobility, which will alter infilling patterns as bed mobility has been shown to increase the rate of infiltration and alter the grain size composition of the samples. Traps can also alter the flow field and flow conditions above the trap surface so affecting depositional processes. Another problem, is that when the traps are emptied of fine sediment and re-set for the next sample period, this is in effect equivalent to a 'flushing' flow removing the fine sediment reservoir. Thus the trap infiltration rates are different to that of the gravel framework around it as it has experienced this extra 'event'. This is an important factor to consider, as it mimicks the removal of fine sediment from gravel framework material during the spawning process. Experiments that investigate both disturbed and undisturbed infiltration rates would aid in the understanding of modification of bed composition by spawning adult salmon.

The tracing techniques and methods of quantifying percentages of tracer material could also be made more efficient. Ultimately, it would have been preferable to use superparamagnetic enhancement and tracing the particles with a magnetic susceptibility meter similar to Oldfield et al

(1981) and Arkell et al (1983), or even using magnetic separation of the retrieved samples to quantify percentages of tracer by mass. This was would have removed some of the problems encountered using fluorescent tracer, such as particle size alterations due to aggregation and quantification techniques, but it was proven to be unfeasible. Implanting tagged material at the bank could also be modified to simulate natural bank collapse. The tracer in this study would have been gradually entrained as discharge rose due to it being placed on the bank, which models winnowing of the bank sediment and gradual removal from the bank, whereas the majority of sediment input from the bank in its natural state is by sporadic bank overhang toppling and subsequent bank collapse. This injects a sediment 'slug' into the channel unlike the tracer sediment. This 'slug' may differ in its transport and sediment delivery to potential depositional areas downstream so altering its redistributional pattern. Therefore, other studies may need to appraise more efficient methods of tracer impregnation so that it mimics a 'slug' or pulse of sediment release.

5.6 - FUTURE RESEARCH

This study has investigated and appraised some of the problems being encountered in the Water of Mark, and given a quantitative analysis of the significance of bank erosion. Other areas within this field have been identified to be in need of more detailed analysis. The most important factor that has emerged that this study did not take into account, is that of horizontal movement of intragravel sediment in framework gravels. The use of impermeable traps in this study prevented any horizontal infiltration which is due to weak interstitial currents. This interstitial current is vital to the survival of incubating salmonid eggs as mentioned in the review chapter. This requires revised design of sediment traps to allow both horizontal and vertical infiltration. This may prove to be difficult due to the problems that would be encountered when trying to empty and reset the traps, such as the loss of some sediment as the trap is removed and emptied.

Work by Lisle (1989) and Diplas & Parker (1992) on the infiltration of sediments and their depositional variations in the vertical dimension could be furthered. There is an opportunity to quantitatively analyse characteristics such as vertical size sorting and the formation of seals and sediment layers, if the vertical structure of infiltrated sediments can be preserved on retrieval. This could aid in linking laboratory flume and modelling work previously undertaken (Diplas & Parker 1992; Alonso et al. 1988), to work being carried out in the field (Frostick et al. 1984). The sediment tagging and tracing technique could also be developed and improved along with the quantitative analysis of bank contributions to the sediment load of the river. The process of quantifying proportions of sediment samples using image processing, manipulation and analysis software that was set up in this study could also be further developed to improve both the quality of the images and the accuracy of the image threshold analysis operation. This computer analysis technique could also have other applications in research, such as the estimation of percentages of surface pores in gravel beds of differing framework grain size, which is very important in the understanding of infiltration.

Finally, from a site-specific viewpoint, there is scope for on-going work to be carried out on the Water of Mark, particularly a more detailed and wide ranging investigation into the sources of fine sediment within this part of the river system. Hassan (1995) suggests likely sources for bedload and suspended load for gravel-bed rivers and divides them into internal and external sources (relative to the channel). This type of analysis of sediment supply could be applied to this catchment, thus giving a more scientifically based evaluation of sources of fine sediment that are believed to be detrimental to the gravel spawning beds. This would give a broader picture of sediment storage and supply in the area, rather than simply presuming that bank erosion is the primary contributor, and it gives a superior basis for catchment management for fisheries purposes

CHAPTER 6 - CONCLUSION

The central theme that formed the basis of this research was :

> ***to ascertain and evaluate the direct consequences of river bank erosion on the quantity and quality of salmon spawning beds in an upland gravel-bed river.***

Investigating this central theme was carried out by undertaking a series of specific aims that were stated at the outset of this piece of work. Each aim was examined individually and an attempt was made to try and tie them together as a coherent unit in the results analysis chapter, thus serving as an overview of the processes occurring at this site. The aims were designed to be progressive steps towards an understanding of the geomorphological, sedimentological and hydrological processes occurring at this location. They also provided some quantitative indication of the level of gravel-bed degradation occurring in this reach and a suggestion as to what the primary sources of the problem are.

The specific aims allowed the pattern of sediment infiltration in this reach to be identified and the nature and influence of controlling factors on this pattern were established. The direct consequences of bank erosion were evaluated by determining where eroded bank sediment is redistributed on its release, which was done by developing and implementing trapping and tracing techniques. This then allowed an estimation of the significance of eroding banks in clogging gravel-beds to be evaluated in terms of its contribution to the total sediment load of the river. The effects of bank revetment as a measure to eradicate the bank as a sediment source could then be determined as to their efficacy and suggestions as to the future management of the river for fisheries purposes could be provided. To this end, the aims of the research have been achieved.

6.1 - Controls on fine sediment infiltration

The research has identified that there are several physical factors which control the infiltration of fines into gravel-beds. These were found to be;

sediment supply
magnitude and frequency of floods
distance from sediment source
water depth
gravel-bed surface grain size
infiltrating material grain size
water velocity

The interaction of these dictates a complex pattern of sediment infilling and matrix development. Any trend that may have been detectable might have been masked by the intensity of highly local conditions at each trap surface, such as turbulence that can affect the trajectories of fine grains and their depositional settling patterns into gravel-beds. But it is also shown that infiltration rates are largely dominated by sediment supply control. As a result, the level of intersticial fine sediment infilling within this reach is largely associated with sediment availability within the catchment, both within and outwith the channel. The actual process of infiltration is conditioned by the flow regime and the frequency and magnitude of floods, irrespective of the availability of fine sediment, as this controls the delivery of sediment to depositional areas. The size and the source of infiltrated sediment is dependant on these discharge levels and the depositional variations are locally controlled by site specific conditions.

6.2 - The contribution of bank erosion to habitat degradation

The direct consequences of bank erosion in terms of effects on salmonid habitat are shown to be channel widening and shallowing and gravel bed siltation. The actual contribution of bank eroded sediment to gravel infilling was found to be significant, both locally and further downstream. But, the problems of habitat loss and degradation may not have been fully addressed by the bank revetment work. Stabilisation of the reach has been established at present, although the longer term stability and the longevity of the bank work can only be assessed by post-implementation monitoring. This stabilisation should prevent further channel widening, but channel deepening has been initiated which is of benefit to fisheries, as long as it does not undermine the revetment. In this respect, although the bank work has been successful presently, its success in reducing sedimentation in the long term has been difficult to assess.

6.3 - The effects of bank protection on sediment infiltration rates

It has been shown that reduction in gravel-bed infilling cannot be achieved by stretches of isolated bank protection alone. Sediment sources and 'sinks' further afield must be identified and their contribution to the sediment load of the river estimated. As previously mentioned Hassan (1995) suggested that sediment supply can be split into two categories of bedload and suspended load, which can be sub-divided further into external and internal supplies (relative to the channel) and these need to be investigated collectively to understand sediment loads in rivers. The sediment transfer mechanisms from the initial source into the river also need to be considered, which includes rapid mass movements or episodic failures such as debris flows or slides, rockfalls or slides. Also surface processes such as rainsplash, slopewash, wind transport, animal tracking, mini avalanches and creep processes such as slow mass deformation, wet-dry and freeze-thaw induced settlement are all important factors controlling the sediment supply and consequently the sediment load of the river. This means that a project plan with a wider scope than remedial bank work must be formulated and initiated which addresses collectively the problems of sediment sources, transport, delivery and deposition and how they can be controlled on a catchment scale. Therefore, the research has identified that problems of spawning bed infilling must be tackled in a more holistic manner and not as a just local point source problem.

6.4 - Applications in other catchments

In terms of applying the findings of this research on the Water of Mark to other rivers, there must be some caution. The problem with research in fluvial environments is that the precise morphology of every river reach is both varied and indeterminate because it is the result of a combination of controls unique to that reach, such as the channel boundary material and its composition and the history of flow events experienced at that reach. Although the exact morphology of each reach is different, the processes involved in their evolution are similar. Therefore, any attempt to produce general descriptions for flow patterns, sedimentation variations and morphological formations have to be limited to the major features and avoid the unique details and peculiarities that are associated with each reach. This limits the implications of this research to within the study area, although it does provide a basis for initiating a wider understanding of river processes at a catchment scale and highlights the importance of involving a greater geomorphological input into projects that involve modifications to natural river processes.

