The effect of roughness elements on the interstitial sedimentation of lowland gravel-bed rivers.

by

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Abstract.

This thesis aims to examine effects that different configurations of roughness elements have on interstitial sedimentation of fines within lowland gravel-bed rivers. Three configurations of roughness elements were used; Configuration I and II have half the interstitial area of Configuration III, $1.81*10^{-3}$ and $3.62*10^{-3}$ m^2 respectively. These were designed to replicate shapes of interstitial components commonly found within gravel-bed rivers. Three reaches were located on Burleigh Brook, Loughborough, Leicestershire, UK, where each configuration was represented. Replication of configurations at each reach allowed for hydraulic differences between reaches to be overcome. The main aim is to examine whether different roughness configurations affect infiltration rates and grain size distributions. Sediment traps operated for 12 months, being removed and replaced after each flood or elongated period of base flow. The material collected was dried, weighed and in cases during which a single flood event occurred, the material was sieved. Elongated periods of base flow allowed corrections to be made to the collected weights, subtracting estimates of base flow sediment deposition that occurred within that event. The flood hydrographs have different time spans, therefore average hourly infiltration rates were determined, kg m^{-2} hr^{-1}, to allow comparisons to be made. Data were examined to assess if any relationships could be seen between these rates and peak flood stage or roughness configuration. Results from statistical analysis clearly demonstrate that the sedimentation rates observed within this study differ between each of the three reaches, therefore validating the need to analyse each individual reach separately with regard to infiltration rates. Analysis shows average infiltration rates increasing with non-linearly stage. The container beneath the traps was filled with material in events when stage exceeded 0.40m. Results obtained for higher flows are therefore only estimates of minimum infiltration rates. With regard to effects that the configurations have on infiltration rates, Configurations I and II are statistically derived from the same population, whereas Configuration III has lower rates. Of those events when the collected sediment was sieved, the statistical analysis reveals that only stage has a significant effect on size distributions of the infiltrated sediment. Events in which flow depth was greater depict coarser infiltrated material than events with a lower peak stage. However, statistical analysis examining the effect that trap type have on the size of infiltrated material does not reveal any consistent conclusions throughout the complete data set.

Keywords

lowland gravel-bed, infiltration rates of fine material, size of infiltrated material, roughness elements, storm hydrographs

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Chapter 1.

Introduction and Scope of the Study.

1.0 Definition of the study.

The aim of this thesis is to examine the effects that artificial roughness elements have on the interstitial sedimentation of fine material within lowland gravel-bed rivers. The study was undertaken on Burleigh Brook, a tributary of the River Soar, Leicestershire. The objectives are two-fold, one regarding the sedimentation rates and second, the size of infiltrated particles. The infiltration rates and variation in grain size within the deposited material are complex. They are believed to relate to the sediment supply (Petts, 1984, Reid *et al.*, 1997), transport mechanisms operating (Sear, 1996, Shih and Komar, 1990), local hydraulics (Einstein, 1968), dimensions of the interstices (Frostick *et al.*, 1984, Reid and Frostick, 1985), reach morphology (Diplas, 1994, Laronne and Carson, 1976) and scour and fill sequences (Diplas and Parker, 1992, Haschenburger, 1999). This study aims to examine both the rates of sedimentation and the size properties of the deposited material in relation to the size and shape of interstitial components of the bed. Other components examined in this study include the physical characteristics of individual flood hydrographs and their timing, in relation to other hydrographs temporaly.

The sedimentation of fine material into gravel-bed rivers is of major importance. The implications of the intrusion of fine material into the framework of lowland gravel-bed rivers are highly variable. These include the loss of habitat for benthic organisms ranging in size from invertebrate larvae up to large aquatic vertebrates (e.g. Wood and Armitage, 1997, Sear, 1993). Siltation of many gravel-bed rivers has resulted in the loss of trout and salmon fisheries (e.g. Lisle, 1989). Gravel rivers are not the only fluvial environment that are affected by an influx of fine material. During the well documented low flow periods of the past few summers within the United Kingdom, (1988 – 1992, 1995 – 1997) the extent to which riverbeds have become covered in finer grained material has increased on a seasonal basis (Wood and Armitage, 1999). However, it is the sedimentation within pores that is of primary interest in this thesis, not processes occurring within backwater zones.

Research reported in this thesis assesses the role that roughness elements have in promoting the sedimentation of fine material in lowland gravel-bed rivers. The roughness elements used provide simulations of different sized and shaped interstitial components of a gravel bed. For ease of replication and simplification of the hydraulic processes occurring in the vicinity of the studied interstices, hemispheres were used as the roughness elements (see Chapter 3.1). Spherical particles have often been used in initial studies of processes occurring in gravel-bed rivers (e.g. Ling, 1995). Use of hemispheres allows stylised interstitial pore spaces to be determined. Those used in this study are similar to the three and four pointed pores of Frostick *et al.*, (1984). The interstitial components and hemispheres can be seen in Chapter 3.1.

1.1 Fine material in gravel-bed rivers.

Fine material within the fluvial environment includes both organic and inorganic particles. The inorganic fraction comprises around 70 – 80% of the suspended load (Davies and Nelson, 1993). Fines can cover a number of size classes ranging from clay (less than 2μm) through sand to granules (64μm – 4mm). Their relative abundance depends upon flow characteristics, the surrounding geology and local land use.

Most rivers in the United Kingdom have been influenced by anthropogenic activity leading to an increase in the volume of sediment mobilised by river systems in many instances (e.g. Sear, 1995, Pender *et al.*, 1998). This additional sediment, especially within gravel-bed rivers, has lead to detrimental modifications of the riverbed, mainly through increased clogging of gravel pores (e.g. Thoms, 1987). The sedimentation of fines has brought about the loss of benthic habitats (Wood and Armitage, 1999), altered hydraulics (Einstein and Chein, 1955) and changed sediment transport patterns (Laronne and Carson, 1976). Siltation has also affected the recreational use of waterways (Clark, 1985).

The composition of the suspended load differs from the sediment which is deposited within the gravel bed, with a large proportion of silt and clay carried in suspension, but comparably little of these size grades are caught in sediment traps, as observed by Lisle (1989). Large volumes of sediment are transported episodically - the ingress of sediment into interstices is not constant over time and it also varies spatially within the channel (Adams and Beschta, 1980). Furthermore, the concentration of infiltrated fines changes with depth (Schälchi, 1992). Indeed, Davies and Nelson (1993) observed that, after a storm event, the infiltration of fines was to a depth less than 1mm. This corroborates Beschta and Jackson's (1979) assessment that fines constitute only between 2 – 8% of the total volume of bed material.

1.1.1 Introduction of fines into rivers.

Sources of fine material within a catchment are variable. Sediment yield depends upon climate, geology and soil type, relief of the surrounding catchment, vegetation and land use. Climate, vegetation cover and land use are variables that change either on an annual basis or as a result of an alteration in land management strategies. Erodability and erosivity are important factors when examining the surrounding geology and soil types. The climate of the United Kingdom is low in terms of erosivity, but on removal of the vegetation, the unprotected soils are of medium erodability. Walling and Webb (1983) produced a world map assessing the sediment yield of catchments. Catchments within the United Kingdom yield up to 100 t km^{-2} yr^{-1}, but there are areas around the world which exceed 1000 t km^{-2} yr^{-1}. These are typically high relief catchments in the loess regions of Asia (Walling and Webb, 1983).

The introduction of fine material, via bank erosion, surface run-off, mobilisation of surface materials, brings problems of pollution. The sediment can often have an increased heavy metal content (e.g. Macklin and Dowsett, 1989), a higher concentration of pesticides (e.g. Foster *et al.*, 1996), and radionuclides (e.g. Walling and Woodward, 1992). These potentially bring detrimental effects to the riverine system, affecting the chemical composition of the water and sediment and leading to changes in the benthic community and stream macrophytes (e.g. Saltveit *et al.*, 1994, Wolfenden and Lewin, 1978). In Norway suspended sediment concentrations are monitored as a water quality parameter (Faugli *et al.*, 1998).

1.2 Movement of fine material through the fluvial system.

There are two processes by which sediment moves through river systems either as bedload or in suspension. Both methods of transport are widely discussed within the academic literature. The next two sections give an insight into the mechanisms involved and academic questions currently being discussed, along with sampling strategies which have been deployed to quantify fluxes of both sediment pathways. Bedload transport is more difficult to measure and quantify and will be dealt with first.

1.2.1 Bedload transport.

The literature concerned with the movement of particles along the bed is divided into two main themes, the first being the mechanisms by which the sediment is entrained from the bed and second the distance over which these particles are moved. Within both these themes there are a number of different schools of thought.

1.2.1.1 Entrainment.

Initiation of sediment movement, entrainment, occurs when the particle's weight is overcome by the drag force of the flowing fluid pulling the grain out of its position and moving it downstream. This depends upon the magnitude of the critical drag velocity and bed stress (Pye, 1994). Much of the existing literature concentrates on the mechanisms by which individual particles are brought into motion, with recent debate being concerned with the precise timing of movement (Buffington and

Montgomery, 1997). It is this observation on the exact timing of entrainment that is difficult to determine because of the difficulty of precisely defining the moment of initial movement. Shields (1936) extensively studied entrainment, culminating in the construction of the Sheilds' diagram, which shows how the entrainment function, θ, varies with the particle Reynolds number. θ describes shear at incipient motion in dimensionless form. At high Reynolds number (> 200), viscous forces become unimportant and the entrainment function tends to a constant value that depends on such factors as particle shape, degree of protrusion from the bed, and the overall degree of particle sorting and bed roughness. Traditionally this value has been determined to be 0.06 for well-sorted sediment and 0.047 for poorly sorted material (Miller *et al.*, 1977).

These values are very conditional on how each researcher defines the initiation of movement. Many different definitions for the beginning of particle motion have been used to identify the threshold of movement. Buffington and Montgomery (1997) report that there are four common methods for defining incipient motion.

1) visual observation

2) extrapolation of bedload transport rates to either a low reference value or zero

3) development of competence functions that relate shear stress to the largest mobile grain size, from which the critical shear stress for a given size of interest can be established, and

4) theoretical calculation.

Komar (1987) states that despite the control of variables (flow velocity and sediment size) within his flume experimentation, thresholds of movement still show a considerable amount of scatter.

The critical dimensionless shear stress is the ratio of the fluid forces tending to initiate motion of a particle to the inertial force tending to keep the particle at rest. Shields (1936) determined that τ_{ci*} was solely a function of the Reynolds number. For Reynolds values larger than 100, τ_{ci*} approaches a constant number. Researchers since 1936 have reanalysed Shields original data set, and Gessler (1971) reports a value of τ_{c*50} of around 0.046 while Miller *et al.*, (1977) ascertained a value of 0.045.

There have been a number of studies that have attempted to add information to the Shields diagram or redefine the value attributed to incipient motion. The presence of bedforms increases the shear stress necessary to initiate particle motion when compared to a plain bed (Brayshaw, 1985; Hassan, 1993). A further problem identified by Andrews (1983) is that associated with grain size-distributions found in natural channels. Most rivers do not possess a substrate of uniform size distribution, and therefore this can affect the forces acting on individual particles. Andrews (1983) ascertained that the forces changed in two distinct manners, 1) the smaller particles within a natural river bed can be hidden in the turbulent wake of larger particles; and 2) the force necessary to initiate a larger pebble rolling over smaller particles is less than that required to move a small particle over larger ones. Andrews (1983) concluded that τ_{ci*} value 0.06 given by Shields is a good average for variable size distributions and justifies ignoring the of determination of different values for different mixtures of sediment. In reality there is a frequency distribution of dimensionless critical shear stress for a range of grain sizes.

Sorting and shape affect the mobility and therefore the value of θ. Greater sorting and an increase in angularity causes the grains to be more resistant to movement and therefore an increase in τ_{c*50} values. In contrast, increased sphericity, and a looser packing arrangement and surfaces with protruding grains have increased grain mobility, resulting in lower τ_{c*50} values (Fenton and Abbott, 1977).

Fenton and Abbott (1977) assessed the influence of particle intrusion into flow and the subsequent ease of entrainment. From first principles, the disturbing forces acting on a particle increase and resistance decreases as a particle is protruded further into the flow. Protrusion effects are not consistent with Shields curve and show considerable deviation from it. Fenton and Abbott's experimentation concentrated on three particle shapes; regular spheres, gravel and over riding grains. Experimentation with different sizes of regular spheres showed that as the size of the particles increased, resulting in a grain Reynolds number increase from 100 to 1000, values of θ decreased, from 0.06 to 0.03. Those experiments involving gravel produced a markedly different set of results. It was observed that θ was more dependent upon a ratio of protrusion to grain diameter, p / D (where p is the measure of protrusion and D the particle diameter). Under turbulent flow conditions protrusion is an important factor governing grain stability. When investigating over riding, it was observed that in some instances, the protruded grains had to be nearly a full grain diameter into the flow prior to the initiation of movement. Andrews (1983) in his research on relative protrusion stated that the effect of protrusion is compensated for by difference in particle weight. From this it was concluded that bed material within a factor of three of the median particle diameter of the subsurface material would be entrained within a small range of shear stress, τ_*. Brayshaw *et al.*, (1983) examined the mechanisms by which particle protrusion affected entrainment. They found that a protruding particle causes a change in the surrounding pressure field, which results in a deviation of particle entrainment from the Sheilds curve. This change in flow field affects both the upstream and downstream faces of the protruded particle by altering the magnitude of the lift and drag forces.

Another important factor when examining entrainment is the pivot angle. Li and Komar (1986) and Komar and Li (1986) have closely examined this effect. They deduced that the pivot angle (ϕ) of the grains resting upon one another was responsible for selective entrainment. The size of ϕ depends upon the ratio of diameter between the particle to be entrained and those upon which it rests. The larger the ratio, the smaller ϕ and therefore the easier it can be pivoted out of position. The equation for determining the pivot angle is

$$\phi = e\left(\frac{D}{K}\right)^{-f} \qquad \text{Equation 1.1}$$

(where e and f are coefficients, D is the grain diameter of the pivoting particle and K is the diameter of grains upon which D rests)

This pattern is self evident for spherical grains, but other particle shapes causes complications especially in defining the pivot angle. Ellipsoidal grains produce a change in the constant e of proportionality, which means that ϕ will now depend upon both the grain shape as well as its size. This change in the e coefficient is determined by the orientation of the ellipsoidal grain on the bed surface and in particular, whether it is more likely to pivot or slide. This is dependent upon the D_c / D_b ratio of the particles involved. A further deviation away from the values of ϕ for spherical grains depends upon the ability of angular grains to interlock. This greatly increases the value of ϕ, as the pivot angle is now the sum of the angle of contact plus the angle associated with imbrication. Again as ϕ increases so does θ. Smaller particles within a mixed bed tend to 'hide', having greater pivoting angles that inhibit entrainment despite their smaller weights. Additions to this theory include placement of the upper grain and the form of pivoting (Johnston, 1996). The form of pivoting is dependent upon where the grain sits on top of another particle, or in the saddle between two or more. Johnston (1996) ascertained that the distribution of pivot angles for the entrainment of individual size fractions in a mixed-size sediment is lognormal in form.

Both the pivot angle and the degree of protrusion affect the timing of entrainment with respect to the value of the critical shear stress needed. Another factor which is related to the above is the hiding factor. This has an effect by reducing the fluid forces acting directly on the particle (Andrews, 1983).

The continuing debate is over the exact timing of particle entrainment, and therefore the relationships that exists between entrainment and bed material size. If the threshold for movement is one or two grains moving, then entrainment is thought to be governed by median grain size, whereas weak movement of grains is an indication that a coarser grain size is responsible for the threshold of motion (Komar, 1987).

Recent literature is concerned with the debate between equal mobility and size selective transport. Andrews and Parker (1987) define the occurrence of equal mobility as the period when the grain size distribution of the bedload is equal to that of the bed. Ashworth and Ferguson (1989) argue that in precise equal mobility the mean diameter of the bedload would be equal to that of the bed. Parker *et al.*, (1982) first introduced the concept of equal mobility, by stating that all grain sizes have an equal likelihood of transportation when critical conditions of armour layer break-up occur. Data from Oak Creek Oregon, indicated a systematic change in bedload size distribution with increased shear stress, i.e. the higher the stress, the greater the median size of bedload. Wilcock (1993) agreed with this statement, and added that any size distributions of bed material became entrained at nearly equal flow conditions. Wathern *et al.*, (1995), however, showed that differing size fractions possess different properties. It is only sands that are endowed with equal mobility and as particle size increases the entrainment becomes more size selective. Church *et al.*, (1991) have addressed the behaviour of the sand fraction with regard to equal mobility, and state through their observations that there is near equal mobility within the sand fraction.

In opposition to the theory of equal mobility are those who believe that particle entrainment is size selective. Ashworth and Ferguson (1989) are two of the many proponents. Their data set demonstrated that in six of the eight reaches examined, mobility decreased with increasing particle size. They also highlighted that downstream fining, apparent in the Allt Dubhaig and River Feshie, was indicative of size selective entrainment. Ashworth and Ferguson, do concede that at high shear stresses some bedload samples were nearly as coarse as the bed. These might have matched the bed if the samples had not been limited, as a consequence of the size of the bedload sampler, causing under-representation of the coarser material. However, in concluding, they state that during low flows, entrainment by size selection was more prominent, but near attainment of equal mobility occurred at greater critical stresses before complete armour break-up. This point of armour break-up has important implications for the determination of flushing flows which are designed to mobilise the bed surface and remove fine material from the subsurface. A total lack of selective entrainment and sorting would yield a horizontal line, on the Shields curve, where τ_{ti} equals a constant that is independent of D_i. Komar and Carling (1991) concluded that one measurement of bed material, either D_{50} or D_{95} could be used to determine flow competence equations. This would mean that each stream has its own unique flow competence that is resultant upon grain sorting and material sources.

The current debate within entrainment theory concerns partial and complete transport (Wilcock and McArdell, 1997). Wilcock and McArdell stated that only a proportion of exposed grains at the surface are actually transported despite the threshold of dimensionless stress being exceeded for all exposed particles. Grains of a single size within a mixed-sized bed are entrained over a range of flows. Within this range, some grains exposed on the bed surface are active whilst the remaining surface grains are immobile, leading to concept of partial transport. It is understood that complete transport occurs during periods when there is complete break-up of the armour layer. Partial transport determines the active proportion of the bed surface, therefore playing a direct role in controlling both the rate and size of sediment exchange between the grains in motion, the bed surface and subsurface. This drives any grain sorting processes, e.g. armouring, selective entrainment and deposition, downstream fining and the introduction and removal of fines into the subsurface. Wilcock and McArdell's (1997) experiments showed that the bed surface became progressively finer as τ_0 increased. This was attributed to 'mining' of the finer size fractions from the subsurface as a consequence of the entrained proportion of coarse grains increasing with τ_0. This acted by supplying additional fine-grained sediment, which limits the size of vacated bed pockets. This then affects the rate and size distribution of the grain exchange within the bed and between the bed and the active layer. It was found that the transition from immobility ($Y_i = 0$) to full mobility ($Y_i = 1$) occurred over a range shear stresses. Also for a given shear stress, the same transition occurs over a range of grain sizes, i.e. there is not a defined shear stress to initiate motion for a defined grain size. The proportion of active grains is shown to increase rapidly from an initial time and to asymptotically approach a constant value Y_i. Flow turbulence ensures that no absolute maximum proportion of active grains exists for a given size and flow. Each particle size has a minimum velocity, below which there is no movement, however, there also exists a minimum velocity at which all particles belonging to this size fraction will move. It is between these two boundaries that partial transport prevails (Stelczer, 1981). There is a need to understand partial transport as it has important implications for the modelling of movement and entrainment and the exchange of sediment between the bed surface and subsurface.

Other authors have examined further factors that influence entrainment. Reid *et al.*, (1992) assessed the influence that microform roughness elements have on entrainment. Turbulent structures within the flow have been observed to affect entrainment (García *et al.*, 1996, Admiraal *et al.*, 2000).

The main problem with bedload transport studies is the collection of samples. Some report loss of sediment traps during high magnitude events (e.g. Lisle, 1989) or low retrieval rates of tagged particles (e.g. Ashworth and Ferguson, 1989). Another problem experienced is that the majority of bedload movement occurs during daily flows. Andrews (2000) reported that around 75% of the bedload was transported by discharges equal to, or below 6.0 m^3s^{-1}, despite the East Fork Virgin River having flood events that frequently exceeded 50.0 m^3s^{-1}. Data interpretation also causes differences in the results obtained. Milhous (1973) reported more selective entrainment than Parker *et al.*, (1982) when examining the same data set.

In their flume study Shvidchenko and Pender (2000) observed that a higher shear stress value is required to maintain a specified sediment transport rate in higher gradient environments. However, after a critical slope angle, this observation will not occur as slopes approach the angle of repose if the material, therefore the sediment mobility, becomes greatly by gravity. This flume study, also contradicts existing theories on entrainment, by stating that critical Sheilds stress for rough turbulent flow appears to depend on particle Reynolds number, which indicates lower flow resistance for coarse gravel if compared to fine gravel. They suggested that further experimental studies were required to clarify this point.

The transition between entrainment of bedload and complete suspension of sediment is often difficult to ascertain. Andrews (2000) observed that particles greater than 1mm were transported via the motion of bedload, whereas those below this arbitrary value are carried in suspension. Entrainment of sediment in suspension occurs via turbulence ejections within the near-wall region of the fluid (e.g. Lapointe, 1992).

1.2.1.2 Deposition of bedload material.

The main emphasis of the research in this thesis is concerned with the deposition of material into the gravel framework. Research into sedimentation has been divided into two areas, the first being the processes occurring between the transportation mechanisms and sedimentation; and second the implications of sedimentation with respect to in-stream biota and management strategies. It is however, the research into the former that is most relevant to the study undertaken here.

Einstein (1968) undertook a comprehensive study examining the deposition of sediment out of suspension over a gravel bed surface. His theory was that the probability of a sediment particle depositing anywhere on the bed was the same providing that the particle was in corresponding positions above the bed. He stated that particles could only be affected by turbulence if they were deposited above it. Once these particles had settled through this layer they could no longer be affected by the processes and therefore settled out. Murray (1970) ascertained that the fall velocity determined from several different turbulent fields is reduced by 30% compared to that found under still water conditions. Einstein (1968) also stated that the average velocity greatly influenced the location of deposition. Schälchi (1995) stated that sedimentation is gravity driven; his methodology was to examine changes in hydraulic conductivity of an initially matrix-free gravel bed and assess conductivity changes against the rate of sedimentation. Peloutier *et al.*, (1997*) proposed that the bed surface tends to reduce the differences in fall velocities between coarse and fine sand particles.

There are a number of important factors that affect the degree of ingress of fines. These include the concentration of fines within suspension (e.g. Einstein, 1968, Carling, 1984, Schälchi, 1995), the nature of sedimentation of the fines (e.g. Beschta and Jackson, 1979, Diplas and Parker, 1992) and the properties of the surface and subsurface of the gravel bed (e.g. Frostick *et al.*, 1984).

The concentration of suspended sediment within close proximity to the bed is an important factor for a number of reasons. Einstein (1968) stated that the concentration of each particle class affected the sedimentation as each size fraction showed an exponential reduction in concentration over time. Also the larger classes settled out first. Carling (1984) also maintains that depositional rates are primarily correlated to near-bed suspended sediment concentrations, rather than hydraulic controls and Schälchi (1995) places this first on his list of quantities that affect siltation rates. However, further into the discussion concerning the governing equations, Schälchi stated that the concentration of fine material within suspension does not affect the specific infiltration rate. Sear (1993) observed that in areas of the channel where high concentrations of suspended sediment existed, the infiltrated particles were coarser. High suspended sediment concentrations in the near-bed region may alter the vertical eddy diffusivity, thus increasing deposition. However, Coleman (1981) stated that the velocity defect law is not affected by changes in suspended load. Lisle (1989) suggests that the infiltration rate for a given sediment transport rate decreases as the total sediment flux increases, i.e. the surficial interstices are free of fine material during the initial stages of infiltration and become plugged as infiltration progresses, inhibiting further infiltration.

The other two properties, the nature of sedimentation and the role played by the surface and subsurface materials, may be inter-linked. The first of these properties is the manner in which the pore spaces are initially filled, i.e. do the infiltrated fines fall down through the pore throats, or sit between particles within the bed, forming a seal. Beschta and Jackson (1979) examined how different factors influence the manner in which the interstitial component is filled. Size was the most important factor, with larger sand particles not being intruded as far into the bed as finer particles. In addition to size being a factor, Beschta and Jackson (1979) discovered that at low Froude numbers a sand seal developed, which was not present as the Froude numbers increased, as the turbulent pulses inhibited its formation. Depth of seal formation is also dependent upon the energy of individual events, with deeper penetration occurring with increased energy (Lisle, 1989). Diplas and Parker (1992) have further investigated this seal formation. The mechanism by which matrix development is favoured over seal development is a result of the ratio between fines settling out and the size of the voids into which they are falling. Lisle (1989) stated that unobstructed settling is favoured where $D_f / D_m > 60$, (where D_f is the diameter of the D_{50} of the framework, and D_m is the D_{50} of the fines). Where there is a distinct difference in the size distributions of suspended load and the framework gravels, no seal is formed, however, distinct bimodality rarely occurs in nature and consequently is not reported in the literature. Einstein (1968) reported this occurring in flume experiments. This is thought to happen when most of the deposited material is initially carried in suspension.

The nature of the fines and that of the surface and subsurface are closely linked. Frostick *et al.*, (1984) demonstrated that the subsurface framework is an important factor in the depth and degree of infiltration. This is consequential of the packing arrangements, incomplete packing stopped ingress, thus creating a seal, whereas complete packing allowed the infiltrated material to settle through the framework, rendering it matrix supported. The size differences between the surface and subsurface encourages the clogging of the upper pores. However, during periods when bed activation took place, during periods of increased flow, elevated volumes of fines infiltrated into the bed. The limiting factor on the size of the matrix is the size distribution of the surface pore throats. The size distribution of the framework also affects the degree of infiltration. A coarser framework encourages accumulation of matrices that are finer than those frameworks with a lower median grain size. The greatest grain size present in a closely packed framework will be 0.40 of the median framework particle size (Frostick *et al.*, 1984). However, Peloutier *et al.*, (1997) state that their results suggest that gravel size does not have a significant influence on the infiltration rate of sand for a given near-bed concentration.

Lisle (1989) found that the depth of infiltrated material, less than 2mm, into well-sorted sub-angular gravel, showed little consistent variation over the area examined. This contradicts earlier work by Adams and Beschta (1980), where it was observed that there was significant stratification of fines within a gravel bed. Within the first 10cm, 17.4% of bed material was fines, within the next 30cm of substrate, the average content of fines was 22.3%. Lisle (1989), however, does concede that the methodology adopted in retrieval of fines could have dislodged the natural pattern, thus compromising results. Sear (1993) found that only slackwater deposits possessed any degree of vertical size sorting. As a consequence or pore throats dominating the size of material that can infiltrate into the framework, it is often observed that the matrix tends to become coarser towards the surface.

Adams and Beschta (1980) observed that the percentage of infiltrated fines varied between each streambed. Schälchi (1992, 1995) has demonstrated that each individual gravel bed has its own specific hydraulic conductivity that changes through time with sedimentation. The initial hydraulic conductivity of a matrix-free streambed will also vary over time as a consequence of the packing arrangements changing after specific bed altering events. Deposition of fines, less than 1mm, is not homogeneous laterally across the streambed or longitudinally downstream (Adams and Beschta, 1980). It was observed that the variation is more pronounced across-channel than downstream. However, Carling and McCahon (1987) observed that on a week by week basis there was no statistical difference at the 10% level in the across-stream variation in the rate of sediment accumulation, in either the pools or the riffles. Lateral variation within a cross-section is deemed to be a consequence of velocity patterns, with the highest concentrations of fines corresponding to areas of greatest flow velocity (e.g. Frostick *et al.*, 1984, Sear, 1993). Diplas and Parker (1992), however, state that the absolute quantity of fines that can be infiltrated into a subpavement layer within a gravel bed is independent of boundary stress and other flow parameters. Adams and Beschta (1980) also attribute the lateral changes in the concentration of fines to aerial channel changes in surface and subsurface material, as outlined above (see Chapter 1.1).

Frostick *et al.*, (1984) also found enhanced concentrations of fines deposited in pools. Wohl and Cenderelli (2000) observed features associated with a reservoir release that introduced around $7000m^3$ of silt sized particles into the North Fork Poudre River, Colorado. It was observed that the deposition occurring mainly within pools, filling some by a depth of 3m, whereas adjacent riffles showed a lack of infiltrated material. It has also been demonstrated that on a stream with regulated tributaries, the matrix is finer than in systems with unregulated tributary inputs (Sear, 1993).

Values reported on sedimentation vary, mainly resultant on the methods and factors that are dependent upon individual stream characteristics. Adams and Beschta (1980) report a number of different quantities of infiltrated fines within gravel-bed rivers, dependent upon antecedent conditions. During low summer flows the bed is comprised, on average, of 19.4% of material below 1mm, rising to 49.3% within catchments where land management strategies increase the amount of fine material available for transport.

Davies and Nelson (1993) observed that after a storm event, infiltration of fines was less than 1mm in depth. This value corresponds to Beschta and Jackson's (1979) value that fines constitute only between 2 and 8% of the total volume of bed material. An indicator, often used as a surrogate variable for depth is a multiple of the D_{90} of the subsurface material. This can be used to compare results across different rivers. Diplas and Parker (1992) reported that a seal depth is never greater than a depth measured by five times D_{90}. Allan and Frostick (1999), however, report that depth of seal development is equal to 2 times D_{max}. Sear (1993) observed that the depth of infiltration can reach depths of 300mm without the surface sediments being mobilised.

There is also a temporal variation in the rate of infiltration. This is caused by annual hysteresis in both the suspended (Meade, 1982) and bedload transport rates (Moog and Whiting, 1998). A report by ASCE (1992) stated that during summer months, silt and sand deposition within coarse gravel frameworks increased, however, these were removed by higher flows during the autumn and winter months. Sear (1993) observed that it was the availability of fines that predominates infiltration, irrespective of local flow hydraulics or framework composition.

Allan and Frostick (1999), through the use of digital photography and image analysis, have suggested a mechanism by which fines are ingressed into a gravel bed. It was observed that prior to erosion, the surface layer of the gravel bed lifts and dilates. During the lifting and dilation of the framework the volume of sediment increases by 50%. This causes fluid to be drawn into the bed. This fluid also contains fine particles, and thus the subsurface gravels are filled with finer material. This study is the first to report such a mechanism. It, however, demonstrates that with new visualisation techniques the mechanisms behind the processes can be further understood.

1.2.1.3 Removal of fines from a gravel bed.

The removal of fines is important, as a matrix-free bed is vital for spawning fish and other benthic organisms. It is agreed that the removal of fines occurs when flow conditions are such that the fines are mobilised, but the coarse framework essentially remains stable. In gravel-bed rivers, at low flow strengths, the vertical extent to which there is activity is limited to the surface layer. At greater flow strengths, this is thought to increase to depths equivalent to twice the surface layer (Wilcock and McArdell, 1997). Allan and Frostick (1999) have shown winnowing is the most effective when the velocity is slightly greater than u_{*c}, the theoretical critical value of shear velocity for the matrix particles. This value is below that required to entrain the framework. This means that the coarse particles largely remain undisturbed, whereas the finer particles are transported downstream. The situation explained here, only results in the surface layer being winnowed of fines.

Flow conditions required to remove fines have implications for the implementation of maintenance flows released from reservoirs to ensure that the gravel framework is purged of fines. This is clearly important in river systems that have their annual variation in flood discharges reduced as a consequence of upstream impoundment of streams. Milhous (1998) has suggested that there are three components that need to be addressed to determine the in-stream flow requirements to provide a balanced system. These are, first, biological components that set the objectives of sediment management, second, the hydraulic components to accomplish the biological goals and third, a component that links the above to determine in-stream flow needs for the management of sediment.

When defining flushing flow requirements, it is important to determine the size of particles that need to be removed from the gravel bed. In many cases, this will be determined by the desired end use for the river, e.g. it may be imperative to understand the spawning requirements of the fish in the stream. From this, a series of calculations can be used to determine flow requirements in terms of frequency and magnitude (Milhous, 1998).

1.2.2 Suspended Load.

This study is concerned with the sedimentation of fines that have primarily been transported as bedload. However, the role that suspended sediment plays cannot be overlooked or ignored. Suspended sediment is episodic in its nature, with high concentrations associated with high magnitude, low frequency events (Walling *et al.*, 1992). This section provides a brief chronological examination of previous research undertaken in examining the physical processes by which sediment is suspended and moved downstream.

Coleman (1970) introduced the sediment coefficient, ε_g, as an important factor in sediment suspension. ε_g is the momentum transfer coefficient, or kinetic eddy viscosity that is present in the theory of diffusion of momentum. This coefficient varies with distance from the bed, describing changes in suspended sediment concentrations over depth. ε_g can be derived from a graph if the suspended sediment concentration at certain depths is plotted against reliable depth measurements.

Coleman considered effects of increasing suspended sediment concentrations on the fall velocity of suspended sediment particles in still water, but no clear conclusions were drawn. However, Coleman did concede that the data set worked upon did not consider effects including bed configuration and roughness and therefore shear velocity at the bed. This effects replication and comparison of these results to data sets obtained from actual river systems. Carling (1984) stated that an increase in suspended sediment concentrations in the near-bed region reduced eddy viscosity in the vertical plane, which led to an increase in the availability of fines to settle out. Elevated suspended sediment concentrations have also been observed to increase shear stress within the near-bed region, therefore changing turbulence structure and often the general velocity profile (Nnadi and Wilson, 1992).

Murray (1970) examining the effect that turbulence had on the settling velocity of a particle, stated that this was reduced by 30% in a turbulent flow field to its corresponding still water value, i.e. Reynolds number increases turbulence, therefore decreasing particle fall velocity. Sumer and Deigaard (1981) stated that turbulence was the mechanism that prevented particles from settling. Therefore, they stated that a rougher bed creates a greater turbulence intensity above it, which increases the height of sediment suspensions. However, the individual downstream movement of a particle was reduced by roughness, which ties in the earlier work by Sumer and Oguz (1978) and the break-up of 'bursting' flow structure that leads to settlement.

Leeder (1983) looked at advection of masses of fluid away from the bed and subsequent sediment suspensions, confirming Bagnold's theory on sediment suspensions by residual Reynolds stresses. Bagnold's theory required that the immersed weight of suspended grains were supported by Reynolds stress τ_{yy}, which is an upward-directed residual, arising from asymmetrical shear turbulence. It was concluded that vertical stress was sufficient to balance the equal and opposite down thrust of suspended sediment's immersed weight.

Nielsen (1984) presented a comprehensive study on the motion of suspended sand particles. He stated that vortices trap and subsequently convect particles downstream. Complications to this include oscillatory flow and other turbulence structures that affect both downstream movement and entrapment of particles.

Carling (1996) in his review of in-stream hydraulics and sediment transfer stated that turbulence transferred frictional forces throughout the fluid and redistributed suspended particles. He simplified the concept outlined above by stating that the shear velocity u_* should exceed the velocity at which grains would settle out of still water, thus keeping material in suspension.

Alonso and Mendoza (1992) designed a model to predict the near-bed sediment concentration within gravel-bed streams. This model was applicable to high gradient, poorly sorted gravel-bed rivers. One major assumption made, which contradicts the other literature reviewed above, was that the influence of both turbulent flow fluctuations and sediment concentrations had limited effects on the settling velocity of sediment particles. However, they concluded that their model was very sensitive to changes in the variation of gravel bed roughness, and the depth at which concentrations were evaluated above the virtual bed.

With this research topic in mind, it is the motion and concentration of suspended sediment in the near-bed region that is of particular interest. If the 'bursting' theories of Sumer and Oguz (1978) and Sumer and Deigaard (1981) are correct, then the duration of these events decrease with increasing roughness, which therefore has implications for suspended sediment dynamics in gravel-bed rivers.

Andrews (2000) has examined the temporal variations in transport of various size fractions of both bed and suspended load. Different flow parameters move certain discreet sized particles more effectively than others. It was observed that on the East Fork Virgin River, the most effective discharge for both suspended sediment and bedload was equalled or exceeded on average only 5.5 days a year.

1.3 Basic Hydraulics.

Despite firstly discussing bedload and suspended load prior to examining water flow, it must be remembered that the hydraulics are very important in the movement of sediment through the fluvial system. I have left this subject last in the discussion as the measurements of basic hydraulic conditions were not undertaken in this study.

Open-channel flow involves a free surface between the water and the atmosphere. The main driving force in these situations is gravity, which forces the fluid to flow downhill. The geometry of open channel-flow is more complex than that of pipe flow, as the cross-sectional area of rivers is not constant. Existence of a free surface leads to additional types of flow occurring to those found in pipes. Open-channel flow can be laminar, transitional or turbulent depending upon the Reynolds number of the surface material. As a consequence of the free surface, deformation can occur, with the generation of waves.

Rivers operate over a number of scales with differing complexities (Carling, 1996). Observation of these scales depends upon the overall objectives of the study and resolution of the instrumentation employed. Gravitational gradients and quantity of water within the system drive large-scale hydraulic features. The flow structure, however, is resultant upon frictional forces generated by the banks and bed materials, be this from individual grains, pebble clusters (Brayshaw *et al.*, 1983, Buffin-Bélanger and Roy, 1998), or bedforms (Nelson *et al.*, 1993).

Velocity distribution within open-channel flow is not constant, resultant upon the friction of the fluid to the boundary walls. Fluid velocity at the wall is zero with the maximum occurring below the free surface. However, within a uniform channel, the wall shear stress can vary across and along the wetted perimeter. The basic equations for flow in open-channels were derived many years ago, but have been continually refined as more advanced measurement techniques have become available. Flow in rivers can be divided into a number of different layers depending upon the depth of flow and the contribution of roughness elements. Distinctive layers within the flow are the bed, logarithmic and outer layer and free stream flow. The latter, however, is only present in deep rivers. The time-average velocity increases from zero at the bed to the free-stream velocity. The bed layer is normally thin and can be either laminar or turbulent. The former is rarely present apart from over beds of smooth clays.

The boundary layer is the region within the river where the frictional effects of the water with the bed and banks are felt. Velocity distribution with the boundary layer is obtained by the integration of Newton's Law of Viscosity. When the flow is fully turbulent the logarithmic profile is universally applied. There is a wide variety in the thickness of the boundary layer, which depends upon the nature of the bed and therefore varying the composition of the flow. However, in gravel-bed rivers, this boundary layer is often disrupted or absent as a consequence of the turbulence generated by the roughness elements. In shallow flow the logarithmic layer may extend throughout the majority of the flow. Degani *et al.*, (1993) provides a comprehensive account of the structure of the three-dimensional turbulent boundary layer. Their in-depth study demonstrates that the streamwise velocity distribution is similar to that of two-dimensional flow studies undertaken previously (Yajnik, 1970).

Turbulence strongly influences the structure of the velocity profile, shear stress, energy structure, sediment transport and the spread of pollutants in river channels. Turbulence is the most important, yet complicated type of fluid motion. Grass (1971) developed the first physical model of turbulence, a semi-theoretical relationship describing shear stress, mean velocities, turbulence intensities and energy budget distributions together with basic hydraulics. Since the initial statement on turbulence was made, its recognition in many systems has increased, but it still remains difficult to incorporate into many physically based models (Clifford and French, 1993). In turbulent flow, there is a mechanism that produces relative motions in directions other than that of the applied shear, i.e. the movement of water in the vertical and cross-stream dimensions. The value of vertical and cross-stream flow can differ by an order of magnitude to that of downstream flow (Rouse, 1961).

Although many of these concepts were introduced around 40 years ago, it is only recently that flow visualisation has provided a greater insight into these structures and their affect on sediment transport. Most studies of this type have been undertaken within flumes (e.g. Nelson *et al.*, 1993, Bennett and Best, 1995). This laboratory work has lead to the adoption of a number of assumptions, which have been used to underpin physical models. These assumptions, however, rarely hold within the natural environment, as turbulence in rivers is generally non-uniform and strongly three-dimensional, whereas flumes are mainly two-dimensional. One problem that seems to be evident, where experimentation has taken place within a controlled flume situation, is that many of the theories established cannot be imposed onto observations made in the fluvial environment. This difficulty has meant that modelling the physical environment is proving arduous.

Experiments using hydrogen bubbles and dye (Kline *et al.*, 1967 and Grass, 1971) established that turbulence is comprised of event structures as opposed to random fluid motions. Smooth wall experiments revealed streaks of flow that are concentrated within the boundary layer that interact with the rest of the flow through a mechanism known as 'bursting' (Kline *et al.*, 1967). These 'burstings' are associated with a large proportion of the shear stress generated in the turbulent region. These streaks are now known to exist in flows over rough beds and over a range of Reynolds numbers. 'Bursts' act as an exchange in momentum between the near-wall viscous layer and the more turbulent layer over-lying it. The ejection of low momentum fluid into the outer flow is compensated by an inrush, 'sweep' which then continues to generate further streaks and subsequent ejections by distorting the viscous sublayer. This is known as the 'burst-sweep' model. Lapointe (1992) observed these ejections associated with the suspension of sediment. Kostaschuk and Church (1993) established flow patterns around microturbulent 'bursting' cycles and found that low velocity bottom water was ejected towards the surface and replaced by an inrush of higher velocity water.

Many authors (e.g. Leeder, 1983) have stated that it is important to have a comprehensive knowledge of turbulence in order to understand sediment entrainment, transport, both traction and suspension, and deposition. The concentration of sediment moving in the boundary layer can alter the turbulence structure (Wang and Larsen, 1994). The method of particle entrainment depends upon the turbulent structure within the boundary layer. Larger particles are entrained by the downstream rushes that are resultant upon the high-velocity fluid impacting on the stoss side of the obstacle. From this, high-speed fluid is convected over the obstacle creating a low-pressure area in the lee. The attached vortex expands ejecting low momentum fluid into the outer zone. Smaller particles lodged in the interstitial components are moved by chaotic vertical flows (Kirkbride, 1993).

Velocity profiles are a result of the interaction of the shape, orientation, space and size distribution of roughness elements that comprise the bed. It is generally agreed that velocity profiles are logarithmic in nature, with the greatest velocity change present in the region nearest the bed. This is primarily a consequence of frictional stresses that are generated between fluid particles and the solid walls of the riverbed and bank.

Concavity of logarithmic profiles is a consequence of the form drag factor on the bed. Reasoning behind the logarithmic transformation in velocity profiles is a consequence of a change in the contributing elements. At the base of the profile, the flow reflects boundary resistance associated with grain shear stress. With increasing height above the bed, velocity measurements are a reflection of larger roughness elements upstream. Research in this area has lead to the development of the velocity defect law that is applicable throughout the turbulent velocity profile (Giles *et al.*, 1994).

If accurate velocity profiles can be ascertained, then evaluations of boundary shear stress can be made, increasing the understanding of the work undertaken by rivers (Wilcock, 1996). Bathurst (1978) commented that the main basis for examining velocity profiles was to obtain from them a numerical value / estimate of the boundary shear stress and roughness length. Figures for local boundary shear stress are valuable as they aid in the interpretation of sediment transport, depth of scour and deposition, which can then be related to channel change and therefore used as a management tool by engineers.

1.4 Scope of this study.

This thesis aims to examine the relationship between the rate of material infiltrated into a single interstitial pore, within a lowland gravel-bed river. The study examines the role that different sized and shaped interstitial arrangements have on this. The study is carried out over three individual reaches within Burleigh Brook. Chapter 2 sets Burleigh Brook within the larger regional context, and then continues to examine each of the individual reaches in greater detail, Chapter 2.3. The traps used in this study were especially designed for this purpose and the methodology behind their construction is outlined in Chapter 3.1. Chapter 3 concludes by looking at the rationale behind the sampling design and the methodology behind sample preparation.

The main aims of this thesis is to examine 1) the rate of sedimentation and 2) the size of the infiltrated material. As a consequence of these aims, the sediment traps used in this study were not filled with the material to constitute the subsurface bed material. These rates are assessed against peak stage, deemed as an important flow parameter in the quantity of fines present (e.g. Adams and Beschta, 1980). The effect of configuration shape and orientation in the flow are addressed to ascertain if these parameters affect rates or size. Frostick *et al.*, (1984) have found the surface interstices to be a factor in the infiltration of fines. The observations here, differ from Frostick *et al.*, (1984) in that there is an absence of subsurface gravels. The results concerning rates of deposition are addressed in Chapter 4. Chapter 5 examines the effect that the parameters described above, have the size of the infiltrated particles. Without a subsurface framework, the size of infiltrated particles will be easier to assess.

Chapter 2

Study area and site description.

Burleigh Brook is a small stream that drains an area to the south west of Loughborough, Leicestershire. Burleigh Brook is a second order stream at the point of measurement, draining an area of around 8km^2 at the downstream sampling location. This stream is a tributary of the River Soar, which flows in a northerly direction to the River Trent. The Soar rises in Hinckley and drains an area in excess of 1300km^2 (Whitby, 1994). It is, however, the River Trent to the north that dominates the drainage pattern of the East Midlands. Burleigh Brook is classified as a lowland-gravel bed river. Details of the substrate are given in Section 2.3.1. The overall drainage pattern of the area is a reflection of the relief, with drainage networks flowing in a north - north-westerly direction.

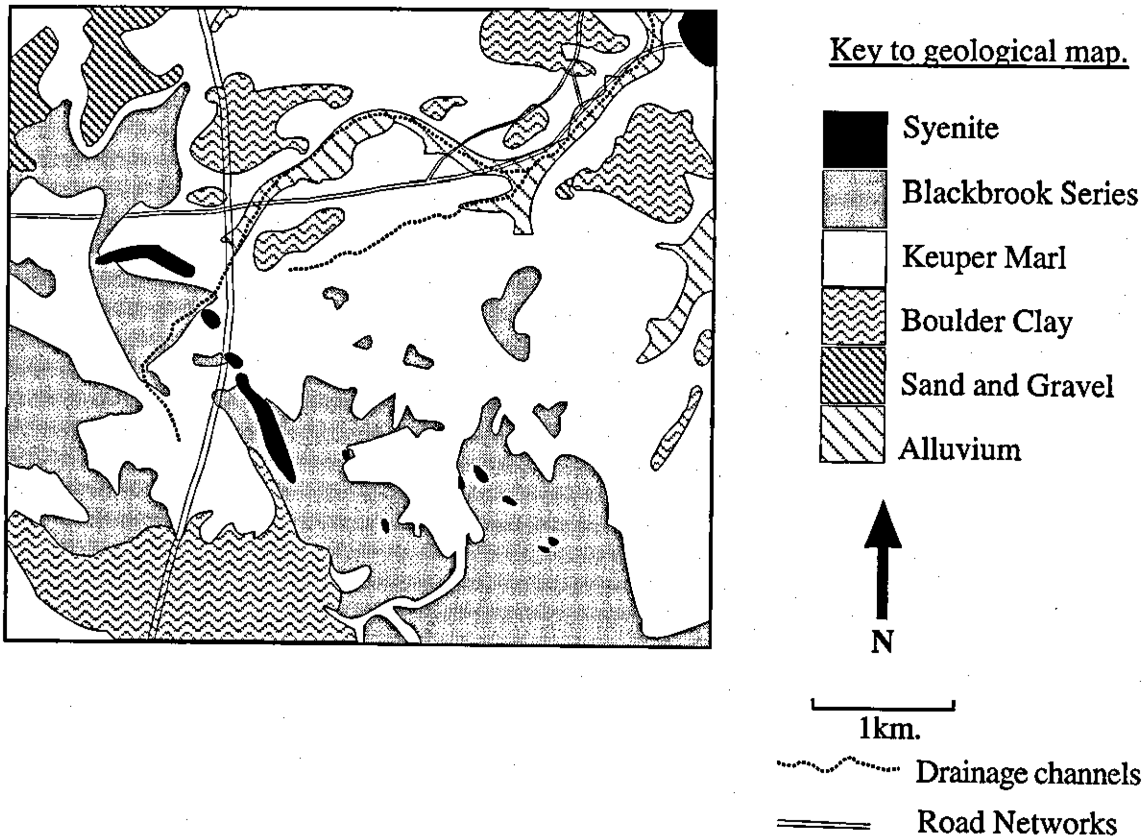
2.1 Geology and general physiography.

The area from which Burleigh Brook drains is underlain by some of the oldest rocks in the area, Pre-Cambrian (Charnian) in age. These are overlain and obscured by the Triassic cover, Keuper Marl. There is a difference in the nature of the surface in these areas. The Pre-Cambrian outcrops are distinctly angular, forming the higher ridges above the Triassic-blanketed valleys, with gentle contours. Watts (1927) likens the physical structure of the older rocks to a double horseshoe that opens to the north-west. The inner range consists of the highest point within the watershed for Burleigh Brook, Ives Head. Contouring of the exposed rocks has revealed a general inclination towards the east and north-east. Detailed analysis of the nature and structure of the ancient rocks is difficult, but it is understood that they have a pitching anticlinal structure, elliptical in plan, with the larger axis orientated in a south-east – north-west direction. However, subsequent fault movements have extensively affected what was a simple structure (Marshall, 1948). One of these fault lines runs in a north-westerly direction across Ives Head. Burleigh Brook shares a common feature with the large majority of the streams originating in this area, with it flowing eastwards, eventually draining into the Soar. In the upper course, the flow of Burleigh Brook upon the Keuper Marl, is parallel to the strike of the older formations.

The outcrop at Ives Head is hornstones and grit of the Blackbrook series. This series consists of fine grained, green-grey or buff coloured ash, that is typically well banded with purple staining along the bedding and cleavage planes. This staining is thought to have originated from the former covering of marl. The Blackbrook series also outcrops to a large extent in the south-east portion of the catchment. Another outcrop of the Blackbrook series is at Charley Knoll; an area of Boulder Clay, separates this from Ives Head.

The remaining solid geology, laid down in the Triassic is Keuper Marl. This rock is red marl, with beds of sandstone and bands of gypsum. To the north-western edge of the catchment, Keuper Marl is more sandstone rich with bands of Marl. On the lower slopes of the catchment, glacial deposits of Boulder Clay overlie the solid geology. Burleigh Brook does not flow over any of these deposits. On the margins of the channel, especially in the lower reaches, alluvium comprises the most recent addition to the geological time-scale. The geology of the area is shown in Figure 2.1.