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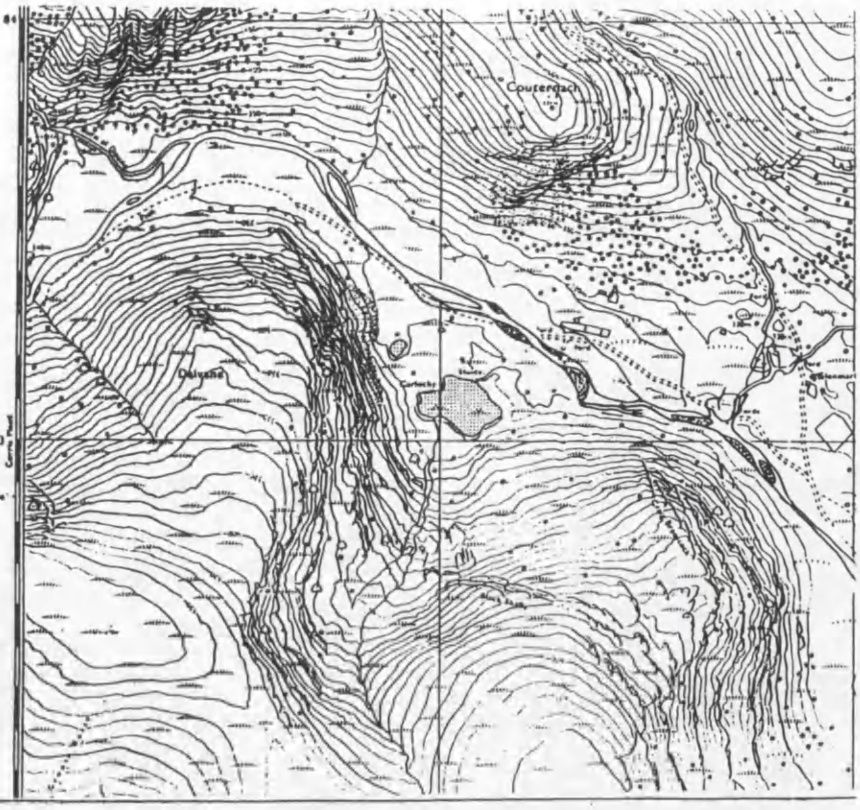
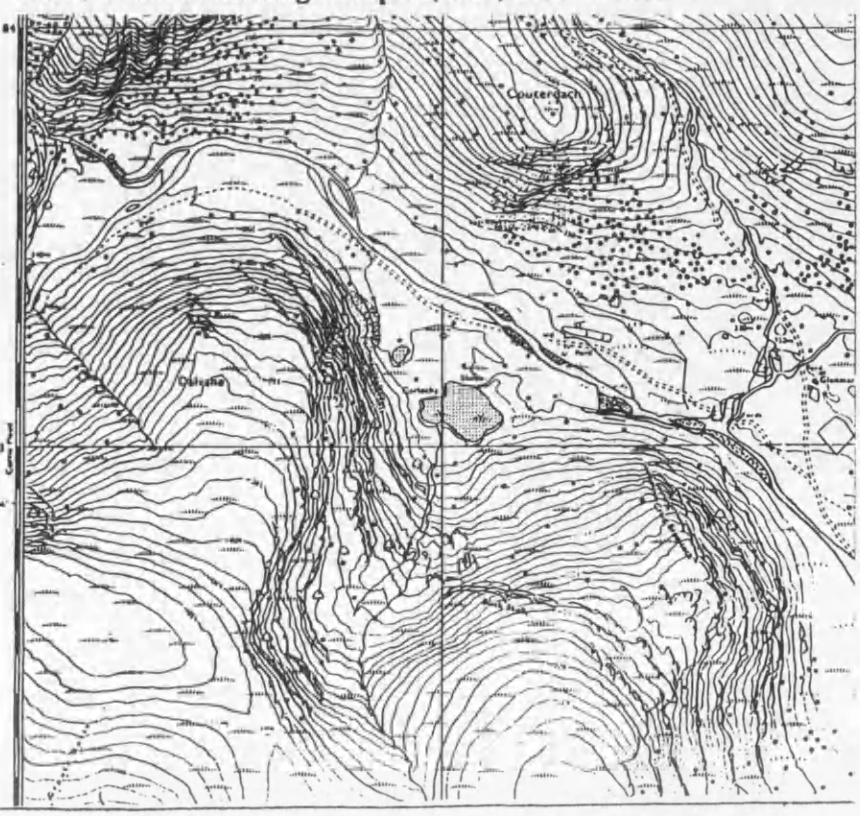
APPENDIX A

Historical maps of river channel dynamism the Water of Mark from 1862 to 1988



River Channel Change Map 6 (1862): 1st Edition OS 6" series



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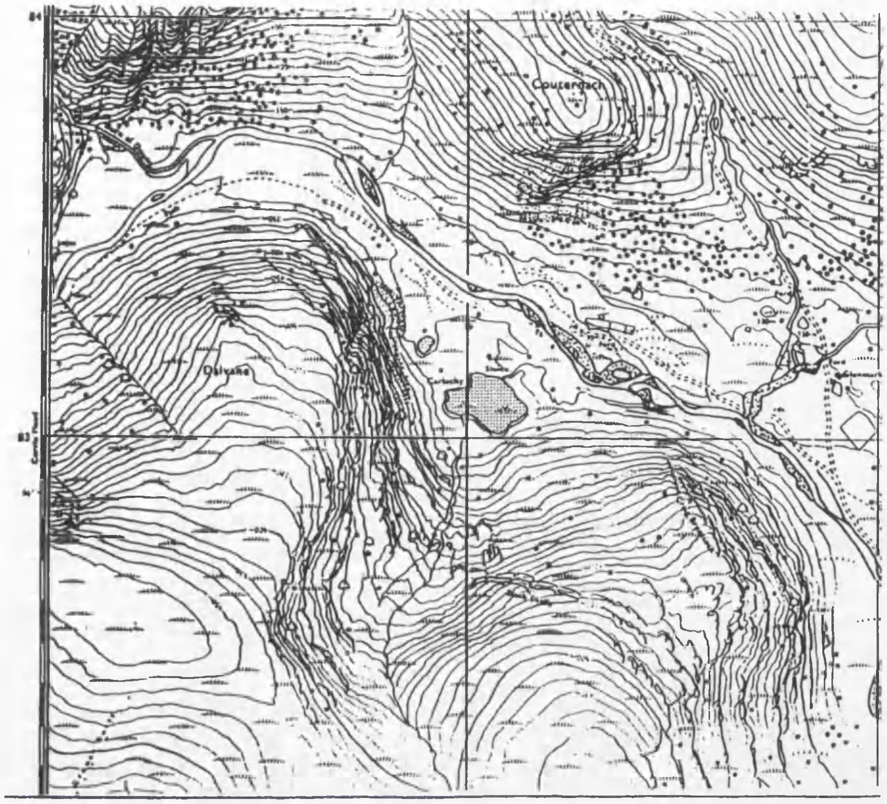
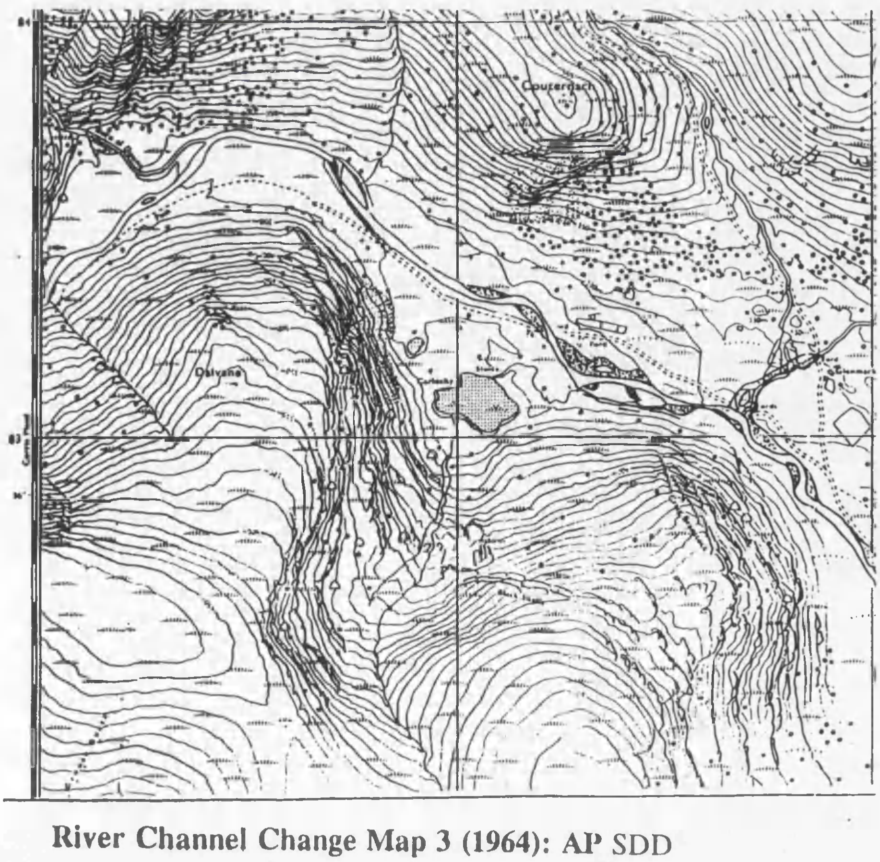
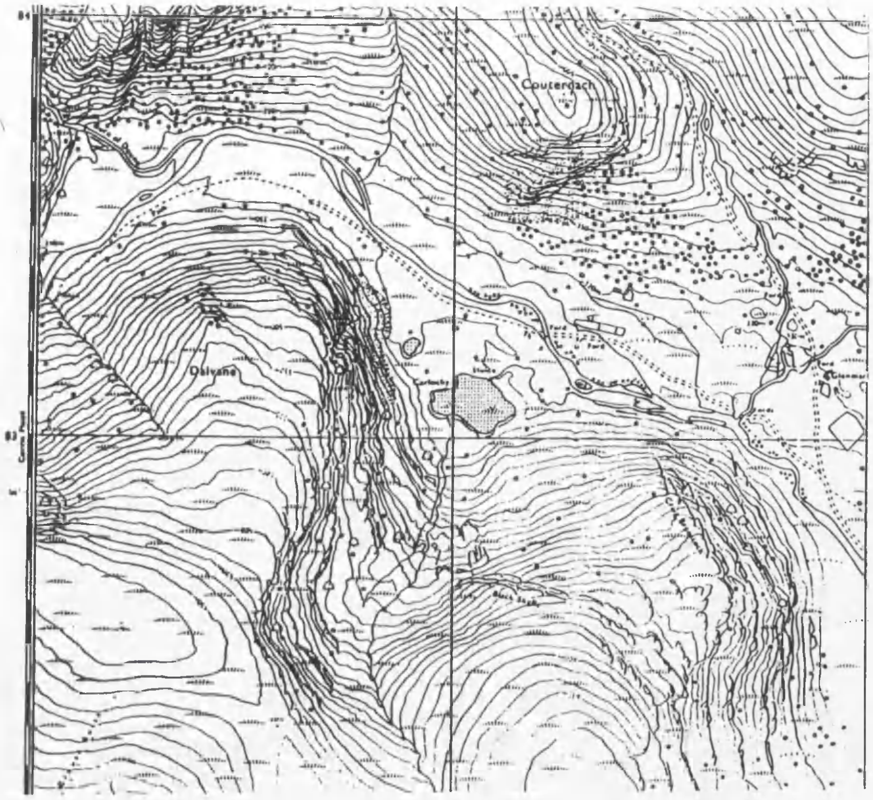


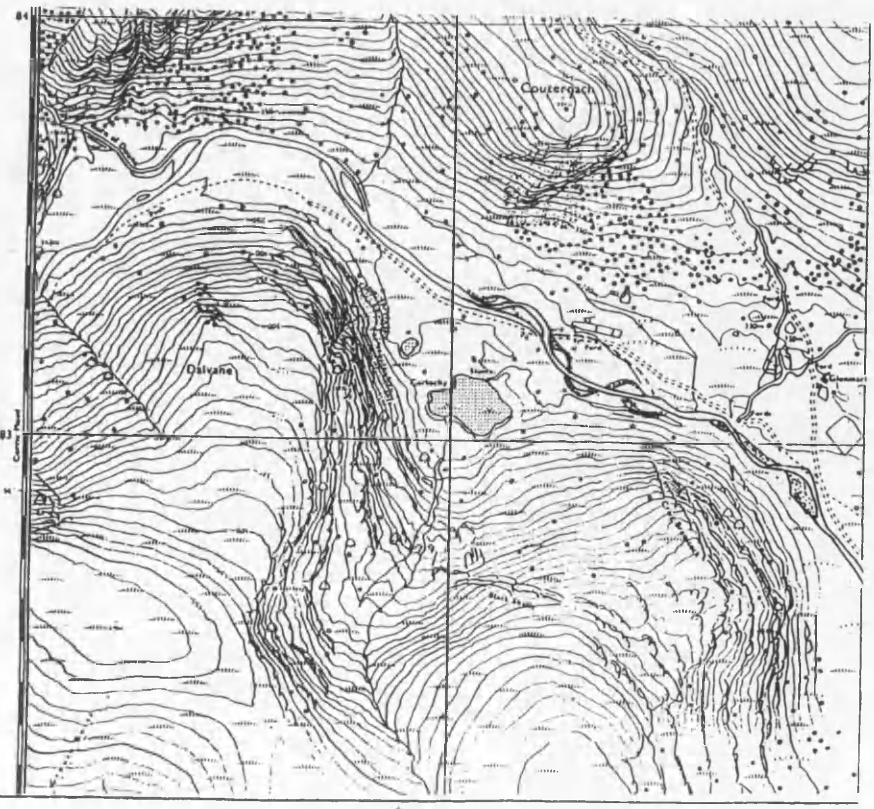
River Channel Change Map 4 (1946): AP RAF



River Channel Change Map 3 (1964): AP SDD



River Channel Change Map 2 (1969): OS resurvey, revised 6" series



River Channel Change Map 1 (1988): AP SDD (1988/256)

APPENDIX B

1 - Web site address for NIH Image

NIH Image is a public domain freeware package developed by the United States National Institute of Health and available from the Internet by anonymous FTP. The address is :

zippy.nimh.nih.gov

It is also available on floppy disc from the National Technical Information Service, Springfiled, Virginia part number PB95-500195GEI. The address for the NIH Image home page for more information is : *http://www.rsb.info.nih.gov/nih-image/manual/contents.html*

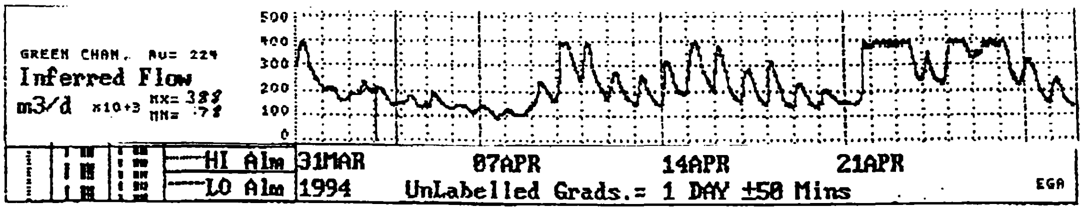
2 - Web site address for EXECUTOR

The address for information on EXECUTOR the Macintosh emulator software is:

http://www2env.uea.ac.uk/gmmc/index.html.

APPENDIX C

Example of Teletrend print outs of discharge for Water of Mark



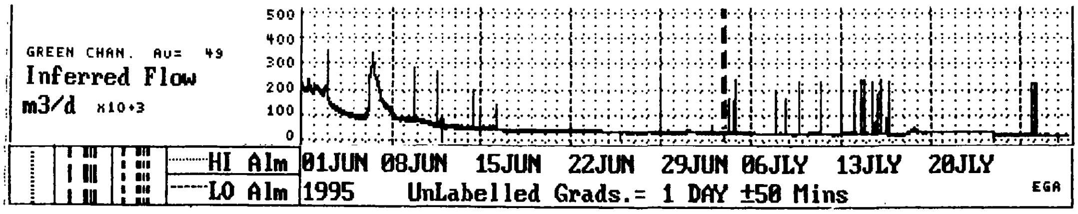
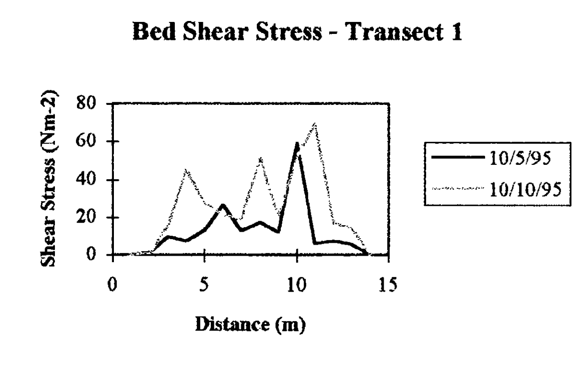


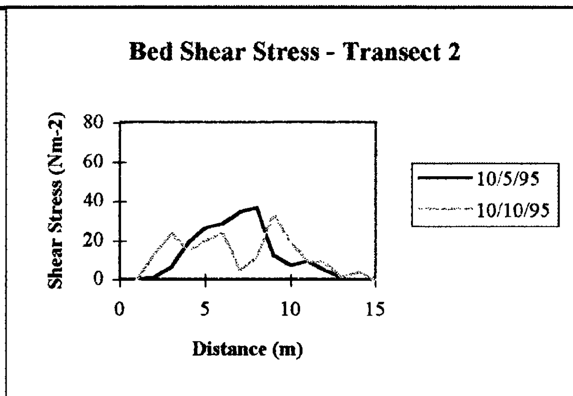
Table 4. ***Discharge ($m^3 s^{-1}$) on days of velocity readings***

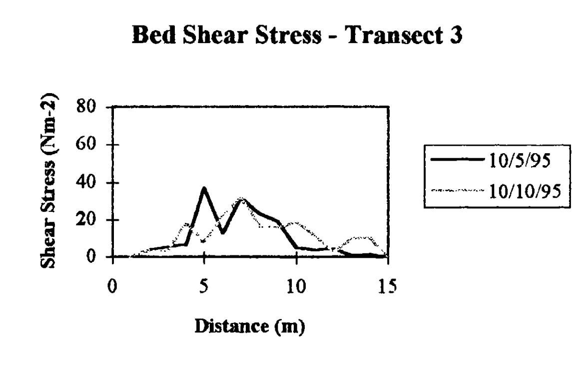
TRANSECT	DISCHARGE 10/5/95	DISCHARGE 10/10/95
T1	1.42	1.89
T2	1.38	1.57
T3	1.13	1.29
T4	0.83	1.23
T5	2.48	1.17
T6	1.34	0.84
T8	1.00	0.97
T10	1.48	1.38
T12	1.54	1.33
T14	1.22	1.15/s
T15	1.76	1.23
AVERAGE	1.42 m^3s^{-1}	1.27 m^3s^{-1}

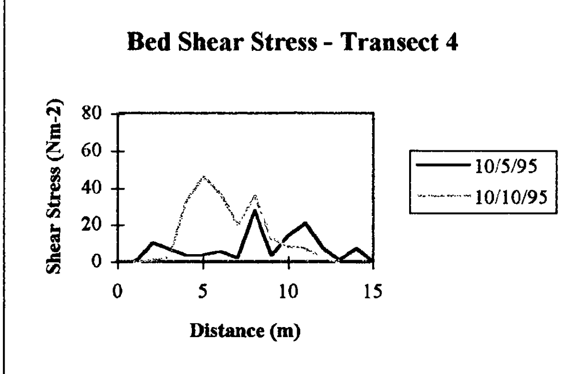
Both of these readings were taken in periods of normal flow which registered as 5.0 and 5.1 on the stage recorder located at the flume/fishcounter at Invermark. The discharge data provided by TRCWSD shows that the Water of Mark experienced flood peaks over $60m^3/s$ on 15 occasions throughout the study period. Most of these were of short duration (24-36 hours), except a prolonged peak of 4 or 5 days in length in early September 1995 and early January 1996.