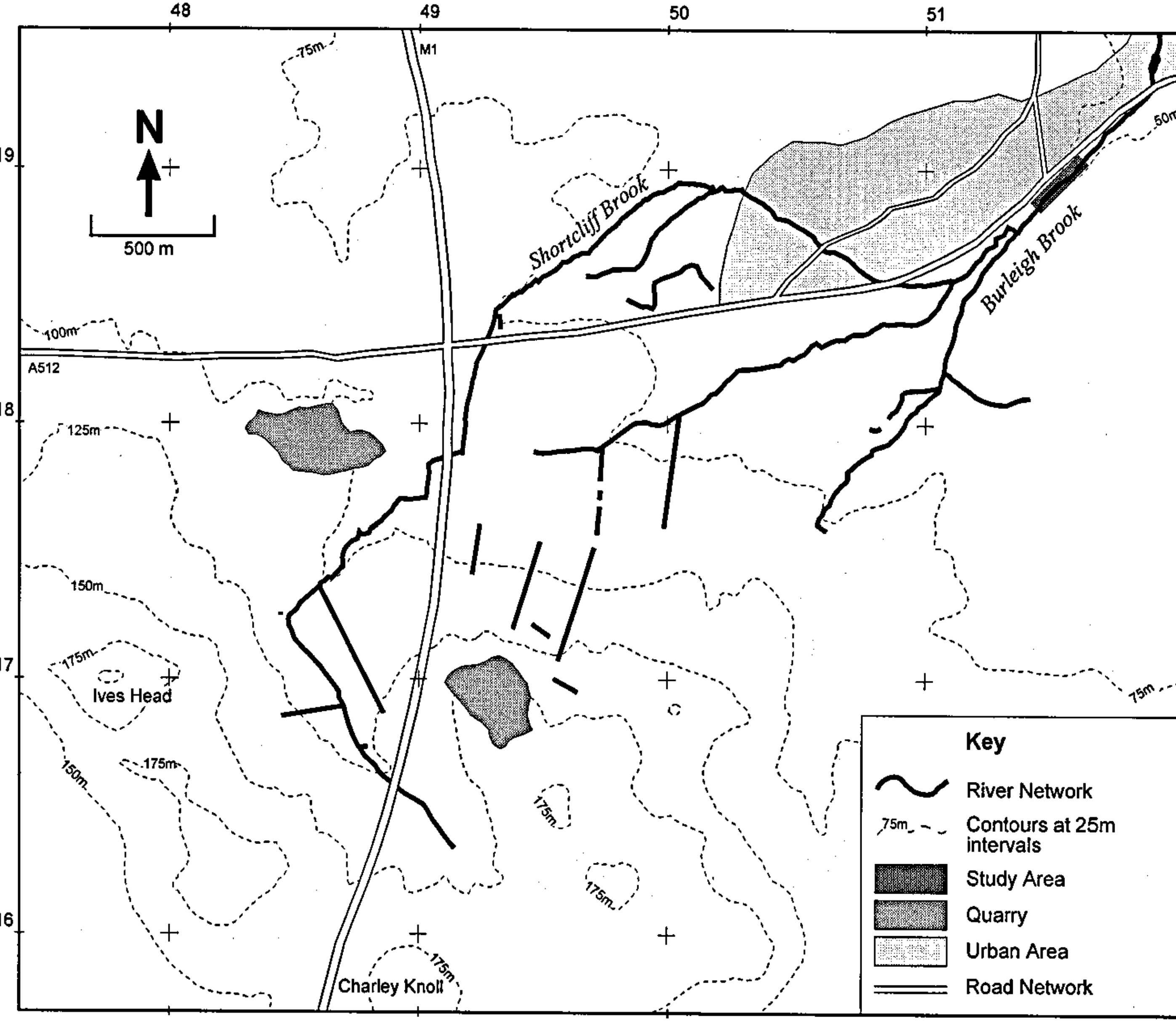
Figure 2.1 shows the geology of the area through which Burleigh Brook flows.



The headwaters of Burleigh Brook drain the higher ground to the south and west of the catchment. The highest point of the catchment is Ives Head at 201m above sea level, with the southerly point of the upper catchment being Charley Knoll at 183m. In this upper part of the catchment, beyond the M1, there is a spring near Shortcliffe Farm (GR SK 484 173) from which Shortcliff Brook originates. There are a further two springs within the catchment, one near Hurst Farm (GR SK 497 178), the origin of Burleigh Brook and the third at Holy Well (GR SK 505 176). Shortcliff Brook is the longest stream and has its confluence with Burleigh Brook at GR 512 186. The third stream joins further downstream at GR 514 188. This last major confluence is less than 100m above the first monitoring reach of this study. Despite Shortcliff Brook being the longest, the stream is known as Burleigh Brook as a consequence of past local landowners. The drainage pattern is shown in Figure 2.2.

A large proportion of the land draining into the downstream reach of Shortcliff Brook and the stream beyond its confluence with Burleigh Brook is urbanised. This is in marked contrast to the rural headwaters. There are also a number of other factors that could affect the downstream progression of water through the catchment. These included significant quarrying of the ancient rocks in the upper reach of Shortcliff Brook and the influence the M1, that crosses the headwaters in a northerly direction. The influence of the M1, quarrying, and downstream urbanisation affect the quality and quantity of water passing through the drainage network. These anthropogenic influences decrease the time to rise within the flood hydrograph. Therefore, the current flow regime of Burleigh Brook is very flashy, with the rising limb of the hydrograph often only being a matter of hours in response to sharp showers. The recession limb is considerably longer. Furthermore, with a large proportion of the

Figure 2.2 A topographical map showing Burleigh Brook.



contributing geology comprised Boulder Clay, it is difficult to determine how the anthropogenic features have unbalanced the natural flow regime. As stated there is also a detrimental effect to the water quality as a consequence of urbanisation and the M1. Hydraulic conductivity is seen to rise after winter storms, as a consequence of road salt being washed into the drainage network. Despite the lower catchment being used for housing, it is also possible to observe rural influences on the stream chemistry. Again chemical analysis has shown that concentrations of nitrates and phosphates, associated with farming practices, fluctuate throughout the hydrograph.

2.2 Climate

Loughborough's inland location and close proximity to the Pennines and Peak District to the north-west, are the dominant factors in controlling the climate of the area. Although further away, precipitation and temperatures are affected by the Southern Welsh Mountains. Within this study there is no attempt made to link rainfall measurement within the vicinity of Burleigh Brook catchment to the flow regime. One of the reasons is that using an assumption of equal rainfall throughout the whole catchment is not valid. The monitoring station in this area is situated within the lower catchment, and therefore may provide an inaccurate picture of the rainfall within the upper catchment. This validity was questioned as a consequence of living within the lower catchment, and therefore inspecting Burleigh Brook on a daily basis. Often heavy rainfall in the lower catchment is not matched throughout the catchment, and a perceived rainfall event is not shown on the stage trace recorder. In addition, the opposite of this has occurred, with limited rainfall in the lower catchment, however, a significant flood event occurs on the Brook, as depicted by the continuous monitoring equipment (see Chapter 2.3.2)

2.2.1 Rainfall.

The relief around Loughborough has the greatest influence on the amount of precipitation, with up to 800mm received on the upper slopes to the south-west of Loughborough, falling to less that 600mm in the east of the area. The headwaters of Burleigh Brook lie in an area which receives 740mm of rainfall on average (Boucher, 1994). Precipitation records spanning 100 years from Nanpantan Reservoir, which is less than one kilometre south of Burleigh Brook, indicate that 70% of the months that experience rainfall over 100mm are between July and December, whilst 56% of the dry months, (precipitation values less than 25mm) occur between February and June.

2.2.2 Temperature

On a wider scale, examining the East Midlands, the expected temperature contrasts between the north and south are affected by altitude, or the continental effects that enhance the east-west temperature gradients (Dury, 1963). Autumn, winter and spring are cooler in the Loughborough Region in comparison to other central England areas. However, the summers are warmer. As a consequence of its location, Loughborough does not regularly experience extremes in temperature. The headwaters of the catchment do experience a few instances of snow fall over the winter period.

Both temperature and rainfall are important parameters in the determination of runoff characteristics for individual flows. As stated above, this study did not ascertain detailed measurements in this way, however, studies on other rivers in the Loughborough region, indicated that the flow regime is highly seasonal. A study on Rothley Brook (to the south-east of the study area) shows that the minimum flows occurred around September, rising to a maxima in February. The continuous stage trace of Burleigh Brook shows that the regime is punctuated by large flood events, after which Burleigh Brook returns to baseflow conditions. However, the baseflow stage during the summer months is higher than that recorded in the winter months during the year December 1998 to December 1999 (see Figure 2.10).

2.3 Burleigh Brook.

Burleigh Brook is a second order stream, draining around 8km^2 at the downstream monitoring point. This section of the thesis links with the Methods Chapter which proceeds this. In this section the physical characteristics of Burleigh Brook will be examined, with the methodology concerned with data collection, for both the background information and the methodology associated with the study discussed in Chapter 3. This section will also introduce the sampling units, from henceforth given the term 'Hydrograph'.

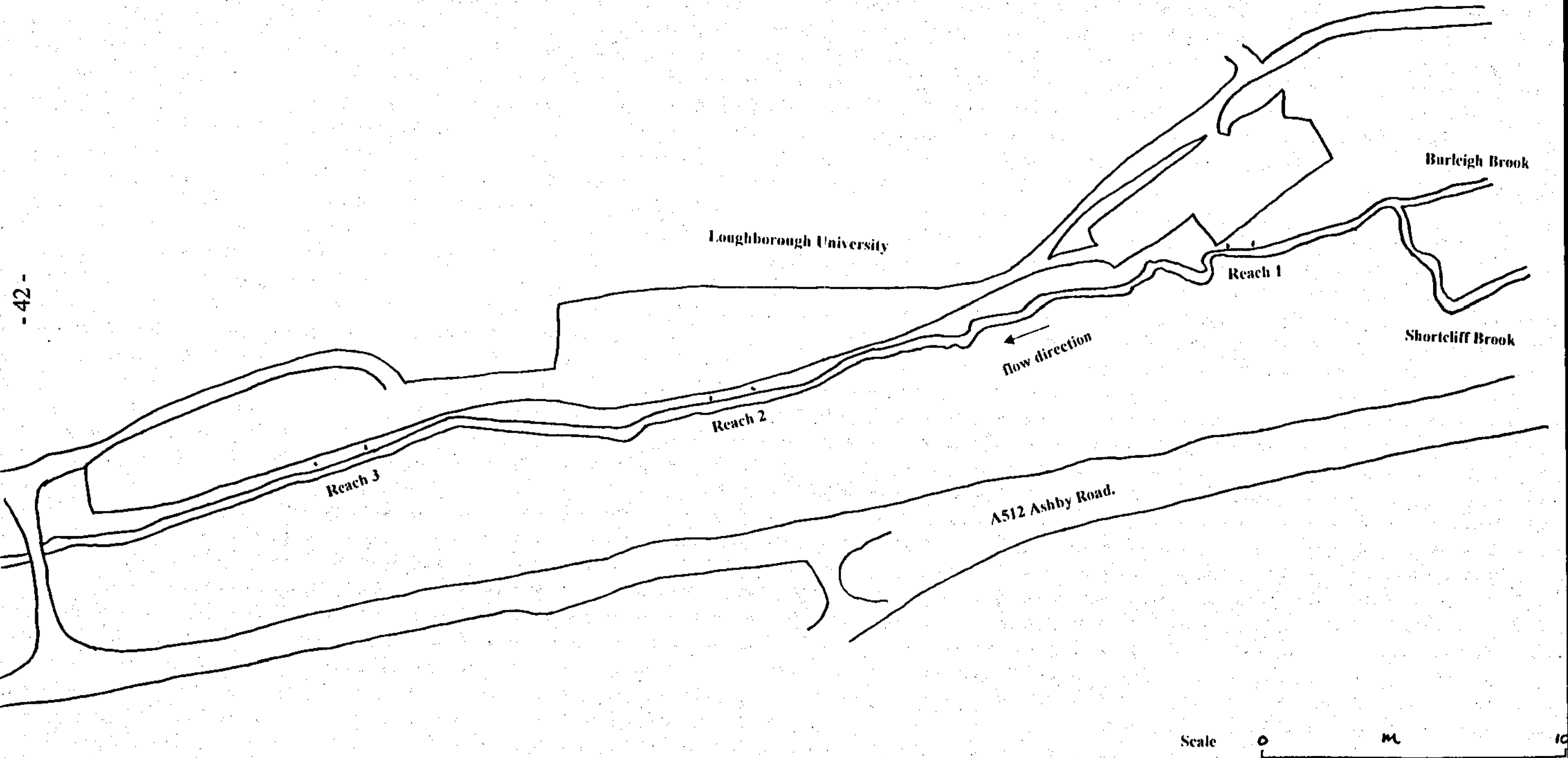
2.3.1 Sampling sites.

Within this study, three reaches were chosen as sampling sites. Three reaches were chosen, to allow comparison between reaches, and ensure a variety of results. Using three sites also allowed for problems associated with vandalism, loss of traps and the possibility that one reach may not behave in a manner consistent to the others. The rationale for choosing individual reaches was that each reach should be a straight riffle of constant width, substrate should be uniform along the length, water depth constant, with the main criterion being that both the upstream and downstream channel features should not detrimentally effect the hydraulics along the reach. The main concern was that hydraulics would not alter as a result of flow backing up at the downstream exit during higher flows. Once a number of suitable reaches had been selected, they were observed at a range of flows to verify that no significant alterations occurred to those observed at lower flows. The three reaches and their downstream positions are shown in Figure 2.3.

Reach 1.

Reach 1 is the upper most sampling area. It is about 100m downstream of the last main confluence along this section of the Brook. Between the confluence and the monitoring site, the Brook has a meandering character. The major reason that Reach 1 was used as a sampling point is its proximity to the stage and suspended sediment samplers. These had been located in this area for ease of maintenance by the Geography Department of Loughborough University and were used in various undergraduate monitoring programmes. It seemed logical to use this area as both the

Figure 2.3 shows the three reaches and relative positions to each other. This Figure also shows the proximity of Burleigh Brook to the A512 and the edge of Loughborough University boundary.

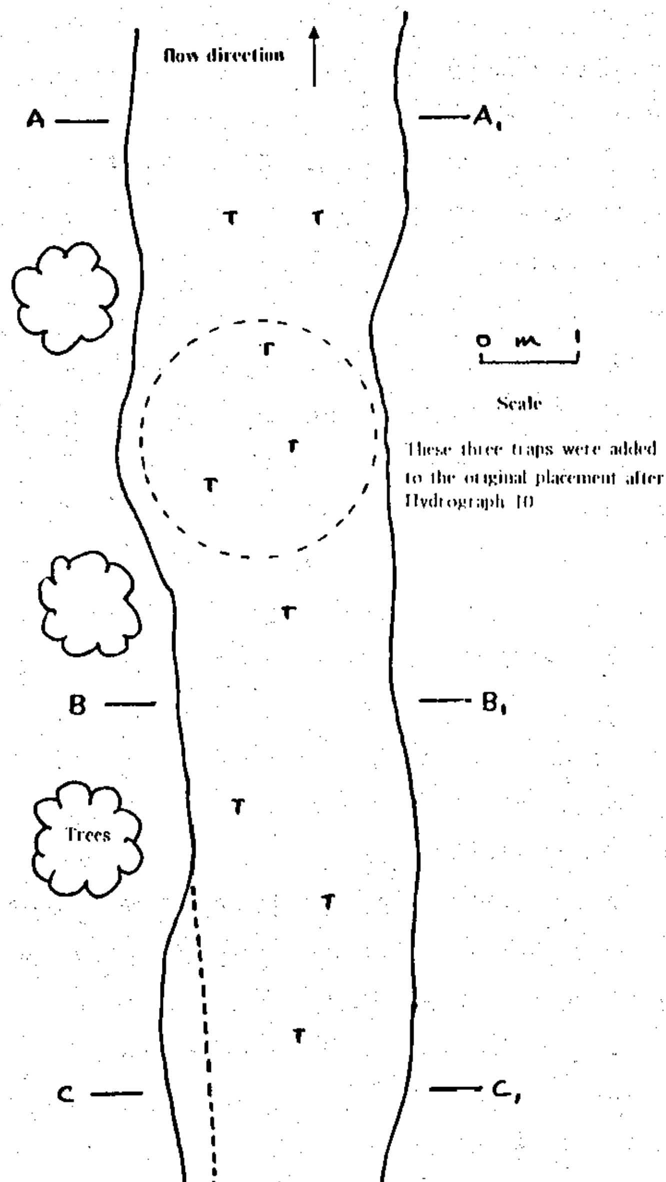


hydrological monitoring site as well as a sample site. In hindsight, the choice of this stretch of Burleigh Brook was poorer than the two downstream reaches. A large pool developing around a tree affected the downstream exit, and there was bar development in the upper region of the riffle.

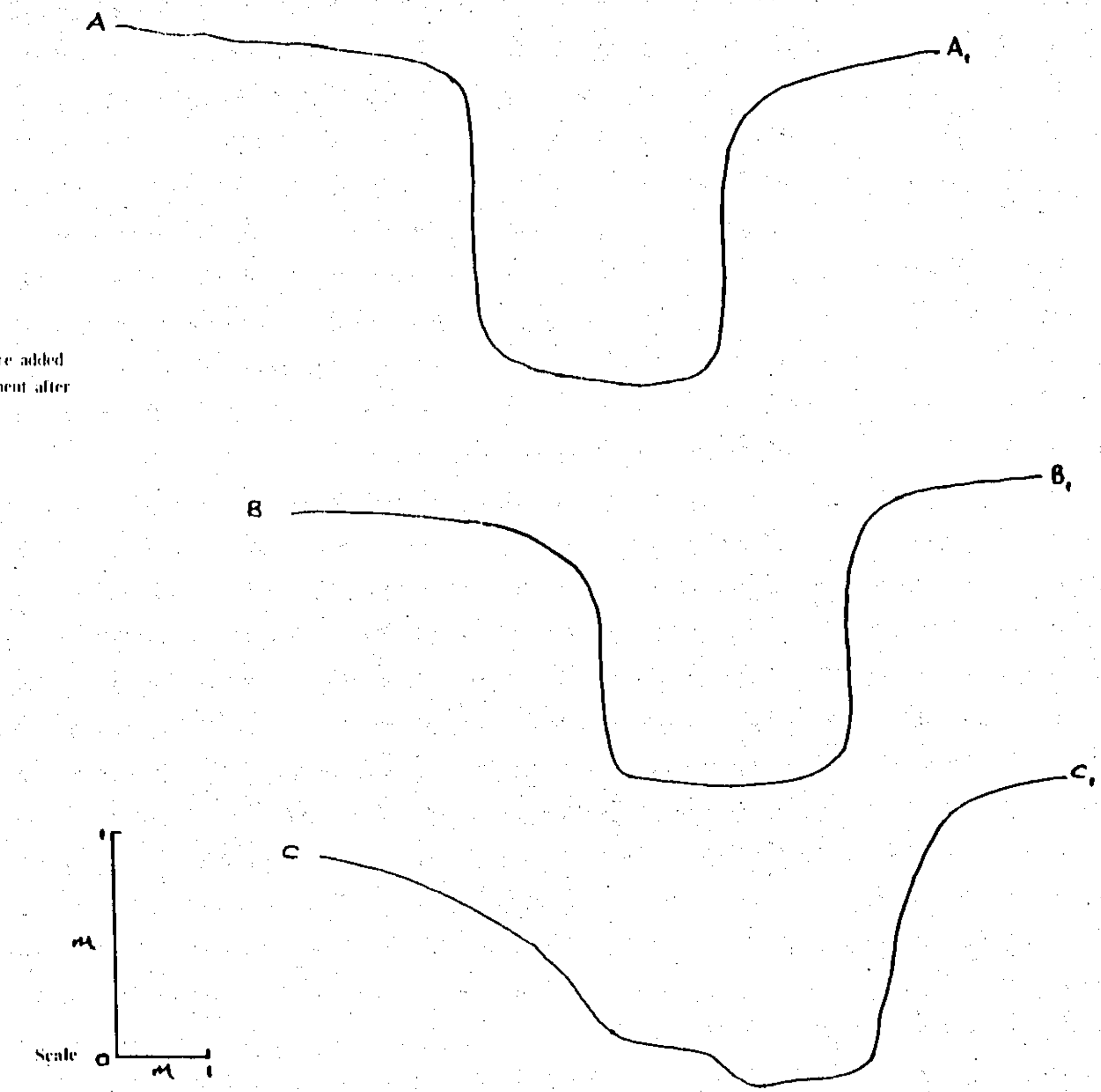
Figure 2.4 is a plan drawing of the reach along with three cross-sectional diagrams. These figures depict the positioning of traps in this sampling region. Within the first ten Hydrographs, it was discovered that only six sediment traps were in the correct locations, however, this was increased to nine after the winter floods.

Figure 2.5 depicts the surface size grain distribution of Reach 1. The methodology used here was a Wolman grid sample (1954). The reaches were sampled by pacing transects across the stream. The pacing used on Burleigh Brook was one foot directly against the other, as a consequence of the small areas that needed to the surveyed. A piece of bed material was picked up every second foot, from below my big toe. The spacing of the cross-stream transects were repeated in a downstream progression. The material retrieved was taken back to the lab and all three axes measured. This sampling method was chosen above other standards of areal sampling (Lane and Carson, 1953) and volumetric sampling of the armour layer (Klingeman and Emmett, 1982), for a number of reasons. The first being that the material retrieved was initially classified into longitudinal sections of the riffle. Second taking areal samples, either by using a material such as wax or clay to remove all the surface material, or picking the complete surface layer by the 'cookie principle' would not have provided the appropriate downstream spatial coverage of the reach. The volumetric method would have

Figure 2.4 shows a plan diagram and cross-sections from Reach 1.

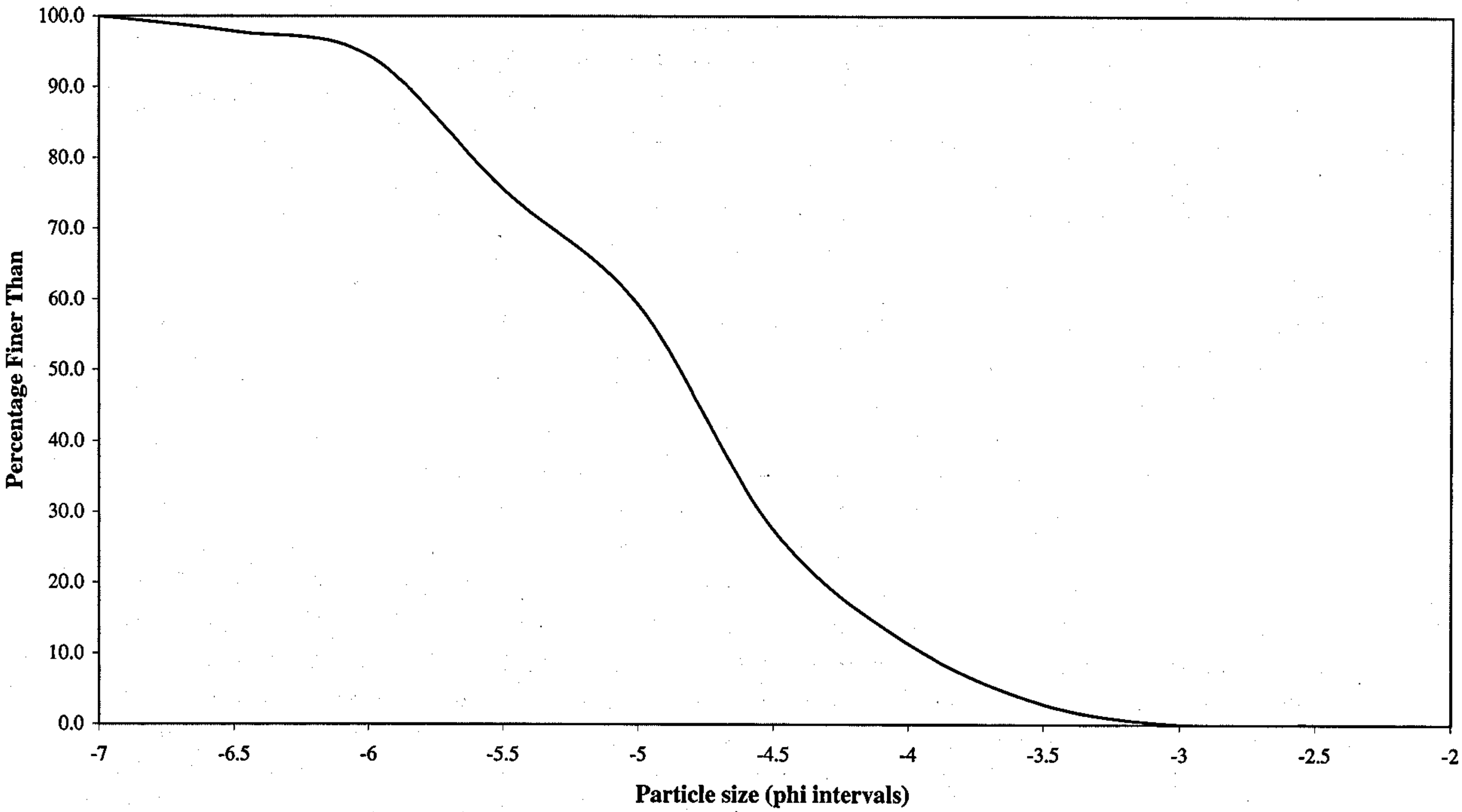


Dashed line indicates areas of channel bed which were exposed under baseflow conditions.



The cross sections have been drawn with an exaggerated vertical scale.

Figure 2.5 depicts the Percentage Finer Curve for the surface grain size distribution for Reach 1.

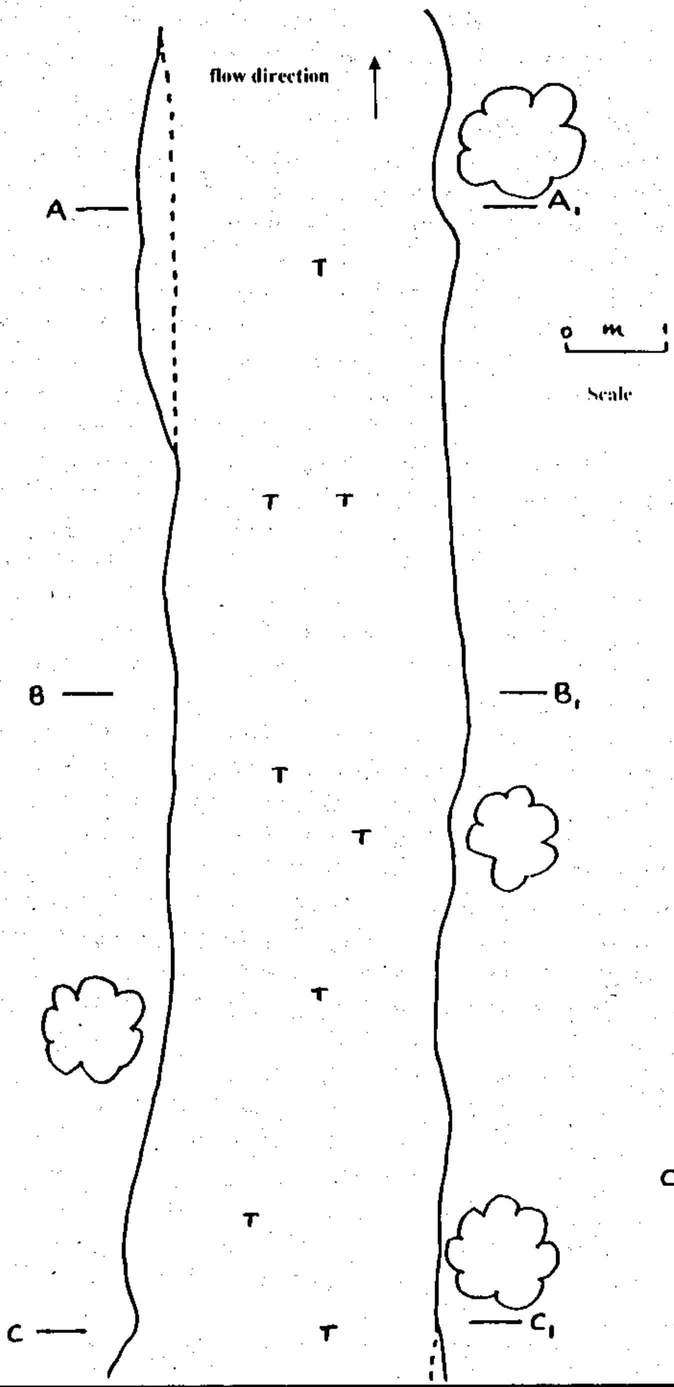


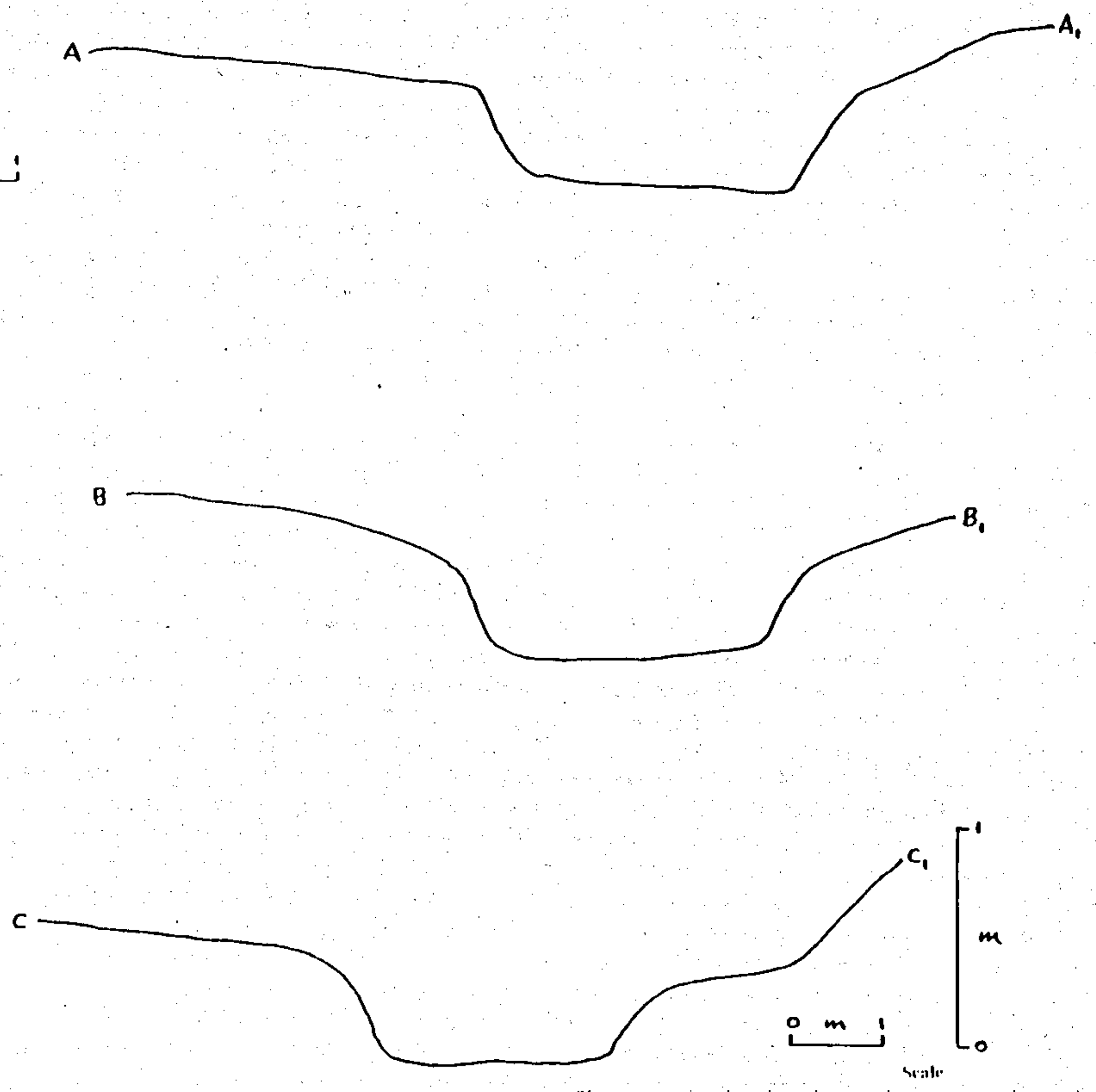
destroyed the surface of the reach during the sampling period. However, both these methods reduce the amount of truncation that occurs at the lower end of the size distribution curve. A subsurface sample was not taken of any of the reaches for two reasons, first, during the data collection for this study such a measurement would have compromised the successive measurements. Second, after the termination of the monitoring undertaken in this study, the undergraduates carried out a comprehensive study of the bed material of Burleigh Brook. This meant that the students used many of the techniques described above to remove large quantities of bed material. Therefore, the representative bed was removed almost immediately after the termination of monitoring for this study. As a consequence sampling of the bed for aerial or volumetric particles size analysis did not happen, as it was felt that the results obtained would not provide representative data on the streambed as it was during monitoring. However, I do comprehend that a size distribution for the subsurface material is of interest in the study of sediment transport within gravel-bed rivers, but at no point within the study was the timing of sampling conducive to disturbance of the bed material. The methodology was adopted for the other two reaches.

Reach 2.

Figure 2.6 shows a plan diagram of Reach 2 with three vertical cross-sections. Figure 2.7 shows the size distribution of the bed material. This reach showed a more constant response to the change in flow conditions. The hydraulics here were more constant, the straight length was greater and the upstream section was not as sinuous as that at Reach 1. The only negative aspect of this reach, is that the left bank was

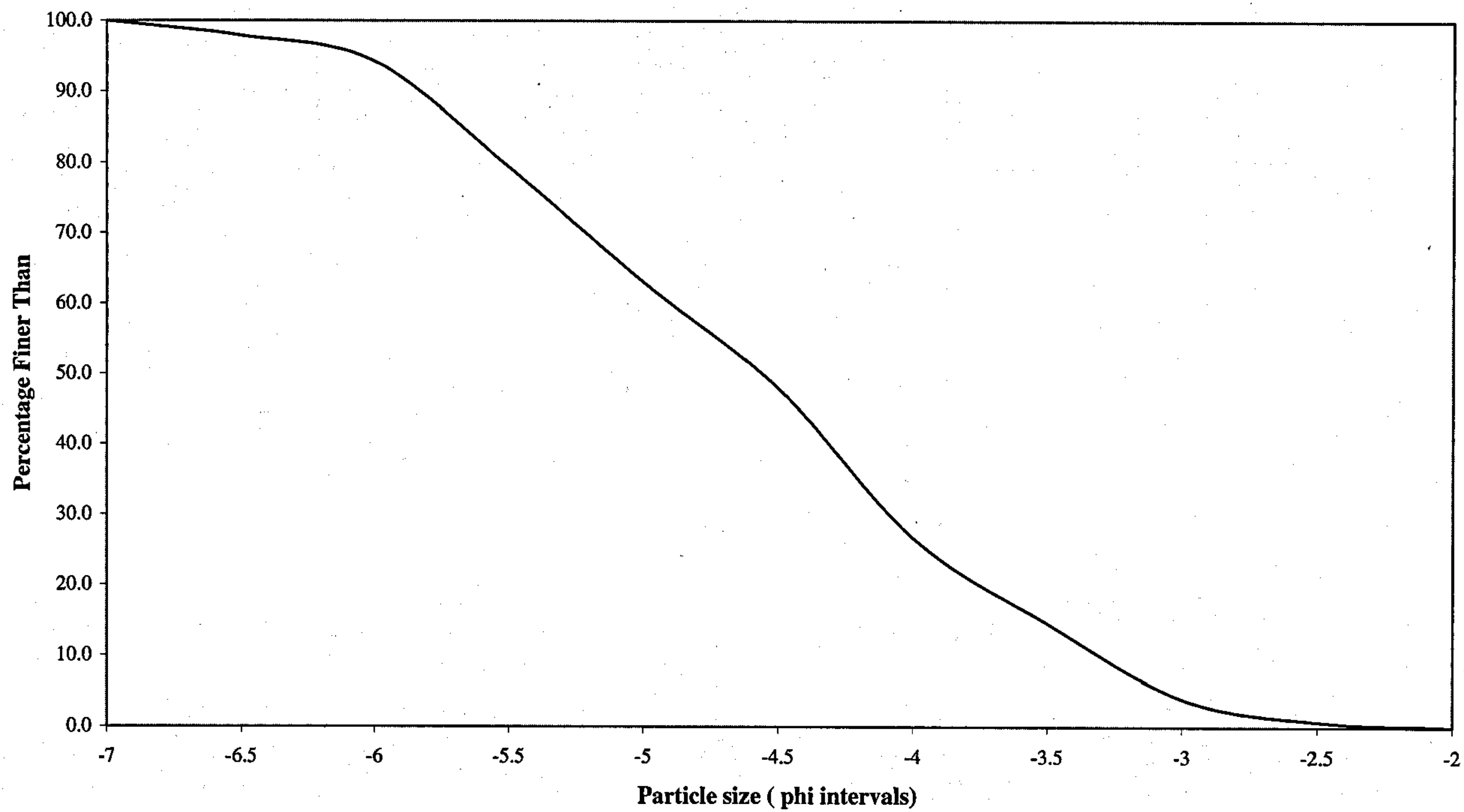
Figure 2.6 shows a plan diagram and cross-sections from Reach 2.





The cross sections have been drawn with an exaggerated vertical scale

Figure 2.7 depicts the Percentage Finer Curve for the surface grain size distribution for Reach 2.



considerably lower than other banks, and therefore over banking may have occurred during the highest magnitude events. As will be demonstrated later (Chapter 4.02), these high magnitude events have been excluded from the data analysis.

Reach 3.

Figure 2.8 shows the plan diagram along with three vertical cross-sections for Reach 3. Figure 2.9 also depicts the size distribution of the bed material. As a consequence of the sampling used here, it is not completely apparent that the bed surface material here was finer than the two upstream reaches. This was observed when collecting the receivers, and during the construction of the traps (See Chapter 3). The subsurface material in this reach was composed of large areas of clay and silt material, which made excavation of holes easier than digging in gravel patches in the upper reaches.

2.3.2 Monitoring equipment.

The primary monitoring station Burleigh Brook was located within Reach 1. The monitoring equipment used was a pressure transducer to monitor stage and an automatic water sampler (ISCO 3700). The pressure transducer was installed within a stilling well, and via a data logger recorded readings every 15 minutes. The data logger was downloaded every week and the pressure measurements converted using a simple equation to depth of water. These readings provide a base from which information for individual Hydrographs was derived. It has also been used in the

Figure 2.8 shows a plan diagram and cross-sections from Reach 3.

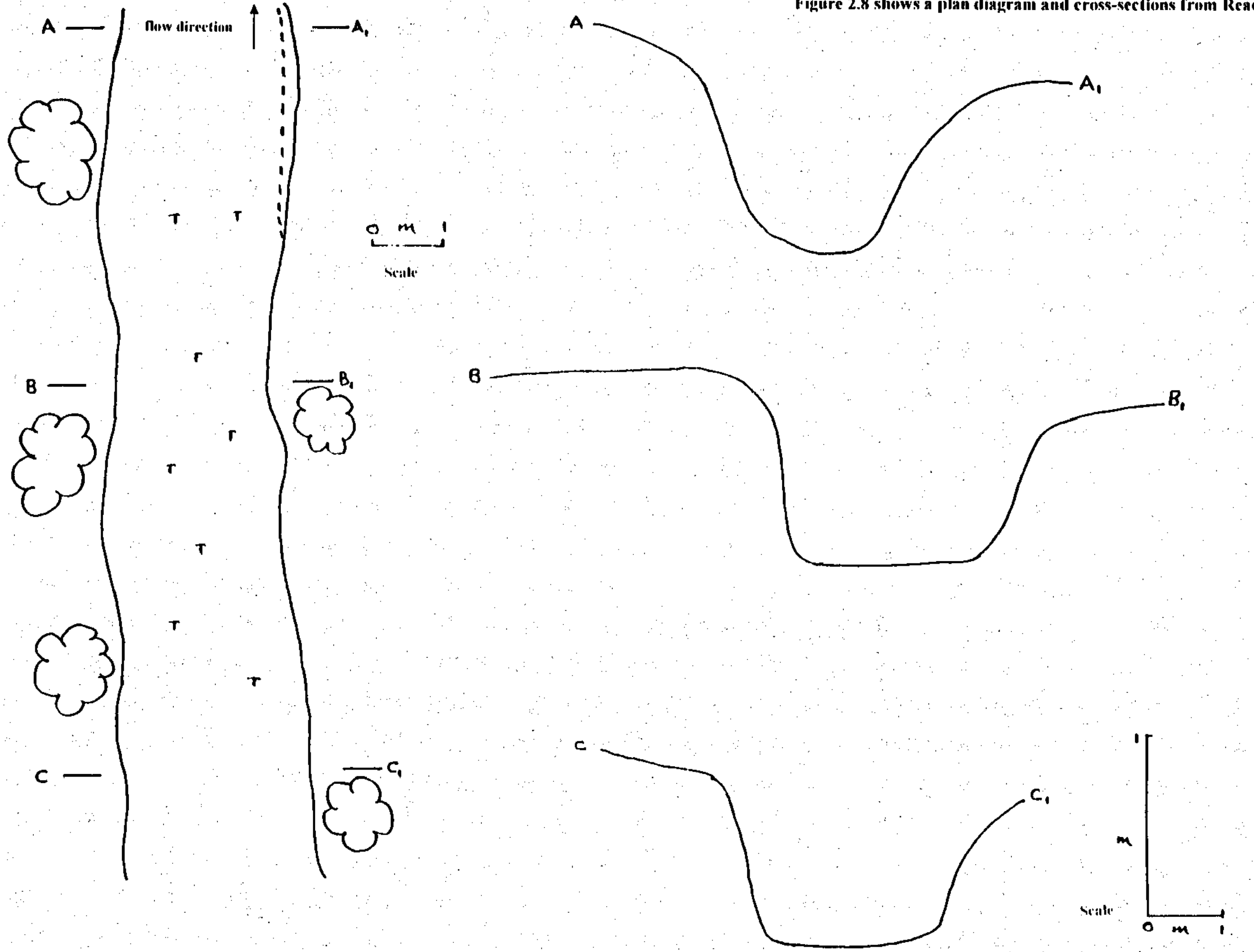
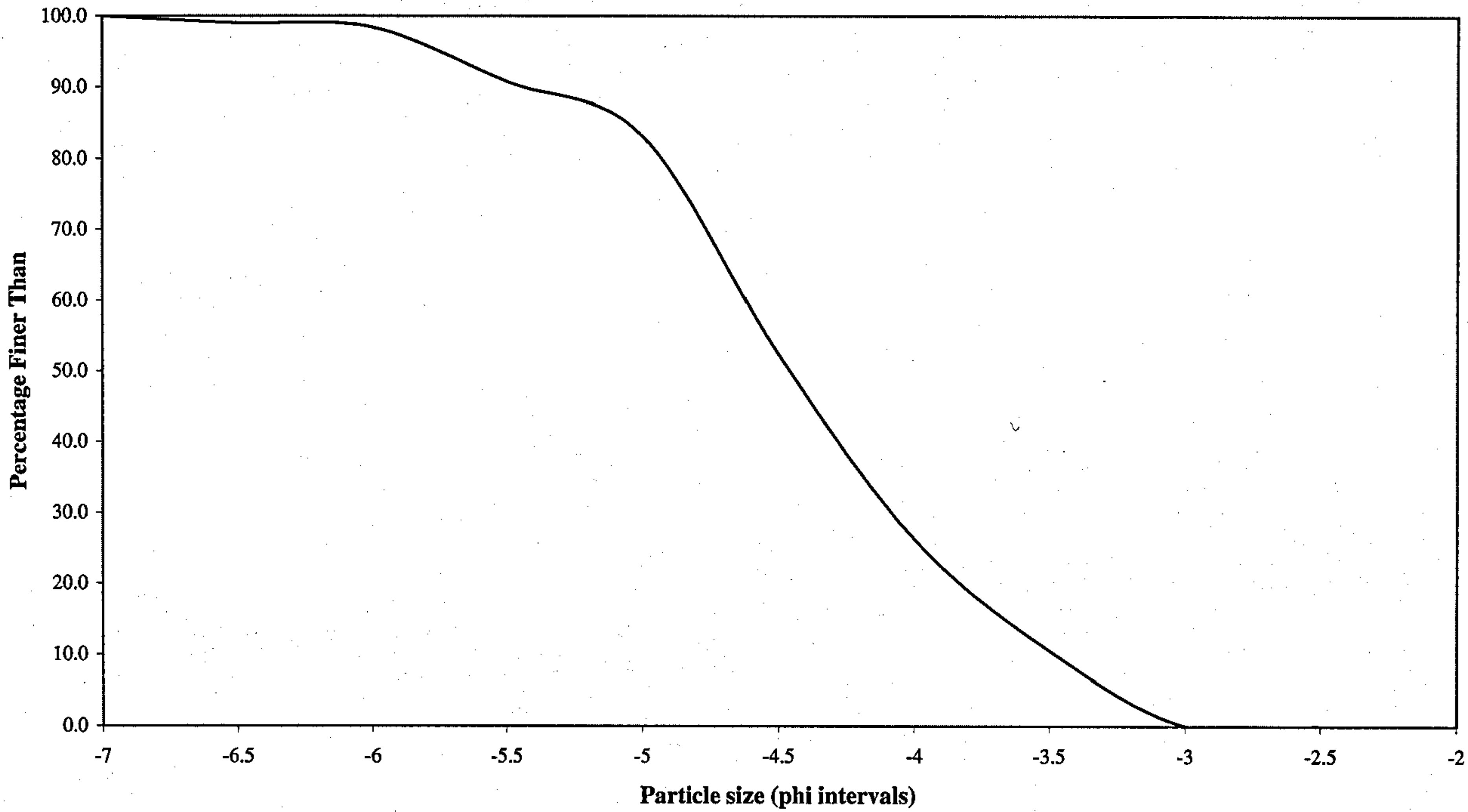


Figure 2.9 depicts the Percentage Finer Curve for the surface grain size distribution for Reach 3.



stage discharge relationship. The complete stage trace for the monitoring periods is shown in Figure 2.10.

The water sampler was programmed, for the majority of monitoring, to sample every eight hours. The volume of water removed from Burleigh Brook was around one litre. These samples were used to examine suspended sediment concentrations within Burleigh Brook. The methodology employed here was filtration of known aliquots of water, under vacuum. This left an amount of sediment on pre-dried and weighed filter paper. These filter papers were then dried at 110°C overnight. Once dried they were removed from the oven, placed in a desiccator and once cool re-weighed. Once the weight of sediment was known for the aliquot of water, the suspended sediment concentration (mg l^{-1}) was ascertained. These values were then plotted on a graph against the stage of extraction to produce a suspended sediment-rating curve. This is shown in Figure 2.11.

During the sampling period, a stage-discharge relationship was established. Discharge was calculated using the salt dilution method. A salt solution of known concentration was added to Burleigh Brook at a predetermined discharge at the upstream limit of Reach 1. At the downstream end, the conductivity of the Brook's discharge was recorded at ten second intervals until the conductivity returned to the background measurement. Using a simple equation the discharge of Burleigh Brook could be determined. This discharge was then plotted against the stage recorded, during the monitoring period, from the pressure transducer. As is shown in Figure 2.12, a good graphical relationship has been established allowing the peak stage measurements within each Hydrograph to be converted to discharge

Figure 2.10 depicts the complete stage trace between December 1998 and December 1999.
Key: circles around the data indicate when the pressure transducer was not functioning properly.

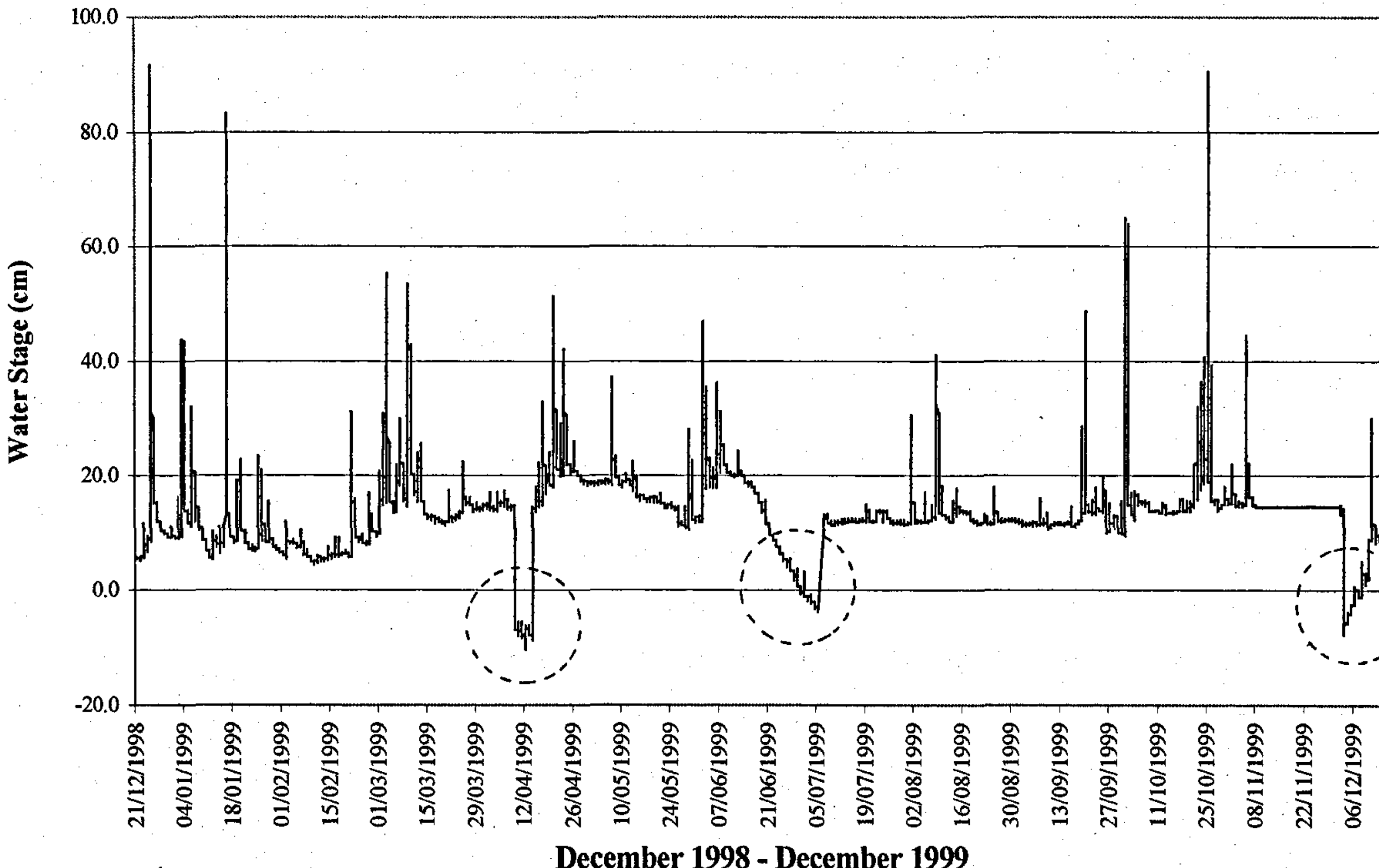


Figure 2.11 showing the relationship between suspended sediment concentrations and stage measurements between September 1998 and September 1999.