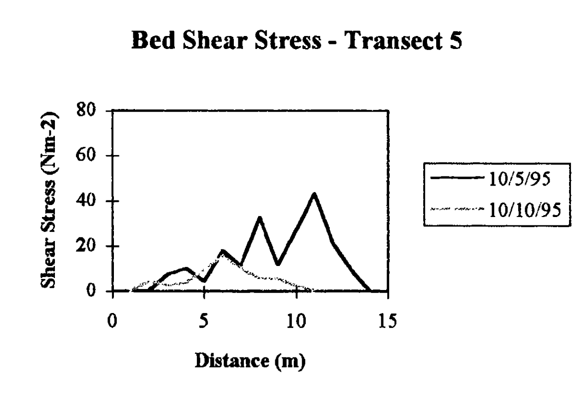
Shear Stress plots for the study reach before and after engineering

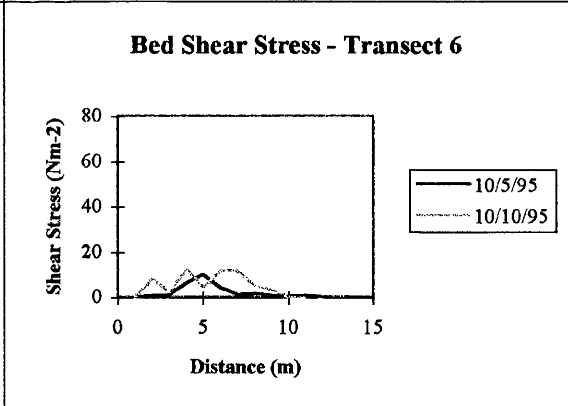


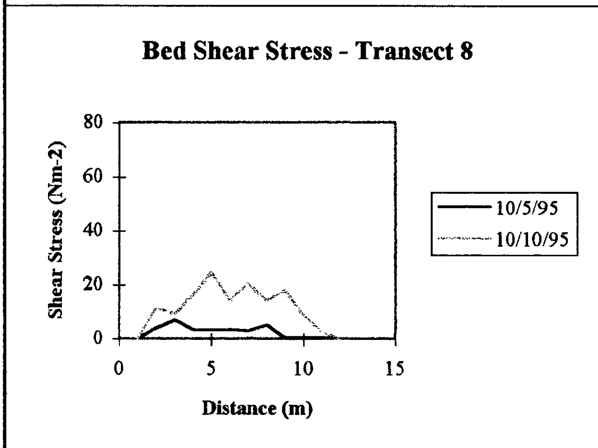


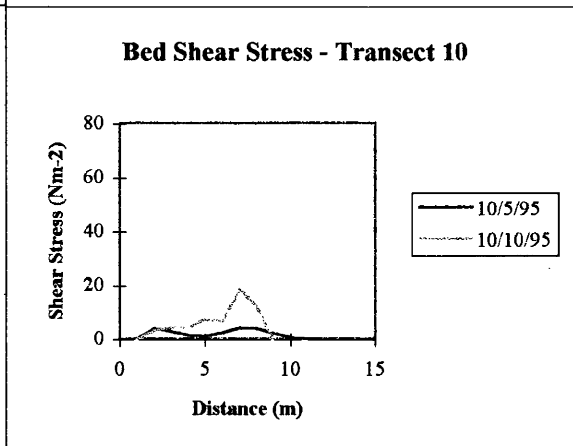


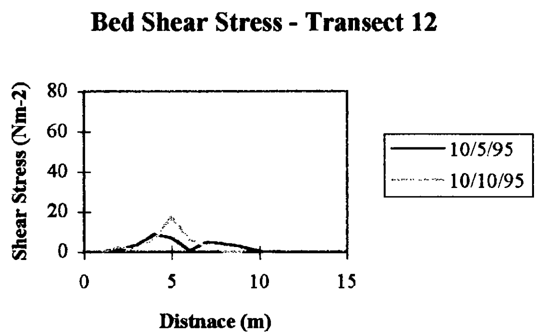


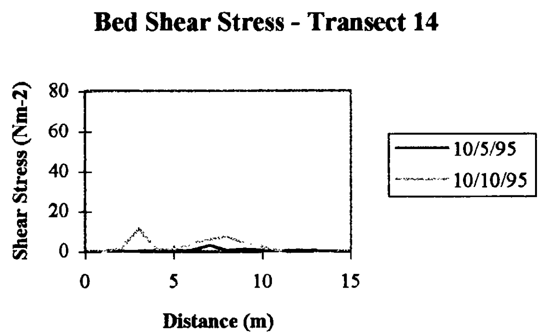


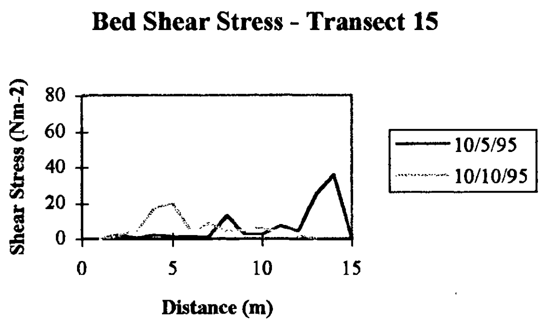







Bed Shear Stress - Transect 12
Shear Stress (Nm-2)
80
60
40
20
0
0
5
10
15
Distnace (m)
10/5/95
10/10/95


Bed Shear Stress - Transect 14
Shear Stress (Nm-2)
80
60
40
20
0
0
5
10
15
Distance (m)
10/5/95
10/10/95


Bed Shear Stress - Transect 15
Shear Stress (Nm-2)
80
60
40
20
0
0
5
10
15
Distance (m)
10/5/95
10/10/95

APPENDIX D

1 - Width:Depth ratio calculations for bankfull stage

	Before Engineering	After Engineering
Transect 1	23.3	23.3
Transect 2	20.9	17.5
Transect 3	23.7	18.7
Transect 4	20.7	16.0
Transect 5	23.4	17.4
Transect 6	21.4	18.9
Transect 7	25.0	24.3
Transect 8	29.4	25.6
Transect 9	32.3	29.6
Transect 10	26.4	24.1
Transect 11	24.8	23.5
Transect 12	25.7	23.6
Transect 13	27.9	21.7
Transect 14	21.8	21.4
Transect 15	32.5	27.8

2 - Example of the calculations for estimating mass of bank loss

The Prism Formula is :

$$V = \frac{h_i \,.\, r_i \,.\, L\,(2 + a + b + 2ab)}{6}$$

where V = Volume lost

h_i = vertical distance between each pin at one end of the section (0.5m)

r_i = overall retreat rate of pin at same end of the section

h_j = vertical distance between each pin at the other end (0.5m)

r_j = overall retreat rate of pin at the other end

L = distance between each set of pins ie.length of section (10m)

$a = h_j / h_i = 1$

$b = r_j / r_i$

therfore :

$$V = \frac{50 \times 6.2 \times 1000\,(2 + 1 + 2.26 + 4.52)}{6}$$

$$V = \frac{310000 \times 9.78}{6}$$

$$V = 505300\text{cm}^3$$

Mass = Volume x Bulk Density

The bulk density of the bank material was calculated for a previous study (Smart, 1994) by using a core sampler. Volume of the core sampler 939.7cm^3 and the mass of material in the sampler 1.447kg allow bulk density calculations.

$$\text{Mass of material lost} = \frac{505300\text{cm}^3}{939.7\text{ cm}^3} = 537.72 \times 1.447\text{kg}$$

$$= 778\text{kg}$$

Therefore the mass of material lost for this section is ***778kg.***

3 - Calculations of percentages of void space infilling

The volume of the sediment trap is 3500cm^3

The percentage void space within the gravel-beds in this reach are calculated at about 28%

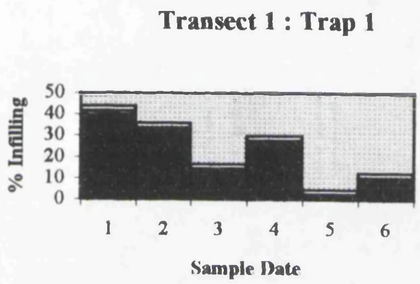
28% void space in the trap = (3500 / 100) x 28 = 980 cm^3

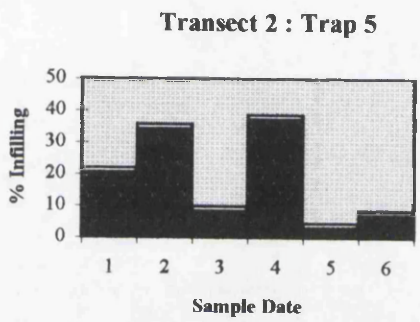
The volume of fines $= \dfrac{\text{mass of fines}}{\text{density}}$ where density $= 2.338$ g/cm^3

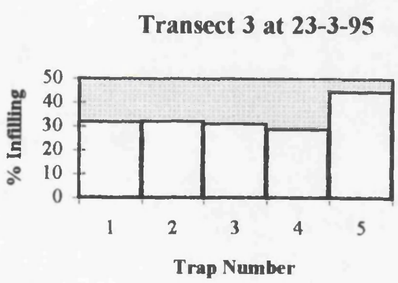
Therefore for T1P1the percentage of fine infiltration is:

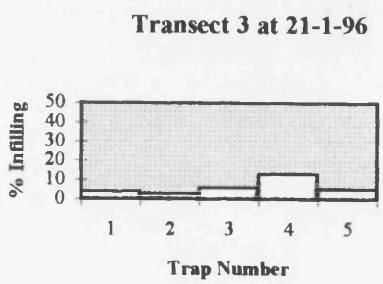
: $\dfrac{991.5\text{g}}{2.338} = 424.1$ cm^3 so $\dfrac{424.1 \times 100}{980} =$ ***43.1%***

Graphs of percentage voids infilled









APPENDIX E

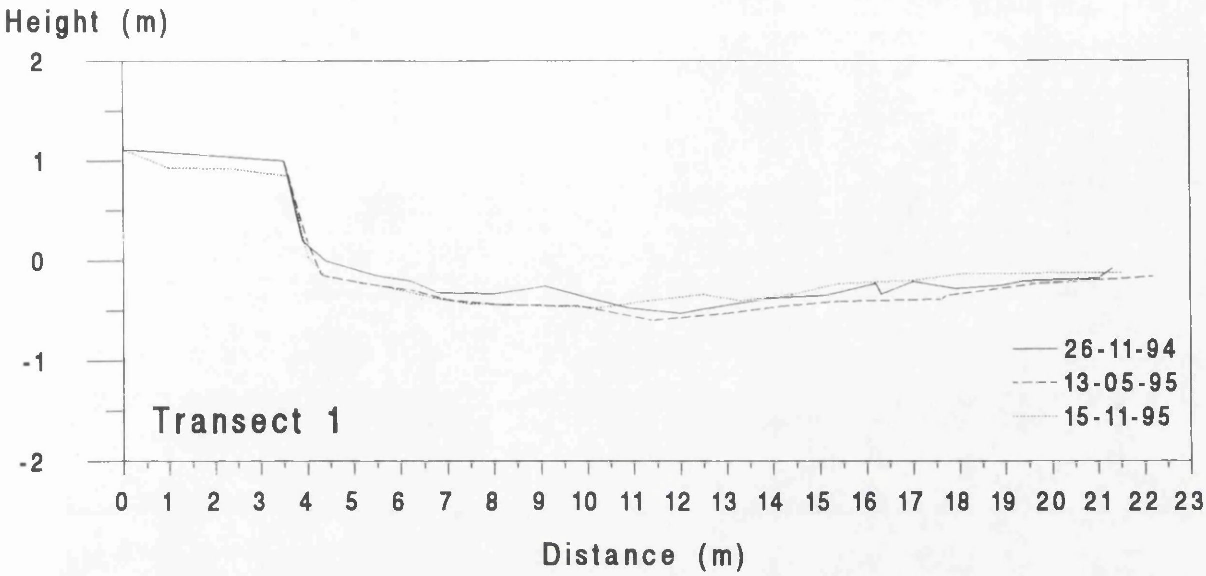
Summary chart for %'s of fluorescing particles within each sample size range													
Sample Date 15/11/95			(grain sizes in mm)										
Size	2.8	2	1.4	1	0.71	0.5	0.355	0.25	0.18	0.125	0.09	0.063	pan
T2P1	0.11	0.4	0.62	1.93	2.43	1.84	1.95	1.54	0.5	0.34	0.16	0.09	0.016
T2P2	missing	missing	missing	missing	missing	missing	missing	missing	missing	missing	missing	missing	missing
T2P3	1.47	2.43	3.43	2.56	3.39	2.81	2.8	1.98	0.65	0.35	0.15	0.06	0.003
T2P4	0.13	0.51	0.38	1.69	1.75	2.69	1.69	1.72	0.43	0.93	0.19	0.07	0.14
T2P5	0	0.07	0.18	1.88	2.39	1.2	1.1	0.78	1.08	0.39	0.26	0.06	0
T3P1	0	0	0.02	2.22	1.99	3.27	2.35	1.22	0.92	0.51	0.27	0.05	0.02
T3P2	0	0	0.04	2.17	3.19	3.67	2.22	1.77	0.9	0.68	0.3	0.18	0
T3P3	0	0	0.04	1.63	1.88	2	1.74	2.28	0.95	0.64	0.36	0.04	0.01
T3P4	0	0	0	2.74	2.52	4.23	2.3	4.39	2.08	0.6	0.26	0.04	0.007
T3P5	0.47	0.04	0.11	6.19	3.56	2.81	1.99	1.61	0.87	0.18	1.23	0.24	0.06
T4P1	0	0	0	0	0	0	0	0	0.72	0.33	0.13	0.29	0.16
T4P2	0	0	0	0	0	0	1.17	0.93	0.63	0.38	0.07	0.03	0.008
T4P3	0	0	0	0	0	2.01	1.23	1.21	0.81	0.34	0.13	0.09	0.01
T4P4	0	0	0	0	0	1.29	1.12	1.23	0.93	0.57	0.37	0.11	0
T4P5	0	0	0	0	0.12	1.02	1.66	1.67	0.71	0.42	0.15	0.1	0.05
T5P1	0	0	0	0	0	0	1.03	1.17	0.45	0.15	0.07	0.02	0.02
T5P2	0	0	0	0	0	0	1.13	1.02	0.56	0.26	0.11	0.02	0.16
Sample Date 21/1/96			(grain sizes in mm)										
T2P3	0	0	0	4.3	3.42	2.68	2.02	1.52	0	0	0	0	0
T2P4	0	0	0.6	2.87	2.38	2.04	1.71	1.28	0	0	0	0	0
T2P5	0	0	1.23	2.58	1.67	1.61	1.33	1.38	0	0	0	0	0
T3P1	0	0	0	2.08	2.77	1.59	0	0	0	0	0	0	0
T3P2	0	0	0.29	2.81	3.16	1.64	0	0	0	0	0	0	0
T3P3	0	0	0.29	2.11	3.1	2.4	0	0	0	0	0	0	0
T3P4	0	0	0.15	1.95	2.86	2.83	0	0	0	0	0	0	0
T3P5	0	0	0	0	0.15	0.11	0	0	0	0	0	0	0

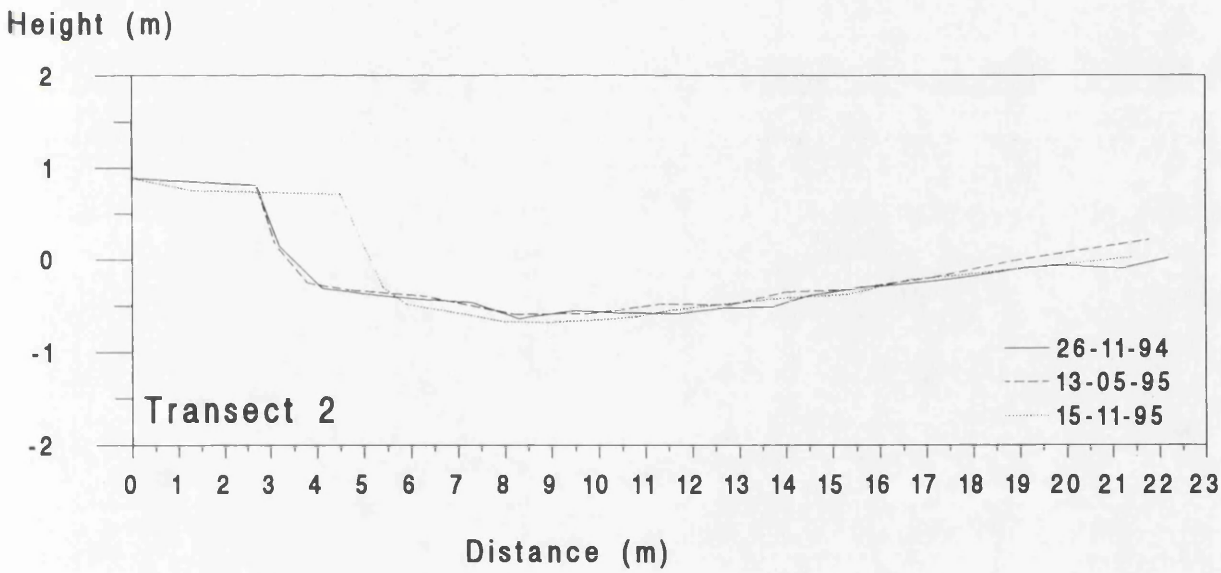
Summary chart for particle size analysis data