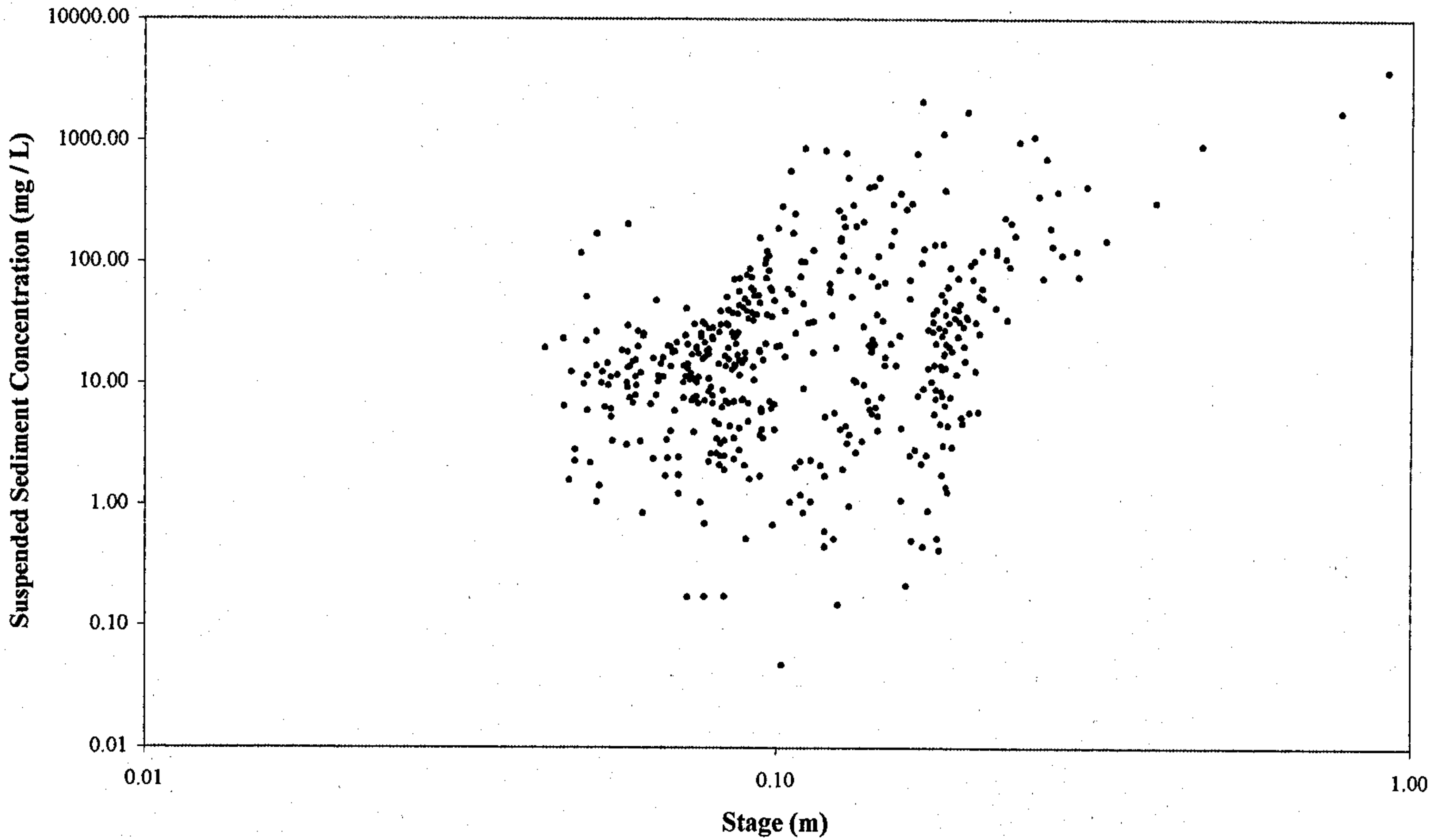
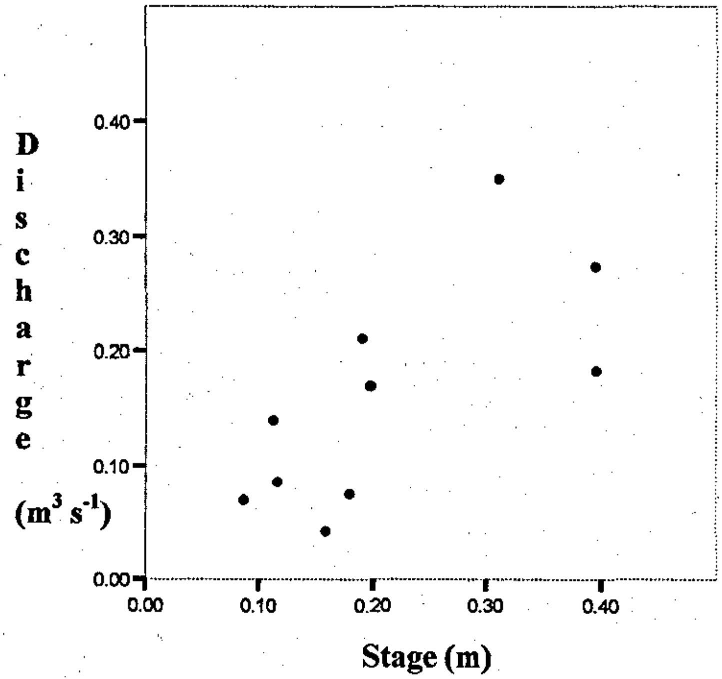


Figure 2.12 shows the stage discharge relationship for Reach 1 on Burleigh Brook.



Regression analysis on the data shown here gives the equation of

$$\text{Discharge} = 0.617 * \text{stage} + 2.479*10^{-2}. \qquad \text{Equation 2.1.}$$

From this the stages used in this study can be turned into discharge measurements, as shown by the list below.

Baseflow is equated to a discharge below 0.117 m^3 s^{-1}.
The peak flow monitored over the complete monitoring period was 0.586 m^3 s^{-1}.

A 0.30m stage equates to a discharge of 0.209 m^3 s^{-1}.
A 0.40m stage equates to a discharge of 0.272 m^3 s^{-1}.
A 0.50m stage equates to a discharge of 0.333 m^3 s^{-1}.

As a consequence of the relationship shown above not being statistically significant, the stage measurements used during the monitoring period have not been converted to discharge using Equation 2.1. In the detailed analysis, Chapters 4 and 5, the sedimentation rates and particles size are assessed against stage rather than discharge. To relate the stage measurements to discharge, the paragraph above gives a rough guide to the discharge within Burleigh Brook. It is because of the statistical evidence supplied by the r^2 value – 0.510 that it was decided to undertake analysis with stage rather than discharge.

measurements using Equation 2.1. There are a limited number of graphical points on this graph as a consequence of the detrimental effect that salt dilution can have on the biotic life of a stream. This was shown by the capture of a crayfish during one of the monitoring periods.

2.4 Summary of recorded Hydrographs.

As has been stated the aim of this study was to examine the rate of deposition of fine material into a lowland gravel-bed river. One of the objectives is to examine the factors that affect this relationship. The main physical characteristic under observation is the effect that an increase in stage can have on the sedimentation rates and the size of material that is infiltrated into a gravel bed. Therefore, as will be shown in the methodology, it was aimed to isolate flood events. In this section of the background the individual periods on measurement are reported. These are summarised in Table 2.1. This table lists a number of characteristics of each of the recorded events. In total 26 sampling periods were taken throughout 1999. The majority of these are reported in Table 2.1, however, those that are absent are a consequence of pressure transducer failure which lead to the removal of these events from the complete data set. Appendix 1 depicts graphically each hydrograph along with some of the results from that Hydrograph. Chapter 3 discusses the methodology concerned with the collection of data that is specific to this study.

Table 2.1 depicting some of the details and characteristics of the recorded hydrographs.

Hydrograph	Date	Peak Stage (m)	Peak Discharge (m^3s^{-1})	Total Duration of monitoring (hr)	Flood Duration (hr)	Lapse time (hr)	Number of retrieved traps
1	05.01.99	0.92		361.25	120.0	-	21
2	08.01.99	0.32		70.0	36.25	289.50	21
3	14.01.99		Base Flow	144.0	-	-	20
4	18.01.99	0.83		98.75	28.45	223.75	22
5	21.01.99	0.22		72.75	31.15	99.75	22
6	28.01.99	0.23		167.75	45.30	121.50	22
7	15.02.99		Base Flow	432.0	-	-	22
8	23.02.99	0.31		189.0	26.25	651.25	22
9	11.03.99	0.55		384.0	236.25	248.50	22
10	19.03.99	0.25		191.75	57.25	22.75	21
11	26.03.99	0.17		182.25	49.25	197.50	23
12	28.04.99	0.51		792.0	304.0	733.50	25
13	24.05.99	0.37		624.5	46.0	429.0	24
14	01.06.99	0.28		190.5	13.25	531.0	25
15	04.06.99	0.47		72.0	50.75	96.0	25
16	18.06.99	0.36		333.75	265.45	95.25	25
17	19.07.99		Base Flow	744.0	-	-	9
18	09.08.99	0.41		508.0	46.25	1516.5	22
19	25.08.99		Base Flow	384.0	-	-	24
20	26.08.99	0.16		24.0	24.0	384.0	10
21	15.09.99		Base Flow	480.0	-	-	8
22	21.09.99	0.48		146.25	29.0	752.0	8
26	08.11.99	0.44		286.25	41.0	unknown	21

(Hydrographs with an asterisk depict that these hydrographs were sieved.)

Chapter 3

Methods

3.1 Trap Design.

Simple interstice geometry was chosen for this study. In designing the traps, two different pore arrangements were selected, representing the interstitial openings created by using 3 and 4 roughness elements, respectively. Frostick *et al.*, (1984) stated that over 75% of all pore spaces within a gravel bed river are bounded by either 3 or 4 particles. In this study these particles around individual interstices are simplified to hemispheres, and the arrangements used are modifications of those illustrated by Frostick *et al.*, (1984).

In this study two different interstices are used. Configuration I and II possess the same interstice shape formed by three particles, but when placed in the flow, their orientation will be different. Configuration III is comprised of four particles and has a greater interstice pore mouth. These three different configurations are shown in Figures 3.4 to 3.6.

3.1.1 Rationale behind design.

The objective of this study is to examine the effects that different interstice types have on sedimentation of fine material. The study differs from many others concerned with sedimentation in lowland gravel-bed rivers (e.g. Frostick *et al.*, 1984, Diplas and Parker, 1992 and Sear, 1993) because it focuses on material infiltrating through individual pore spaces.

Each trap consists of a lid, comprising a single interstitial pore space, in one of two types, mounted above a container that collects infiltrating material. Two elements of trap design isolate the role of processes occurring within and around the mouth of the pore and precluded additional complications. First, the containers are impervious to lateral flows within the bed that precludes any hydraulic or sedimentary effect associated with intra-gravel flow. Fine material cannot be introduced from, and lost to the surrounding subsurface. The emphasis of this study is on sediment infiltrating vertically through a pore space. Usage of an impervious container also had practical advantages of retaining deposited material when the receivers were removed during sampling. Sear (1993) reported problems of loss of fines, 26-40% loss, when using pervious material for the collecting receptacle. Second, the containers do not contain any framework material. This allows sedimentation of any material that is small enough to pass through the interstice in the trap lid. Complications associated with both the processes of hindered and unhindered settling and the formation of a seal within the framework, are avoided (see Chapter 1 for discussions on this topic). This study uses the assumption that, after major flood events, the bed is completely flushed of fine material. Therefore, this study differs from many. Frostick *et al.*, (1984) used large traps and examined the role that different surface and subsurface materials had on the sedimentation of fine material. Lisle (1989) also used a framework within in his traps and covered them with original surface gravels.

While these design elements facilitate examination of the processes occurring at the pore mouth, it is clear that the arrangement adopted here is a simplification of nature. However, Kozerski (1994) questions how a cylindrical trap influences the particles carrying eddies around the pore mouth, and suggests that a trap of this nature may size-selectively capture particles.

3.1.2 Construction of traps.

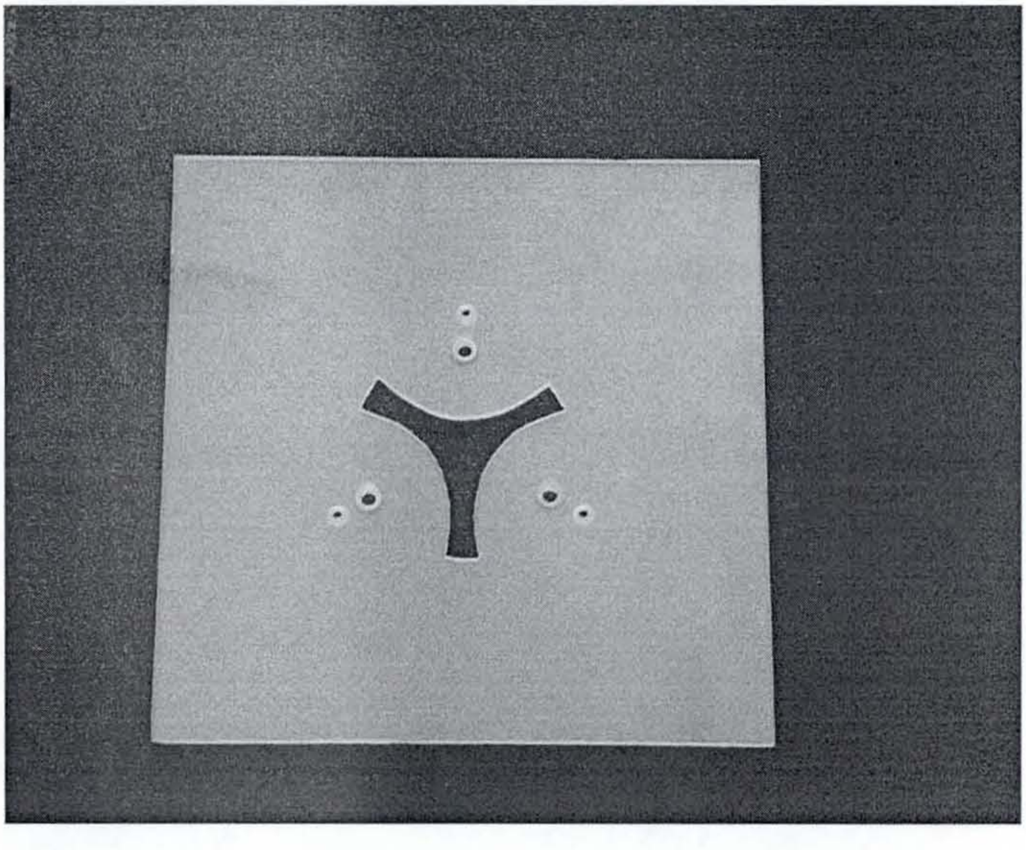
A key consideration when constructing the traps was that of removal and replacement of containers should be as efficient as possible. After some experimentation, the final design utilised a 1-litre, plastic drink container (0.101m external diameter) which fitted snugly into a cut section of standard soil drainage pipe (0.102m internal diameter), that was permanently installed into the river bed. The drink containers used had a small lip on the upper rim that prevents material from collecting between the walls of the pipe and the container itself. The pipe sections were cut longer than the drink container so that the receptacle hangs on its rim within the pipe.

Three reaches were chosen as the test sites. Within each reach it was decided to install a maximum of nine traps (See Section 3.1.3). At each location, holes were dug in the bed; deep enough to enable the top of the drainage pipe to lie just below the surface of the riverbed and thereby preventing any interference with local hydraulics. The bed was then refilled around the drainage pipe and checked to ensure that the container fitted and that the bed level was restored. These drainage pipes were then left in situ for three flood events, enabling the surrounding bed to stabilise and allowing any fine material that had been disturbed to be flushed through the system prior to the commencement of monitoring.

The lids of the traps were constructed from a piece of Perspex sheet onto which concrete roughness elements were attached, and into which an interstice was cut. The concrete roughness elements were made in wooden hemispherical moulds with a radius of 0.045m. To speed up the process, a quick-setting agent was added to the mix of sand and cement (three parts coarse sharp sand to one part cement powder to four parts water). The addition of the quick-setting agent did not produce roughness elements with as smooth a surface as those made without. This was because air bubbles did not rise through the mix before the concrete had gone off (Allen, 1998 per. com.). Release of the hemispheres from the moulds involved banging them on a hard object, which was not ideal, and sometimes resulted in broken and deformed hemispheres. The small minority of hemispheres that had imperfections in their surfaces were discarded.

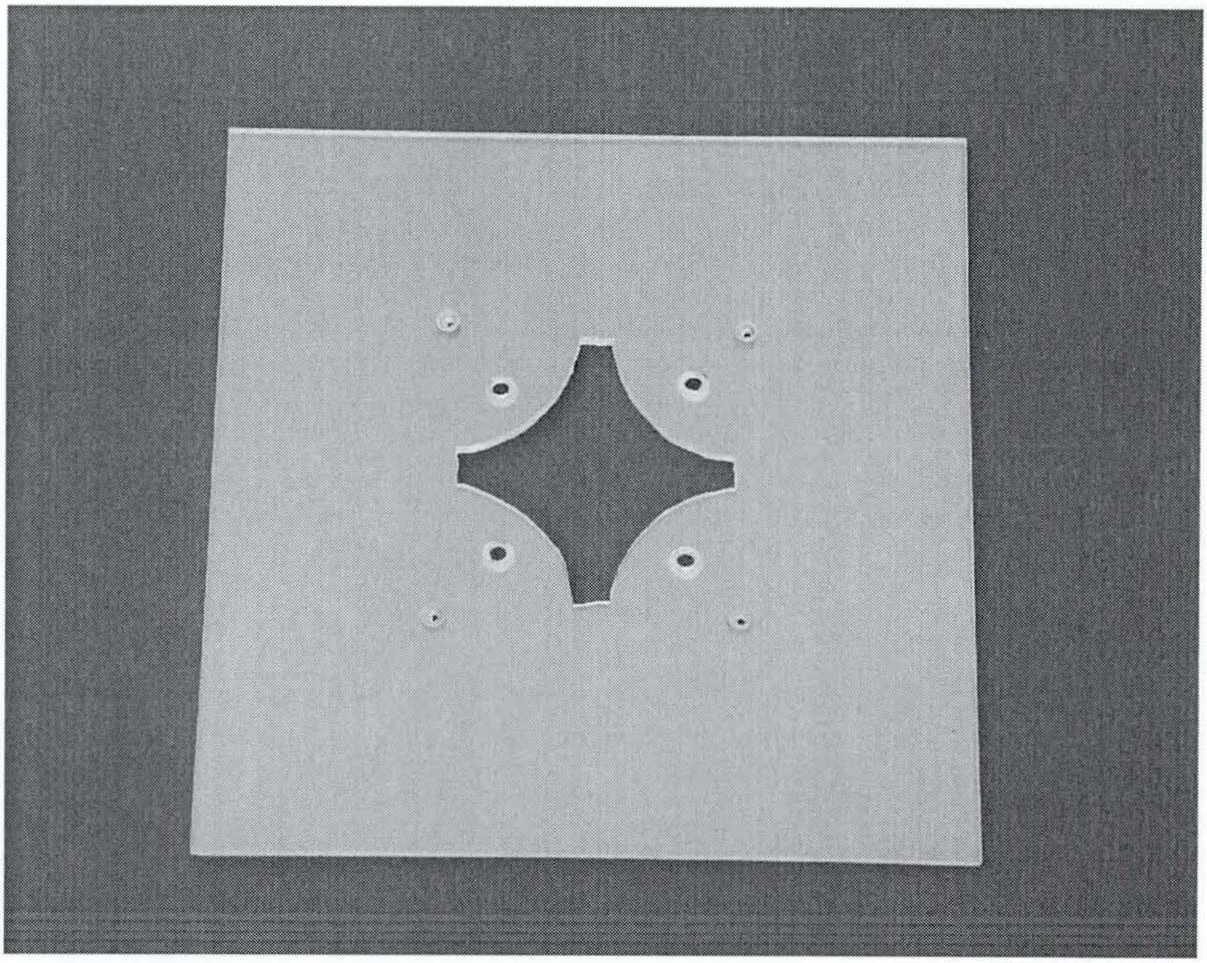
The Perspex was cut into 0.30m by 0.30m squares and templates of the interstices were photocopied, mounted on, and cut out of the Perspex using a jig saw. Figures 3.1 and 3.2 show the Perspex lids. To keep the lids in situ over the containers, a pillar was constructed under each hemisphere and screwed in – Figure 3.3. The finished trap lids for each clast configuration are shown in Figures 3.4 to 3.6. The configurations have been numbered to ease description. Trap type I consists of three roughness elements, with one roughness element directly downstream of the interstice. Trap type II involves a three roughness element configuration, but with the

Figure 3.1 shows the cut Perspex lid for Configurations I and II.



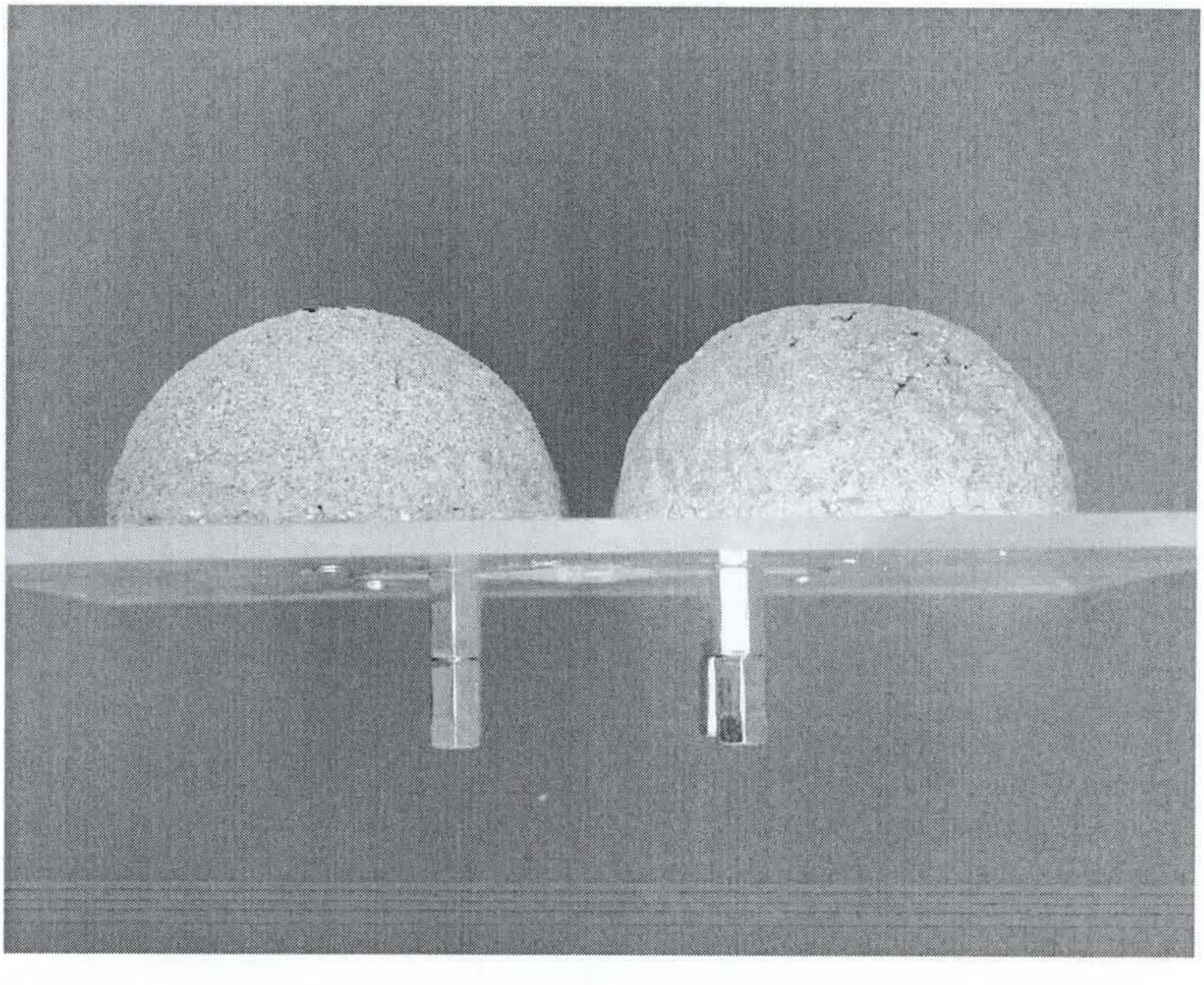
The Perspex lid was cut using a jigsaw and the screw holes were drilled through to allow the concrete hemispheres to be screwed in place.

Figure 3.2 shows the cut Perspex lid for Configuration III.



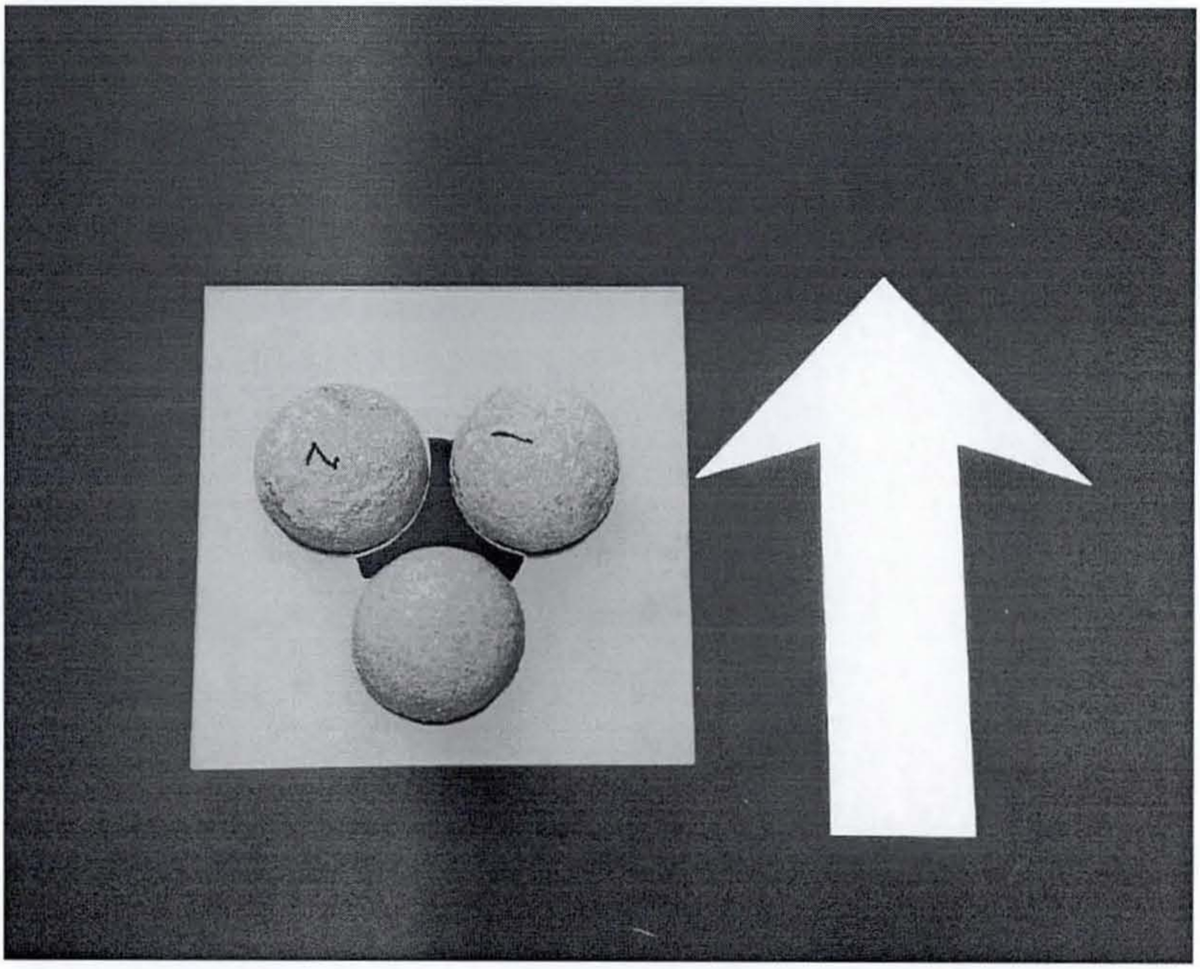
The Perspex lid was cut using a jigsaw and screw holes were drilled through to allow the concrete hemispheres to be screwed in place.

Figure 3.3 showing how the concrete hemispheres were fixed to the Perspex lids.



The pillars under the Perspex served two purposes, one to aid in the fixing of the concrete hemispheres to the Perspex and two to keep the lid on the receivers during placement.

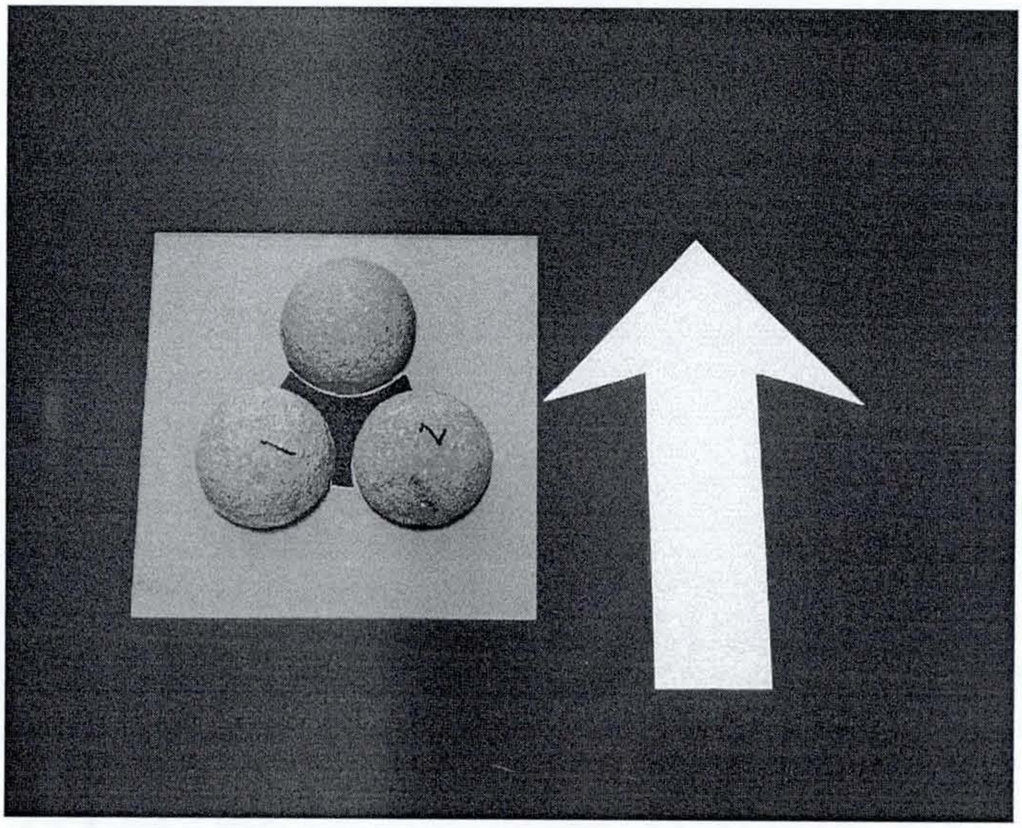
Figure 3.4 shows the clast configuration for trap lid Configuration I.



The arrow indicates the direction of flow.

Each of the roughness elements in 0.09m in diameter

Figure 3.5 showing the clast configuration for the trap lid Confiuration II



The arrow indicates the direction of flow.

Each of the roughness elements is 0.09m in diameter.

Figure 3.6 shows the clast configuration for trap lid Configuration III

This trap lid was placed on the stream bed with the flow direction being from the bottom of the page to the top.

Each of the roughness elements is 0.09m in diameter.

single roughness element upstream of the interstice. Trap type III was constructed of four roughness elements, two sets of in-line hemispheres, leaving a central interstice exposed to the on-coming flow in a fashion similar to type I.

Periodically the lids had to have running repairs made on them, roughness elements became detached and were replaced, but routine maintenance consisted of tightening the screws that held the hemispheres in place. The trap lids all survived a year in Burleigh Brook. However, occasionally, when removing the collecting container, the drainage pipe would unseat. In all instances, this movement was noted and rectified.

3.1.3 Placement of traps.

As outlined in Chapter 2, three reaches were chosen as the sampling sites. To ensure that results obtained could be compared between reaches, without bias the different trap configurations in each of the reaches were mixed. Therefore, there were to be nine traps in each reach, three of each configuration. To enable trap locations to be assessed between the different reaches, the different trap configurations were placed in different areas of the reach. These areas were not consistent across the three reaches, i.e. Configuration I was not always at the top of the reach. This rotation in trap configurations is based on the different hydraulic conditions that operate through out the length of a riffle. Therefore, the traps followed a downstream progression, which was rotated throughout the three reaches. Any effects of upstream trap placement are, therefore, not entirely random. However, it was deemed that the traps would not significantly affect the sediment flux passing the downstream traps. This assumption is speculative and is based upon the area of the trap in comparison with that of the streambed. Also, the traps were not placed directly downstream of one another. The distances between different rows are clearly shown in Figures 2.4, 2.6 and 2.8. It is assumed that these distances are sufficiently large that any changes in flow patterns and sediment transport associated with an upstream trap do not impinge on the results of a downstream trap.

Figure 3.7 - a schematic diagram showing the downstream rotation of the different Configuration throughout the three reaches.

Reach 1.	Configuration I	(times 3)	upstream
	Configuration II	(times 3)	
	Configuration III	(times 3	downstream
Reach 2.	Configuration II	(times 2)	upstream
	Configuration III	(times 3)	
	Configuration I	(times 3)	downstream
Reach 3	Configuration III	(times 2)	upstream
	Configuration I	(times 3)	
	Configuration II	(times 3)	downstream

3.2 Sampling Strategy.

A sampling strategy was devised such that the containers were emptied after flood events, with the aim of isolating floods of different magnitude. Removal of the receivers occurred when Burleigh Brook had returned to base flow conditions. Base flow conditions were selected as a benchmark in the retrieval of containers for four reasons. First, to ensure collection of all the material deposited by the preceding flood, including that carried during the recession limb; second, to avoid flows greater than base flow because turbid conditions made locating the traps difficult; third, to minimise disturbance of the stream bed; and four to minimise the depth of water through which the container had to be raised when removal took place. From an analysis of the flood hydrograph of the complete monitoring period, Figure 2.10, the winter base flow was deemed to be less than 0.15m in depth, or 0.117 m^3 s^{-1}, at the stage recorder (See Chapter 4 for justification).

The aim of the sampling regime was to isolate individual flood events, or longer periods of base flow. Collection of base flow data was as important as event data, because of the need to partition sedimentation data associated to peak and baseflow. Unfortunately, some floods were not easy to isolate, mainly because of safety factors and the difficulty of locating traps during turbid conditions. This has meant that some events consist of multiple peaks and piggybacking, as a result of hydrological persistence and the clustering of rainfall events. In addition, there are instances when the flood event possessed a peak stage that only just exceeded the criteria of base flow (see Table 2.1).

3.2.1 Collection of material.

When the containers were removed and replaced with fresh ones, care was taken to ensure there was minimal disturbance to the riverbed. The receivers were removed in an upstream progression at each riffle. This was carried out to minimise collection of additional sediment caused by bed disturbance. The receivers under each of the traps were marked with a trap number, 1 to 25, and a location code, e.g. R1IIR, representing reach, trap type and lateral location. On retrieval of containers, care was taken to ensure that no sediment was lost when the container was raised through the water column. In many instances fish were found in the receivers and these had to be released without the loss of sediment. The drink containers had lids which were fitted on once the containers were removed from the bed to stop material being lost when they were transported back to the laboratory. In a few instances, during the complete monitoring period, trap lids rotated during the flood hydrograph or were completely removed. In these cases the data has been disregarded as unrepresentative and not used in further analysis.

3.2.2 Drying of material.

In the laboratory, excess water was withdrawn using a water pump, and any cased caddis-flies (sp. *Potamophylax* and *Sericostoma personatum*) found amongst the material were removed. In an extreme case, a layer of cased caddis-flies up to 5cm thick, comprising in excess of 100 individuals were found. The caddis-fly cases would affect both the weight of the deposited material, and more importantly, the size distributions of the sieved material because the cases are comprised of sand grains. Once the caddis-fly cases had been removed, the sediment was emptied into trays. These were chosen to ensure that sediment covered the base, preventing areas being solely occupied by water that, once dried, left baked layers of silt. The containers were then rinsed out with tap water as sparingly as possible to remove remaining sediment. Distilled water was not used because of the large volumes required on a regular basis. The use of tap water was not ideal and it would have been preferable to use water from Burleigh Brook. However, bringing back sufficient quantities was not feasible due to transportation implications and ensuring that it was free from suspended sediment. Once the sediment had been removed, the containers were thoroughly washed and dried in preparation for their next placement.

Sediment was dried in an oven at 110°C for approximately 12 hours depending upon the water content of the sample. Oven drying was used in preference to air drying, because of the shorter time required and the limitations of available ventilated space. Air-drying would have been preferable to oven drying, as this would have minimised the effects of baking clay particles into layers. This false amalgamation of sediment caused problems when the sediment came to be sieved. However, air-drying has the problem of residual water, relative to oven drying, which affects the base weights.

The material, once dried, was allowed to cool, removed from the tray, weighed and bagged. Each trap's material was individually labelled with date, trap number and trap code. This process was repeated for all samples collected over the 12-month monitoring period. Appendix 3' shows the weights collected on each sampling occasion for each of the traps.

3.3 Particle Size Analysis.

There are a number of different standards used with regard to sieving material. Most commence with oven dried sediment. The British Standard for the testing of soils for engineers (1967) states that wet sieving is the preferred method for determining the particle size distribution of soils. This methodology uses sodium hexametaphosphate as a dispersion agent, breaking down any aggregates and producing a size distribution of ultimate particles. These standards then continue to outline a dry sieving standard, and state that a wet-sieved unit should be retained for comparison. If results of particle size from these two methodologies significantly differ, the wet sieving methodology is the preferred option. However, this study does not require particle sizes to be expressed as absolute particle sizes, rather the effective particle sizes are more applicable in this context. Therefore, the dry sieving methodology was used. Many other studies e.g. Davies and Nelson (1993) have used sodium hexametaphosphate to prevent the aggregation of fine material.

3.3.1 Rationale behind dry sieving.

The collected sediment was sieved to get an understanding of the effective particle sizes deposited within the receivers during different events. The choice of dry sieving over wet sieving was based on the requirement for effective particle size, rather than the absolute particle size. The effective particle size is the size in which material is naturally carried downstream, including aggregates formed in this environment. The absolute particle size is the size of the constituent grains that comprise these naturally occurring aggregates.

In the process outlined to dry the collected material, micro-aggregation would have taken place. It was anticipated that during the process of sieving, that any aggregates formed in this process would be broken down. However, naturally formed aggregates could also be broken down.

As a consequence of concentrating on the effective particle size, and on deposition occurring during flood events, the range of particle sizes examined concentrated on material that would have settled out under these conditions. Therefore, a lower limit of particle size determination was chosen to be the pan fraction below the 63μm sieve screen. Any material in the pan was deemed to have derived from the breakdown of larger sized particles. A number of studies e.g. Wood and Armitage (1999) and Sear (1993) have observed that silt-sized particles are only deposited in very low water velocities or where the water begins to stagnate. During this study these conditions of low velocity flow never occurred and therefore it was deemed that determination of particle sizes below the pan fraction by use of a sedigraph was superfluous to this study.

The samples chosen for particle size analysis were dominantly those of events in which one flood peak occurred, and which possessed a short flood duration. However, in order to extend the range of peak flows examined, events in which there were more than one peak have also been used. In these events, the major peak had to be considerably greater than the other subsidiary peaks. An asterisk in Table 2.1 shows those events that were sieved.

3.3.2 Sieving Procedure.

The oven-dried material was loosely shaken within the bag to break up any aggregates that had been formed in the drying process. It was anticipated that the use of a mechanical sieve shaker would break up some particles.

All the material collected was placed a stack of sieves of ½ phi intervals from 22.4mm to 4.0mm. This stack was placed on a mechanical shaker for eight minutes. Once this time had elapsed each sieve screen was emptied into a paper-lined tray, brushed diagonally three times on each side to remove any trapped material and weighed to 0.1g. The material in the pan was also weighed. The second and third sets of sieve stacks were smaller in diameter, and split at 1.00mm. Again, the sieves were arranged in a descending order at ½ phi intervals. To ensure that the screens were not overloaded, leading to damage of the meshes and erroneous results, the maximum weight added to the second set of sieves was 500g, and 100g in the last sieve stack. In order to obtain sediment weights of these amounts, using a riffle box reduced the pan fractions below 4.0mm and 1.0mm, as this is the preferred method of separation outlined in many sample preparation texts (e.g. Gale and Hoare, 1991).

The process of cleaning the screens at the lower sizes was especially important. Along with the brushings, the screens were also weighed after several samples, to ensure that their weight was not increasing as a result of material building up on the screens. Once each sample had been sieved, the weights were added together to ensure that 99% of the original weight had been retrieved, values less than 99% would have required a complete re-sieve of the new sediment weight.

The methodology of using three sieve stacks on two mechanical sieve shakers proved to be a lengthy process. To reduce time, it was suggested to use only phi unit sieve screens. The reliability and reproducibility of these phi unit results compared with the ½ phi results were tested. This involved sieving a sample through ½ phi unit screens, recombining the sample and repeating the process through phi unit sieve screens. Passing of the same material twice through the sets of sieve screens could have added to the problems of breaking up aggregates, thus leading to an inaccurate representation of the weights present on each of the sieve screens. However, there was no other method that could have been used to ascertain if reducing the number of sieve screens affects the results. Construction of the percentage finer than curves and determination of certain size percentiles, indicated that the difference between the results from the two different sieve stacks was minimal. Figures 3.8a and b show the two curves for two samples. Based on these, and similar results which showed a minimal difference, it was decided to reduce the number of sieve screens, thus the samples were processed more quickly, and without a significant reduction in the accuracy of the data retrieved.

Along with inorganic material, organic matter was also present in the samples. Large pieces, including leaves and seeds, were picked off the sieve screens, however, partially decomposed material was not as easy to remove. Any large organic remains were weighed separately and included in the weight to ensure that 99% of the sample had been recovered. The majority of studies report floatation off of organic material (e.g. Sear, 1993). Material that was retrievable from the containers when they were

Figure 3.8a showing the percentage finer curve in 1/2 phi intervls for R3IIL (23.02.99)

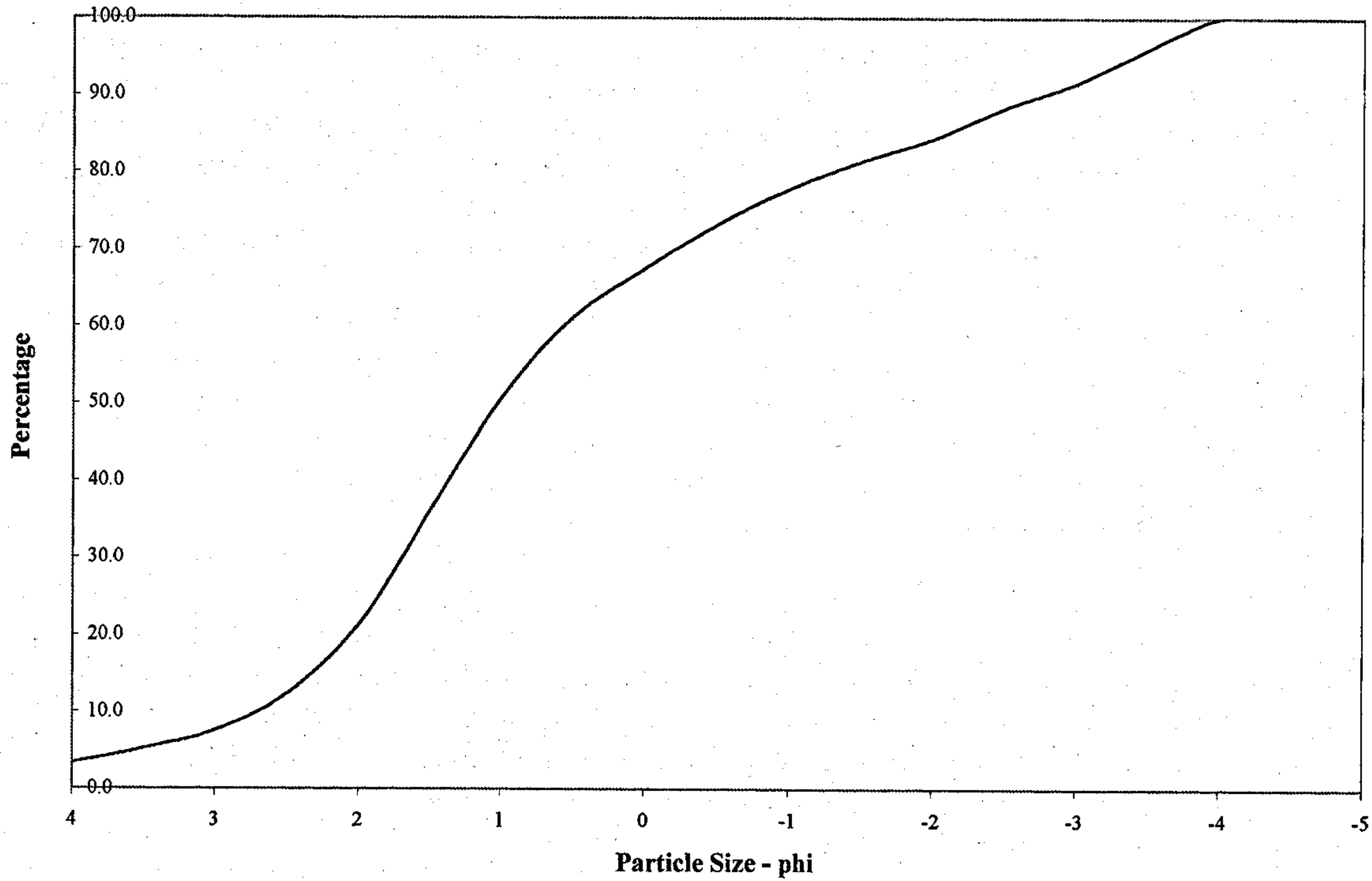
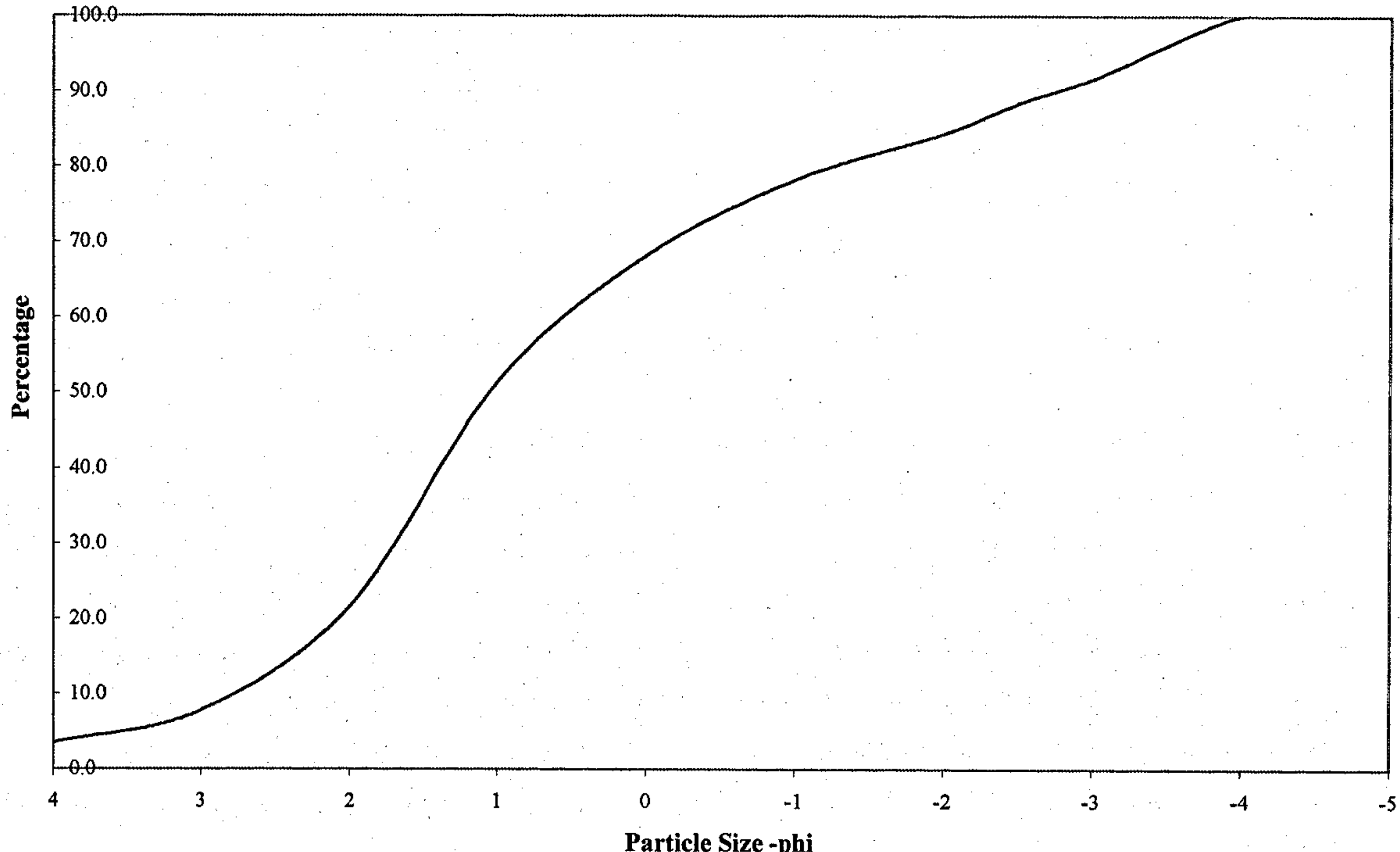


Figure 3.8b showing the percentage finer curve in phi intervals for R3IIL (23.02.99)



brought in was removed, but there was a large amount of organic matter that was buried amongst the infiltrated sediment.

3.3.3 Data Manipulation.

Once the weights for each sieve fraction had been obtained and the overall weight checked to ensure that 99% of the original sample had been recovered, each weight was converted into a percentage of the recovered weight. These were then cumulated in an ascending order from the pan fraction, with them signifying percentage finer than values and plotted as curves. Various size percentiles were then derived from these curves and used in the analysis. Chapter 5 discusses these results in detail.

Chapter 4

Effect of Sedimentation in Burleigh Brook.

4.0 Introduction to sedimentation and deposition rates.

A large number of studies published, have addressed rates of fine material within a flume environment, assessing infiltration rates against known suspended sediment concentration. Within a flume, this concentration can be kept constant over prolonged periods of time, however, within a natural environment, the relationships between stage and suspended sediment concentration are not as clearly defined. Suspended sediment rating curves often contain a large amount of scatter, consequential of hysteresis that occurs over a number of time-scales variation in suspended sediment concentration, ranging from seasonality to within a flood event (Grimshaw and Lewin, 1980). As shown in Figure 2.11, a suspended sediment-rating curve has been constructed for Burleigh Brook.