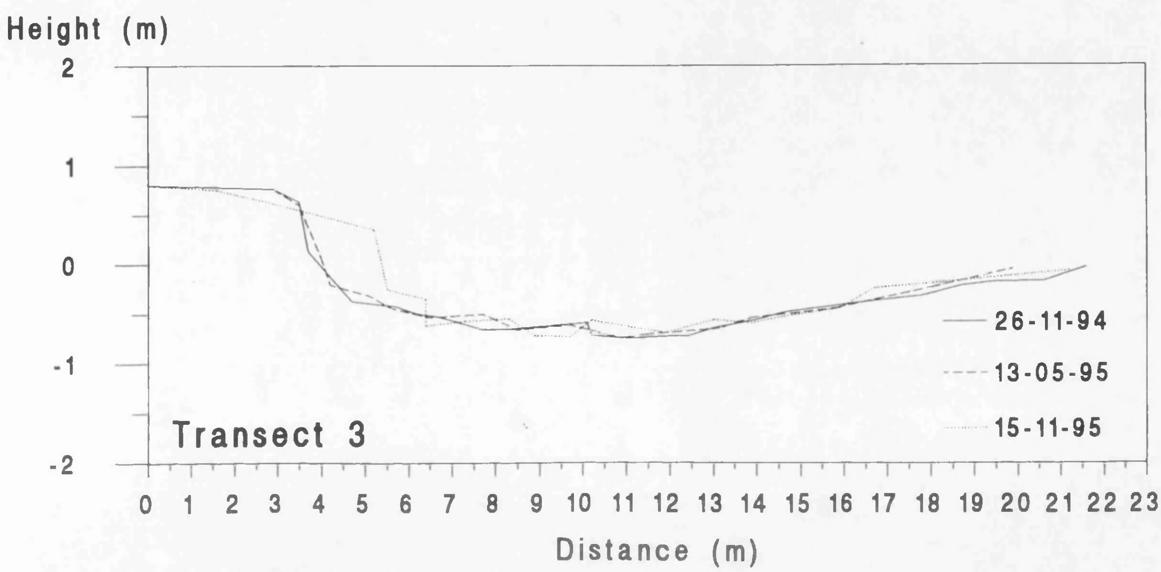
	23/3/95		13/5/95		31/8/95		18/9/95		15/11/95		21/1/96	
	sorting	skewness	sorting	skewness	sorting	skewness	sorting	skewness	sorting	skewness	sorting	skewness
T1P1	mod	sym	mod	sym	poor	sym	mod	fine	poor	sym	mod	sym
T1P2	poor	sym	poor	sym	poor	sym	poor	coarse	poor	coarse	poor	coarse
T1P3	poor	sym	poor	coarse	poor	sym	poor	V.coarse	poor	V.coarse	poor	V.coarse
T1P4	poor	V.coarse	poor	V.coarse	poor	sym	mod	V.coarse	mod	V.coarse	mod	V.fine
T1P5	poor	coarse	poor	V.coarse	poor	sym	poor	V.coarse	poor	fine	V.poor	fine
T2P1	poor	V.coarse	poor	V.coarse	poor	fine	mod	V.coarse	poor	fine	poor	fine
T2P2	poor	coarse	poor	V.coarse	poor	fine	*missing*	*missing*	*missing*	*missing*	*missing*	*missing*
T2P3	poor	coarse	poor	V.coarse	poor	sym	mod	V.coarse	poor	fine	poor	V.fine
T2P4	poor	V.coarse	mod	coarse	poor	sym	mod	V.coarse	poor	sym	poor	coarse
T2P5	poor	coarse	mod	coarse	poor	coarse	mod	sym	poor	coarse	poor	V.coarse
T3P1	poor	coarse	poor	coarse	poor	fine	mod	coarse	well	sym	poor	sym
T3P2	poor	coarse	poor	coarse	poor	sym	poor	V.coarse	mod	V.coarse	poor	sym
T3P3	poor	coarse	poor	V.coarse	poor	sym	mod	V.coarse	poor	coarse	poor	fine
T3P4	poor	V.coarse	poor	V.coarse	poor	coarse	mod	V.coarse	poor	sym	poor	V.coarse
T3P5	poor	coarse	mod	sym	poor	sym	mod	sym	poor	fine	poor	sym
T4P1	poor	coarse	poor	coarse	poor	fine	mod	sym	poor	sym	poor	coarse
T4P2	poor	sym	poor	sym	poor	fine	mod	sym	poor	sym	poor	coarse
T4P3	poor	sym	mod	coarse	poor	sym	mod	sym	poor	sym	poor	coarse
T4P4	poor	coarse	poor	sym	poor	coarse	mod	coarse	mod	coarse	poor	coarse
T4P5	poor	sym	poor	sym	poor	sym	poor	sym	poor	V,coarse	poor	sym
T5P1	poor	V.coarse	poor	V.coarse	poor	coarse	mod	V.coarse	poor	V.coarse	poor	V.coarse
T5P2	poor	fine	poor	coarse	poor	coarse	poor	sym	poor	sym	poor	coarse

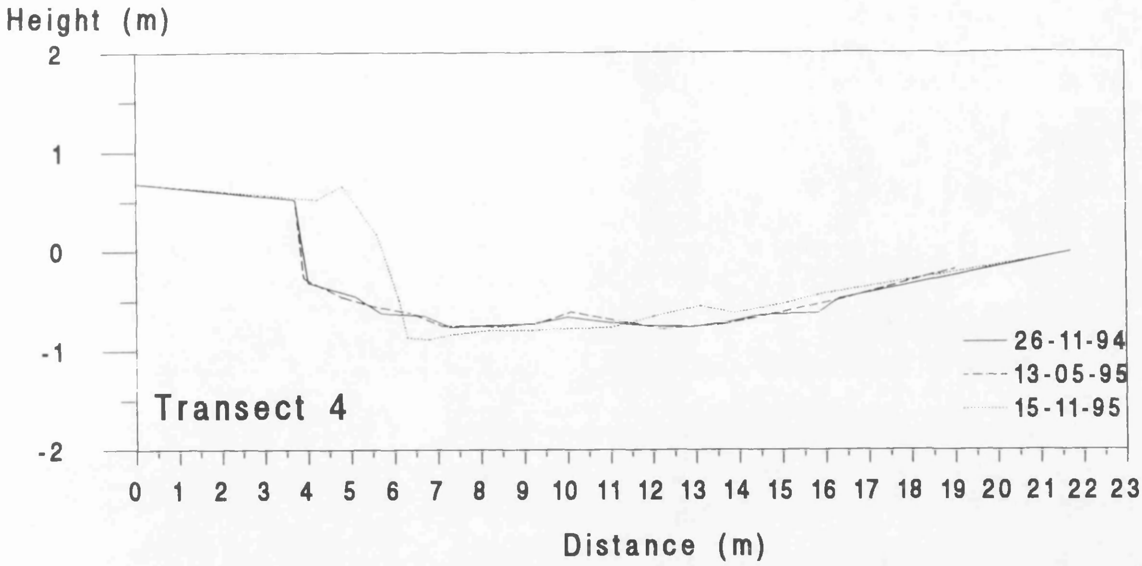
APPENDIX F

Cross-sectional surveys of transects 1 to 15









Height (m)
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0
-1
-2
Transect 4
26-11-94
13-05-95
15-11-95
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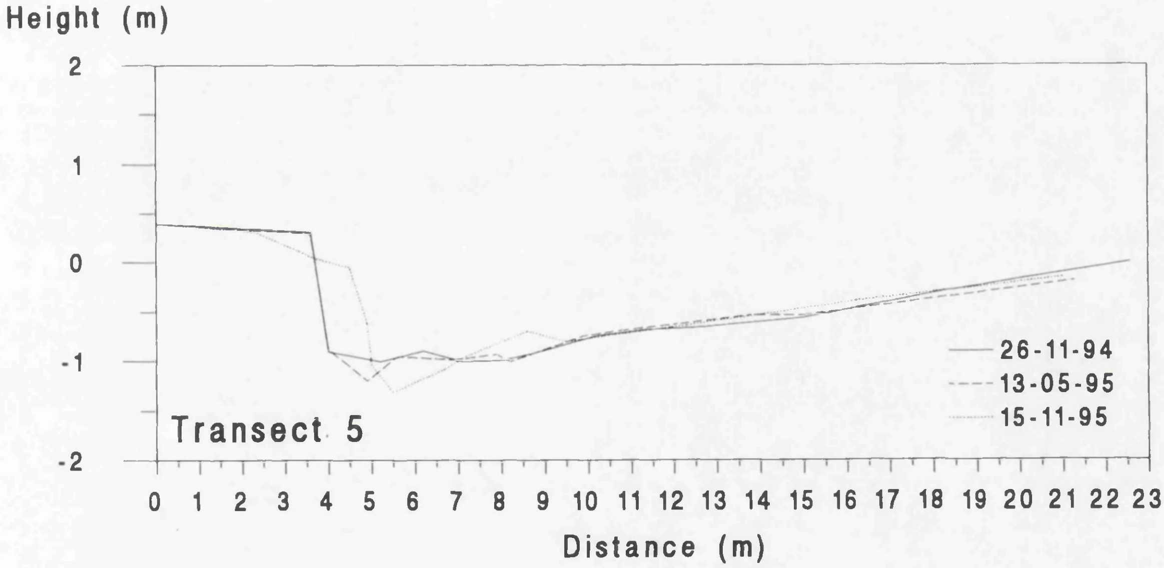
Distance (m)



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15-11-95
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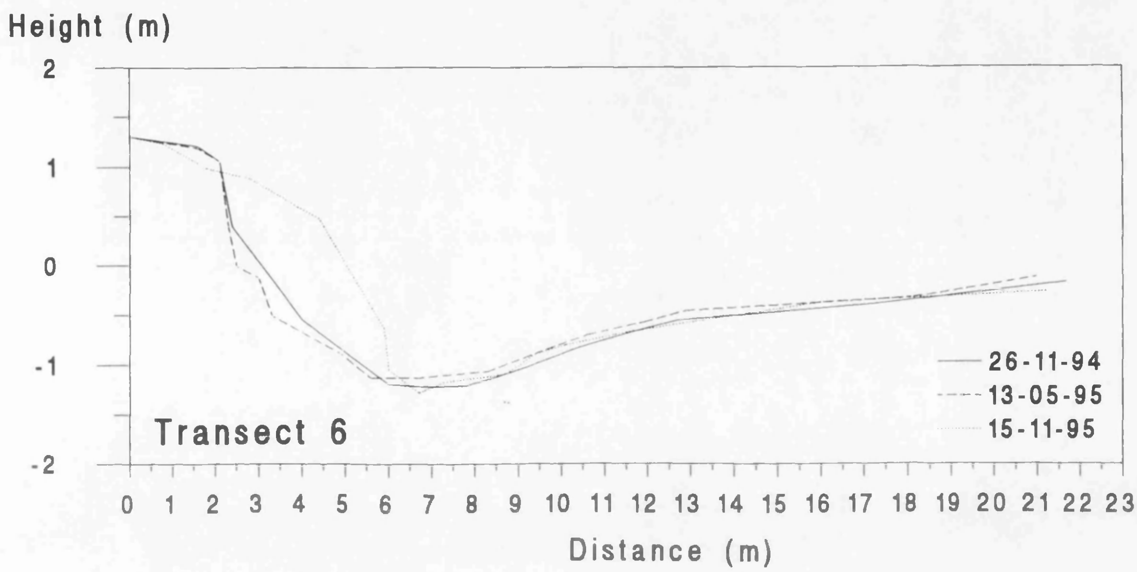