In this Chapter, the results depicted show mean hourly sedimentation rates as integrated over the whole flood event. To relate rates given here to results derived from flumes with a known suspended sediment concentration would have involved using the suspended rating curve and combining it with the stage discharge relationship and integrating concentrations of suspended loads across long time periods. Furthermore, as will be demonstrated, the three reaches surveyed behave in very individualistic manners, with Reach 1 possessing markedly differing characteristics from the other two. It was unfortunate that the suspended sediment sampler was located by Reach 1, and therefore relating suspended sediment concentrations from this location to downstream sites is not a valid assumption that can or should be made in this study. As Carling and McCahon (1987) stated, it is difficult to relate temporally integrated results that samples material that has been collected over a long time base to detailed instantaneous hydraulic parameters affecting sedimentation rates.

During the course of the field experiment, 25 traps were positioned within the bed of Burleigh Brook. These receivers were emptied after periods of increased discharge or after long episodes of base-flow. Inevitably, most sampling intervals contain periods during which base-flow predominated, in addition to individual or multiple flood events. Therefore, the material in the receivers arises from a combination of processes operating during base-flow and those functioning during spate. Furthermore, each flood event possesses its own unique time span, making direct comparisons between events difficult. In order that data can be compared, depositional rates are required.

4.01 Manipulation of data

The raw data set is composed of weights of dried sediment, obtained from the 25 sediment traps for 19 different time periods. As shown by Table 2.1, the flood hydrographs recorded on Burleigh Brook vary in their duration. The use of sedimentation rates, rather than weight of deposited material, allows for comparison of trap efficiency from one hydrograph to another. Of primary interest are the rates of sedimentation during periods of high flow, rather than the longer-term averages that incorporate both base-flow sedimentation with that occurring during periods of flood.

As shown in Table 2.1, the total duration of time that the receivers were in situ is known, along with the dry weight of material deposited over this time period. Base-flow has been designated as water-stage less than 0.15m. The data logger recorded output from the pressure transducer every 15 minutes. This record was converted into a stage reading using a simple calibration equation. This cut-off for base-flow was chosen using an extended record of stage from Burleigh Brook. The long-term trace was examined by eye, and this stage of 0.15m was the upper limit of a narrow range of values to which Burleigh Brook returned after a period in spate. This technique was adopted rather than that suggested by the Low Flow Studies Report (1980), which advises a statistical approach, because continuous measurements of stage within Burleigh Brook over a sufficient number of hydrological years were not available. As a consequence of the study being carried out for only a year, non-stationary tendencies of base-flow stage were not examined.

The record from the stage recorder allows the time period over which a flood event occurred to be determined, along with the prior and post flood base-flow episodes, thus t_{flood} and t_{base} are known (where t_{flood} and t_{base} are the times for flood and base-flow durations, respectively). In order to calculate W_{flood} (weight deposited during the flood event) and, therefore, R_{flood} (sedimentation rate during the flood event), an estimation of R_{base} (deposition rate during periods of base-flow) has to be derived.

Below is a series of equations that indicate the methodology used to ascertain an estimation of the deposition associated with the flood event.

$$R_{ave} = \left(\frac{W_{flood} + W_{base}}{t_{flood} + t_{base}} \right)$$ Equation 4.1

$$R_{flood} = \frac{W_{flood}}{t_{flood}}$$ Equation 4.2

where R_{ave} is the average deposition rate over the complete time period, W_{flood} is the weight of sediment deposited during the flood event, W_{base} is the weight deposited during base-flow conditions, t_{flood} is the duration of the flood event, t_{base} is the time over which base conditions occurred and R_{flood} is the rate of deposition during the flood.

There were six recorded episodes when only base-flow occurred over the whole monitoring period. However, receivers were only recovered from all three reaches in three of these cases, because of vandalism at the two downstream sites during the summer. These episodes allow an estimation of base-flow sedimentation rates to be established. Within each of these occasions a known weight of sediment was deposited in the receivers – W_{base}. The deposition took place over a period of time, which can be quantified from field notes, and the stage trace. This time span has been allocated as t_{base}. Dividing W_{base} by t_{base} produces a value of base-flow sedimentation. Once this was determined, each Hydrograph was split into constituent parts relating to base-flow periods and the flood event. The durations of both base-flow and the flood were determined from the stage trace. Multiplying the time during which Burleigh Brook was discharging at base-flow by the sedimentation rate R_{base}, a weight could be ascertained that relates to the amount of material that was deposited during these episodes within the measured Hydrograph. This weight W_{base} is then subtracted from the recorded weight of material within the receiver, therefore isolating the amount of material that was deposited during the flood – W_{flood}. By dividing this weight by the duration of the flood, t_{flood}, an estimation of the sedimentation rate for the flood can be obtained. This rate is an average value integrated over the whole flood event. Instantaneous depositional rates for certain parts of the flood hydrograph will vary from this value. However, the data set does not allow for peak or other instantaneous rates to be ascertained.

There is a 0.01m difference in the base-flow stage recorded during the three episodes under scrutiny. This was not deemed sufficient to affect sedimentation rates significantly. To ascertain if all reaches behaved in a similar manner, these three populations were statistically tested for significant differences. In this case, the sedimentation rates of all the three different sampler configurations were used as one data set. Each reach, as previously shown, is comprised of up to three of each configuration. Table 4.1 below, reports p-values from t-test analysis of sedimentation rates between the reaches for each base-flow period.

Table 4.1 showing the p-values ascertained from t-tests of differences in sedimentation rate between reaches over three periods of base-flow.

p values	Reach 1 and Reach 2	Reach 2 and Reach 3	Reach 1 and Reach 3
Period 3	0.283	0.022	0.861
Period 7	0.208	0.439	0.014
Period 19	0.118	0.005	0.004

(Single underline is rejection of the null hypothesis of no difference at $\alpha = 0.05$, double underline is rejection of null hypothesis at $\alpha = 0.01$).

In this analysis, all the traps in individual reaches were combined and statistically tested against the other reaches. Individual sedimentation rates between different trap configurations were not addressed. Reach 3 is different from both Reaches 1 and 2 in two of the three periods. Using an average value of base-flow sedimentation rates across all three reaches was therefore rejected. Instead, individual sedimentation rates were determined for each reach. The average base-flow sedimentation rate, R_{base}, is 0.031, 0.040 and 0.106g h^{-1} for Reaches 1 to 3 respectively. A combined average of 0.06g hr^{-1} would have over represented the amount of sediment deposited during periods of base-flow for Reaches 1 and 2, and underestimated that deposited in Reach 3.

Sedimentation rates ascertained for base-flow periods were calculated so that the masses deposited during sampling periods could be corrected for the time during which Burleigh Brook operated under these flow conditions. The rates obtained were small and distinguishing between different trap configurations at this point in the analysis was not considered necessary. In addition, there are only three periods when base-flow conditions predominated, insufficient to provide an estimate of reliability. However, subsequent analysis of data from the flood events suggested that differences in trap type performances should have been examined for base-flow periods. The difference in base-flow sedimentation rates shows that each reach has its own unique sediment source, supplying sediment. As a consequence, the flood-event data is examined reach by reach, thus avoiding the problems of lumping data.

To assess how the baseflow sedimentation rates of Burleigh Brook compare with similar rates in other studies, Table 4.2 has been constructed. It shows that Burleigh Brook has a lower baseflow sedimentation rate than others, in some cases by two orders of magnitude. This could be due to the particle size composition of Burleigh Brook in comparison to the others in this table.

Table 4.2 showing other observed baseflow sedimentation rates from various other field studies.

Author	Comments	Sedimentation Rate ($kg\ m^{-2}day^{-1}$).
Welton (1980)	Chalk lowland stream	0.37 – 0.93
Carling and McCahon (1987)	Baseflow conditions in an upland stream	0.008
Sear (1993)	Compensation flow	0.005 – 0.086
	HEP discharge	0.004 – 0.064
Wood and Armitage (1999)	< 2mm sediment in lowland chalk stream	0.0389
Allen	Burleigh Brook	0.0004 – 0.001

As is shown in the table above there is considerable variation in the baseflow sedimentation rates within these studies. The reasons why Burleigh Brook may have a lower sedimentation rate could be an effect of the geology of the area, along with the nature of the surrounding geology. The base flow discharges within Burleigh Brook at these times equate to below $0.2m^3s^{-1}$. This discharge is lower than many of those quoted above. In these cases more material would be being transported, and therefore available for ingress into interstitial components. The studies reported here, regarding the chalk streams, were examining the sedimentation affects in areas of low velocity, which means that the infiltration rates would be greater. The methodology employed here, may also affect the process of infiltration, via the interaction between the water within Burleigh Brook and that in the collecting receivers.

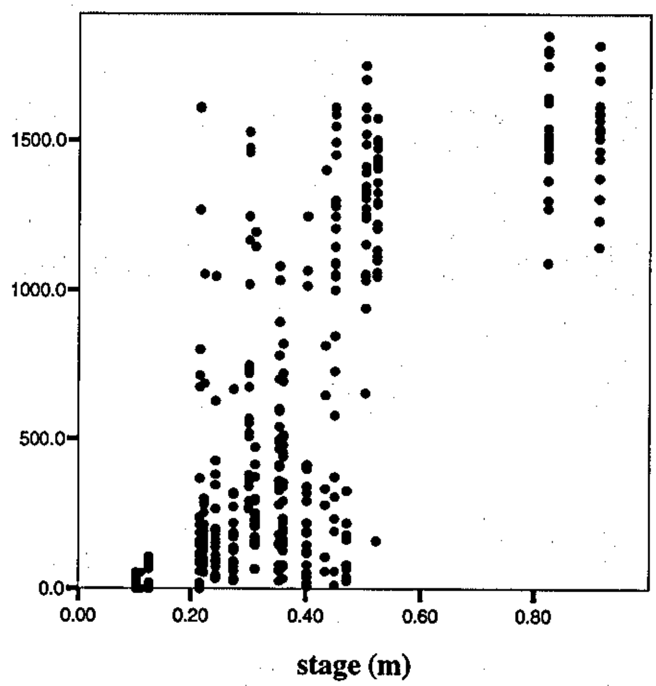
For each flood event, periods of base-flow, t_{base}, were ascertained to the nearest quarter of an hour and the estimated amount of material deposited during this time, W_{base}, was subtracted from the total dry weight collected in each receiver, W_{total}. The remaining sediment, W_{flood}, was then divided by the total number of hours during which the stage of Burleigh Brook exceeded base-flow, 0.15m, t_{flood}. This gave an average value for the amount of sediment deposited per unit time, R_{flood}, within each receiver, allowing comparisons to be made between different events and relating results found here to other studies.

4.02 Removal of High Magnitude Events.

As has been shown, base-flow periods play an important role in the interpretation and analysis of the data set. Given incomplete entrapment there is also a need to ensure that high magnitude events do not affect the analysis.

In high magnitude events, the receivers became full of sediment, and thus sedimentation rates obtained via the methods outlined do not produce meaningful results. The results would represent only minimal estimates of sedimentation, as material available for deposition during flood events would have overridden the full traps. Field notes, graphical evidence and the weights of receivers full of dried Burleigh Brook sediment, revealed that it was sensible to only use traps that contained less than 1000g of sediment. The traps that contained material that weighed over 1000g tended to be associated with peak flows of a stage in excess of 0.5m. This cut-off is the lowest value for a receiver that was full. However, the majority of receivers when full weighed around 1200g, as shown by the levelling off of the graph depicting the weight of dry material removed from Burleigh Brook against Hydrograph peak stage (Figure 4.1). Choosing a lower limit takes into consideration the loss of material by winnowing, and the affect that the flow patterns in the top of the receiver may have on the sedimentation rates. As a consequence of not having any detailed

Figure 4.1 showing the weight of material (g) collected in the receivers over all of the monitoring periods.



The units on the abscissa are grams.

Figure 4.1 clearly shows the grouping of the baseflow rates in the bottom left and the high magnitude events which have been disregarded in the top right.

measurements of flow patterns around the interstitial openings of the traps, it is unclear how water flowing along Burleigh Brook interacts with the fluid in the trap. Therefore, using this lower cut-off point of 1000g allows for loss of material from a filling receiver and the interference of settling-out of sediment caused by the interaction between the two different fluid bodies.

Using 1000g as the cut-off total weight means that the following Hydrographs are not utilised in the remaining analysis; 1, 4, 9, 12 and 15. However, it should be mentioned here that Hydrograph 4 shows the greatest sedimentation rate per unit area. This is greater than the highest sedimentation rate reported in the unfilled receivers. This hydrograph will be discussed at greater detail later in the chapter.

4.1 The Effect of Trap Configuration on Sedimentation Rates.

The first variable within this study that is going to be addressed is that of sampler configuration type. As a consequence of expressing the depositional rates per unit area, the three configurations can be compared. The aim, therefore, is to assess the trapping efficiency of individual configurations within each reach, and determine if this is consistent within all three reaches and within individual hydrographs. In order to interpret the trends within the data set correctly, any inherent differences attributable to trap configuration and placement must be found prior to further detailed analysis. As has been shown previously, there are differences in the base-flow sedimentation rates between each of the reaches, based upon a number of factors including upstream sediment supply, local hydraulics and site specific bed and bank composition. Therefore, analysis of flood hydrographs will be undertaken on a reach by reach basis. Breaking the data set down into constituent reaches follows analysis undertaken by Schälchli (1992, 1995) who showed that each gravel bed has its own unique specific hydraulic conductivity that affects the infiltration of fines. This hydraulic conductivity changes over time and with the ingress of fines. The patterns that emerge will then be assessed to ascertain if trends are consistent across all three reaches. This analysis will also address how sedimentation rates within individual configurations alters with each hydrograph. The effect of increasing stage and therefore discharge, on sedimentation rates will be examined thoroughly in a later section.

As a consequence of the sampling strategy - three reaches with a combination of trap configurations in each - the ways both configuration and reach effect sedimentation rates has to be analysed. To ease the interpretation of the data, the complete data set was split into the constituent reaches. Within each reach, the effect of configuration types would then be established. If there were similarities in the data set, there would be an opportunity to re-combine the data set.

In analysing the effects that trap configuration has on sedimentation rates per unit area, each reach was examined individually and hydrograph by hydrograph. This was carried out to assess whether the different configurations behaved consistently between the reaches and within events. To address this, a series of graphs were plotted and ANOVA tests were undertaken on each hydrograph to determine if there are any statistical differences in the sedimentation rates between the trap types. This also assesses whether the longitudinal placement of the traps has an effect on the sedimentation rates.

One way analysis of variance was used here as the discriminations of the test is based on one variable. The samples are normally distributed and their sample variances are not dissimilar. The ANOVA tests were undertaken to assess whether the samples had been drawn from the same population by decomposing the total variance into within- and between- variable. These tests assess the ratio of variance within each group and the variance between the groups about the grand mean (Shaw and Wheeler, 1985)

As a consequence of the different configurations being used, the area through which sediment infiltrates differs between Configurations I and II and Configuration III. In order to compare the different configurations, rates derived using Equations 4.1 and 4.2 had to adjusted to sedimentation rate per unit area – kg $h^{-1}m^{-2}$. As is shown in the methodology, Configurations I and II are essentially the same, the orientation within the flow being the defining factor. Configuration III is formed by four roughness elements, therefore the interstice is larger. Measurement of these interstitial areas by planimeter reveals that Configurations I and II have an opening of $1.81*10^{-3}$ m^2, whereas the interstitial area of Configuration III is $3.62*10^{-3}$ m^{-2}.

The use of three trap configurations allows the examination of both the effect of localised flow hydraulics and the influence of interstice size on depositional rates. However, these two factors are not independent of each other. The effect of localised flow hydraulics is examined by assessing the differences between Configurations I and II. The defining characteristic is whether the apex clast of the triangular configuration is upstream or downstream. These roughness elements deflect the central streamlines.

4.1.1 Reach 1

Unfortunately, the original placement of soil-drainage pipes within Burleigh Brook did not match the final placement design in Reach 1. Therefore, over the winter period only one trap of Configuration II was in place. This has affected the statistical results for this part of the analysis, both through the loss of this individual set via dislodgement of the trap lid during the passage of a flood, and the affect that only one data point has in statistical testing.

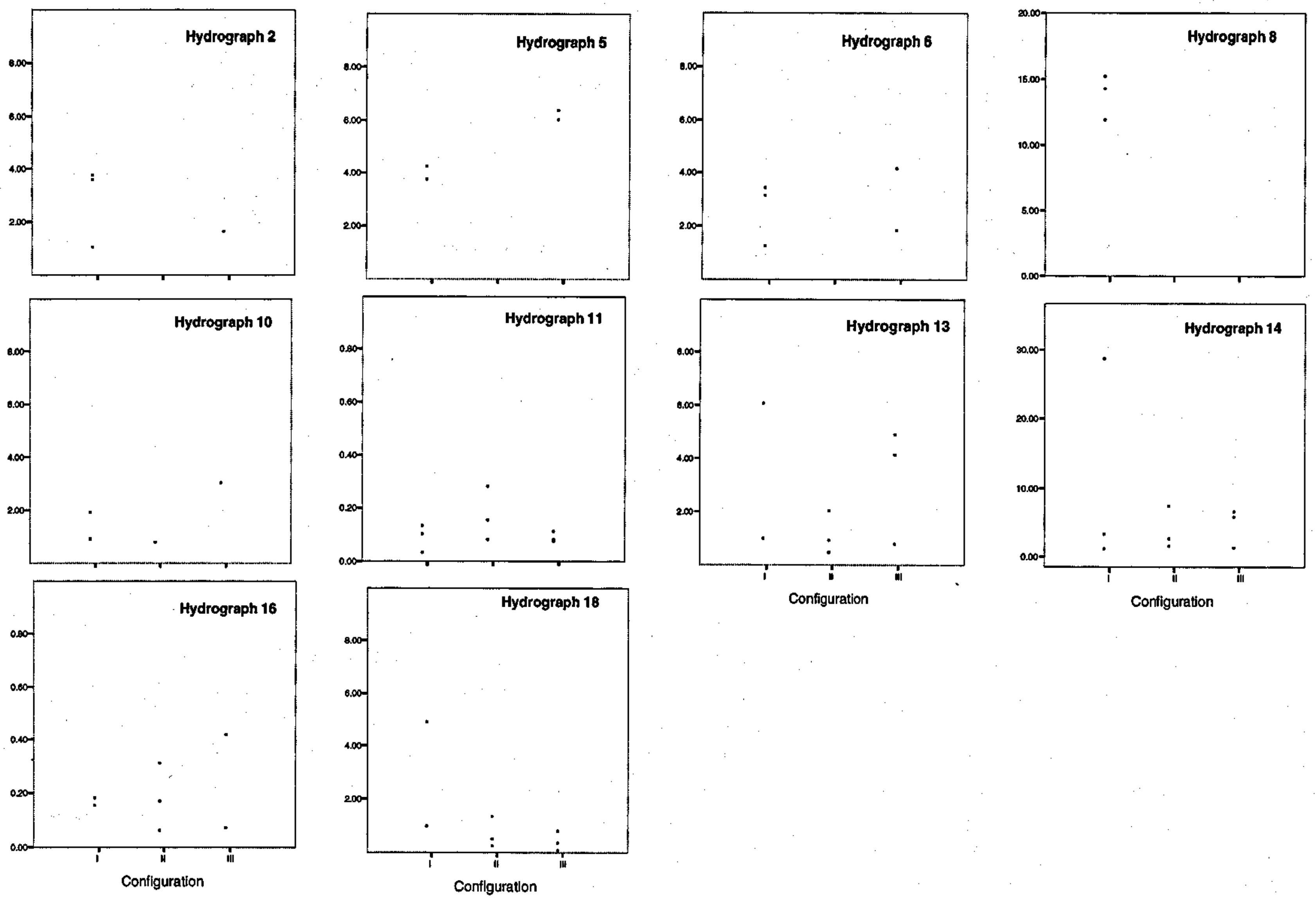
A summary obtained from a series of ANOVA tests shows that, in the majority of hydrographs (80%), the samples from each of the different configurations are derived from statistically the same population. Fifty percent returned an α value of greater then 0.30, the other 30% showing a statistic value having a significance between 0.10 and 0.30. As a consequence, it is difficult to assess which configuration is more efficient at trapping sediment. Where post-hoc analysis of the ANOVA results has been possible, no differences between any of the configurations has been present at the $\alpha = 0.05$ level. Graphical evidence from each of the hydrographs is also inconclusive as to the trapping supremacy of any one of the configurations. Table 4.3 shows the statistical analysis for Reach 1. Graphs of the data of the ten hydrographs are shown in Figure 4.2. It should be noted that the scales of the abscissa vary depending upon rates of sedimentation. However, the units are consistent. These graphical representations are produced to ascertain if the mean sedimentation rates of

Table 4.3 showing the statistics derived from ANOVA tests on Reach 1 for the effects of configuration on sedimentation rates for each hydrograph.

	Hydrograph	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
2	Between Squares	1.021	1	1.021	0.445	**0.574**
	Within Groups	4.592	2	2.296		
	Total	5.613	3			
5	Between Squares	4.731	1	4.731	53.62	<u>0.018</u>
	Within Groups	0.176	2	$8.823*10^{-2}$	0	
	Total	4.907	3			
6	Between Squares	0.187	1	0.187	0.101	**0.771**
	Within Groups	5.537	3	1.846		
	Total	5.724	4			
8	Between Squares					
	Within Groups	n / a	n / a	n / a	n / a	n / a
	Total					
10	Between Squares	3.133	2	1.566	4.424	0.184
	Within Groups	0.708	2	0.354		
	Total	3.841	4			
11	Between Squares	$1.389*10^{-2}$	2	$6.944*10^{-3}$	1.559	0.285
	Within Groups	$2.673*10^{-2}$	6	$4.456*10^{-3}$		
	Total	$4.062*10^{-2}$	8			
13	Between Squares	9.579	2	4.790	1.000	**0.431**
	Within Groups	23.958	5	4.792		
	Total	33.537	7			
14	Between Squares	94.986	2	47.493	0.563	**0.597**
	Within Groups	506.205	6	84.368		
	Total	601.191	8			
16	Between Squares	$7.471*10^{-3}$	2	$3.736*10^{-3}$	0.161	**0.857**
	Within Groups	$9.310*10^{-2}$	4	$2.327*10^{-2}$		
	Total	0.101	6			
18	Between Squares	8.467	2	4.323	2.480	0.179
	Within Groups	8.715	5	1.743		
	Total	17.362	7			

(Figures in bold indicate acceptance of the null hypothesis at $\alpha > 0.300$. Single underline indicates rejection of the null hypothesis at $\alpha < 0.05$).

Figure 4.2 shows the effect that Configuration has on the rate of sedimentation (kg m^{-2} hr^{-1}) for each Hydrograph within Reach 1.



the individual trap configurations behave consistently relative to each other from reach to reach, i.e. whether there is a configuration that always has a greater rate of sedimentation per unit area than the other trap types.

This is difficult to ascertain in Reach 1 for events when there is only one Configuration II present (Hydrographs 1-10). Examining the mean values, the majority of events show that Configuration I has a greater sedimentation rate than Configuration III. Configuration II does not show a consistent trend in relation to Configuration I, but in the majority of hydrographs has a greater sedimentation rate per unit area than Configuration III.

In summary, the statistical analysis does not show if the trap configurations behave differently with the exception of Hydrograph 5. Graphical evidence does not show that one configuration has a greater trapping efficiency than the other two.

4.1.2 Reach 2

Analysis of differences resultant on trap type for the two reaches further downstream yield similar results as Reach 1.

For Reach 2, fifty percent of the hydrographs examined show an α value of > 0.30 returned by ANOVA tests on the different populations of Configurations I to III. A further 40% of hydrographs returned an α value between 0.10 and 0.30. The remaining hydrograph, Hydrograph 16, returned an α value of 0.034. The post-hoc analysis highlighted significant differences at α values below 0.05 between

Configuration I and Configurations II and III, with Configuration I having greater sedimentation rates than those recorded in Configurations II and III. These results are summarised in Table 4.4 and Figure 4.3.

There are clearly some instances where the populations of the configurations differ and the statistics confirm this. Nevertheless, the patterns apparent from analysis of Reach 1 are generally confirmed.

4.1.3 Reach 3.

Examination of Table 4.5 reveals a similar trend for Reach 3 as that observed in Reach 2, with fifty percent of the hydrographs returning ANOVA α values above 0.30. A further thirty percent returned α values between 0.10 and 0.30. There are two hydrographs that produced α values of 0.009 and 0.072, respectively. The post-hoc tests revealed differences between the populations of Configurations I and II and that of Configuration III, with α values lower than 0.05. The deposition rate per unit area for III was lower than that of Configurations I and II. This shows that Configurations I and II have a greater trapping efficiency than that possessed by Configuration III. The results of the statistical analysis are shown in Table 4.5 and graphs are given in Figure 4.4. The graphical representation of the sedimentation values of each configuration shows a trend that is consistent with that observed in Reach 2, where Configuration I has a greater sedimentation rate than III, with that of II being consistently greater than III, but inconsistent in its relations with to Configuration I.

Table 4.4 showing the statistics derived from ANOVA tests on Reach 2 for the effects of configuration on sedimentation rates for each hydrograph.

	Hydrograph	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
2	Between Squares	10.090	2	5.045	3.102	0.133
	Within Groups	8.131	5	1.626		
	Total	18.222	7			
5	Between Squares	6.346	2	3.173	0.871	**0.474**
	Within Groups	18.210	5	3.642		
	Total	24.555	7			
6	Between Squares	3.254	2	1.627	2.456	0.181
	Within Groups	3.313	5	0.663		
	Total	6.566	7			
8	Between Squares	39.156	2	19.578	1.618	0.287
	Within Groups	60.512	5	12.102		
	Total	99.669	7			
10	Between Squares	7.836	2	3.918	2.415	0.185
	Within Groups	8.112	5	1.622		
	Total	15.949	7			
11	Between Squares	$9.571*10^{-3}$	2	$4.785*10^{-3}$	0.670	**0.552**
	Within Groups	$3.572*10^{-2}$	5	$7.143*10^{-3}$		
	Total	$4.529*10^{-2}$	7			
13	Between Squares	3.810	2	1.905	1.526	**0.304**
	Within Groups	6.240	5	1.248		
	Total	10.050	7			
14	Between Squares	8.881	2	4.441	1.473	**0.314**
	Within Groups	15.074	5	3.015		
	Total	23.955	7			
16	Between Squares	0.932	2	0.466	7.129	<u>0.034</u>
	Within Groups	0.327	5	$6.533*10^{-2}$		
	Total	1.258	7			
18	Between Squares	2.402	2	1.201	0.992	**0.447**
	Within Groups	4.845	4	1.211		
	Total	7.247	6			

(Figures in bold indicate acceptance of the null hypothesis at $\alpha > 0.300$. Single underline indicates rejection of the null hypothesis at $\alpha < 0.05$).

Figure 4.3 shows the effect that Configuration has on the sedimentation rate (kg $m^{-2}hr^{-1}$) for each Hydrograph within Reach 2.

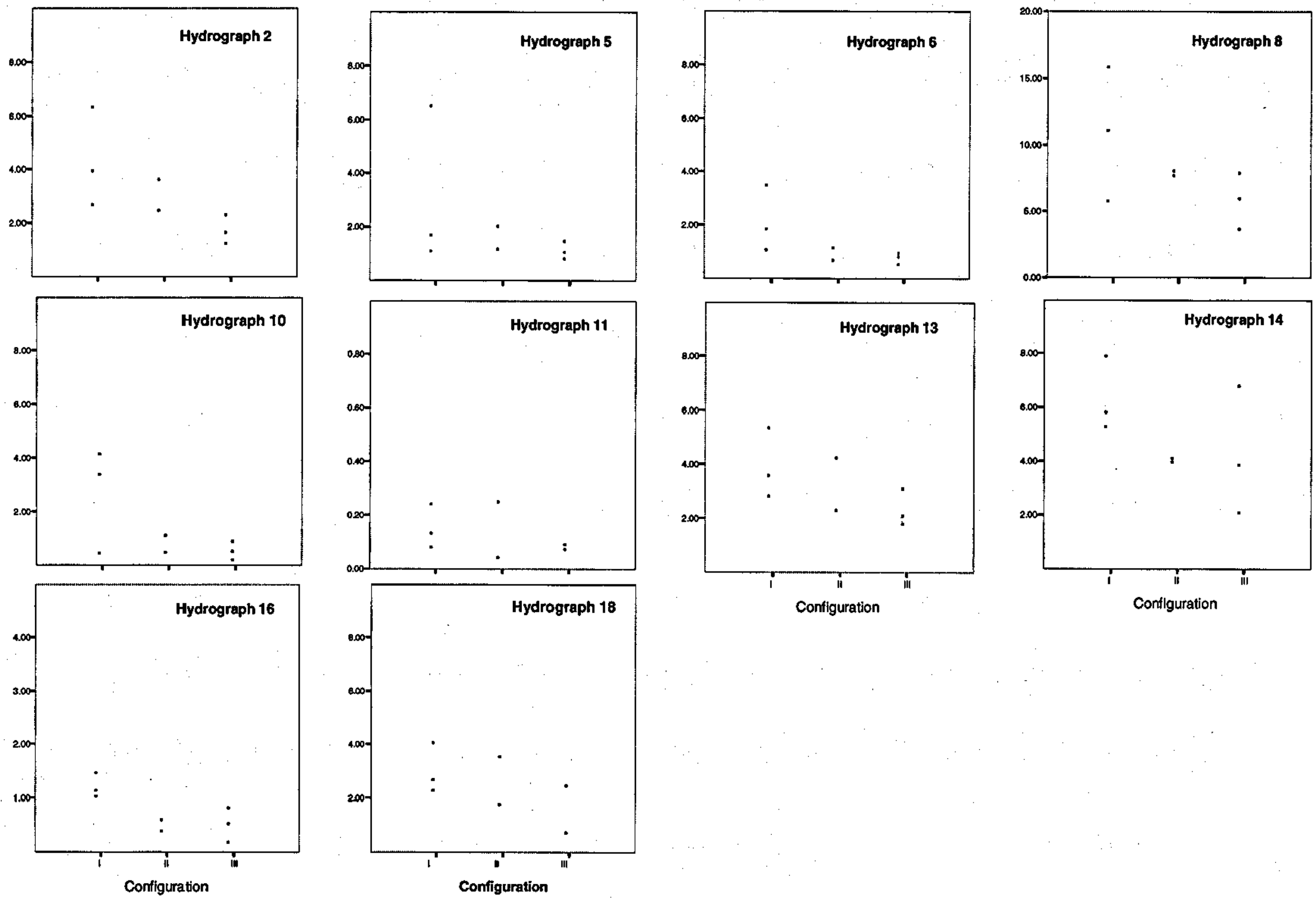
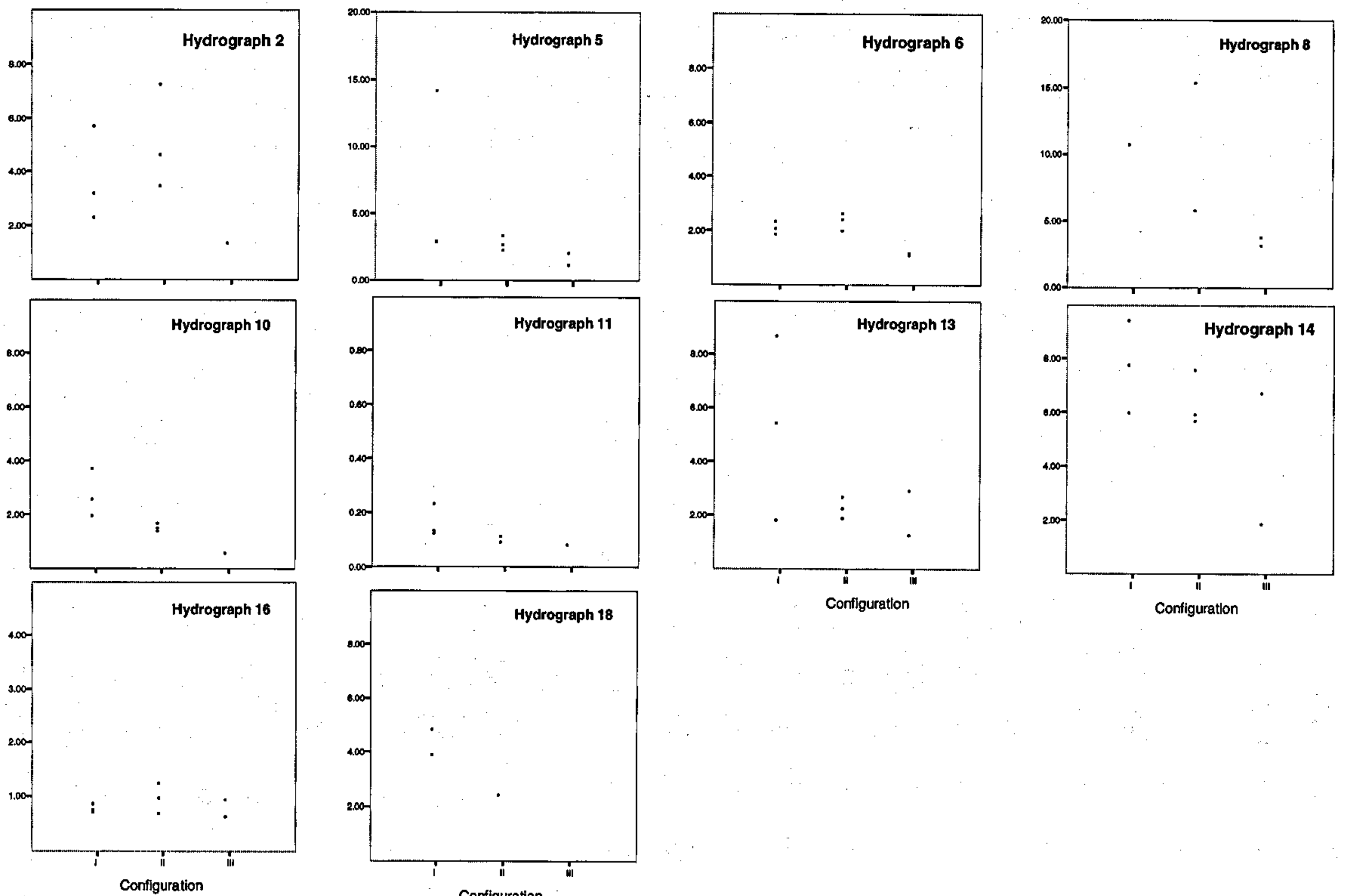


Table 4.5 showing the statistics derived from ANOVA tests on Reach 3 for the effects of configuration on sedimentation rates for each hydrograph.

Hydrograph		Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
2	Between Squares	10.865	2	5.433	1.588	**0.311**
	Within Groups	13.680	4	3.420		
	Total	24.545	6			
5	Between Squares	37.878	2	18.939	1.099	**0.402**
	Within Groups	86.186	5	17.237		
	Total	124.064	7			
6	Between Squares	1.914	2	0.957	14.114	<u>0.009</u>
	Within Groups	0.339	5	$6.780*10^{-2}$		
	Total	2.253	7			
8	Between Squares	61.167	2	30.584	1.330	**0.429**
	Within Groups	45.979	2	22.989		
	Total	107.146	4			
10	Between Squares	4.375	2	2.187	5.432	0.072
	Within Groups	1.611	4	0.403		
	Total	5.985	6			
11	Between Squares	$6.933*10^{-3}$	2	$3.467*10^{-3}$	1.368	**0.378**
	Within Groups	$7.600*10^{-3}$	3	$2.533*10^{-3}$		
	Total	$1.453*10^{-2}$	5			
13	Between Squares	18.244	2	9.122	1.803	0.257
	Within Groups	25.301	5	5.060		
	Total	43.545	7			
14	Between Squares	14.152	2	7.076	1.792	0.259
	Within Groups	19.739	5	3.948		
	Total	33.892	7			
16	Between Squares	$6.585*10^{-2}$	2	$3.293*10^{-2}$	0.770	**0.511**
	Within Groups	0.214	5	$4.279*10^{-2}$		
	Total	0.280	7			
18	Between Squares	2.614	1	2.614	5.672	0.2530
	Within Groups	0.461	1	0.461		
	Total	3.074	2			

(Figures in bold indicate acceptance of the null hypothesis at $\alpha > 0.300$. Double underline indicates rejection of the null hypothesis at $\alpha < 0.01$).

Figure 4.4 shows the effect that Configuration has on the sedimentation rate (kg m^{-2} hr^{-1}) for each Hydrograph within Reach 3.



4.1.4 Summary of findings

The statistics depict that, for the majority of Hydrographs within individual reaches, the three configurations of interstice arrangements trap amounts of sediment per hour per unit area that could be derived from one larger population. The rate connected with Configuration III, however, is often lower than those of the other two configurations. The effect that individual flood events have on each of the three reaches within Burleigh Brook was different, as shown by the lack of consistency between reaches for the same hydrograph. This is seen when comparing Tables 4.3 – 4.5. This demonstrates that analysis must be undertaken on a reach by reach basis. It also shows, to a lesser extent, that the interstice configurations do not behave consistently between flood events. It is because of this that it remains to examine other physical characteristics associated with sedimentation rates by configuration, despite the majority of hydrographs showing no statistically significant difference in the populations. However, if there are instances when all three configuration types show similar results within each reach the data will be lumped together to increase the sample size and thus confidence in the statistic returned.

In summary, it would appear that Configurations I and II are consistent in having a sedimentation rate per unit area that is greater than Configuration III. There is inconsistency between the reaches as to the significance of the differences for individual hydrographs, i.e. the same hydrograph in each of the different reaches produces contrary levels of significance of the differences. However, there is no consistent relations apparent between I and II at this juncture. There is considerable variance within the data sets as shown by the individual data points.

Two factors can be put forward to explain these differences. The presence of a roughness element, either upstream or downstream, in Configurations I and II, along the streamline of the interstice may be the characteristic that is responsible for the differences in sedimentation rates between them and Configuration III. In addition the increased interstice size of Configuration III may affect the rate of deposition.

Configuration III in its current orientation allows some streamlines to pass directly through the roughness elements without deflection. There is no obstruction to the central streamlines. Configurations I and II possess an obstruction, with the water being made to flow over or around a roughness element either prior to or after, the interstice. It can therefore be concluded that obstructions within the streamlines of the flow affect the rate at which sediment is infiltrated into gravel beds. The affect that roughness elements have on streamlines has been identified by Reid *et al.*, (1992) with regard to the effect that pebble clusters have on entrainment and entrapment of sediment. To understand the conclusions drawn here, detailed analysis has to be undertaken on flow structures around cylinders, and the interactions of eddies on sediment transport. Within Configuration III there is an acceleration that would a) discourage sedimentation, (Giles *et al.*, 1993) b) encourage saltation and c) possibly increase winnowing when the trap is near full.

In these cases, of Configuration I and II, the flow structure above the pore space may be such that it promotes deposition, rather than the sediment being maintained within the flow, and passing directly over the interstice. This is as a consequence of the downward deflection caused by the apex roughness element. However, this deflection would also encourage winnowing at high velocity. It would, therefore, seem that deposition of fine material is enhanced by an arrangement of roughness elements in a triangle (Configuration I and II) rather than as a square (Configuration III). The triangular arrangement acts by altering the flow patterns and producing a three-dimensional velocity structure that is conducive to fine material being deposited within pore spaces. However, a detailed analysis of flow patterns is needed to determine the processes that are naturally occurring above these different interstices.

The greatest difference in mean depositional rates is between Configurations I and III. However, these traps possess the same upstream arrangement of roughness elements. It can, therefore, be concluded that the presence of the bluff body downstream in Configuration I is the significant contributing factor in the depositional rates observed between these configurations.

The interstice of Configuration III is double that of I. This means that there is a greater area through which the water of the free-stream is able to interact with that in the receiver. This interaction is greater than in other studies, because of the lack of framework within the receiver. The interaction between the two bodies of water could lead to increased turbulence, resulting in exchanges of fluid and affecting the rate of sedimentation.

It is, therefore, apparent within this study that the configuration of roughness elements above the receiver does affect the rate at which sediment can be deposited. Despite having no data on flow patterns around these different configurations, it is suggested that the presence of the bluff bodies alters the flow direction and velocity and, therefore, deposition of fines.

4.2 The effect of peak stage within hydrographs on the rate of material infiltration.

The analysis of the effect of increasing stage - discharge on the sedimentation rates observed on Burleigh Brook will be carried out in a similar manner to that undertaken in the previous section on the effect of interstice configuration. Data will be analysed for each configuration separately and each reach individually.

The overall aim of this section is to ascertain if rates of sedimentation are related to peak stage within each of the individual hydrographs. The main question here is, does the stage of water within Burleigh Brook affect the amount of sediment transported, and therefore, deposited within containers that are flush with the bed? However, it has to be understood that there would have been alteration in the turbulence structure within the container as it neared capacity. This alteration could have excavated material already deposited and affected the derived rate of infiltration. As has already been stated, only hydrographs above 0.15m and below a stage of 0.5m are analysed. It must be remembered that rates depicted here are estimates of minimum hourly rates per unit area.

The data in the following sections was analysed using ANOVA, with post-hoc tests, and a regression analysis to determine if sedimentation rates are dependent upon stage. The ANOVA tests were undertaken to ascertain if the populations from each of the different hydrographs were obtained from one larger set, i.e. that an increase in stage / discharge does not affect the sedimentation rates. Any results from the ANOVA tests that are statistically significant will suggest that stage / discharge does affect sedimentation rates.

4.2.1 Reach 1.

As has been stated, the data sets are still being split into constituent trap configurations. Table 4.6 shows the results of the ANOVA tests.

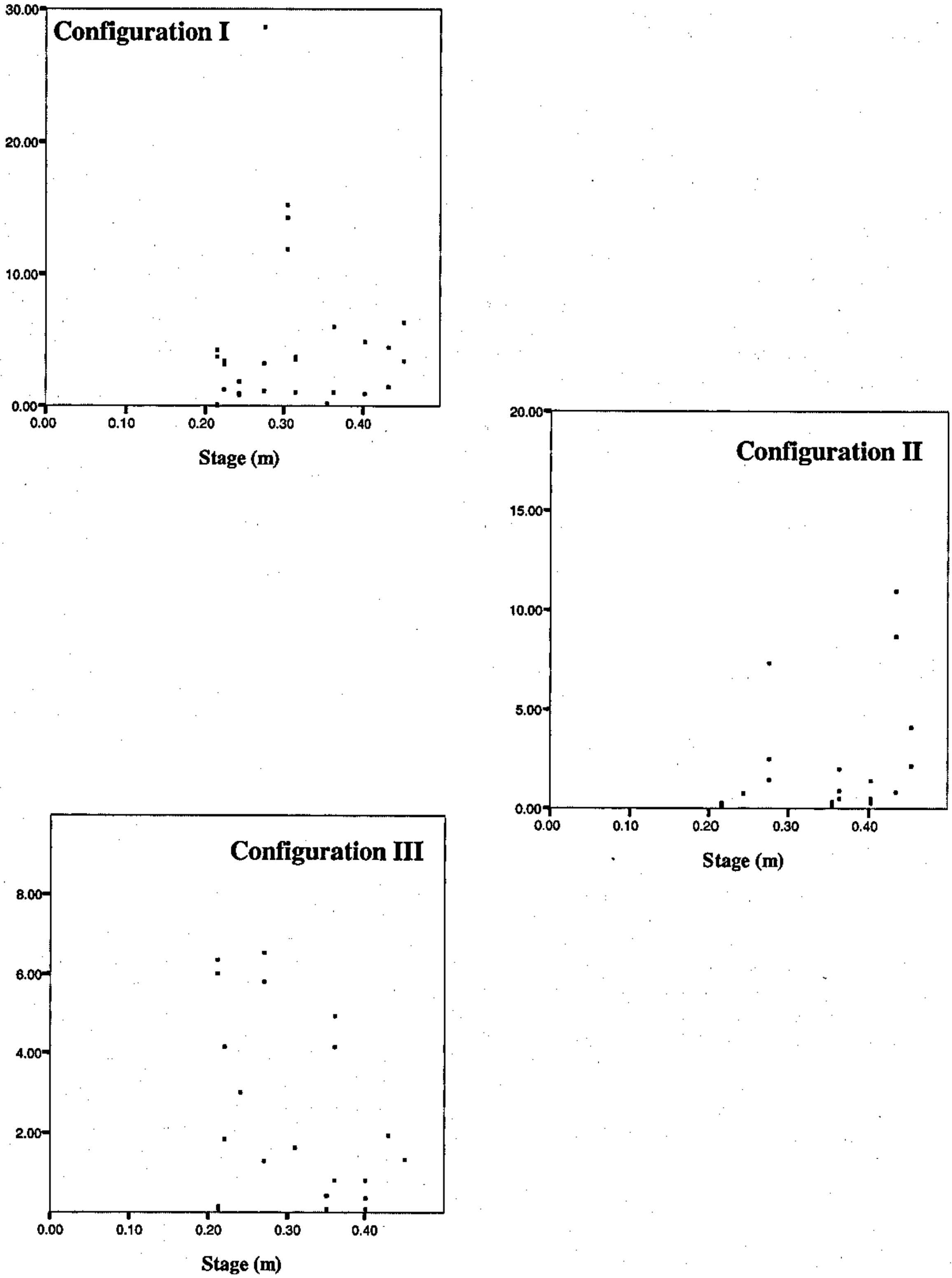
Table 4.6 showing the statistics derived from the ANOVA tests on Reach 1 for the effects of stage on depositional rates.

Configuration		Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
I	Between Squares	545.022	11	49.547	1.736	0.144
	Within Groups	513.795	18	28.544		
	Total	1058.817	29			
II	Between Squares	111.179	8	13.897	2.244	0.094
	Within Groups	80.503	13	6.193		
	Total	191.682	21			
III	Between Squares	85.009	10	8.501	3.226	<u>0.034</u>
	Within Groups	28.988	11	2.635		
	Total	113.997	21			

(Single underline indicates rejection of the null hypothesis at $\alpha < 0.05$).

There is limited statistical evidence to show that there is a difference in the sedimentation populations with regard to an increase in stage. Within this data set, Configuration III shows that the sedimentation rates do vary with an increase in stage. The other two configurations show that the null hypothesis of no difference cannot be rejected at a strict level of significance, but do suggest that there is variation in the populations in relation to changes in stage. This is illustrated by Figure 4.5.

Figure 4.5 shows how depositional rates (kg m^{-2} hr^{-1}) are affected by an increase in stage for Reach 1.



Correlation analyses have been undertaken on the data sets and are shown in Table 4.7.

Table 4.7 showing the correlation statistics relating to sedimentation rates (kg hr^{-1} m^{-2}) and stage for Reach 1.

Configuration	Mean	Std Deviation	N	Pearson Correlation	Significance (2-tailed)
I	4.374	6.0424	32	0.37	0.847
II	2.113	3.0212	22	0.274	0.217
III	2.343	2.3299	22	-0.315	0.153
All	3.098	4.4525	74	-0.013	0.912

There is no clear-cut correlation between an increase in stage and an increase in depositional rate (kg hr^{-1} m^{-2}). Indeed, the correlation coefficient for Configuration III has a negative sign. Overall, the patterns are not what would be expected, as an increase in stage / discharge affects the shear stress on the bed of the stream and therefore increases entrainment. It would be expected that as entrainment increases, there would be more material moving along the bed of the stream, and therefore an increase in the amount of material moving into the interstices.

4.2.2 Reach 2

Tables 4.8 and 4.9 summarise the results of a similar analysis on Reach 2. Graphs in Figure 4.6 depict sedimentation rates for different stage measurements. Reach 2 behaves in a manner that is different from that of Reach 1. The depositional rates for individual hydrographs do come from different populations, suggesting that there is an increase in depositional rate as stage increases. These results depict the trend that was expected.

Table 4.8 showing the statistics derived from the ANOVA tests on Reach 2 for the effects of stage on depositional rates.

Configuration		Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
I	Between Squares	254.053	10	25.405	5.294	0.001
	Within Groups	95.978	20	4.799		
	Total	350.031	30			
II	Between Squares	94.431	9	10.492	21.131	0.000
	Within Groups	4.965	10	0.497		
	Total	99.397	19			
III	Between Squares	133.808	10	13.381	8.179	0.000
	Within Groups	32.719	20	1.636		
	Total	166.527	30			

(Double underline indicates rejection of the null hypothesis at $\alpha < 0.01$.).

Table 4.9 showing the correlation statistics relating to sedimentation rates (kg hr^{-1} m^{-2}) and an increase in stage for Reach 2.

Configuration	Mean	Std Deviation	N	Pearson Correlation	Significance (2-tailed)
I	3.654	3.4158	31	0.061	0.746
II	2.460	2.2872	20	0.304	0.192
III	2.174	2.3560	31	**0.445**	0.012
All	2.803	2.8393	82	**0.226**	0.041

(Figures in bold indicate that the correlation is significant at the 0.05 level for 2-tailed)

In this reach, there is a correlation between an increase in depositional rate with an increase in stage / discharge in the case of Configuration III. The correlation is not that strong, as shown in Figure 4.5, revealing that increase in stage does not completely explain changes in sedimentation rates that were observed during the period of monitoring.

4.2.3 Reach 3

Tables 4.10 and 4.11 show the results of ANOVA and correlation analyses for Reach 3. Graphs are shown in Figure 4.7. They are derived in the same manner as those for the previous two reaches.

Figure 4.6 shows how depositional rates (kg m^{-2} hr^{-1}) are affected by an increase in stage for Reach 2.