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0
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15-11-95
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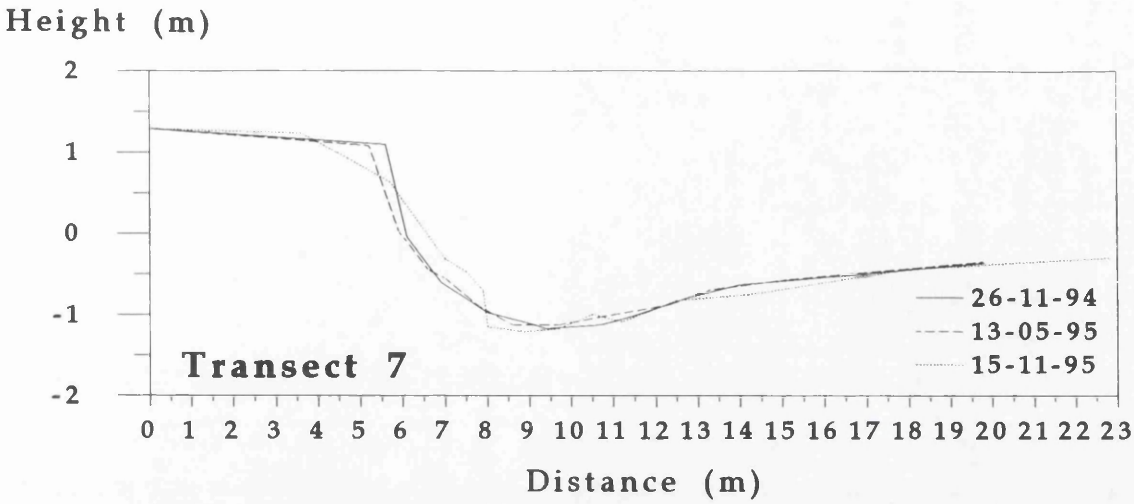
Distance (m)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15-11-95
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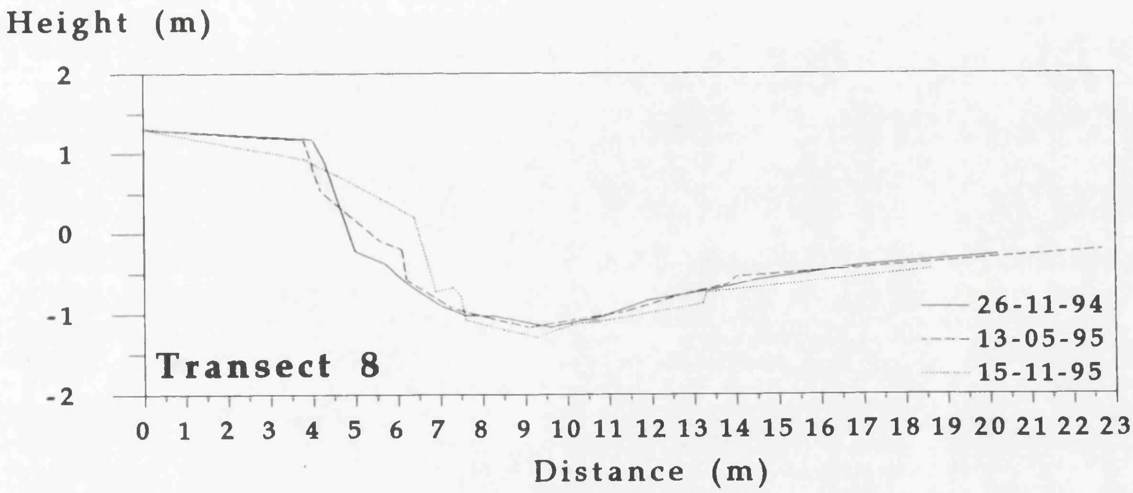
Distance (m)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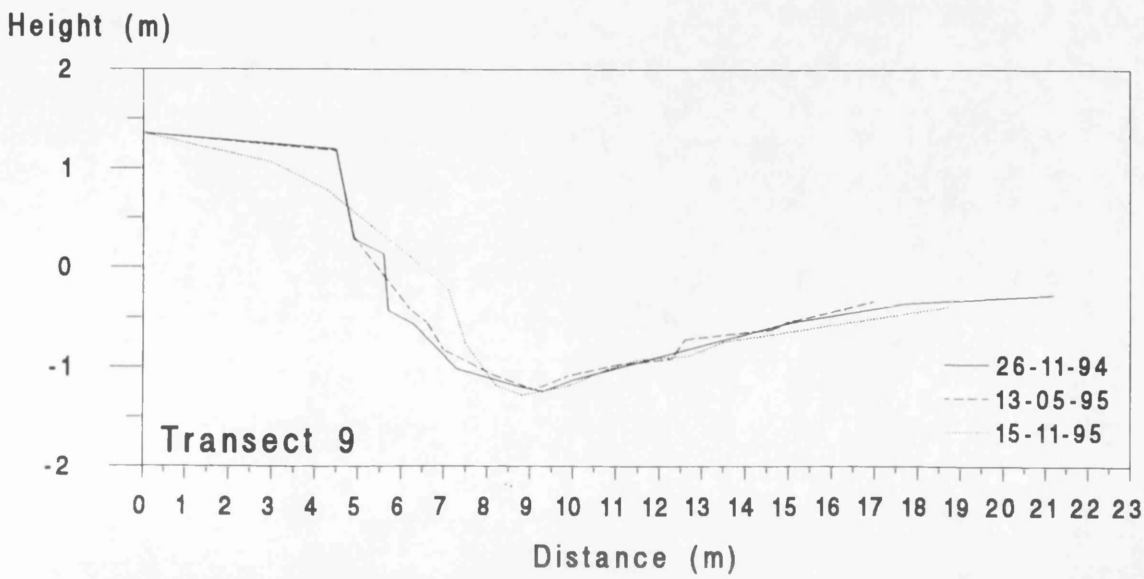
Distance (m)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15-11-95
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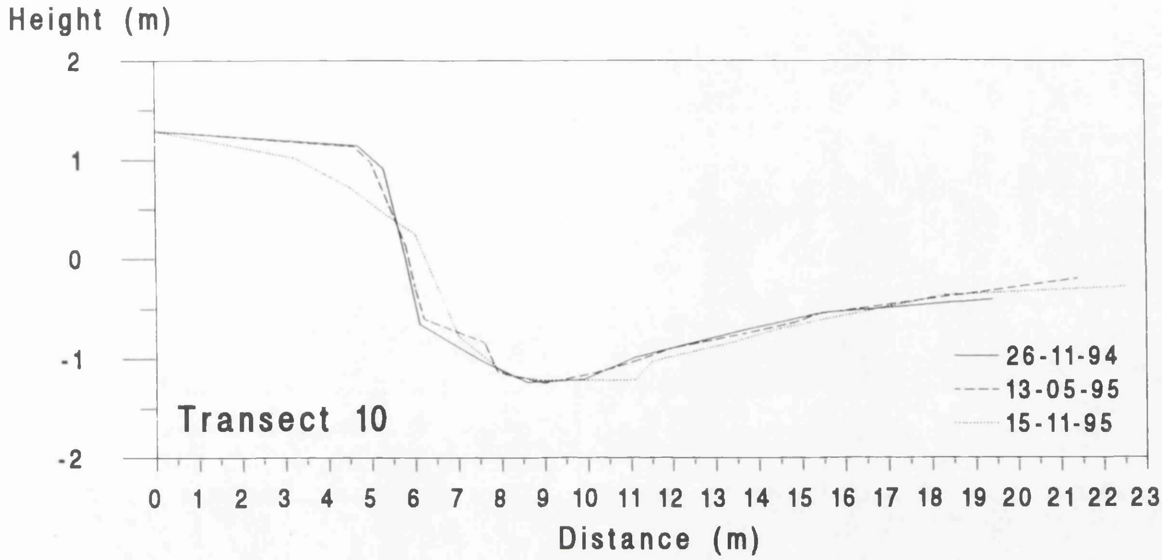
Distance (m)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-2
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15-11-95
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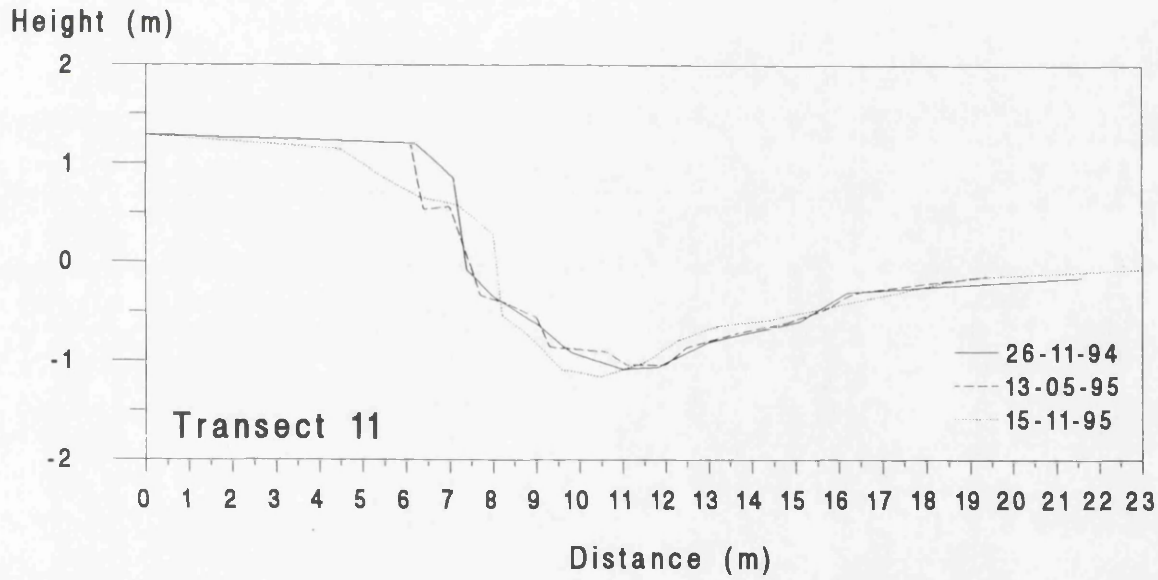
Distance (m)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15-11-95