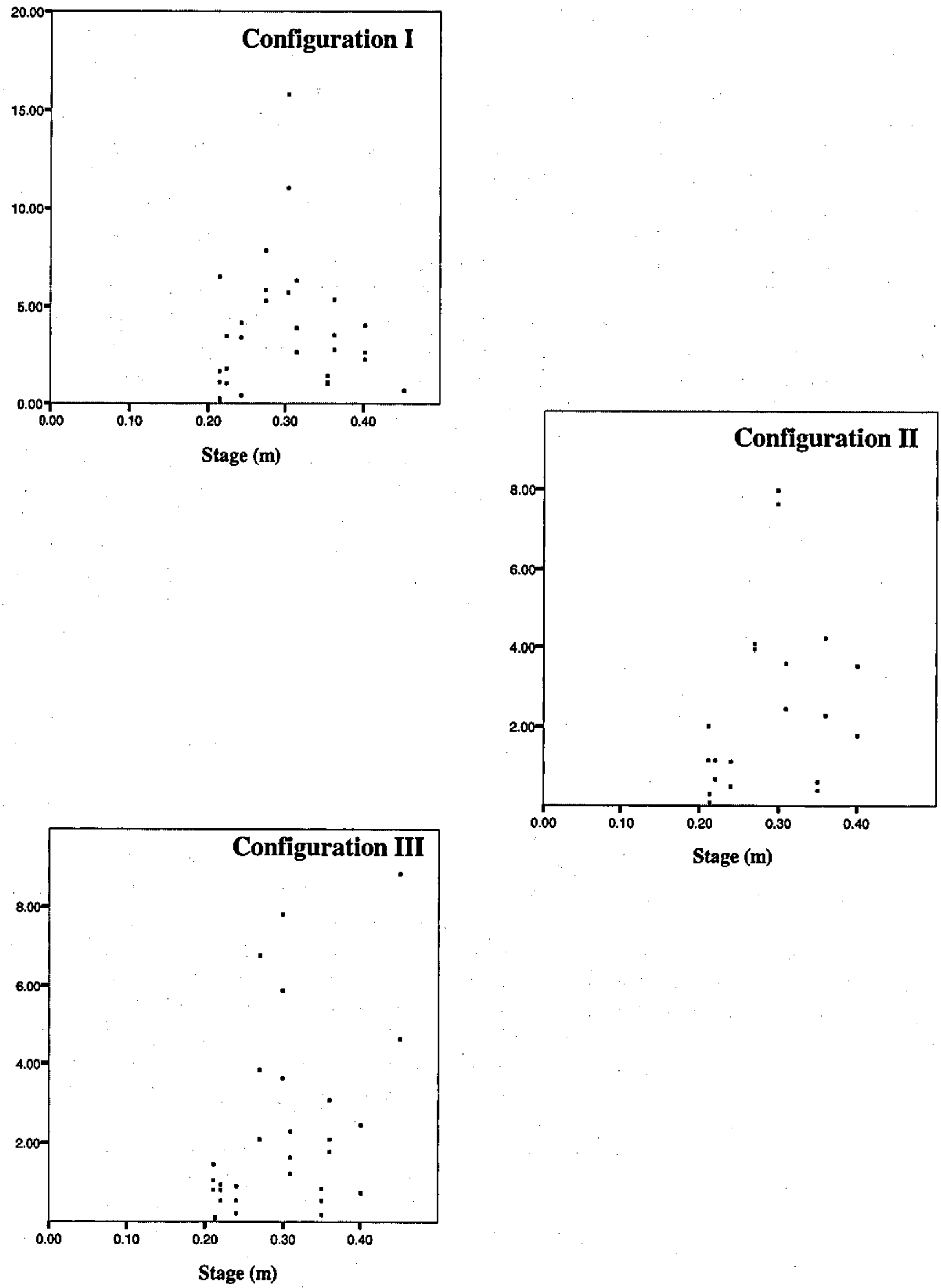


Table 4.10 showing the statistics derived from the ANOVA tests on Reach 3 for the effects of stage on depositional rates.

Configuration		Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
I	Between Squares	231.942	11	21.086	2.917	0.023
	Within Groups	122.884	17	7.228		
	Total	354.827	28			
II	Between Squares	197.109	9	21.901	6.160	0.001
	Within Groups	56.890	16	3.556		
	Total	253.999	25			
III	Between Squares	26.444	9	2.938	1.283	**0.394**
	Within Groups	13.743	6	2.291		
	Total	40.187	15			

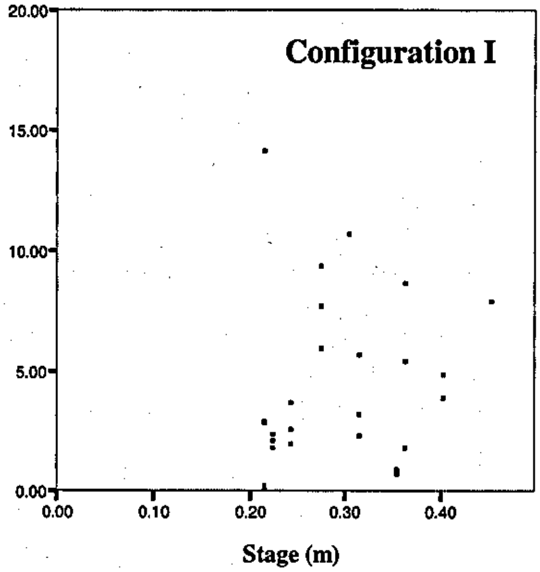
(Figures in bold indicate acceptance of the null hypothesis at $\alpha > 0.300$. Single underline indicates rejection of the null hypothesis at $\alpha < 0.05$. Double underline indicates rejection of the null hypothesis at $\alpha < 0.01$).

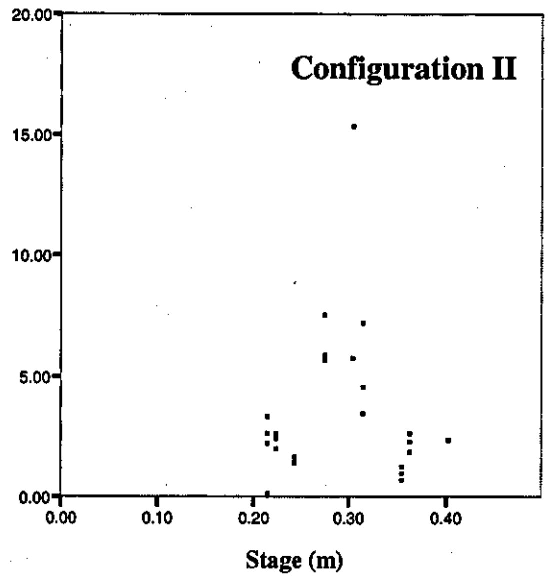
Table 4.11 showing the correlation statistics relating to sedimentation rates (kg hr^{-1} m^{-2}) and an increase in stage for Reach 3.

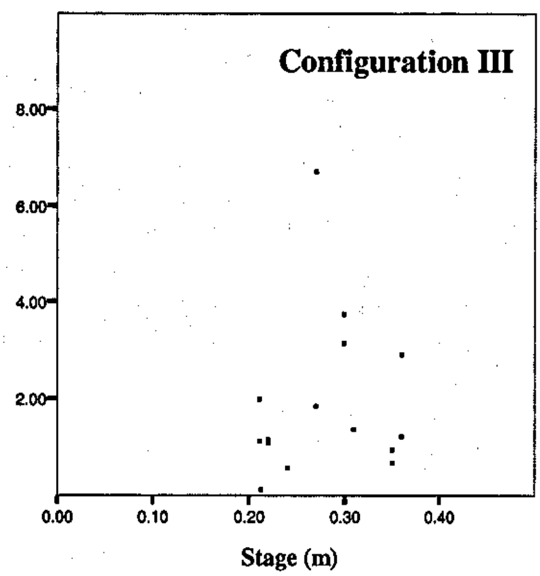
Configuration	Mean	Std Deviation	N	Pearson Correlation	Significance (2-tailed)
I	3.962	3.5598	29	0.032	0.868
II	3.359	3.1875	26	0.094	0.648
III	1.824	1.6368	16	-0.011	0.968
All	3.259	3.1544	71	0.045	0.707

Reach 3 does not behave in a manner consistent with Reach 2. The ANOVA tests suggest that the populations of Configurations I and II do differ between hydrographs, whereas those from Configuration III do not. The number of data points for Configuration III from Reach 3 was lower than other configurations as a consequence of constant dislodgement of a specific trap lid during floods. This means that data from this sampler were discarded, reducing the number of samples. The paucity of samples could have affected the statistical testing, and therefore the result presented here. However, this reasoning is not substantial enough to completely discount the statistics produced.

Figure 4.7 shows how depositional rates (kg m^{-2} hr^{-1}) are affected by an increase in stage for Reach 3.







4.2.4 Summary of the effect of increased stage on sedimentation rates.

In summary, despite the majority of ANOVA test results returning α values below 0.05, there are no visible trends that suggest these differences are solely explained by an increase in stage / discharge. These results show that Reach 1 behaves in a different manner to reaches further downstream. This is a feature that becomes more apparent as the thesis deals with other aspects of the data.

Carling and McCahon (1987) have shown that an increase in discharge resulted in a distinct alteration in sediment accumulation of fines in excess of one order of magnitude, from around 100 g m^{-2} wk^{-1} to between 1 and 10 kg m^{-2} wk^{-1}. This change in magnitude has been replicated when distinguishing between the base flow periods and when Burleigh Brook was in flood. However, as a consequence of the finite volume of the containers, the sedimentation rates of high magnitude floods has not been successfully calculated, leaving only an estimation of the minimal sedimentation rates over periods of peak flow. This is a consequence of the unexpected high amounts of bed load transport experienced during the high magnitude flood events of the winter months. Alteration of the container beneath the traps after the initial results had been analysed would have resulted in a disturbance of the streambed and compromised later results.

As a consequence of the finite volume within the receivers used in this experimentation, the results used for statistical analysis are not derived from a wide range of flows. The data from flows greater than 0.50m in stage have been disregarded as a consequence of the receivers being full. This means that the data is limited and the conclusions that can be drawn as to how an increase in stage / discharge affects the rate of sedimentation within Burleigh Brook are speculative. Sear (1993) observed that the infiltration of fine material was greatest under bankfull conditions, as a consequence of fine material being scoured from pools and deposited further downstream. The maximum stage of 0.50m is below that of bankfull discharge.

This experiment differs in its methodology to that of Carling and McCahon (1987) in that the periods over which infiltration was integrated are consistent with flood events, whereas in Carling and McCahon's study the time span was set at weekly intervals. They observed that in the week subsequent to a flood event, the sedimentation rate increased with regard to base flow rates. If this observation is common to all rivers, then the results here are flawed. However, in defence of this, it is difficult to use data integrated over long time periods and relate these to detailed instantaneous measurements relating to a period within a flood event.

4.3 Effect of intra-reach placement.

As shown in Chapter 3, different trap configurations occupied different zones in the selected riffles. This section addresses whether there is a spatial variation in the sediment flux or trapping efficiency within each reach. As previously outlined, the traps are positioned in three cross-sectional rows. Each downstream row was comprised of three traps with the same trap lid configuration. However, the rows were kept constant throughout all of the monitoring, meaning the data in its current form does not allow for the assessment of intra-reach variation. The reasoning behind this was that there was only one row of each configuration in each reach. As the reaches are statistically different in their sedimentation rates, sedimentation rates from each area of the riffles cannot be compared with a similar area in the other reaches, i.e. the sedimentation rates from the top row of Reach 1 cannot be compared with the sedimentation rates from the top cross-sectional row of Reach 2. Spatial comparison, either laterally across a row, or longitudinally down a riffle cannot be undertaken because each trap configuration has a different sedimentation rate.

To allow spatial variations to be examined, the data sampling needs to be more rigorous and the traps moved around systematically, within each reach and throughout the reaches. The data set needs to be collected over a greater time period and with a greater number of reaches with replicates of positioning to allow ratios of infiltration rates to be constructed.

Published literature on the spatial variation of infiltrated fines is growing. Einstein (1968) noted within a flume environment, that there was a general downstream variation in the rate by which pore spaces were filled. It was observed that the upstream area of the flume was matrix dominated prior to complete accumulation in the downstream areas. Carling (1984) also observes a slight decrease in the deposition coefficient as the flume is progressed downstream. Diplas and Parker (1992) found that higher concentrations of fines deposited within the gravel substrate were located at the bar tail and within the pools. Removal of fines was initiated at the bar head. Within this study, these locations were not chosen, as the main aim of this study was to observe how sedimentation was affected by the different trap configuration in the main body of the riffle where conditions were hydraulically more stable.

Carling and McCahon (1987) comment that it would be expected that a correlation would be observed between water velocity and the depositional rate, as a consequence of stream flow controlling sediment transport. Moreover, it would be expected that the centre channel would have a greater suspended sediment flux and therefore, this area would have greater infiltration rates, (Adams and Beschta 1980, Frostick *et al.*, 1984). The arrangement of traps within Burleigh Brook possibly would not have showed these patterns as the traps to the left and right of the channel were not at the channel margins, but rather nearer the channel centre. These locations were favoured as they were constantly submerged, whereas during conditions of base flow the channel margins became devoid of flow.

Lisle (1989) observed in his study of a Californian gravel-bed stream that the downstream lines of cans did not accumulate as much sediment as those further upstream. When examining the methodology adopted by Lisle, these downstream pots are equivalent to Reach 3 in this study. From results shown here, it is clear that the observation occurring in California are not apparent here. Lisle (1989) suggests a lowering in the sediment flux per unit area for the decline in accumulation rates observed as a consequence of the distance between sites. In this study, the reaches however, are not as separate in terms of sediment supply as the diagrams of the Californian creeks imply. Also in this study, the rationale that has been employed is that each reach has its own unique sediment supply and therefore comparison between rates in one with those of another is not possible without a larger deployment of suspended sediment samplers.

4.4 Effect of seasonality on sedimentation rates within Burleigh Brook.

In this section other factors are assessed for their influence on the sedimentation rates within Burleigh Brook. Some authors (e.g. Frostick *et al.*, 1984) have reported the affects that seasonality can have on the amount and rate at which sediment is deposited. Frostick *et al.*, (1984) report in their study on Turkey Brook that the value of matrix accumulation is on average 1.2 times greater in the summer than winter. This is based upon flood frequency. There are more floods during the winter periods moving available sediment, however, in the summer, with higher flows less frequent, material builds up. ASCE (1992) also comment that infiltration rates are greater in the summer under lower flows, whereas the winter floods tend to remove fines from the gravel framework.

As has been outlined at the beginning of this section, a number of studies have suggested that through their observations of sedimentation records over a number of years, that the summer flood events led to a greater infiltration of fine sediment into the interstices of gravel-bed rivers. This study only took place over one complete season, and vandalism of the lower reaches meant that the data set is very depleted in summer flood observations. Despite this, the following section will attempt to ascertain if Burleigh Brook conforms with current scientific thought.

4.4.1 Reach 1.

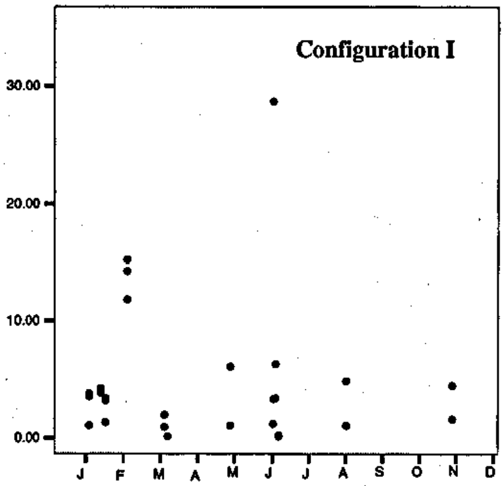
In this section of analysis, only graphical representation of the data was used to assist in comparing the sedimentation rates in summer months (April – September) with those in winter months (October – March). Graphs showing the sedimentation rates for each month are shown in Figure 4.8.

The conclusions about seasonal variations in depositional rates are reliant on graphical evidence that shows that the greatest depositional rate recorded within this configuration did in fact happen in June. However, the depositional rates of a flood hydrograph in February have the greatest average infiltration rate. Within Configuration II, again the highest average depositional rate for one hydrograph occurs in the winter, closely followed by a flood event in June. Configuration III shows some disparity with the published observations. The winter sedimentation rates are comparable with the higher summer rates, however, the majority of summer hydrographs show that sedimentation rates were amongst the lowest of the year.

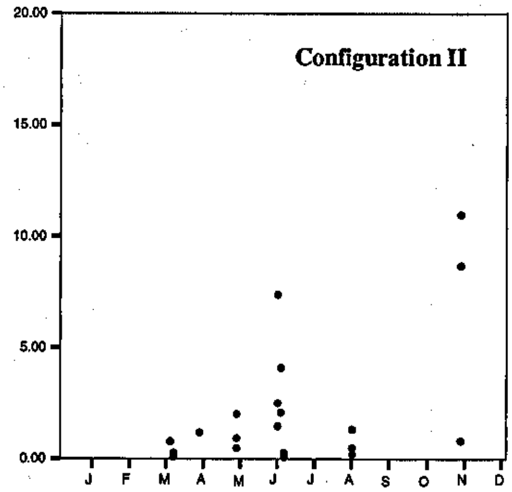
4.4.2 Reach 2

Reach 2 shows a greater variation in the sedimentation, as shown in Figure 4.9. However, this makes analysing the graphical evidence more difficult. Configuration I shows trends that both endorse and counter the published literature. A number of the summer hydrographs produced high sedimentation rates, however, the highest rate is associated with a flood event in February. The majority of hydrographs possess similar average depositional rates. Configuration II also does

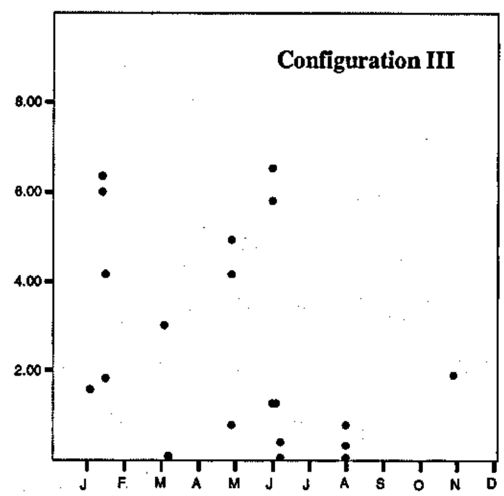
Figure 4.8 shows the affect that seasonality has on depositional rates (kg m^{-2} hr^{-1}) for each of the individual configurations in Reach 1.



1999

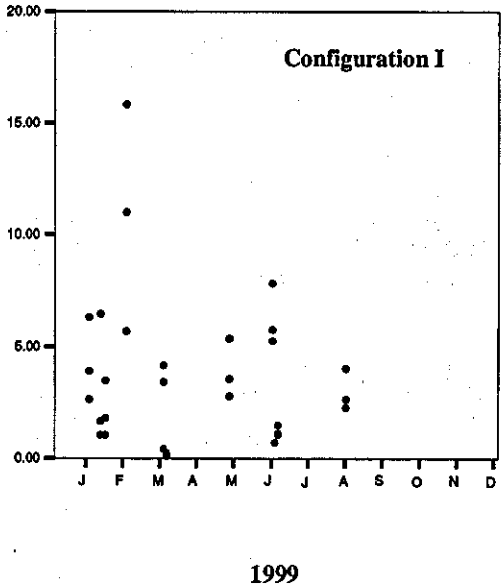


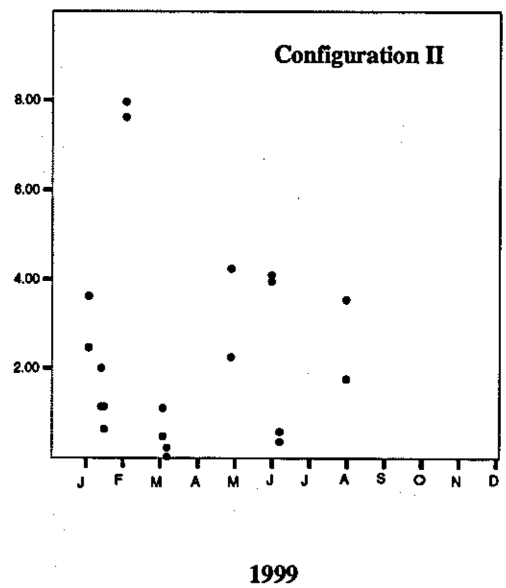
1999

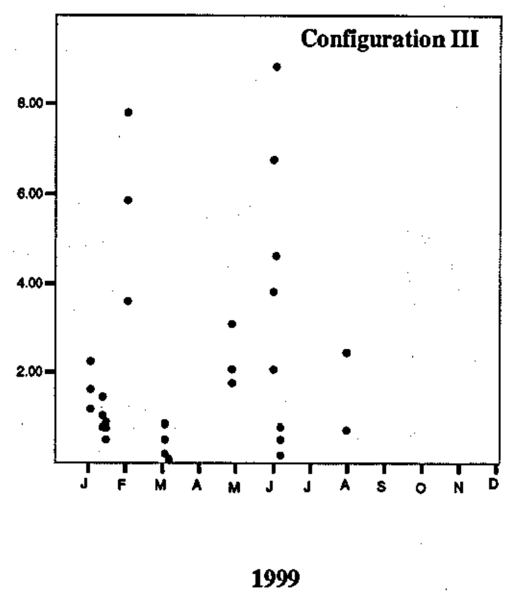


1999

Figure 4.9 shows the affect that seasonality has on depositional rates (kg m^{-2} hr^{-1}) for each of the configurations in Reach 2.







not show a distinct difference in the sedimentation rates between the seasons. This trend is slightly altered when examining Configuration III. The summer infiltration rates are on the whole greater than the majority of the winter rates. In some cases, this is greater than the 1.2 factor increase shown by Frostick *et al.*, (1984).

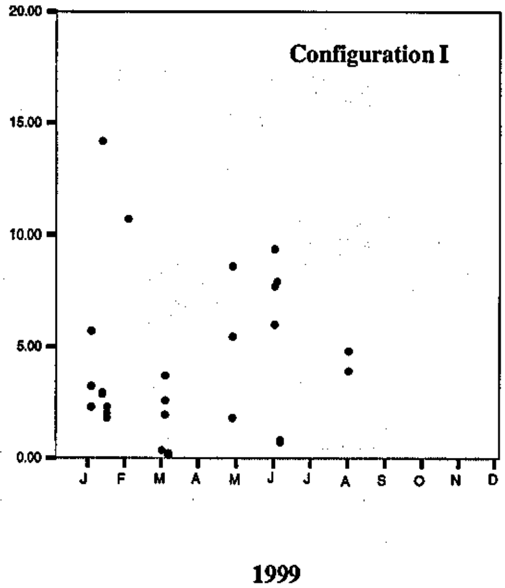
4.4.3 Reach 3

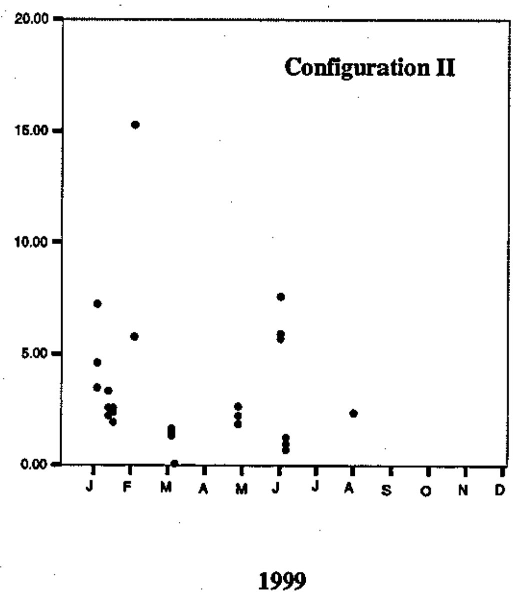
This reach again does not highlight the differences that ASCE (1992) and Frostick *et al.*, (1984) observed. There is considerable scatter between the summer and winter seasons, which is not aided by only one year of monitoring (Figure 4.10). This does not allow for the anomalies to be highlighted.

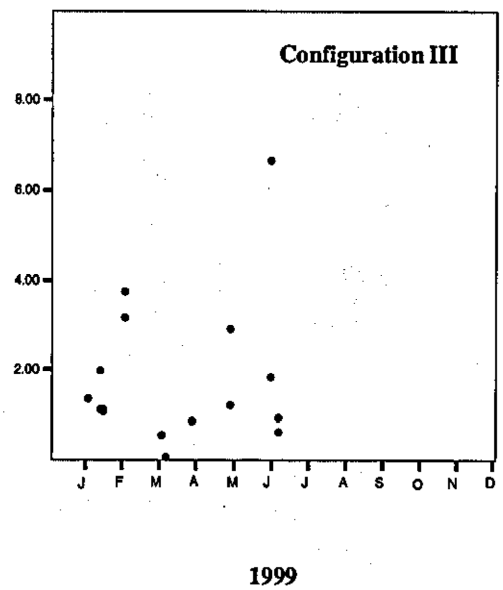
4.4.4 Conclusion on effects of seasonality

The data set, in its current format, does not conform with the conclusions drawn from other studies. Examination of the Figures 4.8 – 4.10 shows that there is a wide variation in the rates of deposition of fine material in Burleigh Brook. However, there is no pattern that shows that the rate of sedimentation of fine material is greater in the summer months. It would seem from this limited data set that the greatest infiltration rates occur in the winter months. As previously stated, Burleigh Brook has a very flashy response to heavy rainfall, which is some cases did not allow for the isolation of individual hydrographs. The lack of isolation could have allowed the data to be compromised in many instances.

Figure 4.10 shows the affect that seasonality has on depositional rates (kg m^{-2} hr^{-1}) for each of the configurations in Reach 3.







4.5 Conclusion.

These results show that the reaches are statistically different agree with the findings that Adams and Beschta (1980) observed, where the percentage of fine material within a gravel bed river could be different between locations within a single stream. Schälchi (1992) has then examined these observations further within a flume, and concluded that flow and suspended load affect the rate and depth of deposition. He also stated that the interaction between turbulence and the settling properties of the suspended particles should not be ignored. In this study, the suspended sediment load rating curve shows considerable variation, and the specific concentrations at the peak flows has not been used as a variable in the analysis. The sediment rating curve, shown in Figure 2.11, however, shows that as stage / discharge increases, the concentration of fine material in suspension also increases. There are, however, discrepancies and variations in the concentrations during lower flows.

As indicated above (Chapter 4.02), Hydrograph 4 has the highest sedimentation rates observed. However, this is one of the hydrographs from which the results were disregarded as a consequence of the weight in the receiver was greater than 1000g. Examination of Hydrograph 4 shows that the duration over which Burleigh Brook was in flood was 28¾ hours, which is one of the lowest durations of flooding by Burleigh Brook recorded during 1999. This may mean that the receivers only became full near the end of the flood event. Therefore, these results may offer estimates on the infiltration rates that occur within Burleigh Brook over periods of peak discharge.

Lisle (1989) observed that as the cumulative volume of bed load passing over a trap increased the actual deposition of fine material into his cans decreased. Lisle (1989) also observed that infiltrated material was derived from fine bedload, as opposed to material carried in suspension.

The seasonality data does not, in its current form, concur with published work on the subject. This is mainly a result of the limited summer floods that occurred during 1999, and the fact that the data only represents one complete calendar year. The small finite volume of the containers in relation to the larger than expected sediment fluxes occurring on Burleigh Brook does not allow complete utilisation of the data set, thus compromising the ability to draw conclusions as to how Burleigh Brook operates.

In all of the results here, the sedimentation rates have not been compromised by the formation of a seal within the interstice, as observed in other studies (e.g. Beschta and Jackson, 1979). This is consequential upon the interstices being far too large for this process, and the lack of framework in the receivers. However, a larger clast from the bed could affect sedimentation rates by sitting over the opening to the receiver. Observations of the traps when collecting reveal that this was not a common occurrence, but this may have occurred during the flood and compromised results.

The results shown here are difficult to relate to studies involving sedimentation of gravel bed rivers because of a number of factors. The first is that the receivers were framework free. The reasoning behind this is that the aim of this study was to assess how the different configurations of roughness elements, comprising the interstitial component, affects sedimentation rates. Filling the receivers with framework gravels would have added complications to the rates and settling of the infiltrated gravels. Second, observations by Wohl and Cenderelli (2000), amongst others, show that the majority of fines are deposited in pools rather than riffles. The practicality of this within Burleigh Brook was not possible. Third, many experiments on natural and man-made systems have examined the depth at which fines infiltrated into the gravel bed (e.g. Diplas and Parker, 1992, Davies and Nelson, 1993 Allan and Frostick, 1999). In this study, receivers were submerged in the gravel bed, making it impossible to record the depth of infiltration. However, a measurement of the depth of sediment within the receivers for each hydrograph, may have added to the analysis. As a consequence of this study having no framework gravels present in the receivers, the exact physical mechanisms by which grains enter the framework were not assessed here. This study therefore does not demonstrate the processes observed and examined by Allan and Frostick (1999), Diplas (1994) and Reid *et al.*, (1992).

Diplas and Parker (1992) have stated that the infiltration of fine material into the subpavement layer within a gravel bed is independent of boundary stress and other flow parameters. Adams and Beschta (1980) also attribute the lateral changes in concentration of infiltrated fines to aerial changes in the surface and subsurface material. The lack of hydraulic data around the man made interstices, compromises the detail into which the rates of infiltration can be related to hydraulic parameters, that most authors state are the most important variables (e.g. Beschta and Jackson, 1979, Frostick *et al.*, 1984).

The exact manner by which sediment is infiltrated into the receivers in this study is unknown as a result of a lack of information on the hydraulic flow patterns around the mouths of the interstices. Detailed flow patterns would have enabled interpretations to be made regarding the influences of eddies on the sedimentation, and why the different configurations differed in their trapping efficiency.

Chapter 5

Particle Size of Infiltrated Material.

5.0 Size of infiltrated material.

The final aim of this thesis is to ascertain whether there are any relationships between the size of infiltrated material and the variables examined in the previous chapter. As outlined previously, not all the events recorded have simple hydrographs, and to aid in the interpretation of the data, only material deposited by individual hydrographs were sieved. Care was also paid to sieve material deposited by events representing the widest range of flows possible. As demonstrated in Chapter 4, storm hydrographs that exceeded 0.50m maximum depth resulted in the receiving container being filled at some point prior to the end of the event. Hydrographs that peaked above 0.40m were not sieved because it could not be assumed that all the material transported during these hydrographs had infiltered into the receiver. Multiple flood peaks enhance the difficulty of interpretation and as a consequence these were avoided when analysing the size distribution of the deposited sediment.

Of the twenty-four events measured, nine were chosen for further examination. Material collected during base flow episodes remained unsieved for two reasons, the first relating to the method employed in sample preparation as outlined in Chapter 3. Oven drying resulted in samples resembling a layer of baked silt. To acquire an accurate picture of particle size, a dispersion technique would have been needed, possibly breaking the primary particles. However, without thorough dispersion, the material would misrepresent the particle size distribution of the material transported during base-flow periods. Second, the weight of sediment collected during base flow episodes was often under 0.05kg, which is below the advised minimum weight for sieving (Rice, 1999, per. com.).

The interstitial components used in this experimental arrangement have larger pores than those commonly present in lowland gravel bed rivers. The reasons for this have been outlined in Chapter 4. As a consequence, larger material is deposited in these traps than would be expected to infiltrate naturally into a lowland gravel bed pore. This must be borne in mind when making comparisons with other work.

5.01 Preliminary Analysis.

For a given event, the contents of each trap were individually sieved and a cumulative percentage finer than curve was constructed. Table 5.1 shows the data obtained from each of the sieved hydrographs. From each of the cumulative percentage finer than curves metric particle sizes were converted into phi units. These curves were then superimposed upon each other to assess the intra-hydrograph variation between different configurations. However, these compound curves only provide a visual representation of the variation, and, as a consequence of the number of traps involved, do not allow for direct comparison between specific traps. In view of the difficulty of comparing cumulative percentage finer than curves, a number of different size percentiles were derived from each. These derived percentiles are those most frequently used to ascertain the mean, skewness and sorting parameters, namely D_5, D_{16}, D_{50}, D_{84}, D_{95}. The complete data set of size percentiles is shown in Appendix 5.1.

Table 5.1a Percentile size in mm for Reach 1 for individual events.

Hydrograph	Peak Stage (m)	D_5		D_{16}		D_{50}		D_{84}		D_{95}	
		Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
1	0.92	0.14	$1.41*10^{-2}$	0.27	$1.94*10^{2}$	1.29	0.48	8.04	6.06	12.97	9.13
2	0.32	0.16	$5.56*10^{-2}$	0.32	0.14	1.44	1.09	6.70	4.03	11.83	7.47
6	0.23	0.18	$6.43*10^{-2}$	0.37	0.13	1.56	0.88	9.21	7.38	13.63	8.10
8	0.31	0.16	$2.75*10^{-2}$	0.39	0.12	2.40	1.77	9.50	6.79	15.45	7.80
10	0.25	0.17	0.13	0.70	1.00	3.28	6.25	6.76	10.20	11.44	10.93
13	0.37	0.13	$6.26*10^{-2}$	0.29	0.15	1.00	0.74	6.77	7.44	13.49	9.98
15	0.46	0.14	$5.13*10^{-2}$	0.27	$9.64*10^{-2}$	1.24	1.04	8.92	8.90	15.18	10.33
18	0.41	0.11	$3.93*10^{-2}$	0.23	$5.35*10^{-2}$	1.01	0.57	3.61	0.99	8.06	8.41

Table 5.1b Percentile size in mm for Reach 2 for individual events.

Hydrograph	Peak Stage (m)	D_5		D_{16}		D_{50}		D_{84}		D_{95}	
		Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
1	0.92	0.18	$2.90*10^{-2}$	0.37	0.13	2.41	2.03	9.87	8.55	16.30	10.47
2	0.32	0.10	$2.42*10^{-2}$	0.21	$4.96*10^{-2}$	0.57	0.47	2.48	2.80	6.29	5.33
6	0.23	0.09	$2.66*10^{-2}$	0.20	$5.16*10^{-2}$	0.62	0.36	4.46	4.50	8.53	6.40
8	0.31	0.12	$5.62*10^{-2}$	0.28	0.12	1.36	1.29	7.78	8.47	18.34	9.04
10	0.25	0.11	$6.61*10^{-2}$	0.22	0.14	0.53	0.40	3.22	3.72	7.36	3.82
13	0.37	0.14	$2.67*10^{-2}$	0.27	$3.27*10^{-2}$	0.80	0.19	4.42	2.75	11.46	7.91
15	0.46	0.16	$8.12*10^{-2}$	0.33	$7.61*10^{-2}$	1.11	0.67	4.97	3.01	9.77	5.29
18	0.41	0.17	$4.12*10^{-2}$	0.31	$5.74*10^{-2}$	1.13	0.50	4.63	1.88	8.04	3.61

Table 5.1c Percentile size in mm for Reach 3 for individual events.

Hydrograph	Peak Stage (m)	D_5		D_{16}		D_{50}		D_{84}		D_{95}	
		Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
1	0.92	0.21	$3.44*10^{-2}$	0.36	$6.87*10^{-2}$	1.46	0.55	8.06	4.55	15.98	9.16
2	0.32	0.12	$3.62*10^{-2}$	0.24	$4.78*10^{-2}$	0.46	0.24	2.48	1.87	7.76	5.71
6	0.23	0.12	$1.27*10^{-2}$	0.25	$1.50*10^{-2}$	0.59	0.12	3.98	0.97	9.25	1.62
8	0.31	0.17	$8.19*10^{-2}$	0.39	0.26	1.24	0.97	4.44	2.15	8.22	4.08
10	0.25	0.12	$5.85*10^{-2}$	0.26	0.10	0.75	0.75	3.55	1.53	8.98	2.69
13	0.37	0.14	$4.45*10^{-2}$	0.27	$6.36*10^{-2}$	0.70	0.35	3.07	1.36	8.69	3.71
15	0.46	0.18	$4.31*10^{-2}$	0.31	0.12	0.84	0.79	3.30	1.90	7.87	2.60
18	0.41	0.20	$3.82*10^{-2}$	0.27	0.12	0.78	0.26	4.31	0.91	10.09	3.50

The material sieved here represents all the material collected during a time period, and therefore includes material that was deposited during periods of base-flow prior to any flood event. Owing to the difficulties of sieving material deposited in base-flow conditions, the results are not corrected for these periods. It was deemed that ascertaining a representation of the range of particle sizes infiltrated during flood flows only was not possible. Particle sizes depicted here represent effective particle size, as there has been no chemical breakdown of the material into its constituent particle sizes (e.g. Woodward and Walling, 1992). The use of absolute particle size was deemed unnecessary, as this is not a representative measure of the manner by which the material is transported downstream. A large percentage of material is transported as aggregates and it is these that are important in this study. The aim is to address the infiltration of particles into a pore space, and the requirement is for them to be characterised as they were carried downstream, not split into their constituent parts.

In the hydrographs where the stage exceeds 0.4m, inferences can only be made concerning the larger percentiles within the cumulative percentage finer than curves, as the actual sizes are only minimum estimates of the larger particles that were transported during these higher magnitude events. It is difficult to surmise how this unaccounted material would have affected the complete particle size distribution; therefore the sizes depicted here are best estimates reflecting the actual processes occurring in these events.

5.02 Effect of the different reaches.

Owning to each reach having its own unique upstream sediment source, it is vital to examine the reaches individually, sediment size being dependent upon upstream sources as well as local hydraulic influences. As was shown in Chapter 4, the individual reaches behave differently with regard to infiltration rates, as do the configuration types. Therefore, with regard to examining the size of infiltrated material, the reaches and configurations will be examined individually. To verify if each reach behaves independently of each other, the D_5 to D_{95} percentiles for each configuration within each reach were statistically analysed using ANOVA tests, hydrograph by hydrograph (Appendix 5.2).

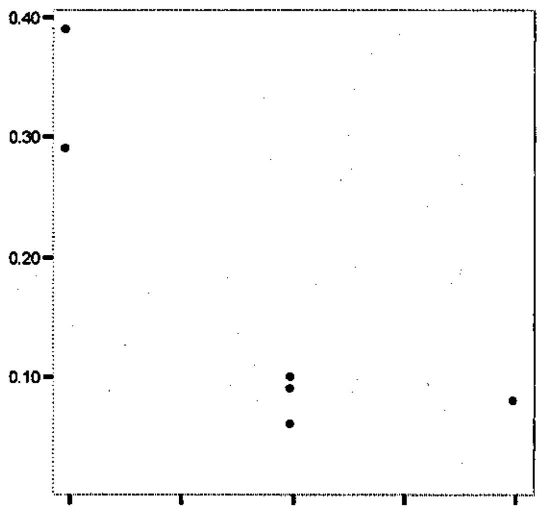
A summary from Appendix 5.2 indicates that Reach 1, Reach 2 and Reach 3 are statistically different. This difference is apparent across all the percentiles, and shows intra-event variation between configurations, and between hydrographs. There is no apparent trend at this point and, consequently, further analysis will use a reach by reach approach within events and a configuration by configuration approach when examining trends between hydrographs.

A graphical summary of some of the information derived from statistical analysis is shown in Figure 5.1. This illustrates that the infiltrated particle size does differ between reaches within a single hydrograph for a single configuration. It also shows that in some cases the particle sizes from a single configuration do not differ between reaches within a single hydrograph for a given percentile.

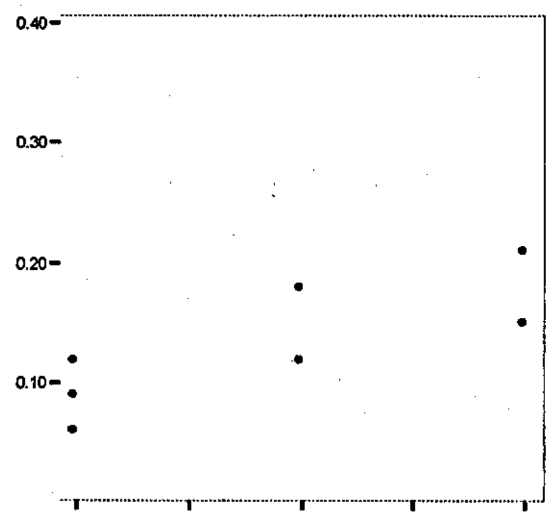
Figure 5.1 showing how the sizes of designated percentiles vary across the reaches. a) and b) show difference between the three reaches, whereas c) and d) show that the reaches show similarities in particle sizes.

(Particle sizes shown in mm)

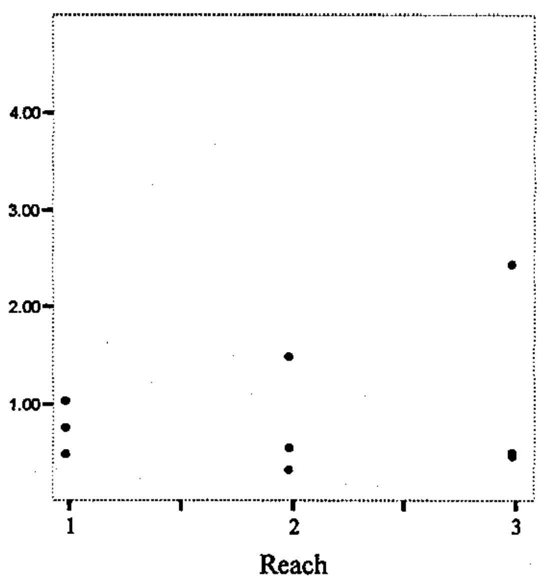
a) Hydrograph 8, Configuration III, D_5.



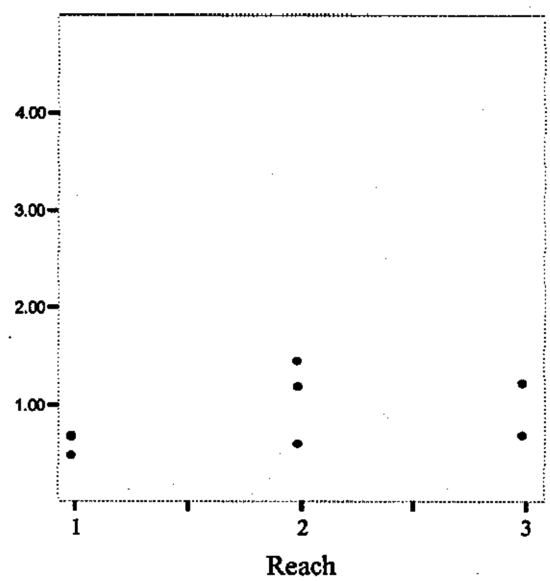
b) Hydrograph 10, Configuration II, D_5.



c) Hydrograph 8, Configuration I, D_{50}.



d) Hydrograph 10, Configuration III, D_{50}.



5.1 An introduction to particle size within Burleigh Brook.

In this chapter, the results presented show the particle sizes of the infiltrated material into the sediment traps below the roughness elements. Kozerski (1994) questions how cylindrical traps influence the eddies around the trap mouth, which could result in particle size selection during infiltration. Unfortunately, detailed flow analysis around these receivers and their roughness elements is not available, and therefore this statement cannot be confirmed. If data on flow patterns had been available from the flume experimentation, this would have added to these discussions despite the lack of fluid below the roughness elements in the flume. Flow analysis with the acoustic Doppler velocimeter (ADV) within Burleigh Brook was not possible for a number of reasons. First, the ADV only operates successfully under relatively clear water conditions, and with a flow depth in excess of 0.10m. Under these conditions many of the roughness elements were above the main flow. Depths greater than this quickly resulted in high suspended sediment concentrations as shown in Chapter 2, thus affecting the derivation of measurements. The second problem is the recognition of boundary for the ADV. The lack of distinct boundary for the ADV to use as a reflection point would have caused many problems in interpretation of the results. Use of other flow recorders did not allow detailed flow analysis to be undertaken within the interstice opening to examine these problems raised by Kozerski (1994).

As described in Chapter 3.1.1, the traps used here do not contain any framework gravels. Consequential of this lack of material within the traps, a larger size range of bed material is found in these traps. Therefore, larger material is recorded in this study than has been observed by other studies (e.g. Frostick *et al.*, 1984). Data shown in Table 5.1 illustrates that the larger size percentiles are of similar size to the lower range of material collected using the Wolman sampling, as shown in Chapter 2. This is in close agreement with observations made by Lisle (1989) who stated that infiltration of sediment into gravel-bed rivers is mainly via fine material carried as bedload rather than material settling out from suspension. As has been commented on during Chapter 1, the size of the infiltrated material is an important factor in the clogging of gravel pores (e.g. Schälchi, 1992, 1995). The nature by which this clogging occurs is dependent upon the ratio of the size of the infiltrating material to the size of pore into which it is entering (e.g. Diplas and Parker, 1992). The size of the deposited material is also an important determinant in assessing flow maintenance for the flushing of matrix dominated gravels, (e.g. Allan and Frostick, 1999) and to improve the aquatic environment (e.g. ASCE, 1992).

The main aim of this study is to assess the influence that roughness elements have on sedimentation of fine material into lowland gravel-bed rivers, therefore emphasis will be placed on the lower percentiles. It is these lower percentiles that cause a detrimental effect on the benthic organisms and other aquatic life within gravel-bed rivers. However, with regard to the sediment transport capability of Burleigh Brook, the larger percentiles are important. These larger percentiles will also give an indication of the size ratio between the infiltrating particles and the pore space into which they have infiltrated.

5.2 The effect of trap configuration on particle size of infiltrated material.

Before any of the physical characteristics concerned with the hydrographs are examined to assess their influence on the size of material infiltrated into the receivers, the effect of individual configurations on particle size has to be addressed.

The question outlined here is to ascertain whether the different roughness configurations above the receivers placed on the stream bed, affect the size of material that is infiltrated. Frostick *et al.*, (1984) state that pore space shape does affect the size of material that is infiltrated. However, within this present study, the artificial pores are greater in size than those naturally found within lowland gravel bed rivers. These interstitial pores were designed to be used within a flume with an ADV to ascertain the three dimensional flow field, however, the laboratory work was affected by equipment failure.

It was decided that using all the derived percentiles was unnecessary, so only the D_5, D_{50} and D_{95} percentiles were examined. These three percentiles were chosen to represent the finer material, important with regard to the clogging of interstice pores, along with the mean particle size, and the larger material, which is used as a measure of flow competence. As a result of Chapter 4, the number of hydrograph units examined was reduced as a consequence of the receiver dry weight being above 1.0 kg. All those receivers sieved in Hydrograph 1 and 15 were removed from the statistical analysis.

Prior to carrying out statistical analysis, hydrograph by hydrograph, reach by reach, graphs were produced to ascertain visually if there are any differences between the different configurations. An example of these can be seen in Figure 5.2. To verify these conclusions, ANOVA tests were undertaken. The complete statistical analysis can be seen in Appendix 5.3.

A summary of these tests is that, within each reach, there is limited statistical evidence that there is a difference in size of the materials infiltrated into the three different configurations. It is, therefore, possible to amalgamate results from all the configurations within each reach for each of the designated percentiles to assess the influence the remaining factors have on the size of material infiltrated into the receivers. However, on a number of occasions there were differences in the size of the selected percentiles between the configurations. These mainly occurred at the D_{95} percentile. Table 5.2 below depicts where there are statistically significant differences in particle's size between the configurations as shown by post-hoc t-tests.

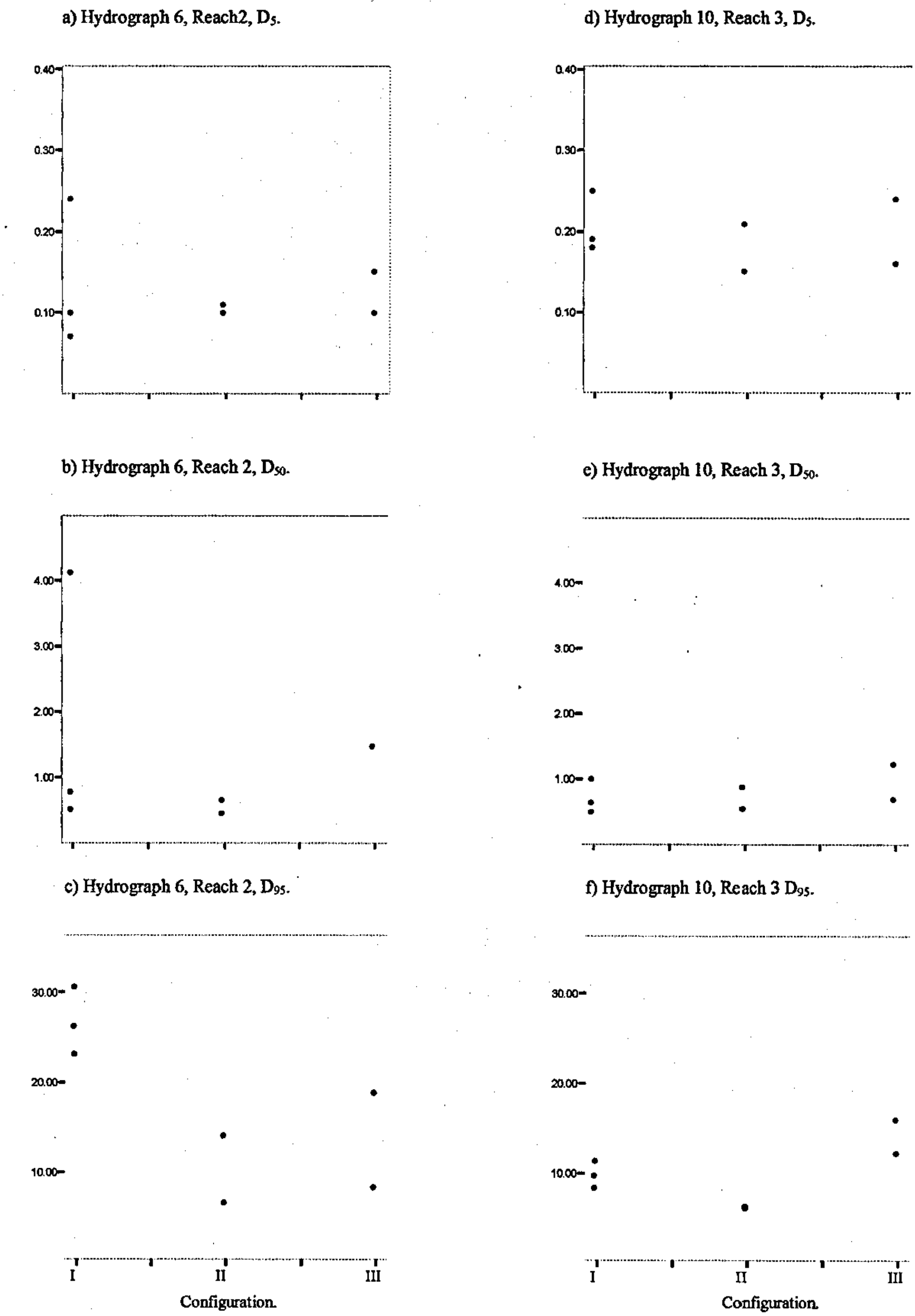
Table 5.2 showing the statistical differences in particle sizes between two configurations.

Hydrograph	Reach	Dependent Variable	Configurations		Mean Difference	Std. Error	Significance
6	2	D_{95}	I	II	16.3167	4.8191	0.028
10	3	D_{95}	I	III	4.2667	1.5326	0.050
10	3	D_{95}	II	III	7.8700	1.6789	0.009
18	3	D_{95}	I	II	3.6333	1.0158	0.016
18	3	D_{95}	I	III	5.4317	1.1357	0.005

(Single underline indicates rejection of the null hypothesis at $\alpha < 0.05$, double underline indicates a rejection of the null hypothesis at $\alpha < 0.01$).

Figure 5.2 showing how configuration effects the size of infiltrated material for different reaches and percentiles.

(Particle sizes shown in mm)



In addition to those listed, there is one instance that is not recorded, because of limited data set led to an inability to undertake post-hoc t-test analysis. This result is that the D_5 percentile in Hydrograph 8 Reach 1 shows a statistical difference between the populations. As a consequence of there being no post-hoc t-test analysis, the graphical representation shows that the statistical difference in the mean of the populations is between Configuration I and III, with Configuration III having a D_5 which is greater than that of Configuration I.

Table 5.2 shows that it is only at the highest percentile that there is a statistically significant difference between the size of the material infiltrated in the sediment traps. In over 50% of the instances, the difference is associated with Configuration III. As has already been illustrated, Configuration III has a greater interstice area, and therefore, it would be expected that the particle size of the 95th percentile in the receivers below this configuration of roughness elements would be greater. Figure 5.2 c and f graphically illustrates the statistically significant differences shown above. In one of the illustrated cases, Configuration I has the greatest size of particle at the 95th percentile. It can, therefore, be concluded that it is not necessarily the size of the interstice opening that is the determining factor in this instance. Can there, therefore, be another common factor for these five instances which results in a significant statistical difference in the mean of the D_{95}? It might have been expected that the larger percentiles for Configuration III would be coarser than I and II, if a threshold for transporting larger sediment was exceeded because of Configuration III's larger opening.

The above statistics show that, overall, the different roughness elements allow infiltration of material that possesses size characteristics that could be derived from the same population. This is not what would be expected. The expectation was that Configuration III would have a mean particle size at the 95^{th} percentile that was greater than those found in Configurations I and II. Configuration II has an upstream obstruction, could significantly alter the manner in which sediment was trapped and infiltrated, and therefore, affect the size distribution. Unfortunately, without precise flow analysis, observing the detailed shedding of flow and any possible reversal in the lee behind the two downstream roughness elements in Configurations II and III, it is impossible to comment with any certainty how the arrangements are altering the flow dynamics and therefore, the sediment transport processes within the vicinity of the interstice.

In summary, it can be concluded that with one exception the D_5 and D_{50}, ANOVA statistics show that the populations from each of the different configurations could be derived from a single population. In addition, the majority of the D_{95} percentiles are also derived from a single population, regardless of the different configurations. These statistics show that despite the interstice opening of Configuration III possessing a circular opening, with double the diameter of Configurations I and II, there is limited statistical difference between the coarser material in these receivers. The fact that one of the trap configurations has an opening twice the area of the other two, yet traps material with the same D_{95} is interesting. In subsequent analysis, all the configurations within individual reaches have been combined together, thus providing a larger data set, which will increase the robustness of statistical results.

5.3 The effect of peak stage within hydrographs on the size of infiltrated material.

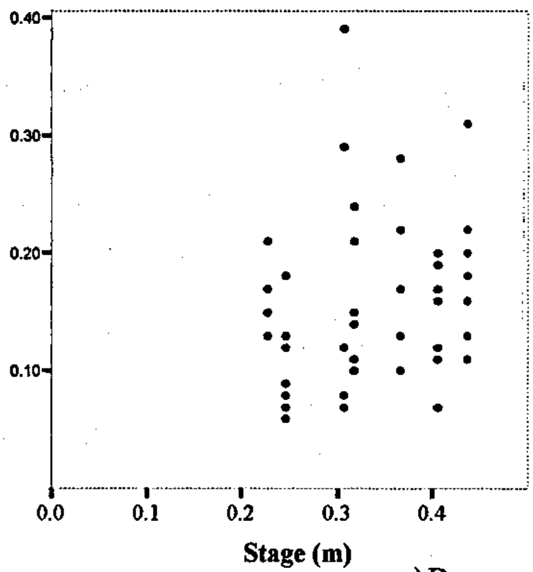
To ascertain if stage has any influence on the size of infiltrated material into the receivers below the roughness elements, a series of graphical and statistical tests were undertaken. As previously stated, analysis has concentrated on three of the selected percentiles, namely D_5, D_{50} and D_{95}. Prior to any statistical tests, scatter plots were produced for each reach. In each of the plots, the particle sizes of the chosen percentile are plotted against peak stage within the hydrograph. The plots for the three reaches for the designated percentiles are shown in Figures 5.3 to 5.5. To accompany these graphical representations, Pearson correlations were carried out on D_5, D_{50} and D_{95} within each reach. These results are shown in Table 5.3.

From these figures, it can be seen that once again, Reach 1 does not follow the trends shown in the two downstream reaches. As is shown by these correlation statistics, which accompany the graphical evidence, it is only at the lower percentiles that a significant correlation is observed between an increase in stage and an increase in particle size. These statistics indicate that as stage increases, so does the size of infiltrated material, at the D_5 percentile. However, this trend does not continue through the larger size percentiles. Analyses examining each configuration within each reach separately shows that in one case, there is a correlation between an increase in stage with an increase in particle size – Reach 2, Configuration II at the D_{50} percentile. The statistics for this correlation are shown in Table 5.4.

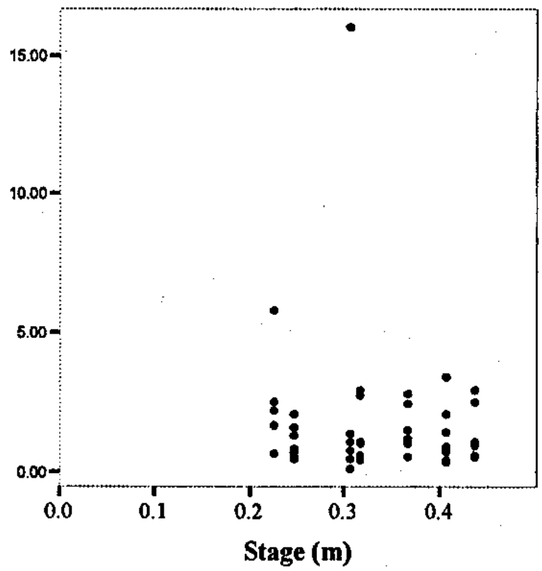
Figure 5.3 showing the effect of stage on the designated size percentiles for Reach 1.

(Particle sizes shown in mm)

a) D_5



b) D_{50}.



c) D_{95}.

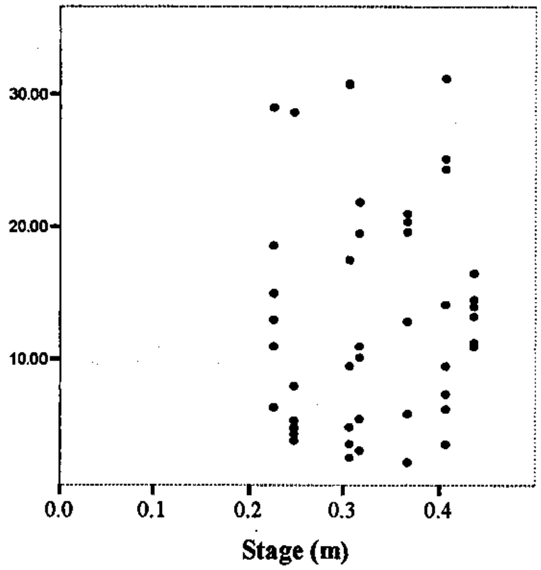
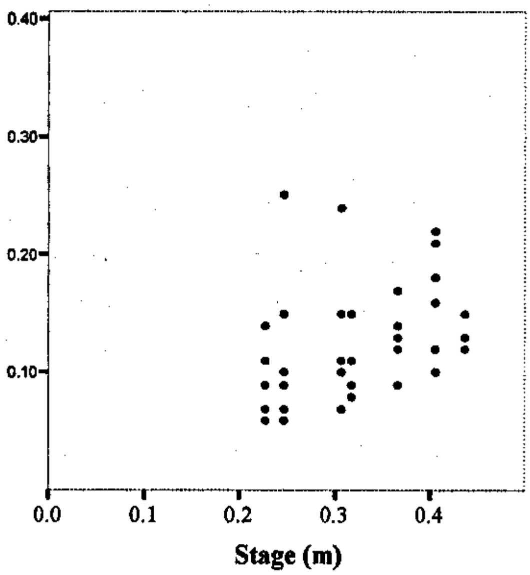


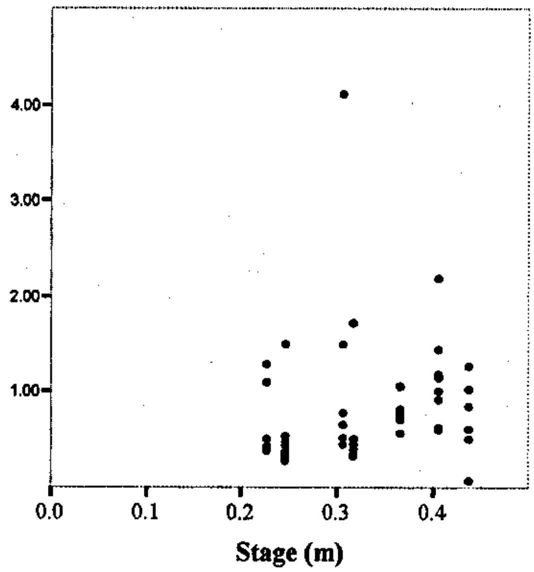
Figure 5.4 showing the effect of stage on the designated size percentiles for Reach 2.

(Particle sizes shown in mm)

a) D_5.



b) D_{50}.



c) D_{95}.

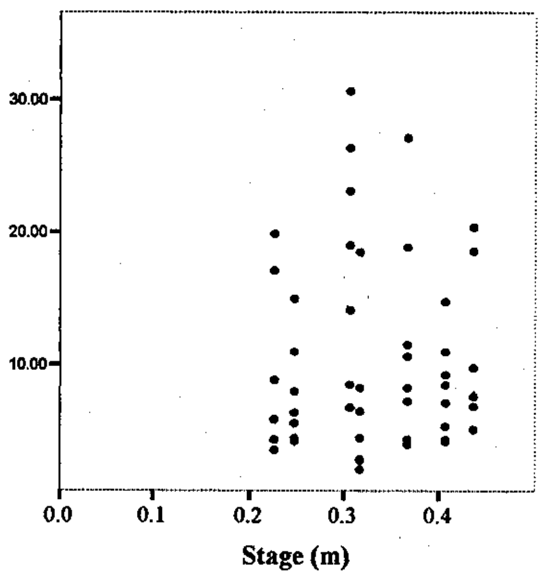
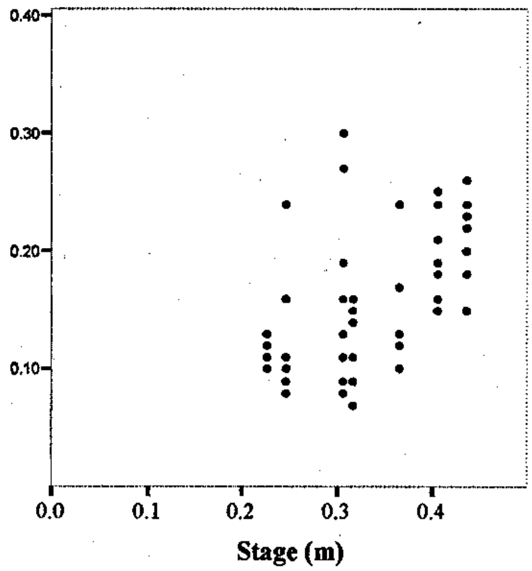


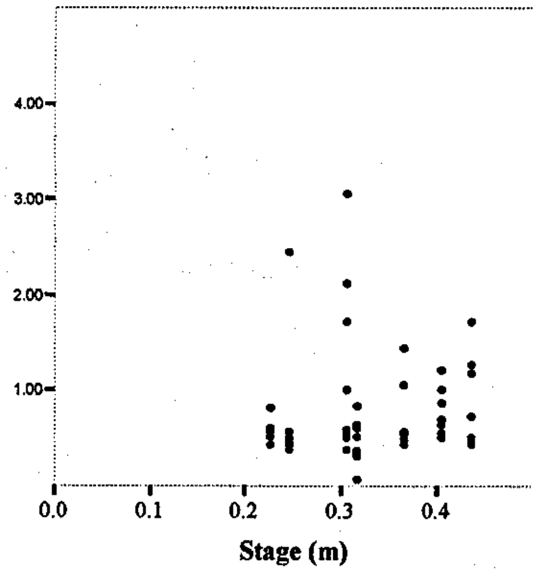
Figure 5.5 showing the effect of stage on the designated size percentiles for Reach 3.

(Particle sizes shown in mm)

a) D_5.



b) D_{50}.



c) D_{95}.

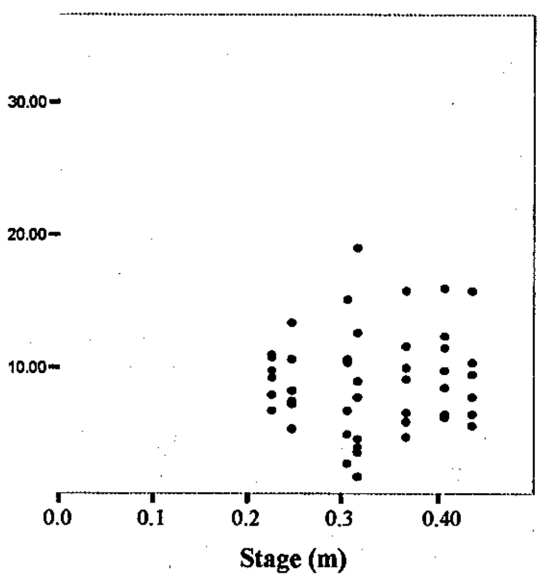


Table 5.3 showing the correlation statistics between an increase in the peak stage and an increase in the size of infiltrated material.

Reach	Percentile	Mean	Std Deviation	N	Pearson Correlation	Significance (2-tailed)
1	5	0.1545	$6.934*10^{-2}$	47	0.186	0.211
1	50	1.7316	2.3853	47	-0.068	0.652
1	95	12.6974	8.1775	47	0.149	0.318
2	5	0.1219	$4.703*10^{-2}$	52	**0.478**	0.000
2	50	0.8189	0.6378	52	0.174	0.217
2	95	10.0977	7.0322	52	0.079	0.577
3	5	0.1535	$5.871*10^{-2}$	51	**0.498**	0.000
3	50	0.7809	0.5653	51	0.077	0.592
3	95	8.8176	3.6466	51	0.052	0.716

(Figures in bold indicate that the correlation is significant at the 0.01 level for 2-tailed).

Table 5.4 shows the correlation statistics from Reach 2, Configuration II at the 50th percentile.

Mean	Std. Deviation	N	Pearson Deviation	Significance (2-tailed)
0.6821	0.4881	14	0.568	0.034

(Single underline indicate that the correlation is significant at the 0.05 level for 2-tailed).

Table 5.5a summarising the models from the regression analysis for Reaches 2 and 3 with regard to D_5 and an increase in stage.

	R	R^2	Adjusted R^2	Std Error of the Estimate	Durbin-Watson
Reach 2	0.478	0.229	0.213	$4.172*10^{-2}$	2.112
Reach 3	0.498	0.248	0.232	$5.144*10^{-2}$	2.135

Table 5.5b shows the ANOVA results associated with the regression analysis for Reaches 2 and 3 with regard to D_5 and an increase in stage.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Reach 2	Regression	$2.580*10^{-2}$	1	$2.580*10^{-2}$	14.825	0.000
	Residual	$8.701*10^{-2}$	50	$1.740*10^{-3}$		
	Total	0.113	51			
Reach 3	Regression	$4.272*10^{-2}$	1	$4.272*10^{-2}$	16.146	0.000
	Residual	0.130	49	$2.646*10^{-3}$		
	Total	0.172	50			

This correlation at the higher percentile is as statistically significant as those shown in Table 5.3. However, it does show that when the large data set is split down into its constituent reaches and configurations that there are trends which are hidden when amalgamation occurs.

Linear regression analysis was undertaken to assess the relation between D_5 and stage in Reaches 2 and 3 (Tables 5.5a and b). From these two tables it is clear to see that there is a poor relationship between D_5 of infiltrated material and stage. From these statistics along with the graphical representations, it can be concluded that Reach 1 behaves differently from Reaches 2 and 3. Its is also demonstrated that statistically, that only the particle size of D_5 increases with an increase in peak stage.

As a consequence of a lack of statistically significant relationships between stage and particles size, a series of ANOVA tests were undertaken to examine if there were any differences in the populations of each reach as peak stage increased. Table 5.6a - c shows the results of these tests.

These tests were used to determine if the particle size at the designated size percentiles were obtained from the same population regardless of changes in stage.

Table 5.6a showing the results of a series of ANOVA tests to determine if there is a statistical difference in the populations of particles size as peak stage is increased for Reach 1

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$3.419*10^{-2}$	6	$5.699*10^{-3}$	1.219	**0.137**
	Within Groups	0.187	40	$4.674*10^{-3}$		
	Total	0.221	46			
D_{50}	Between Groups	24.022	6	4.004	0.674	**0.671**
	Within Groups	237.695	40	5.942		
	Total	261.717	46			
D_{95}	Between Groups	294.963	6	49.160	0.707	**0.646**
	Within Groups	2781.144	40	69.529		
	Total	3076.107	46			

Table 5.6b showing the results of a series of ANOVA tests to determine if there is a statistical difference in the populations of particles size as peak stage is increased for Reach 2

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$3.632*10^{-2}$	6	$6.054*10^{-3}$	3.562	0.006
	Within Groups	$7.649*10^{-2}$	45	$1.700*10^{-3}$		
	Total	0.113	51			
D_{50}	Between Groups	4.275	6	0.713	1.946	0.094
	Within Groups	16.474	45	0.366		
	Total	20.749	51			
D_{95}	Between Groups	705.610	6	117.602	2.913	0.017
	Within Groups	1818.412	45	40.365		
	Total	2522.022	51			

Table 5.6c showing the results of a series of ANOVA tests to determine if there is a statistical difference in the populations of particles size as peak stage is increased for Reach 3

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$6.373*10^{-2}$	6	$1.062*10^{-2}$	4.302	0.002
	Within Groups	0.109	44	$2.469*10^{-3}$		
	Total	0.172	50			
D_{50}	Between Groups	2.877	6	0.480	1.611	0.167
	Within Groups	13.101	44	0.298		
	Total	15.978	50			
D_{95}	Between Groups	24.834	6	4.139	0.285	**0.941**
	Within Groups	640.033	44	14.546		
	Total	664.867	50			

(Single underline indicates a rejection of the null hypothesis at $\alpha < 0.05$, double underline indicates rejection of the null hypothesis at $\alpha < 0.01$. Figures in bold indicate acceptance of the null hypothesis at $\alpha > 0.300$).

These tables clearly show that Reach 1 does not show any significant size difference in the specified size percentiles of the deposited material over the range of recorded hydrographs. This indicates that the actual sizes of the deposited material retrieved from all the hydrographs are derived from the same population. Reaches 2 and 3, however, contradict Reach 1, showing differences in the populations for the selected size percentiles. From these statistics, it can be inferred that the two different modes of entrainment, briefly discussed in Chapter 1 are operating in Burleigh Brook. The statistics from Reach 1 show that the individual size percentiles are derived from the same population, independent of changes in peak stage, and therefore discharge.

This equates to the theory of equal mobility. Parker *et al* (1982) stated that all grain sizes have an equal likelihood of transportation when the critical condition of armour layer break-up occurs. Andrews and Parker (1987) define the occurrence of equal mobility as the period when grain size distribution of the bedload is equal to that of the bed. Wilcock (1993) added that any size distribution of bed material would become entrained at nearly equal flow conditions.

Within Reaches 2 and 3, the populations from which the actual sizes for individual size percentiles are derived are dependent upon stage, with the exception of D_{95} in Reach 3. The dependence of size on stage suggests that size selective entrainment is occurring at these two downstream sites. Ashworth and Ferguson (1989) stated that mobility decreased with increasing particle size especially at low flows. It would seem that the two downstream reaches agree with theory of size selective transport.

5.3.1 Conclusion to the effect of peak stage on the size of infiltrated material.

The conclusions drawn from the effect that peak stage has on the size of infiltrated material is that it is only the finer size percentiles that are affected by this variable. The D_{50} and D_{95} show a limited increase in size as stage increases. This could be due to a number of factors. The first consists of the limiting affect that the interstice has on only allowing a finite range of material to pass through. The second being that the larger particle sizes were only transported at higher flows, which have been removed from this data set.

5.4 The effect of seasonality on particle sizes of the infiltrated material.

Frostick *et al.*, (1984) demonstrated on Turkey Brook that seasonality affected the size distribution of material infiltrated into the streambed. They observed that summer floods with a greater discharge produced accumulations that were finer than matrices derived from a lower discharge event in winter. The finer matrices are produced by greater suspended sediment concentrations within summer floods. As stated earlier, vandalism of the receivers, in the summer months has meant that the data was limited when hydrographs were chosen for size determination. Only two of the hydrographs under discussion here are results from summer floods. As a consequence of the limited data set under observation here, the analysis will concentrate on graphical representation to address if the infiltrated material in the summer months is indeed finer. Analysis will again be undertaken on a reach by reach basis.

5.4.1 Reach 1.

Three of the size percentiles were examined in this analysis (i.e. D_5, D_{50} and D_{95}). With regard to the D_5 particles, the coarsest occur during the winter months. The two finest size distributions are those present in June and August. The size distributions of the D_{50} particles are almost constant throughout the year. However, the range of particle size distribution increases at the 95th percentile. The largest D_{95} particle size was trapped during a summer flood in June, however, with one exception, the D_{95} retrieved in August are the finest of the complete year (Figure 5.6).

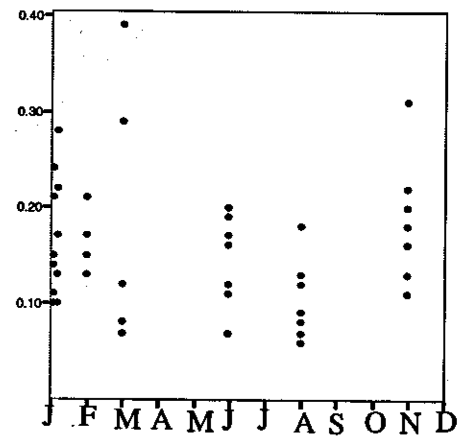
5.4.2 Reaches 2 and 3.

The results from these two reaches are different from Reach 1. The two lower reaches do show some results similar to those observed from Turkey Brook. At the finest percentile examined – D_5, the particle size distribution is coarser, with the exception of two receivers in February and March. The data within the scatter plots, Figure 5.7 and 5.8 for Reaches 2 and 3 respectively, do show that there is an increase in the D_5 between the winter and the summer. As the percentiles are increased, the D_{50} infiltrated into Reach 2 is coarser in the summer than that infiltrated during the winter. This trend is not as apparent at D_{95}, nor within Reach 3. In conclusion, these two reaches do illustrate some agreement to the trends observed in Turkey Brook, however, the limited range of data here, and the inclusion of only one winter and summer season, does not aid in the interpretation of these results to previously published trends.

Figure 5.6 showing the effect of seasonality on the size of infiltrated material for Reach 1

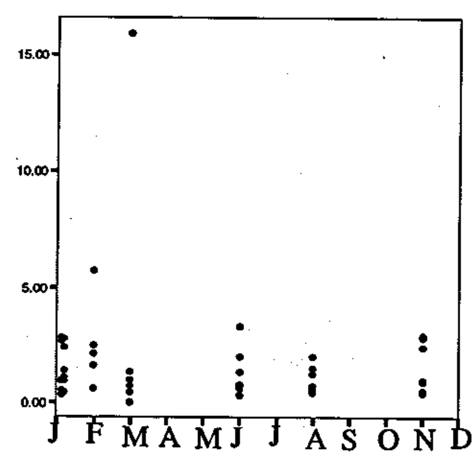
(Particle sizes shown in mm)

a) D_5



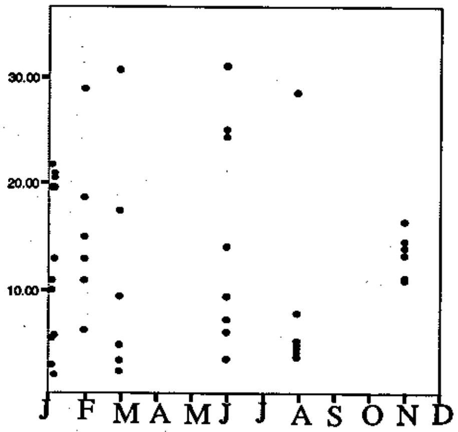
1999

b) D_{50}



1999

c) D_{95}

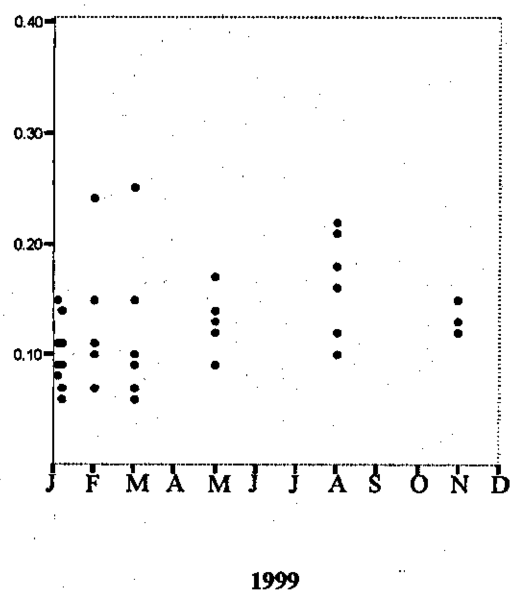


1999

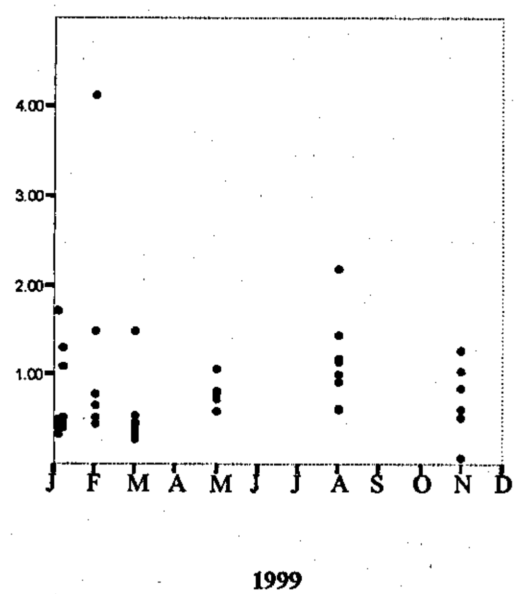
Figure 5.7 showing the effect of seasonality on the size of infiltrated material for Reach 2

(Particle sizes shown in mm)

a) D_5



b) D_{50}



c) D_{95}

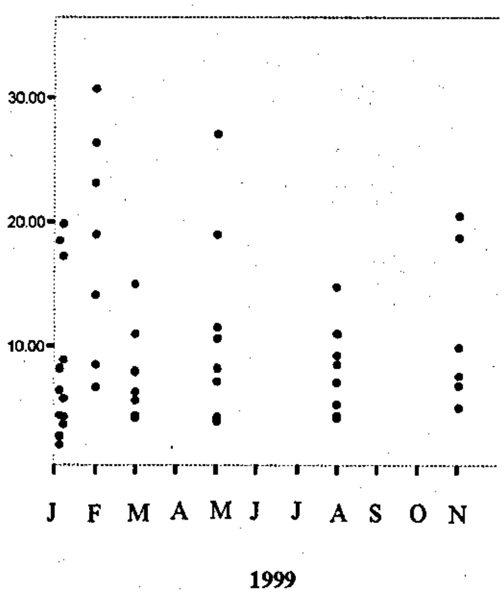
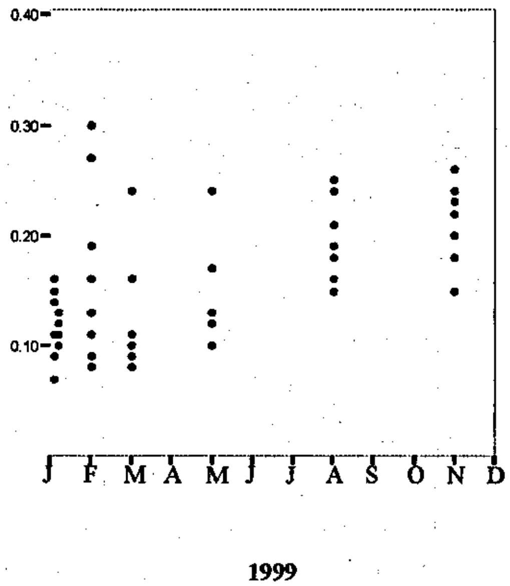


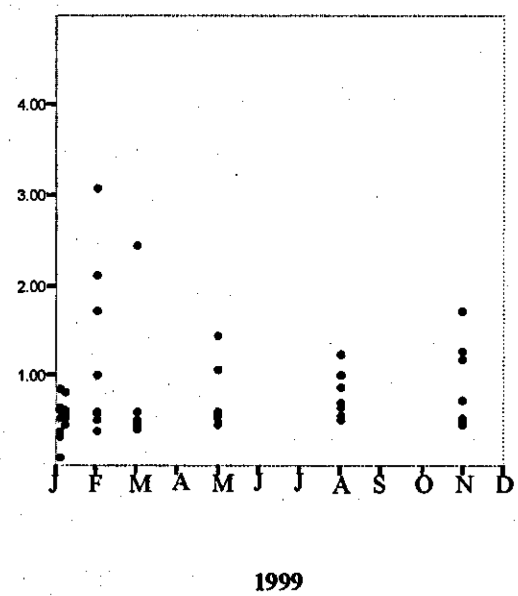
Figure 5.8 showing the effect of seasonality on the size of infiltrated material for Reach 3

(Particle sizes shown in mm)

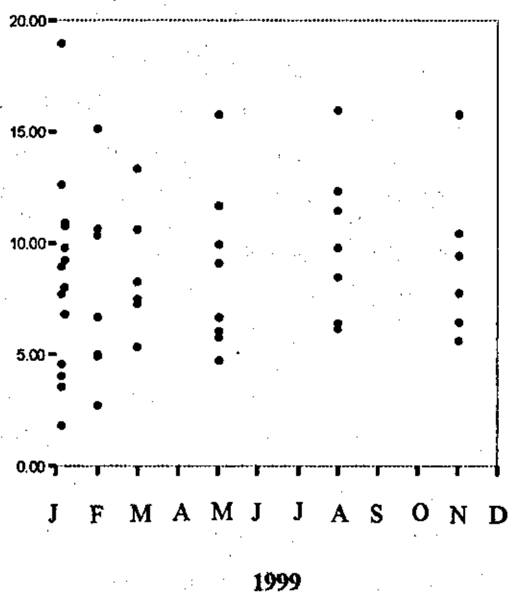
a) D_5



b) D_{16}



c) D_{95}



5.5 Conclusion.

As has been shown in this Chapter, there are many different variables that contribute to the particle size of the infiltrated material. The conclusions drawn here are based in a limited data set, and therefore, have to be used in a constrained manner. The data set is limited in two ways, first, the number of hydrographs, whose deposited material was sieved, is very limited, and second, the results only span one season. This means the conclusions examining the effect of seasonality are based on a very limited data set.

It can be seen that in many instances, Reach 1 does not behave in a manner that is consistent with the two downstream reaches or any previous published literature. The main factors that can be seen to affect the size of the infiltrated material are an increase in stage and an increase in the time between successive flood peaks. There is no statistically significant effect on particle size as a result of an alteration in the interstice opening area, or the orientation of the interstice within the flow. This is the most surprising conclusion drawn from results obtained here. It is well documented in field studies that the pore arrangement affects the size distribution of material found within gravel-bed rivers. These results could be because of a lack of framework within the receivers.

As has been shown, it is only the finer section of the size distribution that is affected by the factors mentioned above. To produce results that are more reliable, a longer monitoring programme is needed. A pilot study to assess the sediment transport of the designated study area is also needed, to address the size of the receiver that is needed to cope with the volumes of sediment available to be infiltrated. The arrangement of receivers within the three study sites allowed comparisons to be made within reaches, it also avoided the problem that could have arisen had Reach 1 contained only one type of configuration.

As has been stated, the main aim of this section of the thesis is to assess the importance of infiltration of the lower percentiles into lowland gravel-bed rivers. The statistical evidence suggests that the finer range of the size distribution of infiltrated material is closely linked to stage, and therefore discharge. As a consequence of the methodology employed here, the base-flow periods could not be sieved, so the size distribution associated with base-flow is undetermined. This means that inferences cannot be made about changes in size distributions from a base-flow level. However, it can be concluded that the D_5 does increase with the increase in stage and therefore discharge. This can have detrimental affects on the survival of biotic organisms as shown in Sear (1993) and Wood and Armitage (1997, 1999). Furthermore, this study does not examine the role that an increase in flow has on the flushing of fine material from gravel beds (e.g. Diplas and Parker, 1992). It would seem that the infiltration of fines into, and their flushing from a gravel bed are processes that can operate simultaneously over a small range of distances.

As has been shown, the size of infiltrated material increases as the lag time between successive flood peaks increases. Seasonality also affects the size distribution of material that comprises the matrix. Both these factors could have detrimental affects of the life cycles of biotic life. In this study, biotic samples were not taken, and therefore this area has not been researched, but conclusions from this study show that this is an avenue of study that could be pursued in future.

Chapter 6

Discussion and Conclusion

As has been demonstrated in the previous chapters, examining the rate of infiltration of sediment and the size of this material, there are a number of characteristics of flood hydrographs that affect the rate and size of material. These parameters have included water stage, trap configuration, placement of the traps and seasonality. Conclusions can be drawn with regard to each of these and the two main subject areas of the thesis. Throughout this study a number of issues have arisen from the analysis. These include the difference that Reach 1 has with regard both to the sedimentation rates, and especially the size of material infiltrated. The period of monitoring is another variable that needs to be further addressed, along with variables that could aid in further interpretation of the study. In this final chapter, the conclusions from each of the sections will be discussed in context, along with interesting features that this study has highlighted.

When assessing the observations made within this study, the separation of unit hydrographs from the long-term annual flow regime proved difficult. This inability to completely isolate floods adds discrepancies to the data set. There are also the problems of antecedent conditions within the drainage basin. In addition to this, a greater hydraulic survey is required at each of the reaches as various characteristics and variables need to be ascertained. These include an estimation of local roughness length, determination of the Froude number and an estimation of shear stress on the bed. These variables can be ascertained from a thorough assessment of the velocity patterns along each of the reaches. These would need to be undertaken at a number of different water depths to ensure that the conclusions drawn are valid over the complete range of flows. An increase in the density of levelling surveys would aid in the interpretation of the results, along with the determination of the characteristics of the long profile of each reach. To aid in the interpretation and comparison of results between different reaches a complete survey, including a long profile, sediment surveys and velocity analysis, should be undertaken on the whole stretch, from above Reach 1 to below Reach 3.

6.1 The effect that the individual reaches have on the sedimentation rates and size of infiltrated material.

The major conclusion of this study is that there are differences in the rates of sedimentation of material, and the size of deposited material within the three reaches examined here. The three reaches are within 1km of each other and are not affected by confluence inputs between them. This study therefore, demonstrates that sedimentation within a river bed is very site specific (Schälchi, 1992 and 1995) and is affected by features on a reach scale as well as the micro-features ((Brayshaw *et al.*, 1983), such as the configuration of roughness elements (see section 6.3).

In particular, Reach 1, is significantly different from Reaches 2 and 3, which show similar trends. The meandering stretch and the final confluence about 100m upstream further complicate Reach 1. Over the monitoring period, prominent bar growth took place in the upper region of the riffle, adjacent to the upstream row of traps. This demonstrates that the overall flow hydraulics in this chosen section were not as uniform as first thought.

6.2 The effect of water stage on sedimentation rates and size of infiltrated material.

With regard to changes in water stage, there is no apparent change in the sedimentation rates as peak stage increases. It would be expected that as stage increases, the power of the stream would intensify and therefore the stream's transport competence should increase. An increase in carrying capacity would mean a greater sediment flux, giving rise to a greater potential for ingress of material. The results would therefore expect to show infiltration rates to increase with stage. As a consequence of there being a limited affect of increased stage on the rate of sedimentation within this study, there are a number of factors that could be responsible for this. These include the hydraulic effects of water flowing over the traps and scouring out material that had already been deposited. This effect would alter the apparent sedimentation rates in events where the traps were close to full. The non-recording nature of the traps together with the impossibility of observing them during flood conditions leaves the effect of winnowing uncertain.

ANOVA results from the tests carried out to ascertain if there was a difference in populations of sedimentation rates as stage increased return α values below 0.05, but the graphical representation does not completely explain these differences. This study agrees with the findings of Carling and McCahon (1987), that stresses that the deposition rates change by an order of magnitude between periods of base-flow and flood conditions.

This study shows that in the reaches examined here, that the competence of sediment transport did not increase with stage, as demonstrated by no increase in sedimentation rates with increased stage. However, the methodology adopted does not allow analysis of the sedimentation rates to be examined for the hydrographs above 0.5m. Sear (1993) observed that the greatest infiltration of fines occurred at bankfull discharge. Unfortunately, these findings could not be replicated as in the cases when the peak stage exceeded 0.5m, only estimations of the minimum rates could be determined as a consequence of the finite volume of the receivers. As has been demonstrated in Chapter 4.5, Hydrograph 4 possesses a sedimentation rate that is greater than those observed for other hydrographs. From this one result it can be seen that there is potentially an increase in sedimentation rates with an increase in stage, however, this will need to be examined further with greater receivers.

The size of the infiltrated material, at the finer percentiles, indicated that an increase in stage was affecting the size distribution of the deposited material. In the case of Burleigh Brook, the results from Reach 1 were significantly different from those of Reaches 2 and 3. In Reach 1, it is apparent that only the D_5 is correlated with an increase in stage. ANOVA tests also revealed that as stage increased, the actual sizes of the material deposited could have been derived from the same population. These results are deemed to relate to the theory of equal mobility as outlined by Parker *et al.*, (1982), Andrews and Parker (1987) and Wilcock (1993), where all sizes of the bed are entrained at nearly equal flow conditions.

Reaches 2 and 3 also show a progression of coarsening of the D_5 as stage increases. A further breakdown of the data set, also reveals in some instances, the coarser percentiles also alter with an increasing stage, e.g. Configuration II at the D_{50} percentile on Reach 2. Analysis on Reaches 2 and 3 conclude that the sizes of infiltrated material are dependent on stage. The only exception here is the D_{95} on Reach 3. The theory proposed by Ashworth and Ferguson (1989), of size selective entrainment is relevant in these lower two reaches. The size material which is moved, and therefore deposited in the receivers within this study change as stage, and therefore discharge increase.

Analysis here indicates that the sedimentation rates, as calculated here, are not affected by increases in stage and therefore discharge. Time to rise, or lag time between successive flood peaks, could possibly be a more appropriate measure of time. However, it would not be conducive if the time taken for Burleigh Brook to reach peak stage if the suspended sediment concentration lagged behind or was in front of the water stage.

6.3 The effect that trap configuration has on the rate of infiltration rate and size of deposited material.

The arrangements of roughness elements used in this study constitute the simplest interstices that are found in gravel-bed rivers, and correspond to the shape of 75% of the interstitial openings found in nature (Frostick *et al.*, 1984). The pore arrangements used in this study are not representative of the interstitial pores found within natural gravel-bed rivers, because of the gaps between the boulders that comprise the roughness elements. Pore spaces found in gravel-bed rivers are usually comprised of a number of particles / roughness elements that touch.

The effect of trap configuration on both rates of sedimentation and size of infiltrated material is difficult to examine. This is as a consequence of not being able to differentiate between the effects of configuration, orientation of the apex roughness element within the flow, and changes in the size of the interstitial opening. Sedimentation rates are reduced in Configuration III (interstitial area of $3.62*10^{-2}$m) relative to those observed in Configurations I and II (interstitial area of $1.81*10^{-2}$m). The difference has been attributed to the lack of an axial roughness element in Configuration III. However, the area of the interstice opening increased as a consequence of using four roughness elements and maintaining the spacing between them consistent with that between Configurations I and II (see Chapter 3.1.2). This increase in area of the trap opening was mirrored by a decline in the rate of sedimentation. Unfortunately, in designing the sampling strategy, the problems associated with being unable to differentiate between the trap lid arrangement and the doubling of the interstitial area were not fully appreciated. In order to comprehend the effect of roughness element configuration, maintenance of size and spacing was important. To maintain interstitial opening size the roughness elements would have to be scaled-up or down.

Particle size analysis of Configuration III, which possessed the increased interstitial opening area, showed that at the coarser limit of the size distribution there was a difference in the size of material infiltrated. The actual size of the deposited material was coarser than that found in Configurations I and II. This difference was only found in the hydrographs where the peak stages recorded lie at the lower end of those measured. Again this truncation of the statistical significance is a consequence of the finite volume of the containers. These findings from this study agree with those observed by Frostick *et al.*, (1984) who demonstrated that an interstitial pore could affect the size distribution of material infiltrated through it. Despite the interstitial circular opening of Configuration III being double that of Configurations I and II, there is no clear statistical evidence to demonstrate that this has an affect on the size of the infiltrated material.

The analyses of sedimentation rates and particles sizes mirror each other in the fact that Configurations I and II show little difference in their results. This is unexpected as the upstream arrangements of roughness elements that comprise these lids are different. The central axial roughness element of Configuration I is downstream of the interstitial pore space, whereas it is upstream of the interstitial opening in Configuration II. It was expected that the orientation of this roughness element would influence the sedimentation rates and particles size of the infiltrated material, as a consequence of an alteration of the flow structures. Analysis by Brayshaw *et al.*, (1983) have shown that entrainment is affected by an alteration of the flow structure around a pebble cluster. It would, therefore, be expected that the roughness elements here would have an effect on the flow structures and therefore rates of deposition and the size of this deposited material.

6.4 The effect of seasonality on depositional rate and the size of the infiltrated material.

This study was undertaken over a period of one year, and therefore the data set is limited here, in both terms of replication of sedimentation rates within a month and especially with regard to the number of events that were sieved. This means that the conclusions drawn here are based on a limited data set and therefore need to be examined with care.

Frostick *et al.*, (1984) ascertained that the sedimentation rates on Turkey Brook during the summer months were greater than those occurring throughout the winter. The accumulation rate was 1.2 times greater. A study by ASCE (1992) also comments that the sedimentation rates are greater under summer flows. However, the data set here does not conform to these other studies. The graphical representation of infiltration of fine material shows a wide amount of scatter. From the limited data set here, it would seem that Burleigh Brook shows a trend that is opposite to that outlined above. The sedimentation rates within Burleigh Brook are greater in the winter months. However, the isolation of individual hydrographs in the winter months was difficult.

The studies on seasonality (e.g. Frostick *et al.*, 1984) also examined the size of the ingressed material, finding that in the summer the matrices were finer than those produced from equal discharges in the winter. As a consequence of the limited data set, the results are conflicting, both between reaches and across the range of size percentiles, leading to problems in drawing valid conclusions.

6.5 Conclusion

The statistical analysis of sedimentation rates clearly show that despite differences between events, there are no strong relationships between peak stage and seasonality. This means that none of the casual parameters measured can be used solely to explain the variation in sedimentation rates over the periods of monitoring. It, therefore, appears that further detailed analysis is required to address linkages between the measured parameters to understand their contribution to, and influence on sedimentation rates.

With regard to particle size, a larger data set is needed in order to gauge with any certainty the effect that any of the parameters used, have in the size of infiltrated material. There is also a need to isolate simple unit hydrographs of different magnitudes and avoid piggybacking, i.e. multiple peaks. The data set used here is not large enough to ensure that the conclusions drawn are statistically significant.

In conclusion, this study has examined the effects of a number of different parameters, namely reach, peak stage, configuration type and seasonality, have on the sedimentation of material into a lowland gravel-bed river. This study has also addressed the size distribution of the material. Comparisons reveal that particle size is correlated with an increase in stage whereas the rate of sedimentation is independent of stage. The sediment traps were designed to assess the sedimentation rates within a framework-free environment, enabling maximum rates to be ascertained and avoiding complications of seal formation within the subsurface material.

One of the aims was to assess the maximum rates by which sediment was infiltrated into a gravel bed. These results clearly show that the rates of infiltration vary between and within reaches and flood events. It is, however, unclear which physical variable measured in this study has the most significant influence on sedimentation rates observed. The second aim was to ascertain if there were any variations in the size distribution of infiltrated material, between reaches, events and different configurations. Unfortunately, although there are trends, they are both truncated as both water stage and particle size increase.

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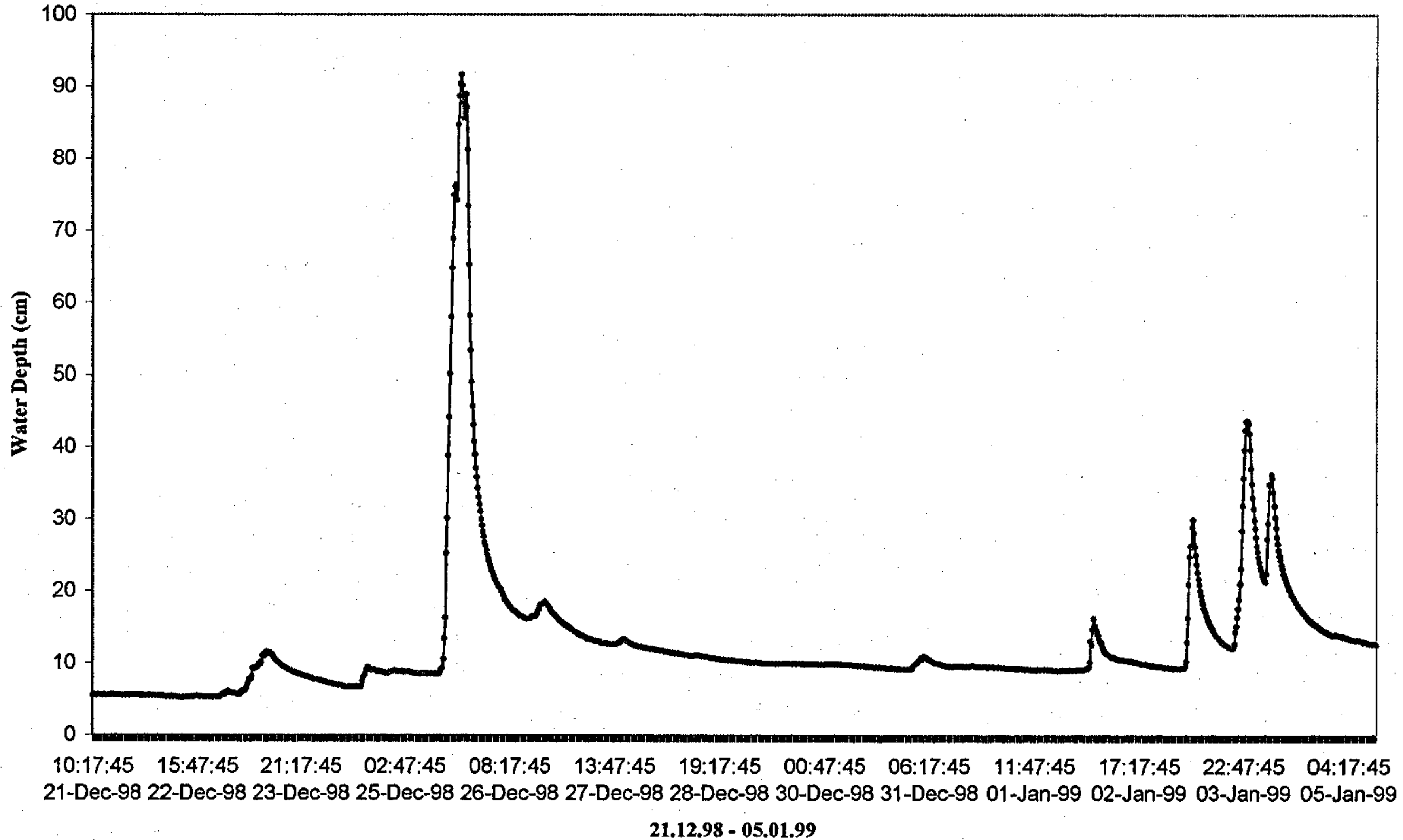
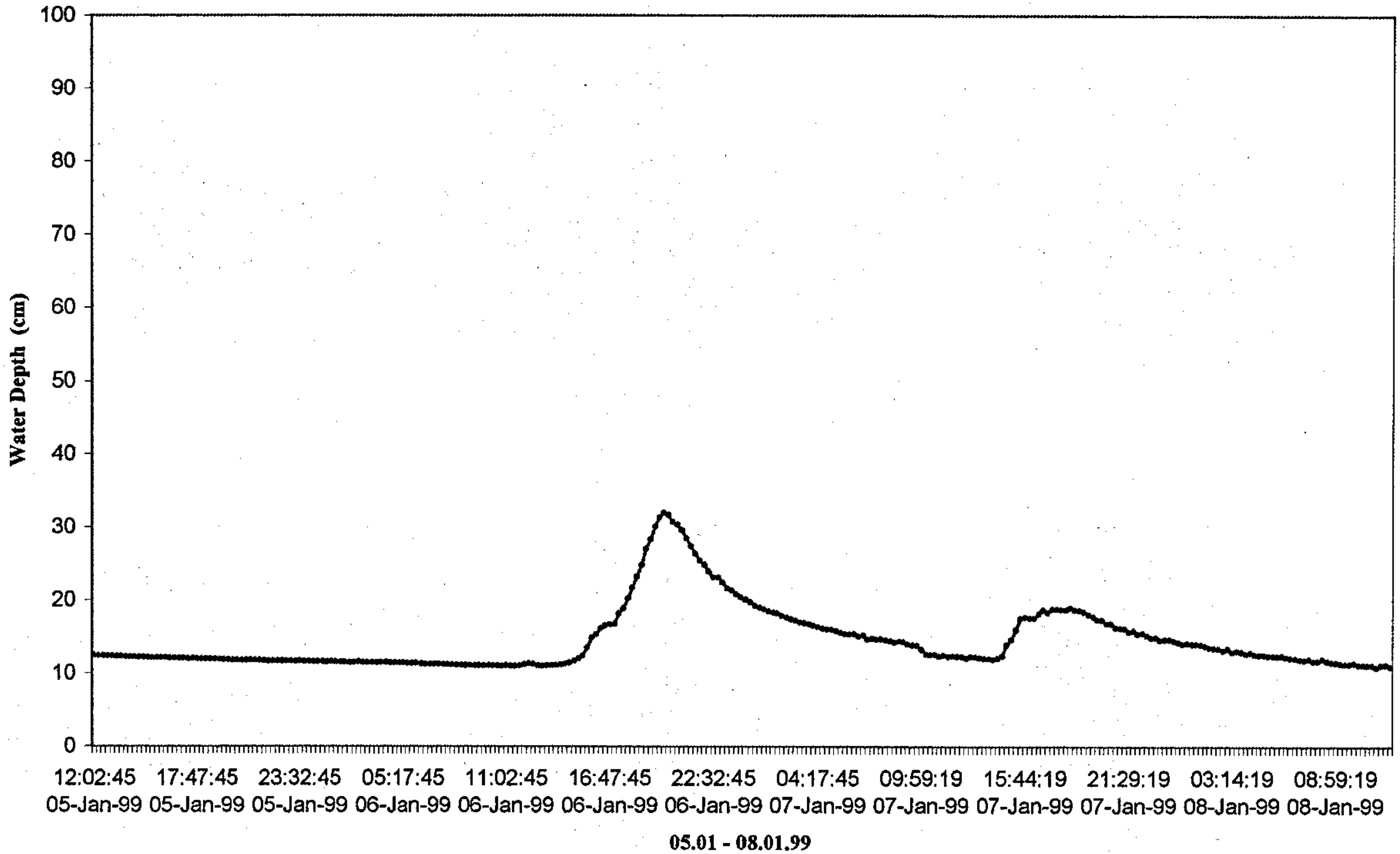
Appendix 2.
Individual Hydrographs.