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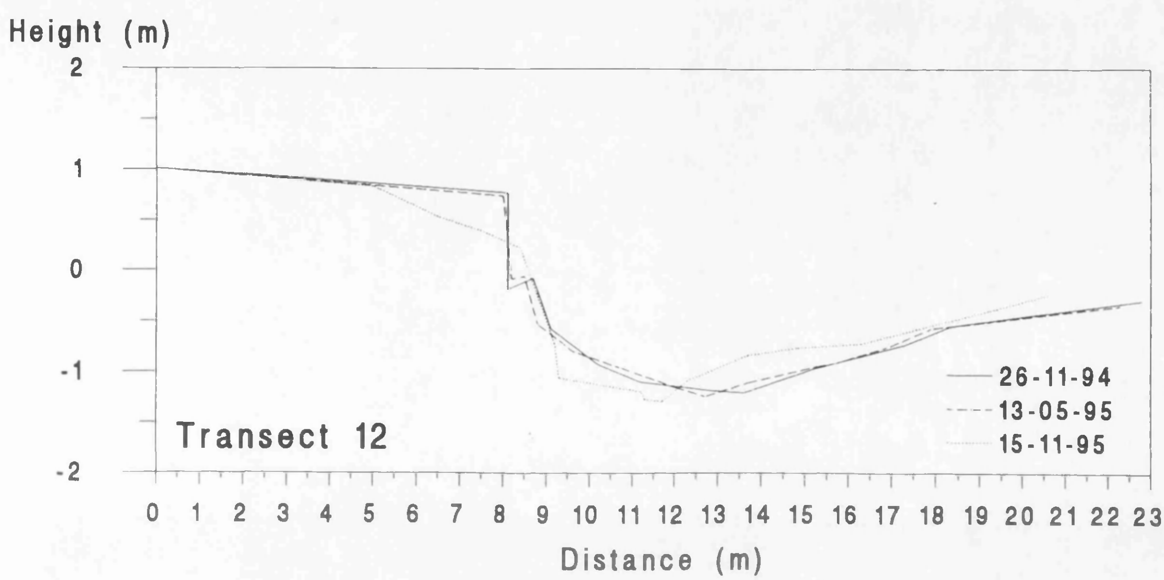
Distance (m)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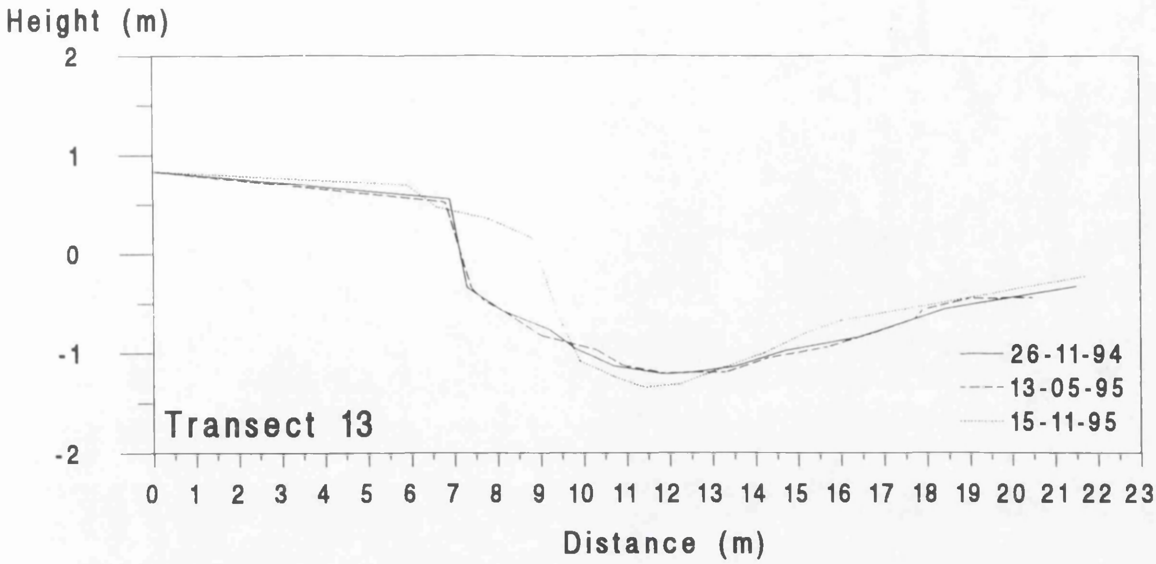
15-11-95
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Distance (m)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Transect 13
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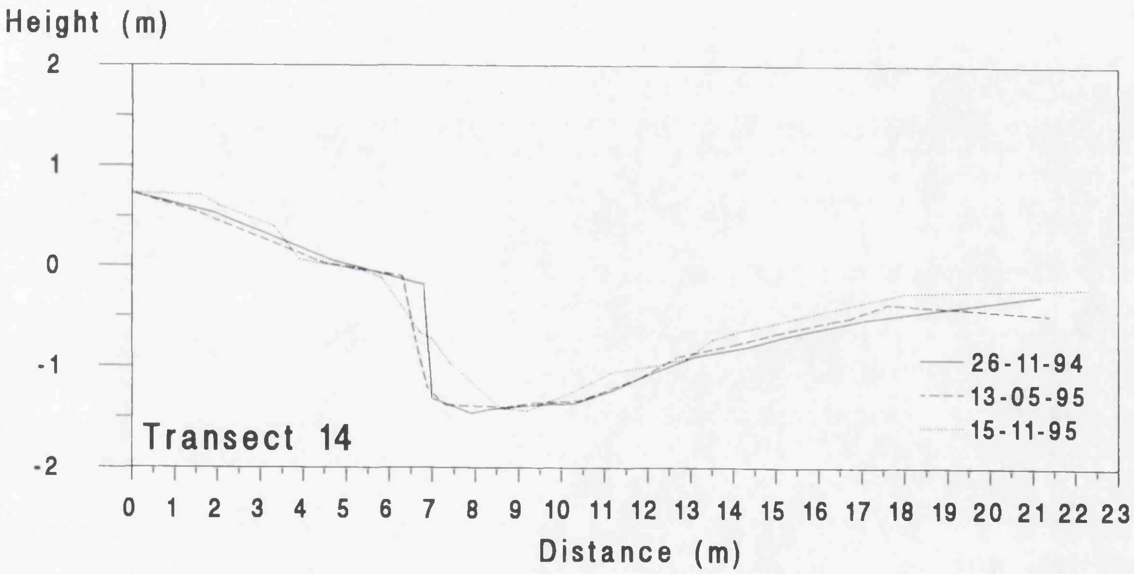
13-05-95
15-11-95
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Distance (m)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-1
-2
Transect 14
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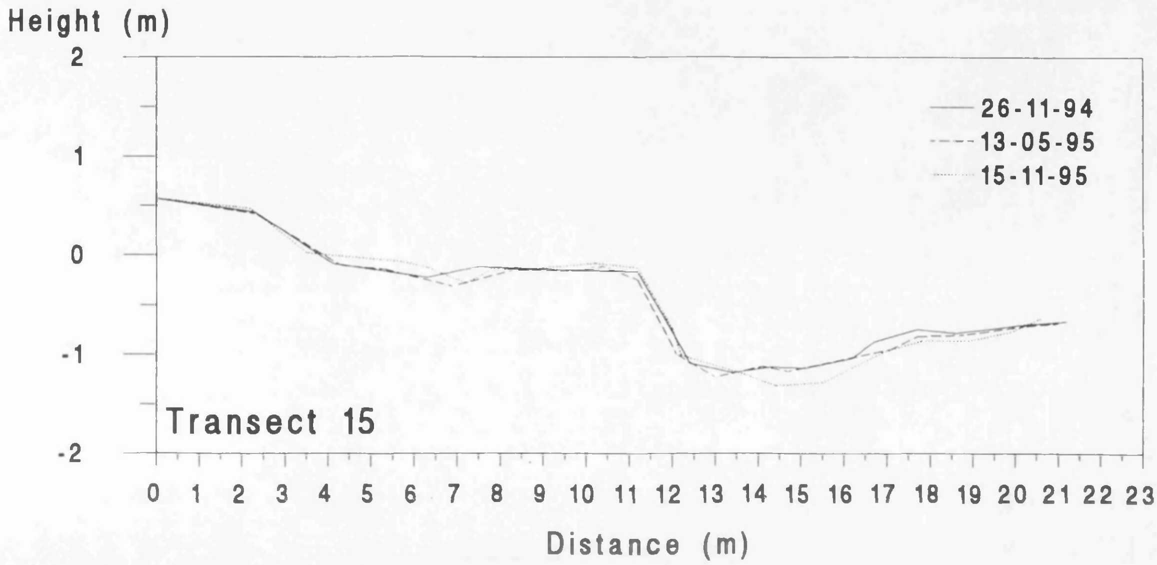
13-05-95
15-11-95
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Distance (m)


Height (m)
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0
-1
-2
Transect 15
26-11-94
13-05-95
15-11-95
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Distance (m)