The monitoring station from which these were recorded is at the upper limit of Reach 1. As is shown by the pressure transducer there are instances where the stilling well became clogged with sediment and affected the water stage readings obtained.

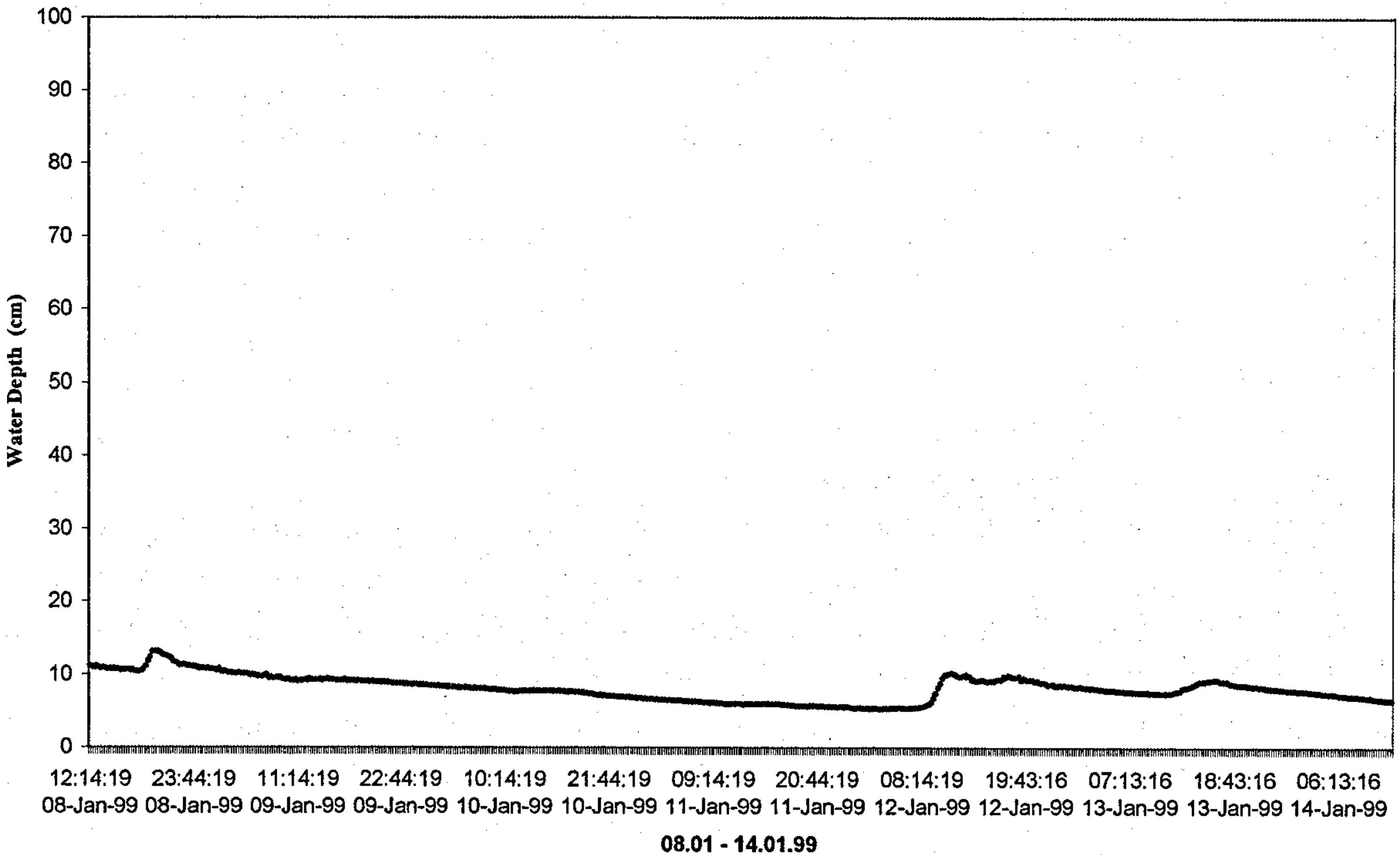
Water Stage during Hydrograph 1.



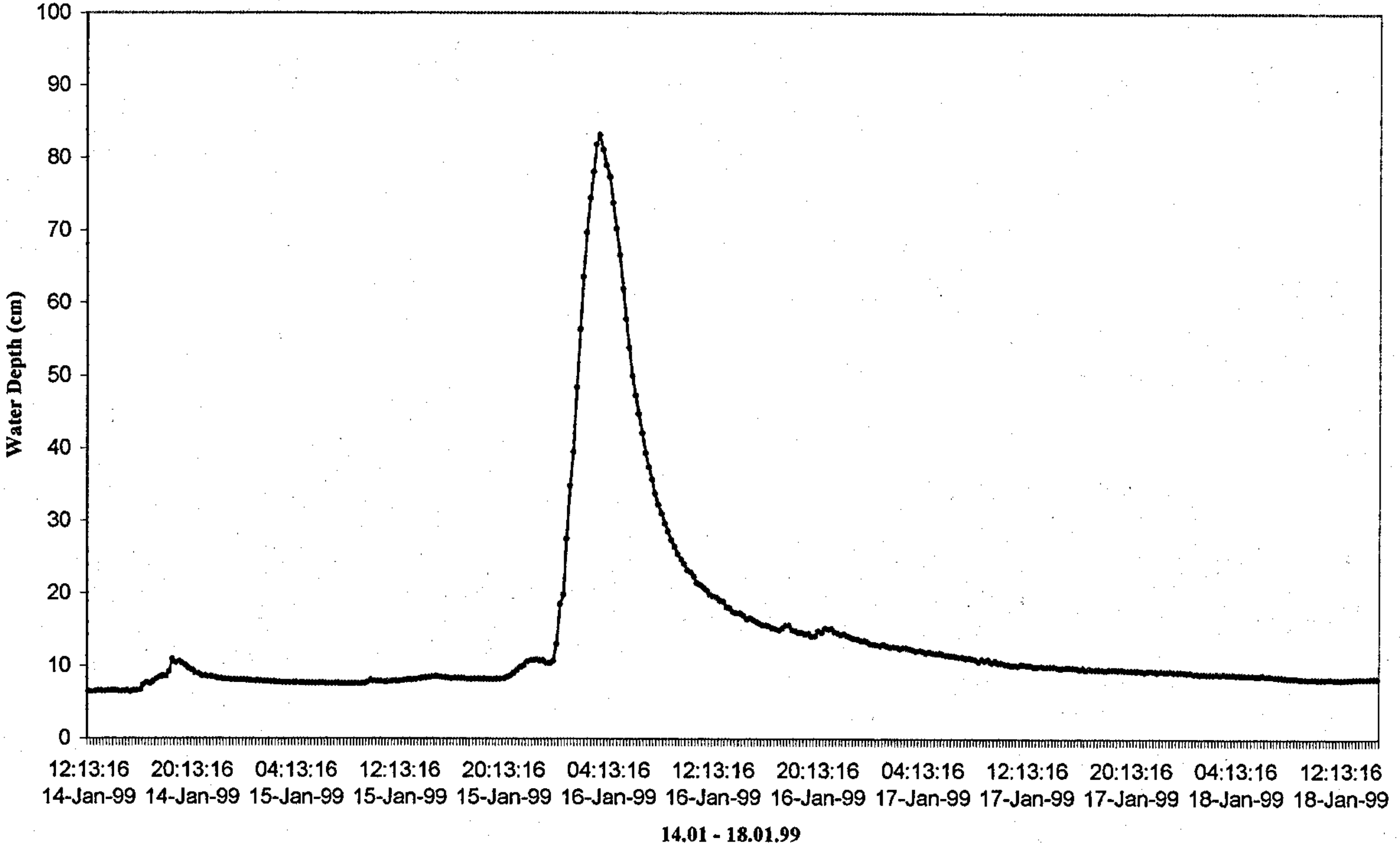
Water Stage during Hydrograph 2

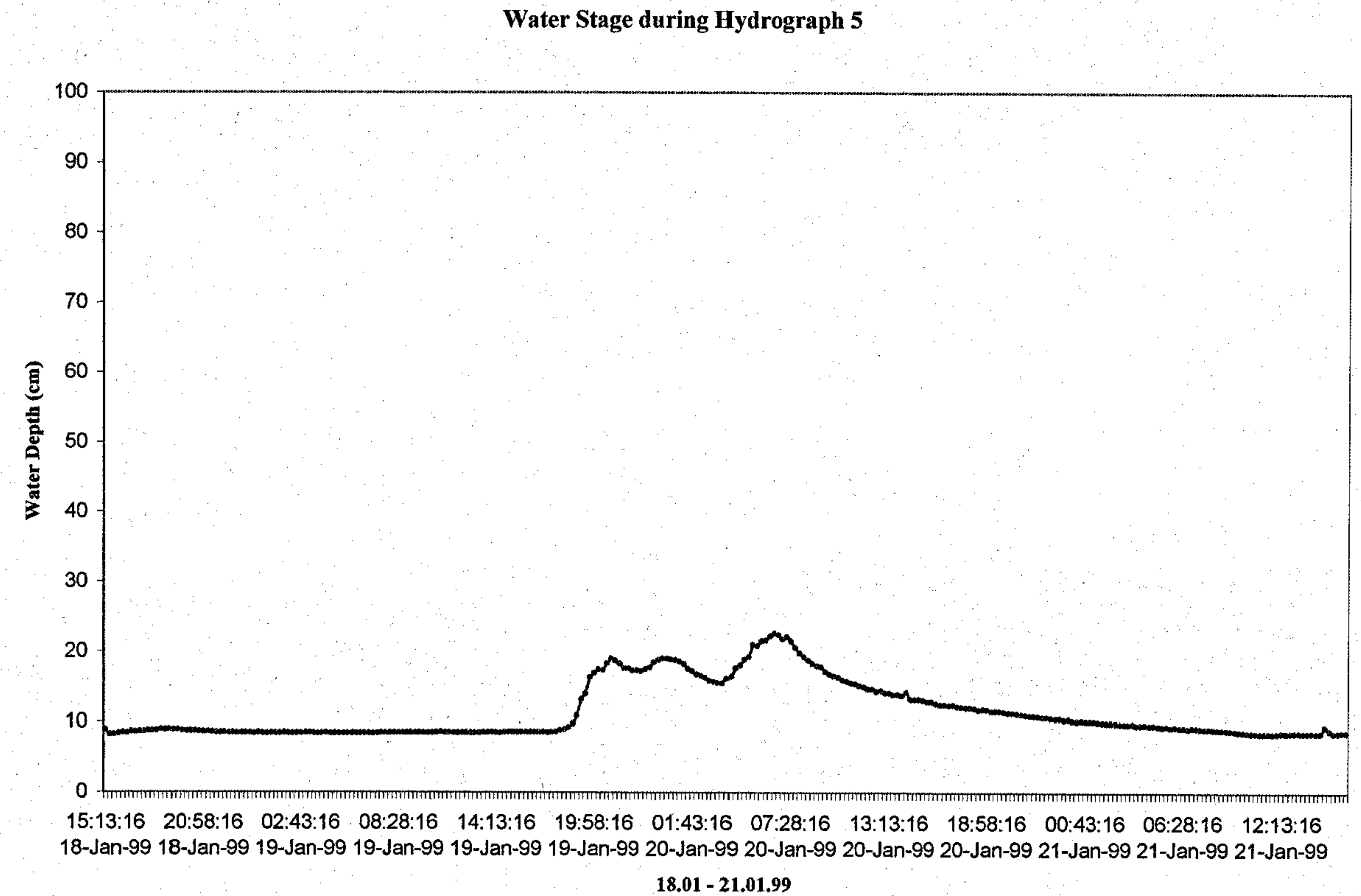


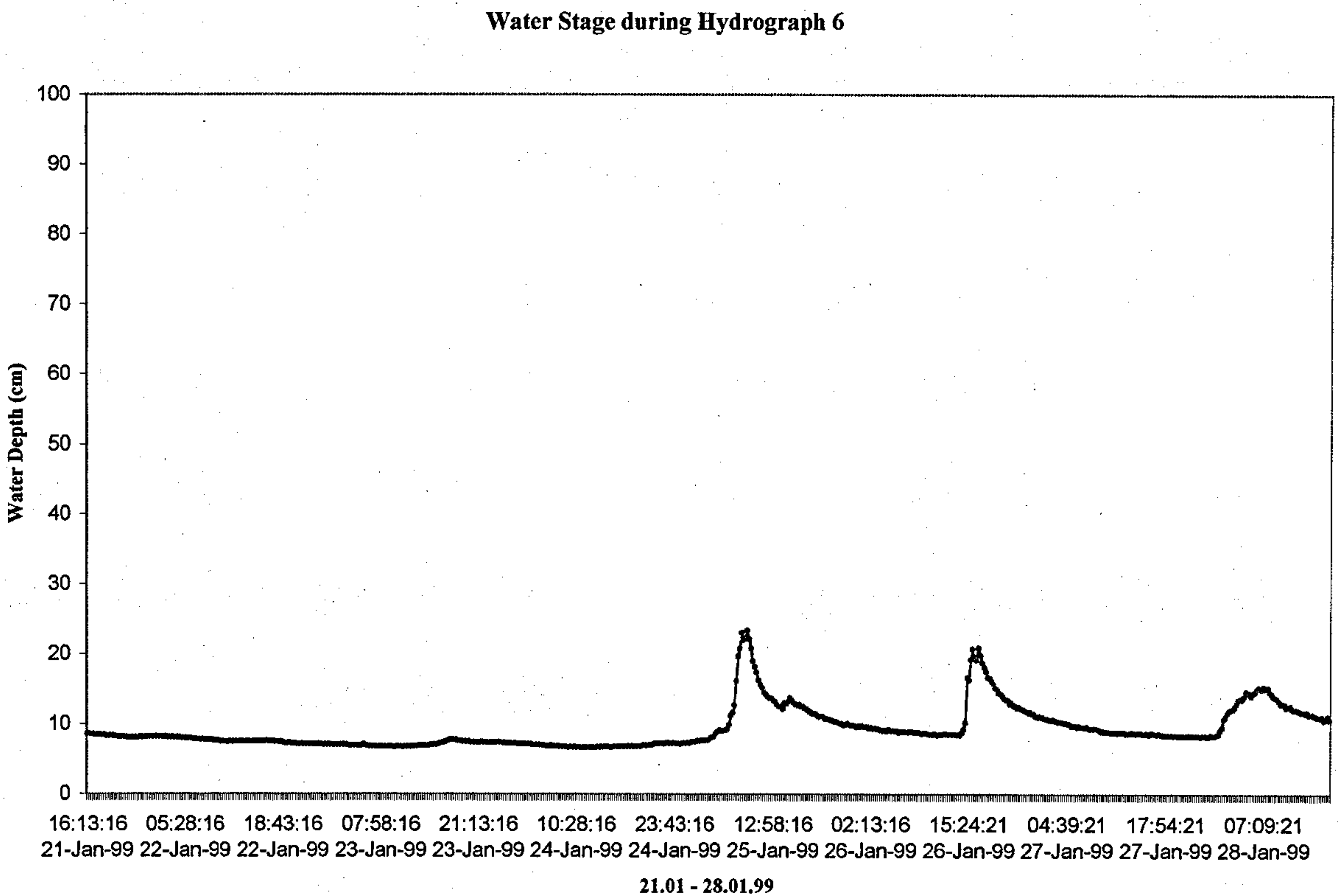
Water Stage during Hydrograph 3



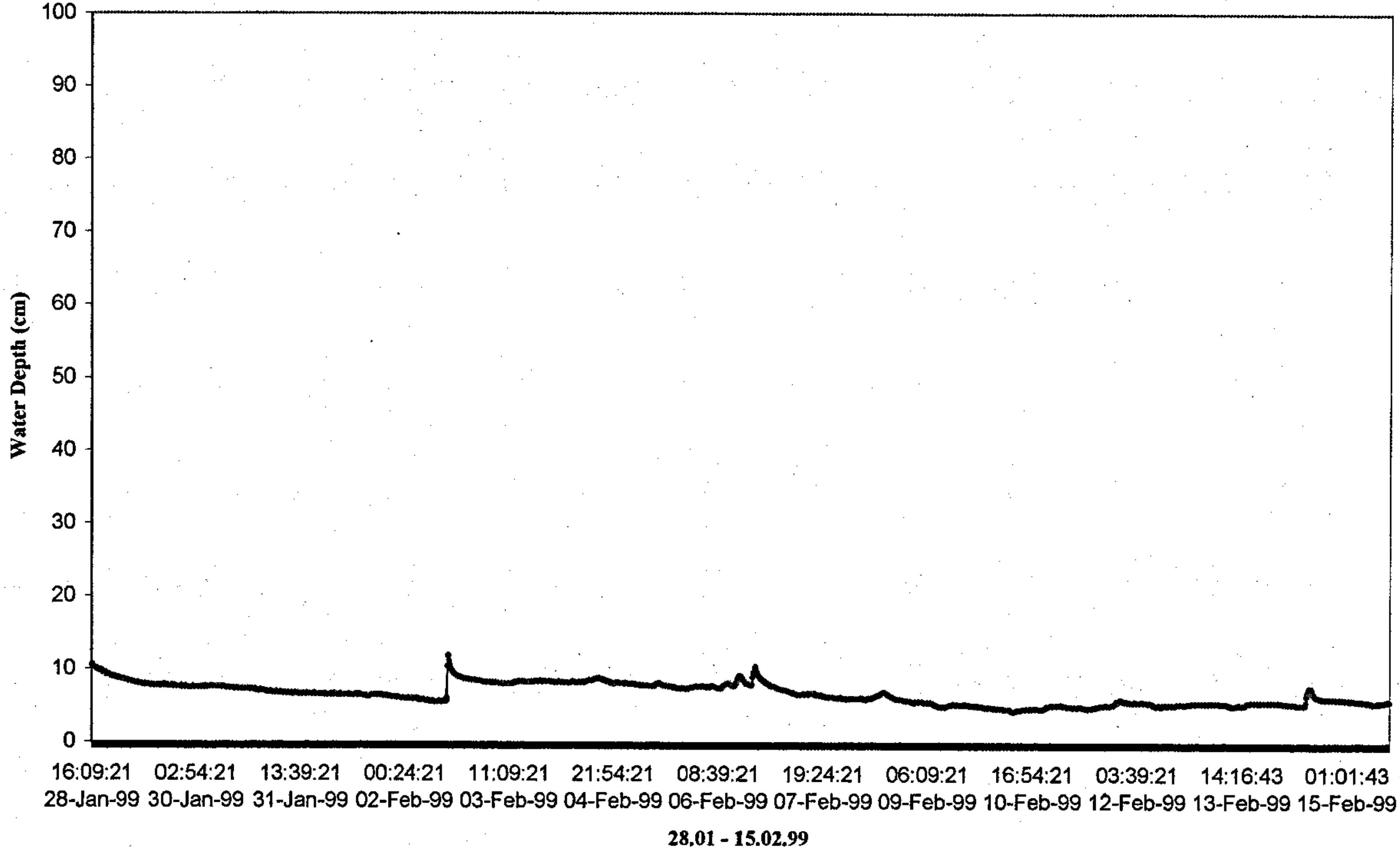
Water Stage during Hydrograph 4



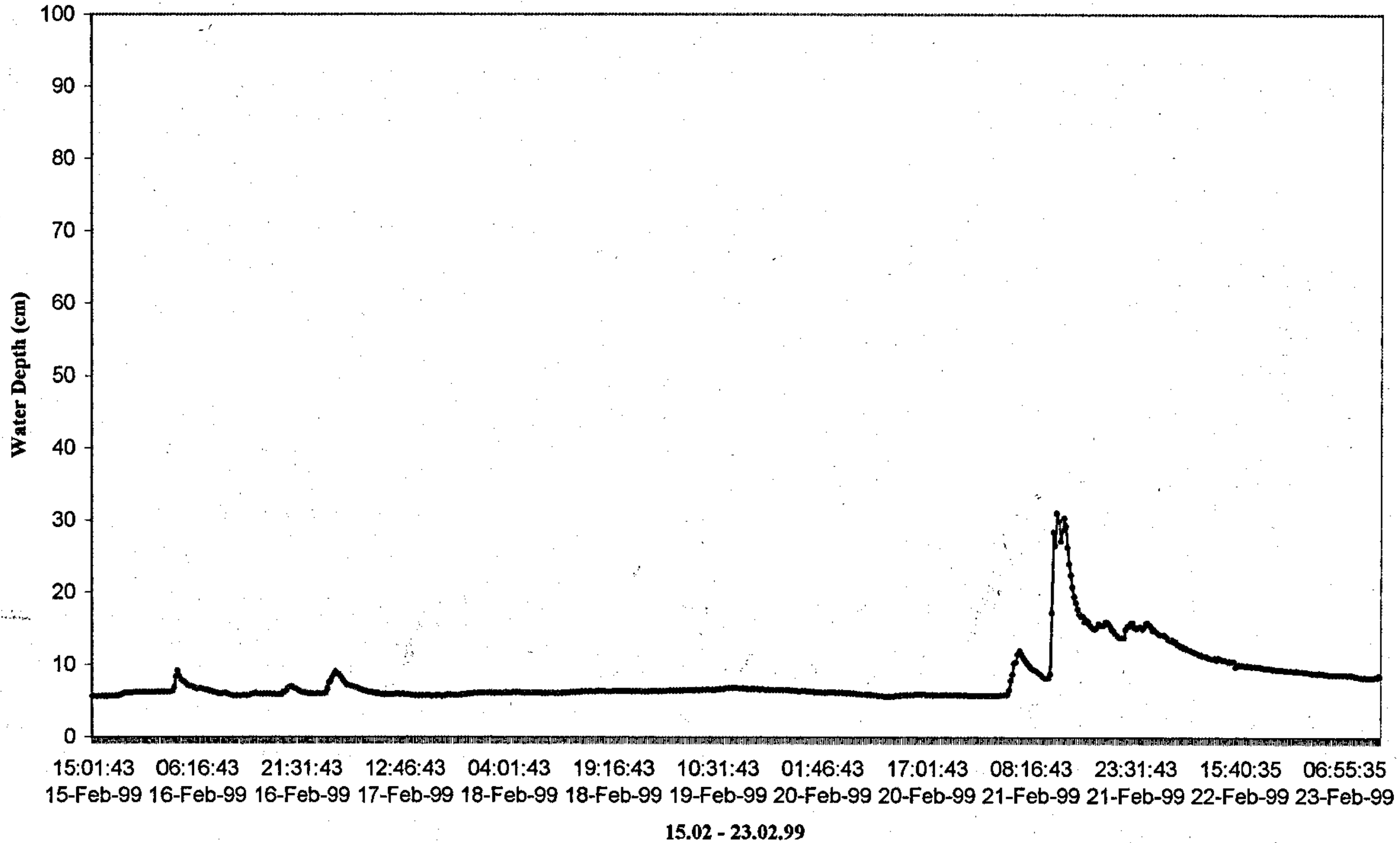

Water Stage during Hydrograph 5
Water Depth (cm)
100
90
80
70
60
50
40
30
20
10
0
15:13:16 18-Jan-99
20:58:16 18-Jan-99
02:43:16 19-Jan-99
08:28:16 19-Jan-99
14:13:16 19-Jan-99
19:58:16 19-Jan-99
01:43:16 20-Jan-99
07:28:16 20-Jan-99
13:13:16 20-Jan-99
18:58:16 20-Jan-99
00:43:16 21-Jan-99
06:28:16 21-Jan-99
12:13:16 21-Jan-99
18.01 - 21.01.99

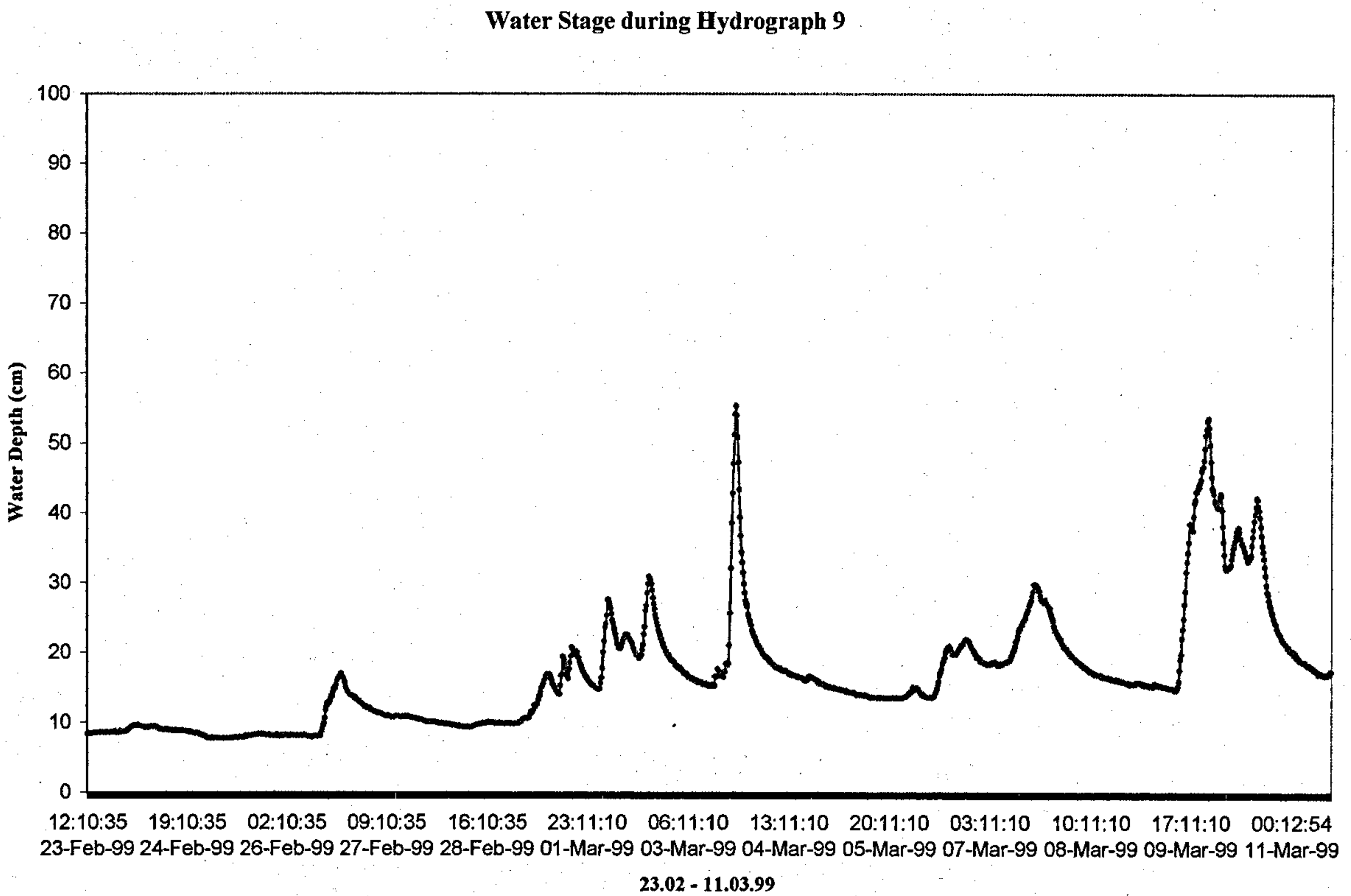

Water Stage during Hydrograph 6
Water Depth (cm)
100
90
80
70
60
50
40
30
20
10
0
16:13:16 21-Jan-99
05:28:16 22-Jan-99
18:43:16 22-Jan-99
07:58:16 23-Jan-99
21:13:16 23-Jan-99
10:28:16 24-Jan-99
23:43:16 24-Jan-99
12:58:16 25-Jan-99
02:13:16 26-Jan-99
15:24:21 26-Jan-99
04:39:21 27-Jan-99
17:54:21 27-Jan-99
07:09:21 28-Jan-99
21.01 - 28.01.99

Water Stage during Hydrograph 7

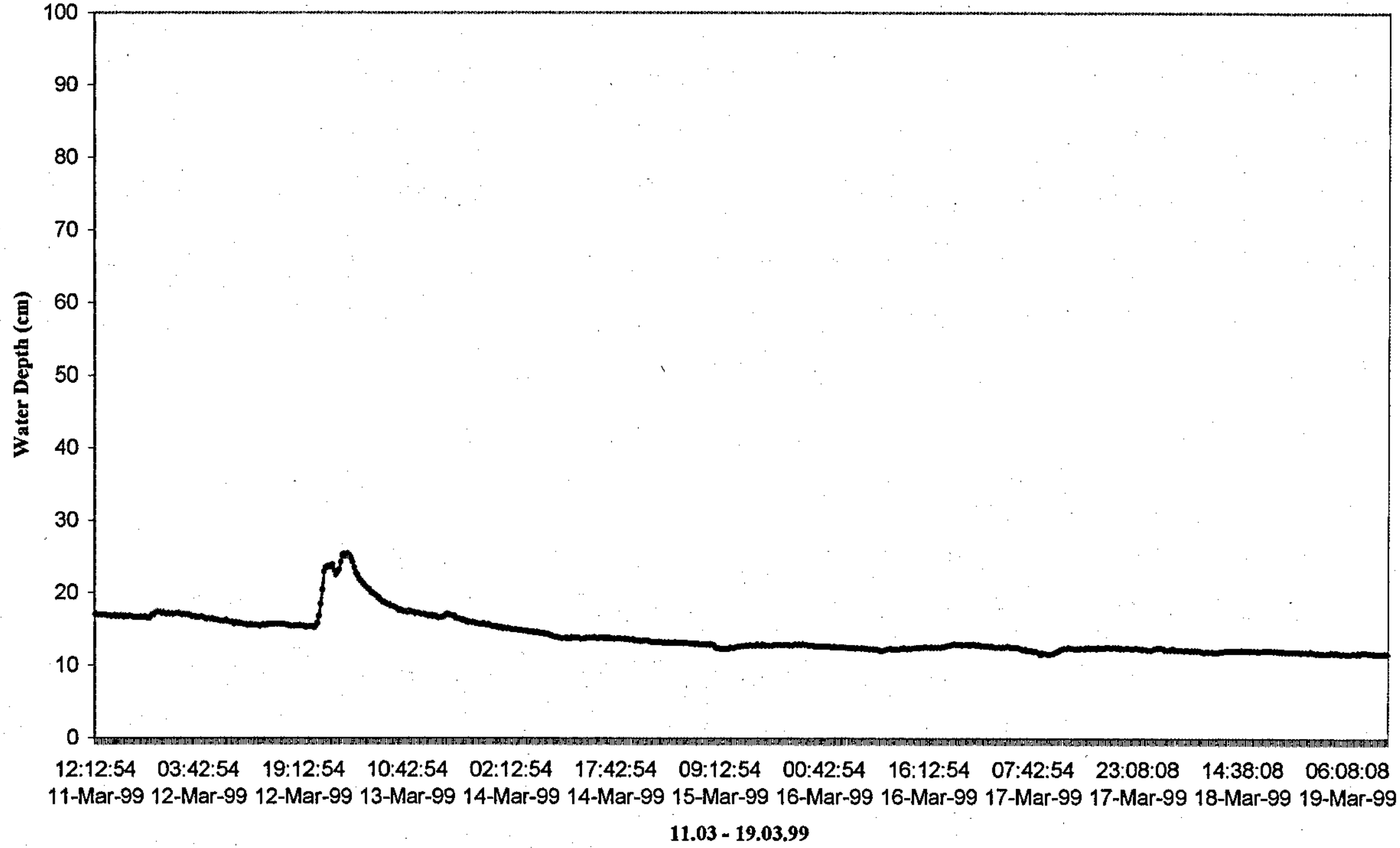


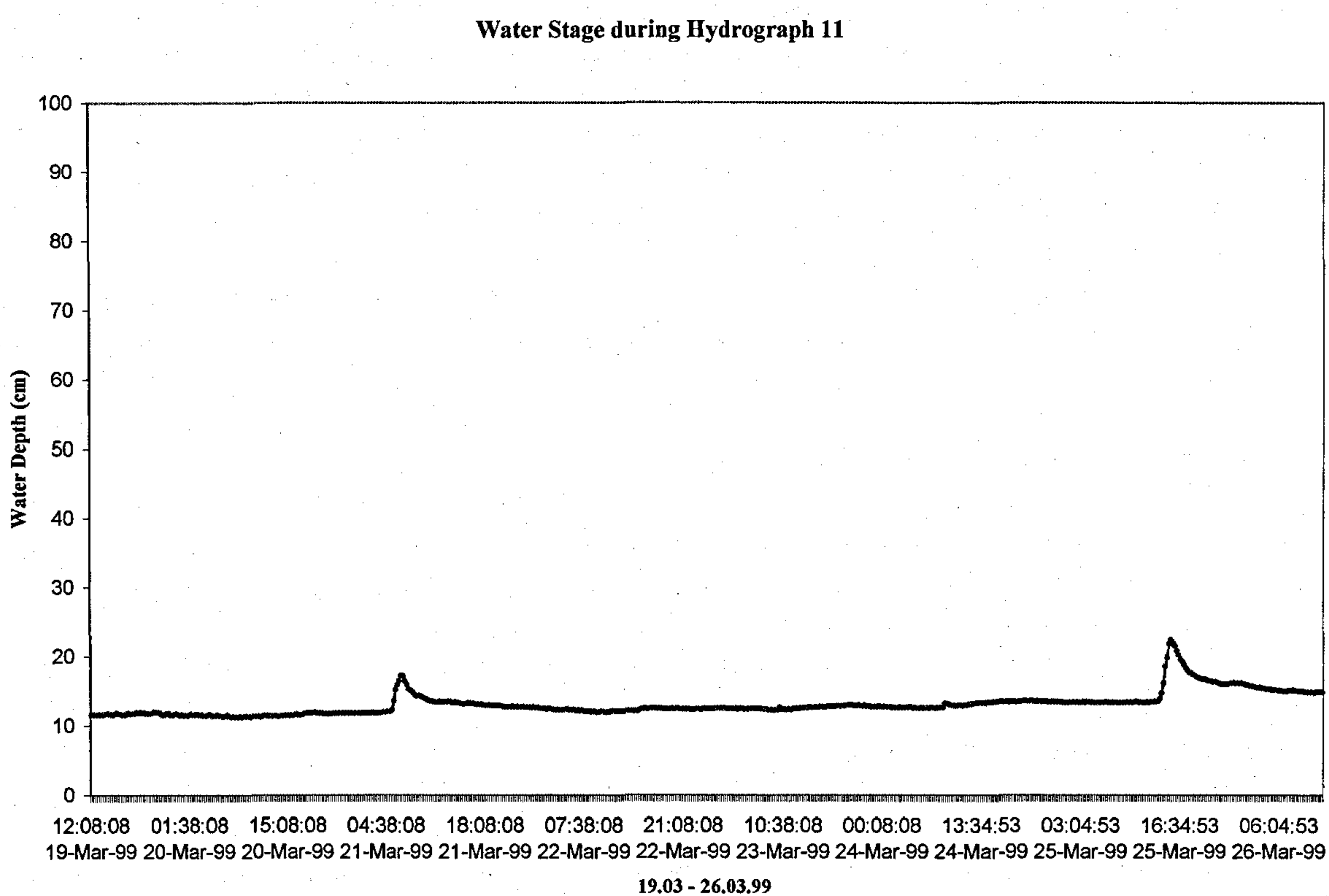
Water Stage during Hydrograph 8



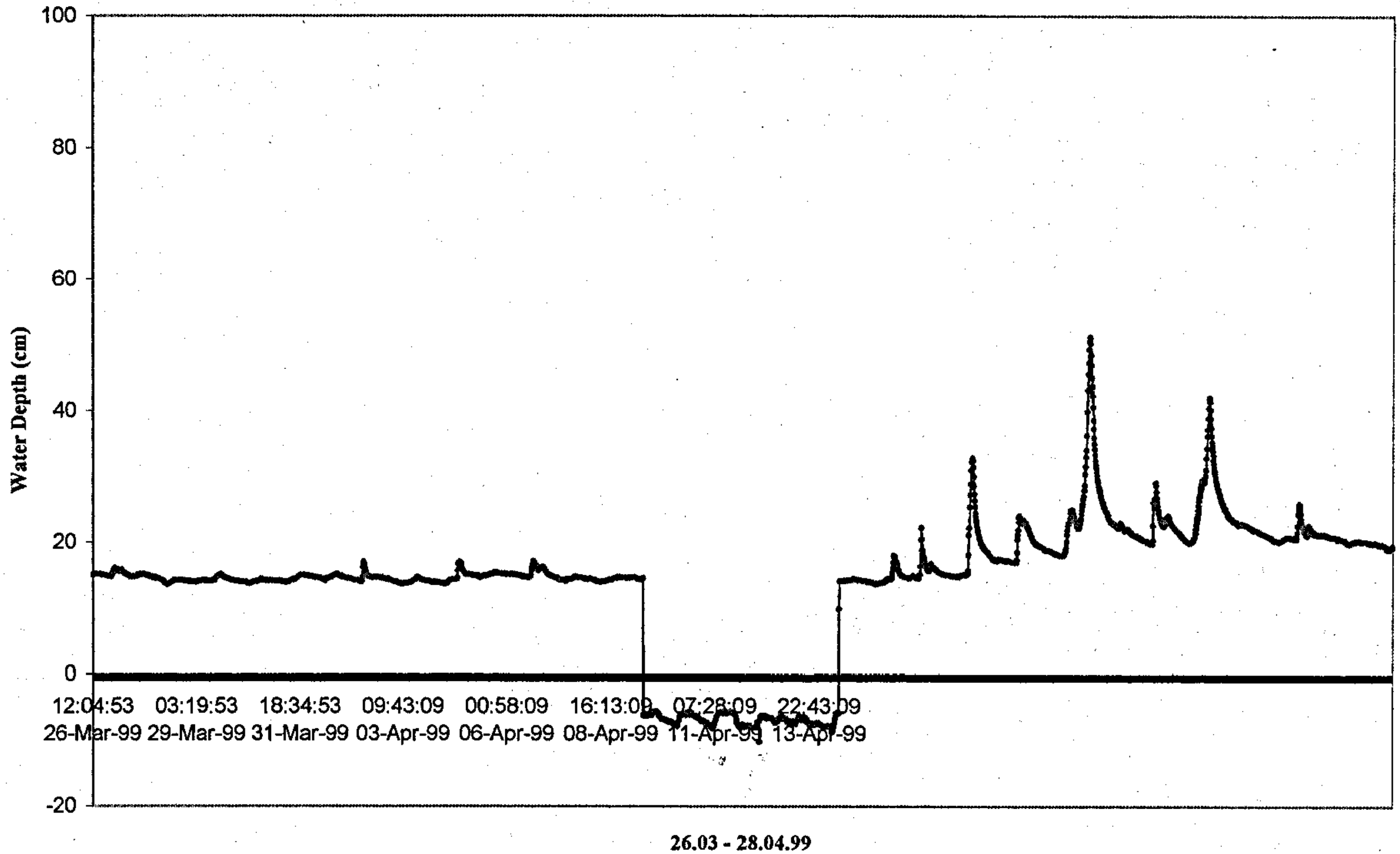

Water Stage during Hydrograph 9
Water Depth (cm)
100
90
80
70
60
50
40
30
20
10
0
12:10:35 23-Feb-99
19:10:35 24-Feb-99
02:10:35 26-Feb-99
09:10:35 27-Feb-99
16:10:35 28-Feb-99
23:11:10 01-Mar-99
06:11:10 03-Mar-99
13:11:10 04-Mar-99
20:11:10 05-Mar-99
03:11:10 07-Mar-99
10:11:10 08-Mar-99
17:11:10 09-Mar-99
00:12:54 11-Mar-99
23.02 - 11.03.99

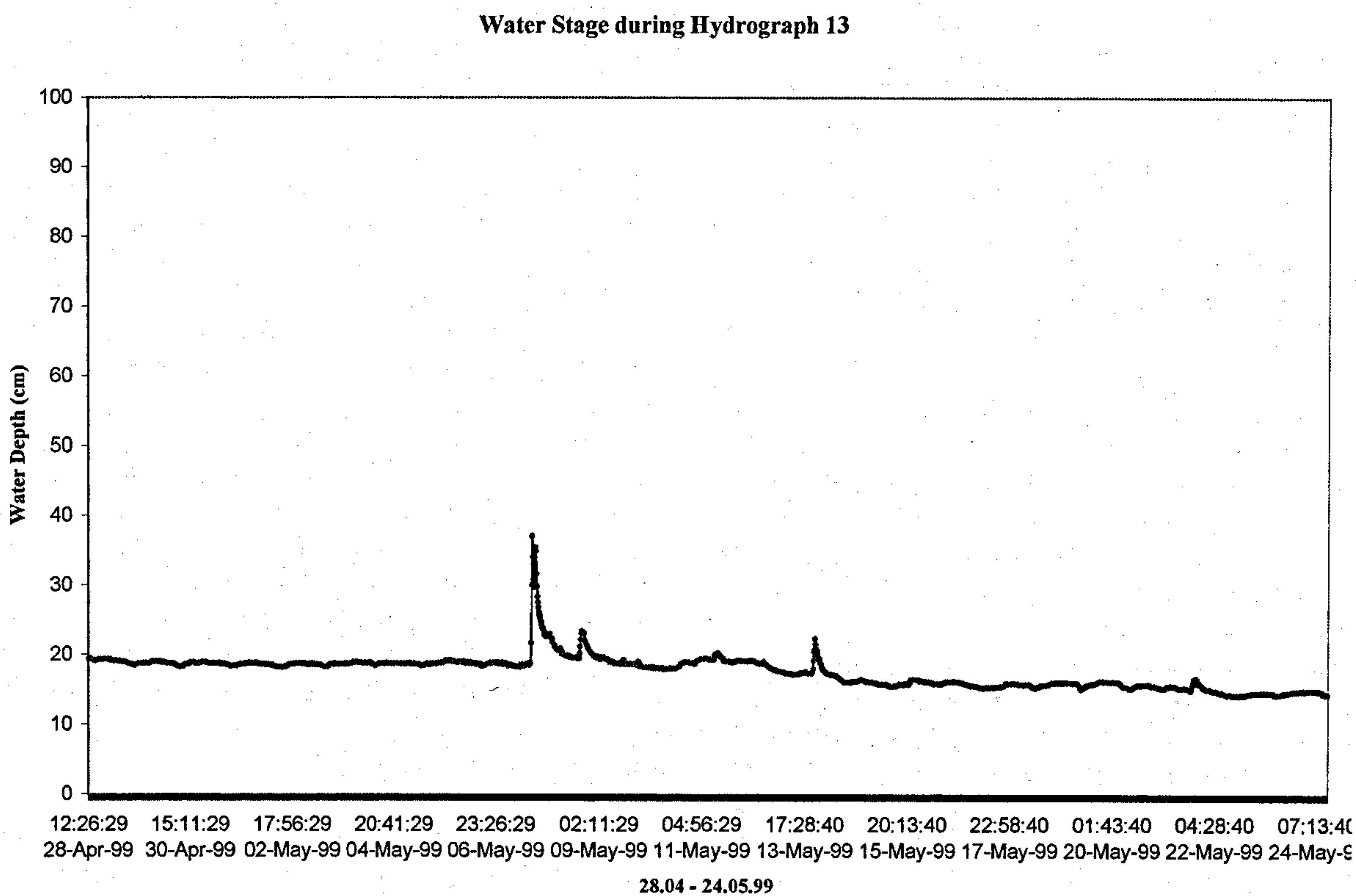
Water Stage during Hydrograph 10

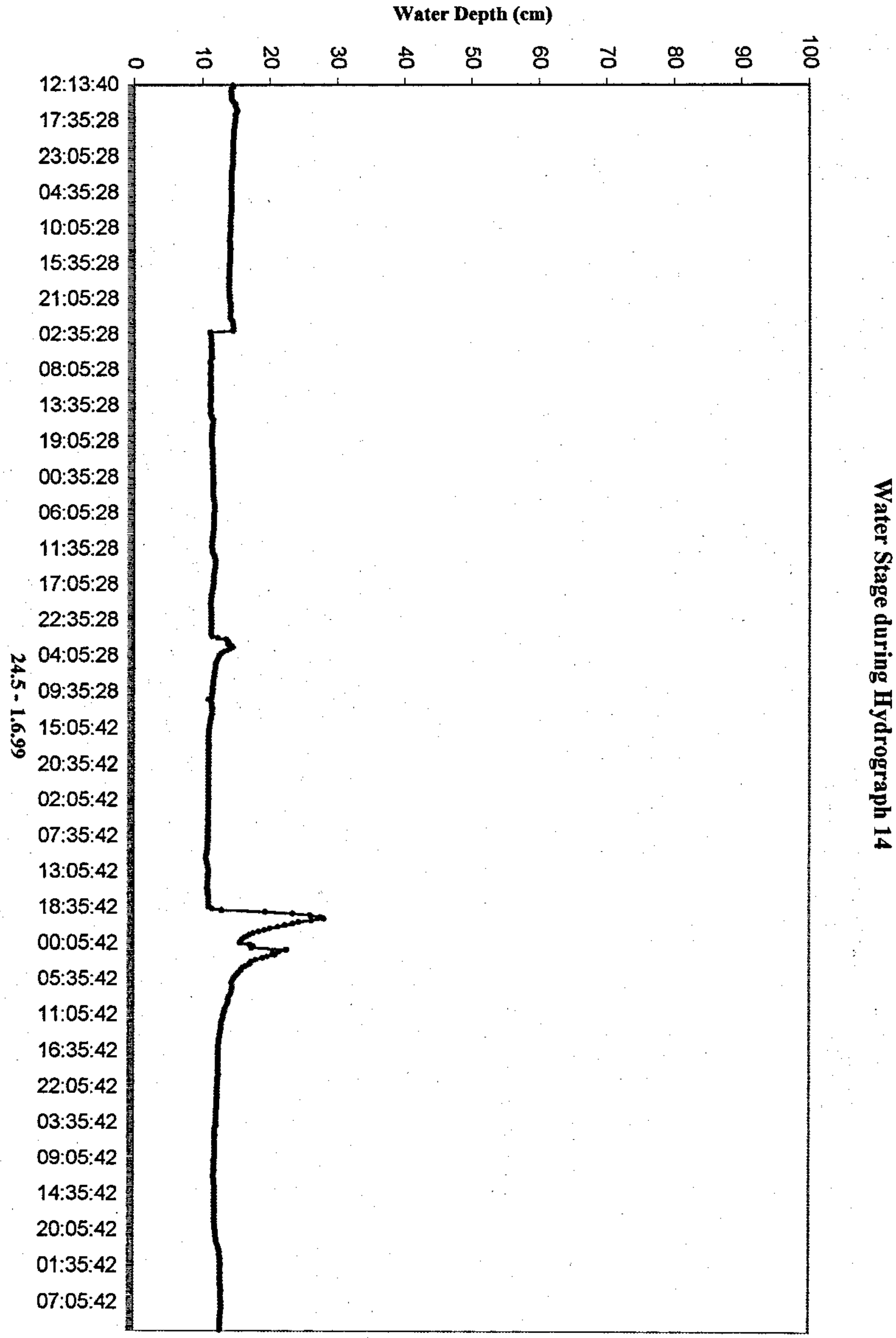


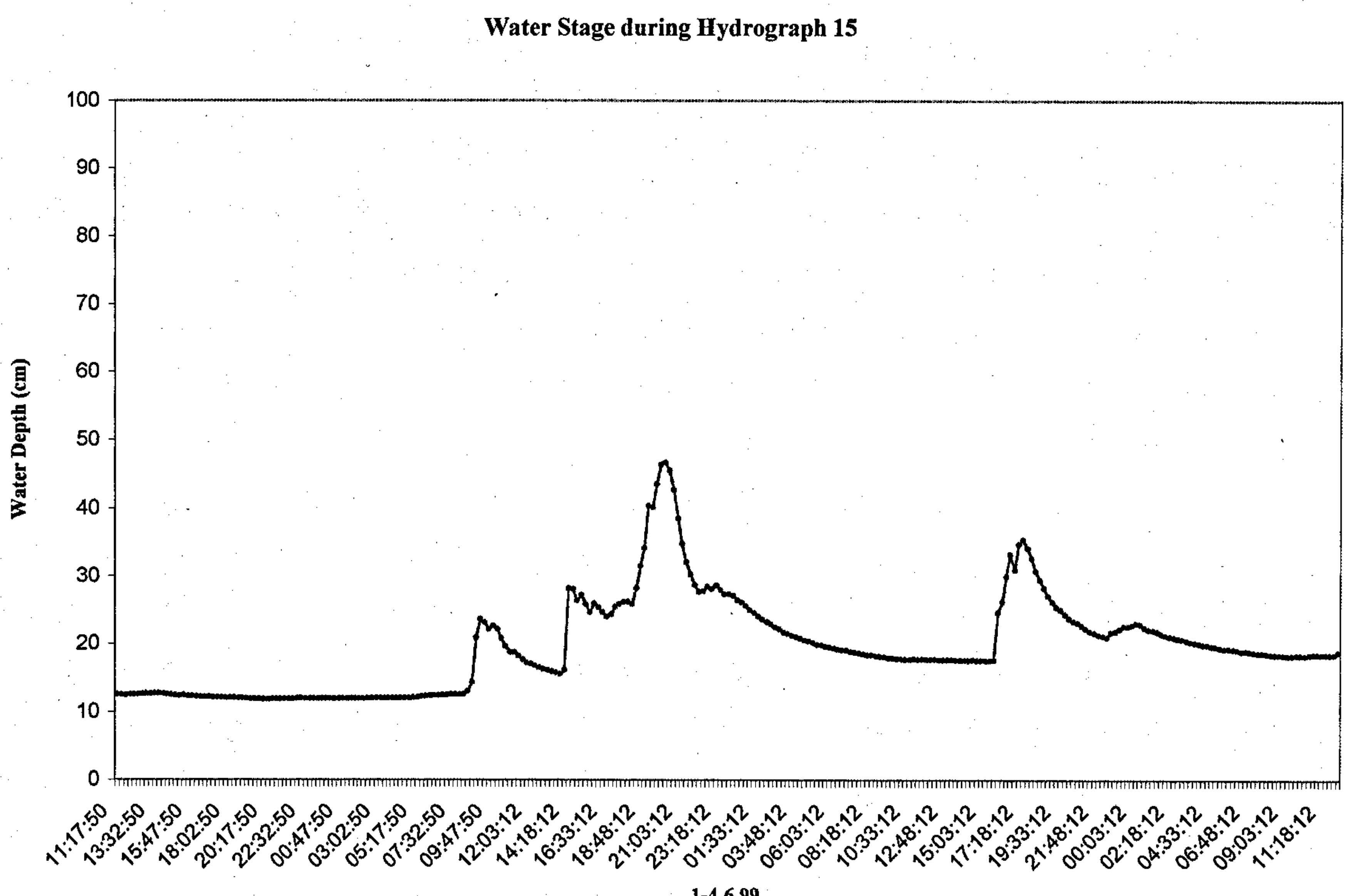

Water Stage during Hydrograph 11
Water Depth (cm)
100
90
80
70
60
50
40
30
20
10
0
12:08:08 19-Mar-99
01:38:08 20-Mar-99
15:08:08 20-Mar-99
04:38:08 21-Mar-99
18:08:08 21-Mar-99
07:38:08 22-Mar-99
21:08:08 22-Mar-99
10:38:08 23-Mar-99
00:08:08 24-Mar-99
13:34:53 24-Mar-99
03:04:53 25-Mar-99
16:34:53 25-Mar-99
06:04:53 26-Mar-99
19.03 - 26.03.99

Water Stage during Hydrograph 12




Water Stage during Hydrograph 13
Water Depth (cm)
100
90
80
70
60
50
40
30
20
10
0
12:26:29 28-Apr-99
15:11:29 30-Apr-99
17:56:29 02-May-99
20:41:29 04-May-99
23:26:29 06-May-99
02:11:29 09-May-99
04:56:29 11-May-99
17:28:40 13-May-99
20:13:40 15-May-99
22:58:40 17-May-99
01:43:40 20-May-99
04:28:40 22-May-99
28.04 - 24.05.99


Water Stage during Hydrograph 14
Water Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
24.5 - 1.6.99
12:13:40
17:35:28
23:05:28
04:35:28
10:05:28
15:35:28
21:05:28
02:35:28
08:05:28
13:35:28
19:05:28
00:35:28
06:05:28
11:35:28
17:05:28
22:35:28
04:05:28
09:35:28
15:05:42
20:35:42
02:05:42
07:35:42
13:05:42
18:35:42
00:05:42
05:35:42
11:05:42
16:35:42
22:05:42
03:35:42
09:05:42
14:35:42
20:05:42
01:35:42
07:05:42


Water Stage during Hydrograph 15
Water Depth (cm)
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90
80
70
60
50
40
30
20
10
0
11:17:50
13:32:50
15:47:50
18:02:50
20:17:50
22:32:50
00:47:50
03:02:50
05:17:50
07:32:50
09:47:50
12:03:12
14:18:12
16:33:12
18:48:12
21:03:12
23:18:12
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03:48:12
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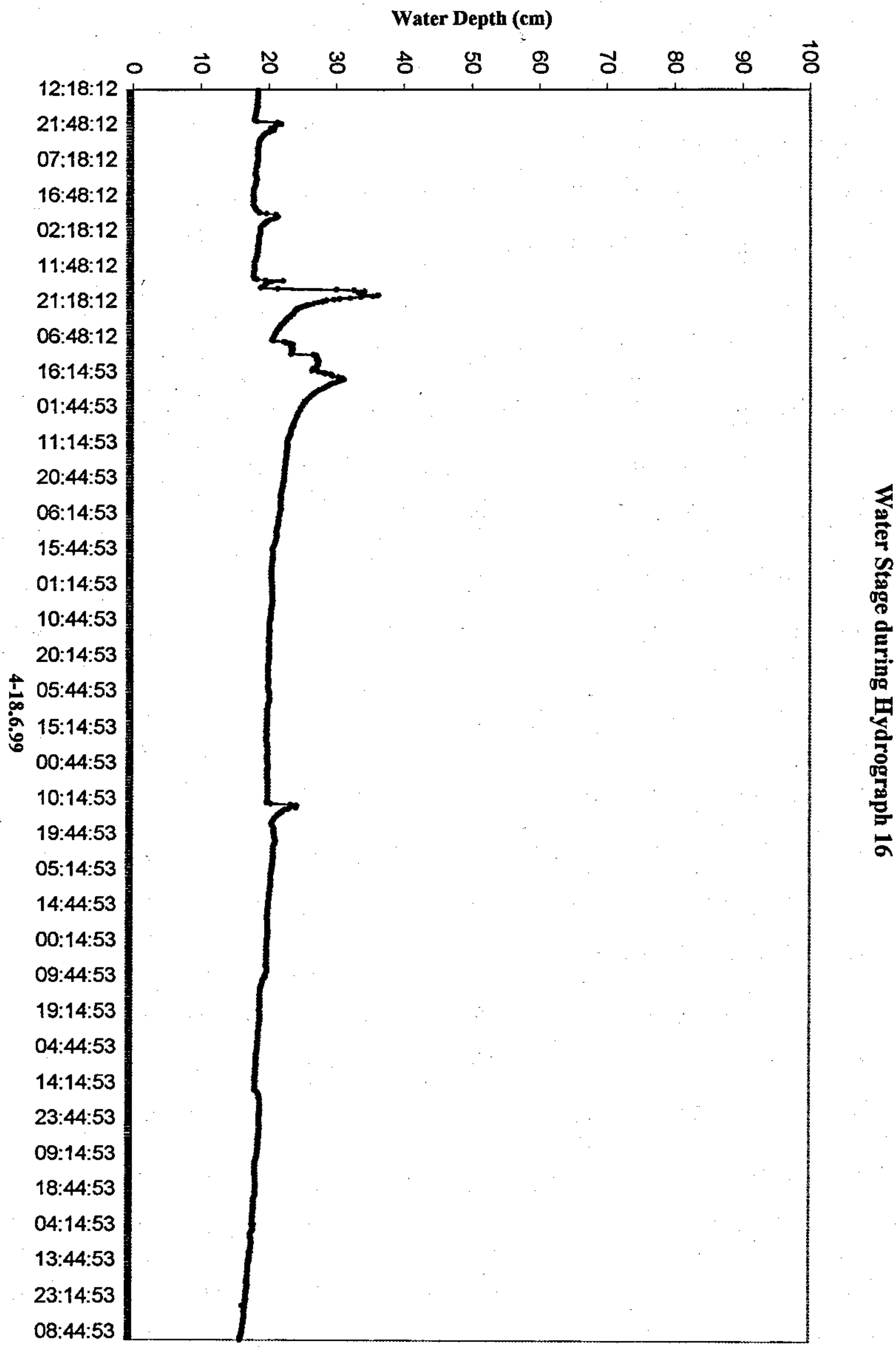
11:18:12
1-4.6.99


Water Stage during Hydrograph 16
Water Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
12:18:12
21:48:12
07:18:12
16:48:12
02:18:12
11:48:12
21:18:12
06:48:12
16:14:53
01:44:53
11:14:53
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19:14:53
04:44:53
14:14:53
23:44:53
09:14:53
18:44:53
04:14:53
13:44:53
23:14:53
08:44:53
4-18.6.99

Appendix 3 shows weights collected for each of the traps for each Hydrograph.

	Hydrograph	1	2	3	4	5	6	7	8	9	10
Reach	Trap Number	Weight (g)									
3	1	1614.1	226.9	8.8	1275.5	189.9	214.8	20.0	273.0	1060.5	141.2
	2	1371.4	302.3	8.6	1628.4	124.9	162.1	15.2	1017.8	1326.0	153.5
	3	1468.4	475.8	15.1	1437.1	147.1	197.6	22.4	728.6	1203.2	169.8
	4	1235.7	150.6	11.5	1300.6	802.5	192.0	33.8	509.0	1102.1	201.2
	5	1591.3	209.7	11.2	1841.6	161.2	150.5	31.3	1462.4	1499.8	267.1
	6	1537.2	372.8	14.4	1469.7	163.6	169.2	50.4	1244.5	163.6	383.4
	7	1700.7	177.5	5.0	1299.9	233.1	184.8	11.2	356.5	1133.8	115.7
	8	-	-	15.4	1782.8	123.1	176.7	25.5	298.4	1571.1	-
2	9	1582.3	174.4	11.1	1367.4	94.7	285.8	8.2	523.3	1291.1	45.9
	10	1611.1	414.3	6.9	1636.5	61.3	150.4	4.6	745.0	1439.0	351.3
	11	1529.5	256.6	8.4	1443.1	367.4	85.5	23.7	270.5	1359.1	430.3
	12	1524.9	297.6	5.9	1796.6	117.6	83.7	55.3	741.8	1428.2	102.8
	13	1309.4	155.9	6.2	1473.9	163.1	149.3	30.5	344.2	1216.7	38.6
	14	1814.4	213.7	6.0	1507.6	89.9	126.3	20.9	556.2	1410.8	181.3
	15	1747.6	235.6	6.0	1742.5	113.5	52.7	8.3	362.5	1409.2	48.6
	16	1436.8	162.0	-	1477.6	64.2	95.2	11.5	379.5	1049.1	112.6
1	17	1504.4	245.6	7.2	1454.0	239.7	257.9	9.5	565.4	1498.7	92.8
	18	1567.1	67.4	3.8	1495.6	212.4	103.1	11.6	676.4	1472.9	88.4
	19	1304.8	233.9	21.1	1092.7	1268.1	282.3	9.0	723.9	1285.2	196.8
	20	1583.8	1190.2	11.3	1517.5	1605.0	1053.7	9.8	1169.4	1115.9	76.8
	21	1594.7	211.4	4.2	1476.5	717.5	299.6	12.8	1525.8	1490.1	625.4
	22	1144.5	1143.8	16.8	1540.6	677.1	686.5	19.3	1471.5	1439.7	1049.3
	23										
	24										
	25										

Hydrograph	11	12	13	14	15	16	18	19	20	21	22	26
Trap Number												
1	-	1043.9	188.7	141.3	1208.2	466.2	-	-	10.2	-	-	-
2	9.6	1390.8	154.3	136.6	1055.0	325.7	198.4	15.2	-	-	-	-
3	7.8	1273.5	222.1	181.8	1279.8	596.8	1013.6	21.0	-	-	-	-
4	20.2	1156.5	149.6	185.7	1087.7	413.8	324.2	106.1	22.7	-	-	-
5	11.6	1394.7	453.8	143.2	1603.0	345.4	1248.3	90.4	-	-	-	-
6	10.8	1323.9	720.8	225.4	727.1	361.6	405.0	79.8	-	-	-	-
7	14.0	941.1	202.5	88.2	1001.8	602.3	-	100.0	-	-	-	-
8	-	1334.7	483.2	320.4	1289.4	891.7	1063.6	72.0	-	-	-	-
9	11.5	1054.7	233.2	126.5	61.5	541.6	222.3	13.2	-	-	-	-
10	7.3	1517.2	444.7	189.0	1543.7	700.4	191.6	4.7	-	-	-	-
11	21.5	1569.5	295.7	139.0	1244.0	491.2	339.1	12.1	5.3	-	-	-
12	11.6	1486.3	513.0	324.7	16.2	780.0	413.0	8.5	-	-	-	-
13	16.2	1321.0	294.9	99.1	850.1	158.9	122.5	10.0	-	-	-	-
14	11.8	1394.4	343.8	183.8	1491.5	499.9	-	5.2	-	-	-	-
15	3.6	1605.6	352.5	98.2	1455.0	182.2	297.0	5.8	-	-	-	-
16	22.1	1254.4	189.2	94.6	1147.1	279.6	146.5	10.5	-	-	-	-
17	11.4	1239.7	81.4	27.3	310.5	85.9	79.9	-	1.6	5.9	85.2	110.5
18	2.7	1031.9	-	77.3	579.5	72.5	-	-	-	-	-	-
19	8.9	1309.5	506.1	668.7	1296.3	1082.3	409.6	3.1	1.1	4.0	330.9	332.2
20	7.1	656.5	76.1	60.3	378.3	80.8	40.6	4.4	0.7	1.1	67.1	645.3
21	15.0	1745.4	131.3	61.5	236.3	65.6	8.9	4.6	0.6	5.2	45.0	284.8
22	21.2	1343.0	821.2	278.2	1588.5	1034.8	131.2	14.7	0.7	5.4	183.2	1398.7
23	12.1	1696.3	693.0	312.4	1092.6	407.3	55.0	2.7	0.9	5.6	222.0	61.1
24	13.5	1746.9	38.0	35.1	195.1	30.7	19.9	2.6	0.5	4.1	27.5	815.6
25	25.3	1415.9	169.1	176.5	1046.6	149.3	122.8	6.4	1.0	57.6	166.7	-

Appendix 4 showing rates of deposition corrected for unit area.

	Hydrograph	1	2	4	5	6	8	9	10	11	12
Reach	Trap Number	Depositional rate (g m^{-2} hr^{-1})									
3	1	7.42	3.45	24.48	3.35	2.60	5.74	2.48	1.36	-	1.89
	2	6.31	4.60	31.25	2.21	1.97	21.39	3.10	1.48	0.11	2.52
	3	6.75	7.24	27.58	2.60	2.40	15.31	2.81	1.64	0.09	2.31
	4	5.68	2.29	24.96	14.17	2.33	10.70	2.57	1.94	0.23	2.10
	5	7.32	3.19	35.34	2.85	1.82	30.74	3.50	2.57	0.13	2.53
	6	7.07	5.67	28.20	2.89	2.05	26.16	0.38	3.69	0.12	2.40
	7	3.92	1.35	12.49	1.97	1.12	3.75	1.33	0.56	0.08	0.86
	8	-	-	17.14	1.09	1.07	3.14	1.84	-	-	1.21
2	9	7.27	2.65	26.24	1.67	3.47	11.00	3.02	0.44	0.13	1.91
	10	7.41	6.31	31.40	1.08	1.82	15.85	3.36	3.39	0.08	2.75
	11	7.03	3.91	27.69	6.49	1.03	5.69	3.17	4.15	0.24	2.85
	12	3.51	2.27	17.27	1.04	0.51	7.81	1.67	0.50	0.07	1.35
	13	3.02	1.19	14.17	1.44	0.91	3.62	1.42	0.19	0.09	1.20
	14	4.18	1.63	14.49	0.79	0.77	5.86	1.65	0.88	0.07	1.27
	15	8.03	3.59	33.44	2.00	0.64	7.62	3.29	0.47	0.04	2.91
	16	6.61	2.47	28.26	1.13	1.15	7.97	2.45	1.09	0.25	2.28
1	17	6.92	3.74	27.90	4.23	3.13	11.88	3.50	0.89	0.13	2.25
	18	7.21	1.03	28.70	3.75	1.25	14.22	3.44	0.85	0.03	1.87
	19	6.00	3.56	20.97	22.39	3.42	15.21	3.00	1.90	0.10	2.38
	20	7.28	8.11	29.12	28.34	12.78	24.58	2.61	0.74	0.08	1.19
	21	3.67	1.61	14.19	6.34	1.82	16.06	1.74	3.02	0.08	1.59
	22	2.63	8.72	14.81	5.25	4.17	15.49	1.68	5.06	0.11	1.22
	23									0.07	1.54
	24									0.15	3.17
	25									0.28	2.57

Hydrograph	13	14	15	16	18	26
Trap Number						
1	2.26	5.88	13.13	0.97	-	-
2	1.85	5.69	11.47	0.68	2.37	-
3	2.66	7.57	13.91	1.24	12.09	-
4	1.79	7.73	11.82	0.86	3.87	-
5	5.44	5.96	17.43	0.71	14.89	-
6	8.65	9.39	7.90	0.75	4.83	-
7	1.22	1.84	5.45	0.63	-	-
8	2.90	6.68	7.02	0.93	6.35	-
9	2.80	5.27	0.67	1.12	2.65	-
10	5.33	7.87	16.78	1.45	2.29	-
11	3.55	5.79	13.52	1.02	4.05	-
12	3.08	6.77	8.84	0.81	2.47	-
13	1.77	2.07	4.63	0.17	0.73	-
14	2.07	3.83	8.12	0.52	-	-
15	4.23	4.09	15.81	0.38	3.54	-
16	2.27	3.94	12.47	0.58	1.75	-
17	0.98	1.14	3.38	0.18	0.95	1.49
18	-	3.22	6.30	0.15	-	-
19	6.07	28.68	14.09	2.25	4.89	4.47
20	0.91	2.51	4.11	0.17	0.48	8.68
21	0.79	1.28	1.29	0.07	0.05	1.92
22	4.93	5.80	8.65	1.08	0.78	9.43
23	4.16	6.52	5.95	0.42	0.33	0.82
24	0.46	1.46	2.12	0.06	0.24	10.98
25	2.03	7.35	11.38	0.31	1.35	-

Appendix 5.1. Particle sizes (mm) for the material from each of the sieved receivers

	Hydrograph	1					2					8					10				
Reach	Trap Number	D5	D16	D50	D84	D95	D5	D16	D50	D84	D95	D5	D16	D50	D84	D95	D5	D16	D50	D84	D95
3	1	0.19	0.32	2.03	9.25	15.18	0.09	0.19	0.34	0.82	4.00	0.08	0.21	0.50	4.11	10.34	0.08	0.20	0.45	2.12	7.47
	2	0.21	0.32	0.86	4.76	9.53	0.14	0.25	0.75	3.24	7.69	0.19	0.41	2.12	6.47	10.32	0.11	0.21	0.43	2.81	7.27
	3	0.18	0.29	0.75	7.16	15.63	0.14	0.25	0.52	5.95	12.61	0.16	0.32	1.00	3.62	5.02	0.10	0.21	0.39	2.98	8.23
	4	0.17	0.30	1.06	3.91	6.76	0.07	0.19	0.37	0.45	3.53	0.13	0.25	0.59	6.68	15.14	0.09	0.24	0.46	3.63	10.63
	5	0.25	0.43	2.00	7.37	16.47	0.11	0.24	0.64	2.51	4.61	0.30	0.97	3.06	7.02	10.63	0.16	0.27	0.50	2.06	5.31
	6	0.26	0.45	1.64	6.37	13.12	0.15	0.29	0.60	2.51	18.97	0.27	0.55	1.71	4.35	6.66	0.24	0.49	2.44	5.95	10.63
	7	0.22	0.42	1.87	17.57	35.14	0.07	0.17	0.31	0.63	1.77	0.09	0.20	0.38	1.13	2.69	0.08	0.20	0.58	5.31	13.30
	8	-	-	-	-		0.16	0.30	0.84	3.74	8.96	0.11	0.24	0.56	2.23	4.96	-	-	-	-	-
2	9	0.18	0.30	1.19	6.19	12.75	0.08	0.18	0.40	1.67	4.48	0.10	0.24	0.78	4.23	23.12	0.06	0.13	0.32	1.77	6.30
	10	0.18	0.33	1.38	5.35	10.40	0.15	0.32	1.72	9.22	18.44	0.24	0.54	4.12	26.63	30.68	0.25	0.55	1.49	3.63	8.00
	11	0.14	0.27	0.67	4.63	10.40	0.11	0.20	0.45	2.06	8.23	0.07	0.19	0.52	5.78	23.35	0.15	0.26	0.54	1.77	4.48
	12	0.23	0.65	6.01	26.25	29.49	0.11	0.22	0.50	1.92	5.02	-	-	-	-	-	0.90	0.20	0.43	12.25	14.95
	13	0.16	0.29	0.71	2.75	5.84	0.08	0.17	0.33	0.84	2.81	0.15	0.30	1.49	7.25	18.96	0.06	0.11	0.28	1.53	4.36
	14	0.19	0.40	4.82	19.90	35.14	0.09	0.18	0.35	0.80	2.11	0.10	0.24	1.49	4.74	8.47	0.10	0.22	0.46	1.87	5.63
	15	0.20	0.40	3.19	9.53	16.96	0.09	0.20	0.50	2.51	6.48	0.11	0.22	0.66	3.78	14.12	0.06	0.14	0.35	1.41	4.23
	16	0.15	0.28	1.34	4.36	9.45	0.08	0.17	0.33	0.80	2.73	0.10	0.22	0.45	2.06	6.68	0.07	0.18	0.37	1.49	10.94
1	17	0.13	0.26	1.00	5.51	5.67	0.15	0.34	2.73	7.69	10.04	0.15	0.38	2.51	8.69	18.64	0.08	0.21	0.75	4.23	9.49
	18	0.15	0.26	1.84	3.48	8.00	0.14	0.25	1.00	2.81	5.50	0.15	0.35	2.17	9.19	14.93	0.08	0.24	1.03	2.24	3.53
	19	0.15	0.30	1.74	7.81	12.75	0.11	0.20	0.37	0.94	3.15	0.15	0.28	0.66	2.48	6.28	0.12	0.26	0.48	1.00	2.58
	20	0.12	0.25	0.73	4.90	9.81	0.24	0.57	2.89	7.47	10.94	0.17	0.34	1.66	6.45	10.92	0.07	0.20	0.73	2.31	4.88
	21	0.15	0.26	1.16	18.51	28.64	0.10	0.20	0.58	10.94	19.52	0.13	0.62	5.78	22.47	28.98	0.39	2.73	16.00	27.46	30.76
	22	-	-	-	-	-	0.21	0.36	1.06	10.33	21.87	0.21	0.39	1.62	7.69	12.94	0.29	0.53	1.37	3.34	17.42
	23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Hydrograph	15					18					26				
Trap Number	D5	D16	D50	D84	D95	D5	D16	D50	D84	D95	D5	D16	D50	D84	D95
1	0.20	0.25	0.52	2.66	6.54	-	-	-	-	-	0.15	0.26	0.48	2.77	7.78
2	0.14	0.26	0.51	2.66	6.63	0.15	0.25	0.55	3.53	6.19	0.24	0.38	1.26	5.31	9.45
3	0.20	0.26	0.49	2.30	7.78	0.21	0.31	0.87	3.68	6.41	0.22	0.34	1.18	5.31	10.40
4	0.15	0.26	0.50	2.66	12.55	0.18	0.26	0.50	3.68	9.78	0.20	0.29	0.50	2.00	7.78
5	0.27	0.61	2.79	7.57	1027.00	0.25	0.38	1.00	4.59	8.46	0.23	0.33	0.73	2.48	5.62
6	0.18	0.30	0.74	4.41	8.94	0.19	0.30	0.64	3.68	11.47	0.26	0.49	1.72	6.63	15.57
7	0.14	0.25	0.48	1.57	5.03	0.16	0.25	0.69	5.82	16.00	0.18	0.27	0.44	2.03	6.45
8	0.19	0.30	0.72	2.57	5.28	0.24	0.35	1.22	5.19	12.34	-	-	-	-	-
9	-	-	-	-	-	0.16	0.28	0.92	4.72	9.19	0.15	0.31	1.26	17.15	20.39
10	0.25	0.46	2.36	8.46	13.55	0.22	0.40	1.15	4.11	7.06	0.12	0.24	0.67	2.69	5.77
11	0.16	0.27	0.92	4.47	8.46	0.18	0.31	1.00	3.10	5.31	-	-	-	-	-
12	0.15	0.32	1.09	8.69	18.38	0.21	0.36	1.44	6.19	8.46	0.15	0.27	0.62	3.39	6.87
13	0.14	0.25	0.45	1.92	4.47	0.10	0.23	0.60	2.41	4.38	0.12	0.22	0.51	3.39	9.78
14	0.22	0.37	1.18	4.35	8.46	0.18	0.31	1.18	6.77	14.72	0.15	0.29	0.85	6.69	5.03
15	-	-	-	-	-	0.18	0.35	2.18	7.11	10.99	0.12	0.24	1.03	6.59	18.64
16	0.17	0.31	0.67	1.92	3.51	0.12	0.25	0.62	2.62	4.23	0.13	0.24	0.60	3.23	7.57
17	0.16	0.30	0.70	4.72	9.45	0.12	0.32	2.08	5.46	28.64	0.13	0.35	2.89	9.78	13.27
18	0.11	0.22	0.87	4.06	7.36	-	-	-	-	-	-	-	-	-	-
19	0.20	0.41	3.39	27.86	31.12	0.18	0.28	0.54	3.42	8.00	0.16	0.28	0.57	6.11	13.93
20	-	-	-	-	-	0.09	0.22	1.26	3.89	4.89	0.31	0.85	2.93	8.00	14.52
21	0.07	0.16	0.37	1.27	3.63	0.07	0.15	0.47	2.58	3.84	0.18	0.37	2.48	10.93	16.45
22	0.17	0.33	1.40	14.93	25.11	0.13	0.25	0.69	2.81	4.35	0.22	0.37	1.03	9.44	16.45
23	0.19	0.38	2.08	10.34	24.42	0.08	0.20	0.67	3.10	4.72	-	-	-	-	-
24	0.07	0.15	0.36	1.76	6.19	0.06	0.19	1.57	4.59	5.28	0.11	0.20	0.50	3.84	11.24
25	0.12	0.26	0.73	6.45	14.12	0.12	0.23	0.82	3.01	4.72	0.20	0.32	0.92	5.46	10.93

Appendix 5.2

ANOVA results to examine if there is a difference in infiltrated particle size based on reach for each configuration.

Results for Hydrograph 1, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.109*10^{-2}$	2	$5.544*10^{-3}$	5.366	0.046
	Within Groups	$6.200*10^{-3}$	6	$1.033*10^{-3}$		
	Total	$1.729*10^{-2}$	8			
D_{16}	Between Groups	$2.382*10^{-2}$	2	$1.191*10^{-2}$	4.430	0.066
	Within Groups	$1.613*10^{-2}$	6	$2.689*10^{-3}$		
	Total	$3.999*10^{-2}$	8			
D_{50}	Between Groups	0.438	2	0.219	1.151	**0.377**
	Within Groups	1.141	6	0.190		
	Total	1.579	8			
D_{84}	Between Groups	0.368	2	0.184	0.065	**0.938**
	Within Groups	16.947	6	2.824		
	Total	17.315	8			
D_{95}	Between Groups	17.476	2	8.738	0.669	**0.547**
	Within Groups	78.373	6	13.062		
	Total	95.849	8			

Results for Hydrograph 1, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$4.033*10^{-3}$	2	$2.017*10^{-3}$	3.524	0.163
	Within Groups	$1.717*10^{-3}$	3	$5.722*10^{-4}$		
	Total	$5.750*10^{-3}$	5			
D_{16}	Between Groups	$5.400*10^{-3}$	2	$2.700*10^{-3}$	1.038	**0.454**
	Within Groups	$7.800*10^{-3}$	3	$2.600*10^{-3}$		
	Total	$1.320*10^{-2}$	5			
D_{50}	Between Groups	2.008	2	1.004	1.1108	**0.436**
	Within Groups	2.718	3	0.906		
	Total	4.726	5			
D_{84}	Between Groups	3.732	2	1.866	0.239	**0.801**
	Within Groups	23.461	3	7.820		
	Total	27.193	5			
D_{95}	Between Groups	10.513	2	5.257	0.307	**0.756**
	Within Groups	51.312	3	17.104		
	Total	61.825	5			

Results for Hydrograph 1, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$2.533*10^{-3}$	2	$1.267*10^{-3}$	1.027	**0.493**
	Within Groups	$2.467*10^{-3}$	2	$1.233*10^{-3}$		
	Total	$5.000*10^{-3}$	4			
D_{16}	Between Groups	$2.645*10^{-2}$	2	$1.323*10^{-2}$	0.389	**0.720**
	Within Groups	$6.807*10^{-2}$	2	$3.403*10^{-2}$		
	Total	$9.452*10^{-2}$	4			
D_{50}	Between Groups	6.776	2	3.388	0.438	**0.695**
	Within Groups	15.466	2	7.733		
	Total	22.242	4			
D_{84}	Between Groups	4.075	2	2.037	0.014	**0.986**
	Within Groups	295.565	2	147.783		
	Total	299.640	4			
D_{95}	Between Groups	105.797	2	52.899	0.219	**0.820**
	Within Groups	483.245	2	241.622		
	Total	589.042	4			

Results for Hydrograph 2, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$9.556*10^{-4}$	2	$4.778*10^{-4}$	0.439	**0.664**
	Within Groups	$6.533*10^{-3}$	6	$1.089*10^{-3}$		
	Total	$7.489*10^{-3}$	8			
D_{16}	Between Groups	$1.489*10^{-3}$	2	$7.444*10^{-4}$	0.168	**0.849**
	Within Groups	$2.653*10^{-2}$	6	$4.422*10^{-3}$		
	Total	$2.802*10^{-2}$	8			
D_{50}	Between Groups	1.051	2	0.526	0.760	**0.508**
	Within Groups	4.148	6	0.691		
	Total	5.200	8			
D_{84}	Between Groups	10.430	2	5.215	0.493	**0.633**
	Within Groups	63.260	6	10.543		
	Total	73.691	8			
D_{95}	Between Groups	26.941	2	13.471	0.291	**0.757**
	Within Groups	277.521	6	46.254		
	Total	304.462	8			

Results for Hydrograph 2, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.628*10^{-2}$	2	$8.142*10^{-3}$	14.228	<u>0.029</u>
	Within Groups	$1.717*10^{-3}$	3	$5.722*10^{-4}$		
	Total	$1.800*10^{-2}$	5			
D_{16}	Between Groups	0.109	2	$5.462*10^{-2}$	57.491	<u>0.004</u>
	Within Groups	$2.850*10^{-3}$	3	$9.500*10^{-4}$		
	Total	0.122	5			
D_{50}	Between Groups	5.376	2	2.688	70.332	<u>0.003</u>
	Within Groups	0.115	3	$3.822*10^{-2}$		
	Total	5.491	5			
D_{84}	Between Groups	22.642	2	11.321	2.321	0.246
	Within Groups	14.635	3	4.878		
	Total	37.276	5			
D_{95}	Between Groups	29.625	2	14.813	1.002	**0.464**
	Within Groups	44.349	3	14.783		
	Total	73.975	5			

Results for Hydrograph 2, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$4.933*10^{-3}$	2	$2.467*10^{-3}$	0.729	**0.552**
	Within Groups	$1.015*10^{-2}$	3	$3.383*10^{-3}$		
	Total	$1.508*10^{-2}$	5			
D_{16}	Between Groups	$1.110*10^{-2}$	2	$5.550*10^{-3}$	0.782	**0.533**
	Within Groups	$2.130*10^{-2}$	3	$7.100*10^{-3}$		
	Total	$3.240*10^{-2}$	5			
D_{50}	Between Groups	0.230	2	0.115	1.351	**0.382**
	Within Groups	0.256	3	$8.528*10^{-2}$		
	Total	0.486	5			
D_{84}	Between Groups	113.067	2	56.533	33.765	<u>0.009</u>
	Within Groups	5.023	3	1.674		
	Total	118.090	5			
D_{95}	Between Groups	383.975	2	191.988	19.961	<u>0.018</u>
	Within Groups	28.854	3	9.618		
	Total	412.830	5			

Results for Hydrograph 6, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.647*10^{-2}$	2	$8.233*10^{-3}$	1.500	0.296
	Within Groups	$3.293*10^{-2}$	6	$5.489*10^{-3}$		
	Total	$4.940*10^{-2}$	8			
D_{16}	Between Groups	0.135	2	$6.773*10^{-2}$	1.200	**0.364**
	Within Groups	0.339	6	$5.642*10^{-2}$		
	Total	0.474	8			
D_{50}	Between Groups	$1.156*10^{-3}$	2	$5.778*10^{-2}$	0.000	**1.000**
	Within Groups	13.060	6	2.177		
	Total	13.061	8			
D_{84}	Between Groups	69.001	2	34.500	0.599	**0.579**
	Within Groups	345.542	6	57.590		
	Total	414.543	8			
D_{95}	Between Groups	439.594	2	219.797	9.080	0.015
	Within Groups	145.234	6	24.206		
	Total	584.828	8			

Results for Hydrograph 6, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$3.233*10^{-3}$	2	$1.617*10^{-3}$	0.744	**0.546**
	Within Groups	$6.517*10^{-3}$	3	$2.172*10^{-3}$		
	Total	$9.750*10^{-3}$	5			
D_{16}	Between Groups	$1.387*10^{-2}$	2	$6.933*10^{-3}$	1.037	**0.455**
	Within Groups	$2.007*10^{-2}$	3	$6.689*10^{-3}$		
	Total	$3.393*10^{-2}$	5			
D_{50}	Between Groups	0.934	2	0.467	1.002	**0.464**
	Within Groups	1.398	3	0.466		
	Total	2.333	5			
D_{84}	Between Groups	8.915	2	4.458	2.184	0.260
	Within Groups	6.123	3	2.041		
	Total	15.039	5			
D_{95}	Between Groups	6.261	2	3.130	0.202	**0.827**
	Within Groups	46.474	3	15.491		
	Total	52.735	5			

Results for Hydrograph 6, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$5.033*10^{-3}$	2	$2.517*10^{-3}$	1.624	**0.333**
	Within Groups	$4.650*10^{-3}$.	3	$1.550*10^{-3}$		
	Total	$9.683*10^{-3}$	5			
D_{16}	Between Groups	$9.263*10^{-2}$	2	$4.632*10^{-2}$	4.783	0.117
	Within Groups	$2.905*10^{-2}$	3	$9.683*10^{-3}$		
	Total	0.122	5			
D_{50}	Between Groups	10.905	2	5.452	1.887	0.295
	Within Groups	8.669	3	2.890		
	Total	19.574	5			
D_{84}	Between Groups	187.0144	2	93.572	2.485	0.231
	Within Groups	112.979	3	37.660		
	Total	300.124	5			
D_{95}	Between Groups	295.940	2	147.970	2.384	0.240
	Within Groups	186.237	3	62.079		
	Total	482.178	5			

Results for Hydrograph 8, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$8.600*10^{-3}$	2	$4.300*10^{-3}$	0.849	**0.474**
	Within Groups	$3.040*10^{-2}$	6	$5.067*10^{-3}$		
	Total	$3.900*10^{-2}$	8			
D_{16}	Between Groups	$1.562*10^{-2}$	2	$7.811*10^{-3}$	0.358	**0.713**
	Within Groups	0.131	6	$2.183*10^{-2}$		
	Total	0.147	8			
D_{50}	Between Groups	0.268	2	0.134	0.230	**0.801**
	Within Groups	3.486	6	0.581		
	Total	3.754	8			
D_{84}	Between Groups	4.126	2	2.081	0.817	**0.485**
	Within Groups	15.276	6	2.546		
	Total	19.439	8			
D_{95}	Between Groups	21.237	2	10.619	1.199	**0.365**
	Within Groups	53.123	6	8.854		
	Total	74.361	8			

Results for Hydrograph 8, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.367*10^{-3}$	2	$6.833*10^{-4}$	3.968	0.144
	Within Groups	$5.167*10^{-4}$	3	$1.722*10^{-4}$		
	Total	$1.883*10^{-3}$	5			
D_{16}	Between Groups	$2.733*10^{-3}$	2	$1.367*10^{-3}$	4.731	0.118
	Within Groups	$8.667*10^{-4}$	3	$2.889*10^{-4}$		
	Total	$3.600*10^{-3}$	5			
D_{50}	Between Groups	$9.283*10^{-2}$	2	$4.642*10^{-2}$	67.380	<u>0.003</u>
	Within Groups	$2.067*10^{-3}$	3	$6.889*10^{-4}$		
	Total	$9.490*10^{-2}$	5			
D_{84}	Between Groups	1.708	2	0.854	6.128	0.087
	Within Groups	0.418	3	0.139		
	Total	2.126	5			
D_{95}	Between Groups	6.299	2	3.150	0.410	**0.696**
	Within Groups	23.025	3	7.675		
	Total	29.324	5			

Results for Hydrograph 8, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$8.842*10^{-2}$	2	$4.421*10^{-2}$	22.607	<u>0.016</u>
	Within Groups	$5.867*10^{-3}$	3	$1.956*10^{-3}$		
	Total	$9.428*10^{-2}$	5			
D_{16}	Between Groups	2.794	2	1.397	1.727	**0.317**
	Within Groups	23.427	3	0.809		
	Total	5.221	5			
D_{50}	Between Groups	90.722	2	45.361	1.271	**0.398**
	Within Groups	107.037	3	35.679		
	Total	197.759	5			
D_{84}	Between Groups	137.641	2	68.820	0.565	**0.619**
	Within Groups	365.147	3	121.716		
	Total	502.787	5			
D_{95}	Between Groups	300.145	2	150.072	2.889	0.200
	Within Groups	155.852	3	51.951		
	Total	455.0997	5			

Results for Hydrograph 10, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$3.867*10^{-3}$	2	$1.933*10^{-3}$	1.480	**0.313**
	Within Groups	$6.533*10^{-3}$	5	$1.307*10^{-3}$		
	Total	$1.040*10^{-2}$	7			
D_{16}	Between Groups	$1.121*10^{-3}$	2	$5.604*10^{-4}$	0.174	**0.845**
	Within Groups	$1.607*10^{-2}$	5	$3.213*10^{-3}$		
	Total	$1.719*10^{-2}$	7			
D_{50}	Between Groups	0.437	2	0.218	0.811	**0.495**
	Within Groups	1.346	5	0.269		
	Total	1.783	7			
D_{84}	Between Groups	0.317	2	0.159	0.200	**0.825**
	Within Groups	3.972	5	0.794		
	Total	4.289	7			
D_{95}	Between Groups	154.396	2	77.198	1.715	0.271
	Within Groups	225.109	5	45.022		
	Total	379.505	7			

Results for Hydrograph 10, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.054*10^{-2}$	2	$5.271*10^{-3}$	3.905	0.115
	Within Groups	$5.400*10^{-3}$	4	$1.350*10^{-3}$		
	Total	$1.594*10^{-2}$	6			
D_{16}	Between Groups	$1.827*10^{-2}$	2	$9.135*10^{-3}$	0.786	**0.515**
	Within Groups	$4.648*10^{-2}$	4	$1.162*10^{-2}$		
	Total	$6.475*10^{-2}$	6			
D_{50}	Between Groups	0.521	2	0.260	0.671	**0.561**
	Within Groups	1.552	4	0.388		
	Total	2.073	6			
D_{84}	Between Groups	1.869	2	0.934	0.329	**0.737**
	Within Groups	11.345	4	2.836		
	Total	13.214	6			
D_{95}	Between Groups	8.516	2	4.258	0.739	**0.533**
	Within Groups	23.038	4	5.759		
	Total	31.554	6			

Results for Hydrograph 10, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.505*10^{-2}$	2	$7.527*10^{-3}$	3.208	0.127
	Within Groups	$1.173*10^{-2}$	5	$2.347*10^{-3}$		
	Total	$2.679*10^{-2}$	7			
D_{16}	Between Groups	$1.875*10^{-2}$	2	$9.375*10^{-3}$	2.520	0.175
	Within Groups	$1.860*10^{-2}$	5	$3.720*10^{-3}$		
	Total	$3.735*10^{-2}$	7			
D_{50}	Between Groups	0.341	2	0.171	1.580	0.294
	Within Groups	0540	5	0.108		
	Total	0.881	7			
D_{84}	Between Groups	11.393	2	5.696	2.467	0.180
	Within Groups	11.546	5	2.309		
	Total	22.938	7			
D_{95}	Between Groups	118.466	2	59.233	4.828	0.068
	Within Groups	61.338	5	12.268		
	Total	179.804	7			

Results for Hydrograph 13, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.067*10^{-3}$	2	$5.333*10^{-4}$	0.623	**0.568**
	Within Groups	$5.133*10^{-3}$	6	$8.556*10^{-4}$		
	Total	$6.200*10^{-3}$	8			
D_{16}	Between Groups	$7.489*10^{-3}$	2	$3.744*10^{-3}$	0.994	**0.424**
	Within Groups	$2.260*10^{-2}$	6	$3.767*10^{-3}$		
	Total	$3.009*10^{-2}$	8			
D_{50}	Between Groups	0.772	2	0.386	1.002	**0.421**
	Within Groups	2.310	6	0.385		
	Total	3.082	8			
D_{84}	Between Groups	60.342	2	30.171	0.769	**0.504**
	Within Groups	235.460	6	39.243		
	Total	295.802	8			
D_{95}	Between Groups	58.772	2	29.386	0.488	**0.636**
	Within Groups	361.449	6	60.242		
	Total	420.222	8			

Results for Hydrograph 13, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$3.123*10^{-2}$	2	$1.562*10^{-2}$	72.077	0.003
	Within Groups	$6.500*10^{-4}$	3	$2.167*10^{-4}$		
	Total	$3.188*10^{-2}$	5			
D_{16}	Between Groups	0.144	2	$7.202*10^{-2}$	418.161	0.000
	Within Groups	$5.167*10^{-4}$	3	$1.722*10^{-4}$		
	Total	0.145	5			
D_{50}	Between Groups	4.554	2	2.277	502.296	0.000
	Within Groups	$1.360*10^{-2}$	3	$4.533*10^{-3}$		
	Total	4.568	5			
D_{84}	Between Groups	163.480	2	78.340	596.932	0.000
	Within Groups	0.411	3	0.137		
	Total	163.891	5			
D_{95}	Between Groups	156.680	2	78.340	36.337	0.008
	Within Groups	6.468	3	2.156		
	Total	163.147	5			

Results for Hydrograph 13, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.496*10^{-2}$	1	$1.496*10^{-2}$	29.598	0.012
	Within Groups	$1.517*10^{-3}$	3	$5.056*10^{-4}$		
	Total	$1.648*10^{-2}$	4			
D_{16}	Between Groups	$3.468*10^{-2}$	1	$3.468*10^{-2}$	104.040	0.002
	Within Groups	$1.000*10^{-3}$	3	$3.333*10^{-4}$		
	Total	$3.568*10^{-2}$	4			
D_{50}	Between Groups	0.666	1	0.666	17.489	0.025
	Within Groups	0.114	3	$3.808*10^{-2}$		
	Total	0.780	4			
D_{84}	Between Groups	4.880	1	4.880	1.323	**0.333**
	Within Groups	11.064	3	3.688		
	Total	15.944	4			
D_{95}	Between Groups	16.830	1	16.830	1.225	**0.349**
	Within Groups	41.230	3	13.743		
	Total	58.060	4			

Results for Hydrograph 15, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$9.800*10^{-3}$	2	$4.900*10^{-3}$	1.771	0.249
	Within Groups	$1.660*10^{-2}$	6	$2.767*10^{-3}$		
	Total	$2.640*10^{-2}$	8			
D_{16}	Between Groups	$1.616*10^{-2}$	2	$8.078*10^{-3}$	1.727	0.256
	Within Groups	$2.870*10^{-2}$	6	$4.678*10^{-3}$		
	Total	$4.422*10^{-2}$	8			
D_{50}	Between Groups	0.293	2	0.146	1.386	**0.320**
	Within Groups	0.634	6	0.106		
	Total	0.926	8			
D_{84}	Between Groups	1.662	2	0.831	0.201	**0.823**
	Within Groups	24.850	6	4.142		
	Total	26.513	8			
D_{95}	Between Groups	7.789	2	3.895	0.149	**0.864**
	Within Groups	156.307	6	26.051		
	Total	164.096	8			

Results for Hydrograph 15, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$2.571*10^{-3}$	2	$1.285*10^{-3}$	5.756	0.050
	Within Groups	$1.117*10^{-3}$	5	$2.233*10^{-4}$		
	Total	$3.687*10^{-3}$	7			
D_{16}	Between Groups	$4.350*10^{-3}$	2	$2.175*10^{-3}$	2.266	0.199
	Within Groups	$4.800*10^{-3}$	5	$9.600*10^{-4}$		
	Total	$9.150*10^{-3}$	7			
D_{50}	Between Groups	0.103	2	$5.147*10^{-2}$	1.242	**0.365**
	Within Groups	0.207	5	$4.145*10^{-2}$		
	Total	0.310	7			
D_{84}	Between Groups	1.322	2	0.661	0.399	**0.691**
	Within Groups	8.287	5	1.657		
	Total	9.608	7			
D_{95}	Between Groups	6.723	2	3.362	0.120	**0.889**
	Within Groups	139.509	5	27.902		
	Total	146.233	7			

Results for Hydrograph 15, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$7.304*10^{-3}$	2	$3.652*10^{-3}$	3.984	0.092
	Within Groups	$4.583*10^{-3}$	5	$9.167*10^{-4}$		
	Total	$1.189*10^{-2}$	7			
D_{16}	Between Groups	$5.737*10^{-2}$	2	$2.868*10^{-2}$	2.465	0.180
	Within Groups	$5.818*10^{-2}$	5	$1.164*10^{-2}$		
	Total	0.116	7			
D_{50}	Between Groups	2.790	2	1.395	7.905	<u>0.028</u>
	Within Groups	0.882	5	0.176		
	Total	3.672	7			
D_{84}	Between Groups	210.946	2	105.473	3.284	0.123
	Within Groups	160.570	5	32.114		
	Total	371.517	7			
D_{95}	Between Groups	236.331	2	118.166	2.822	0.151
	Within Groups	209.367	5	41.873		
	Total	445.699	7			

Results for Hydrograph 18, Configuration I.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$5.456*10^{-3}$	2	$2.726*10^{-3}$	0.303	**0.754**
	Within Groups	$3.598*10^{-2}$	4	$8.995*10^{-3}$		
	Total	$4.143*10^{-2}$	6			
D_{16}	Between Groups	$1.643*10^{-2}$	2	$8.214*10^{-4}$	0.034	**0.967**
	Within Groups	$9.750*10^{-3}$	4	$2.437*10^{-2}$		
	Total	$9.914*10^{-2}$	6			
D_{50}	Between Groups	0.591	2	0.296	0.151	**0.864**
	Within Groups	7.823	4	1.956		
	Total	8.414	6			
D_{84}	Between Groups	168.903	2	84.452	1.173	**0.397**
	Within Groups	288.075	4	72.019		
	Total	456.979	6			
D_{95}	Between Groups	129.981	2	64.991	1.022	**0.438**
	Within Groups	254.415	4	63.604		
	Total	384.396	6			

Results for Hydrograph 18, Configuration II.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.037*10^{-2}$	2	$5.186*10^{-3}$	5.459	0.072
	Within Groups	$3.800*10^{-3}$	4	$9.500*10^{-4}$		
	Total	$1.417*10^{-2}$	6			
D_{16}	Between Groups	$8.305*10^{-3}$	2	$4.152*10^{-3}$	2.650	0.185
	Within Groups	$6.267*10^{-3}$	4	$1.567*10^{-3}$		
	Total	$1.457*10^{-2}$	6			
D_{50}	Between Groups	$3.921*10^{-2}$	2	$1.960*10^{-2}$	0.563	**0.690**
	Within Groups	0.139	4	$3.483*10^{-2}$		
	Total	0.179	6			
D_{84}	Between Groups	5.272	2	2.636	0.951	**0.459**
	Within Groups	11.086	4	2.771		
	Total	16.358	6			
D_{95}	Between Groups	14.346	2	7.173	0.761	**0.525**
	Within Groups	37.692	4	9.423		
	Total	52.037	6			

Results for Hydrograph 18, Configuration III.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.171*10^{-3}$	2	$5.854*10^{-4}$	0.220	**0.810**
	Within Groups	$1.332*10^{-2}$	5	$2.663*10^{-3}$		
	Total	$1.449*10^{-2}$	7			
D_{16}	Between Groups	$1.883*10^{-3}$	2	$9.417*10^{-4}$	0.134	**0.878**
	Within Groups	$3.512*10^{-2}$	5	$7.023*10^{-3}$		
	Total	$3.700*10^{-2}$	7			
D_{50}	Between Groups	0.580	2	0.290	0.794	**0.502**
	Within Groups	1.828	5	0.366		
	Total	2.408	7			
D_{84}	Between Groups	57.396	2	28.698	1.185	**0.379**
	Within Groups	121.123	5	24.225		
	Total	178.519	7			
D_{95}	Between Groups	199.009	2	99.505	1.242	**0.365**
	Within Groups	400.666	5	80.133		
	Total	599.676	7			

Appendix 5.3

ANOVA results to examine if there is a difference in infiltrated particle size based on a difference in configuration.

Results for Hydrograph 2, Reach 1.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$8.567*10^{-3}$	2	$4.283*10^{-3}$	1.858	0.299
	Within Groups	$6.917*10^{-3}$	3	$2.306*10^{-3}$		
	Total	$1.548*10^{-2}$	5			
D_{50}	Between Groups	2.887	2	1.444	1.396	**0.373**
	Within Groups	3.102	3	1.034		
	Total	5.989	5			
D_{95}	Between Groups	252.048	2	126.024	13.851	<u>0.031</u>
	Within Groups	27.297	3	9.099		
	Total	279.345	5			

Results for Hydrograph 2, Reach 2.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.376*10^{-3}$	2	$6.881*10^{-4}$	1.072	**0.424**
	Within Groups	$2.567*10^{-3}$	4	$6.417*10^{-4}$		
	Total	$3.943*10^{-3}$	6			
D_{50}	Between Groups	0.399	2	0.200	0.704	**0.547**
	Within Groups	1.134	4	0.283		
	Total	1.533	6			
D_{95}	Between Groups	85.059	2	42.530	1.523	**0.322**
	Within Groups	111.672	4	27.918		
	Total	196.731	6			

Results for Hydrograph 2, Reach 3.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$2.708*10^{-4}$	2	$1.354*10^{-4}$	0.076	**0.928**
	Within Groups	$8.917*10^{-3}$	5	$1.783*10^{-4}$		
	Total	$9.188*10^{-3}$	7			
D_{50}	Between Groups	0.110	2	$5.503*10^{-2}$	0.972	**0.440**
	Within Groups	0.283	5	$5.663*10^{-3}$		
	Total	0.393	7			
D_{95}	Between Groups	16.708	2	8.354	0.197	**0.827**
	Within Groups	211.756	5	42.351		
	Total	228.464	7			

Results for Hydrograph 6, Reach 1.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$6.000*10^{-4}$	2	$3.000*10^{-4}$	0.281	**0.773**
	Within Groups	$3.200*10^{-3}$	3	$1.067*10^{-3}$		
	Total	$3.800*10^{-3}$	5			
D_{50}	Between Groups	5.081	2	2.540	0.720	**0.556**
	Within Groups	10.592	3	3.531		
	Total	15.673	5			
D_{95}	Between Groups	95.324	2	47.662	0.684	**0.569**
	Within Groups	209.093	3	69.698		
	Total	304.417	5			

Results for Hydrograph 6, Reach 2.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.205*10^{-3}$	2	$6.024*10^{-4}$	0.136	**0.877**
	Within Groups	$1.777*10^{-2}$	4	$4.442*10^{-3}$		
	Total	$1.897*10^{-2}$	6			
D_{50}	Between Groups	1.928	2	0.964	0.477	**0.652**
	Within Groups	8.083	4	2.021		
	Total	10.011	6			
D_{95}	Between Groups	379.374	2	189.687	6.806	0.052
	Within Groups	111.475	4	27.869		
	Total	490.849	6			

Results for Hydrograph 6, Reach 3.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$2.385*10^{-2}$	2	$1.193*10^{-2}$	2.578	0.170
	Within Groups	$2.313*10^{-2}$	5	$4.627*10^{-3}$		
	Total	$4.699*10^{-2}$	7			
D_{50}	Between Groups	2.086	2	1.043	1.171	**0.383**
	Within Groups	4.452	5	0.890		
	Total	6.537	7			
D_{95}	Between Groups	59.103	2	29.552	2.575	0.170
	Within Groups	57.378	5	11.476		
	Total	116.481	7			

Results for Hydrograph 8, Reach 1.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$8.542*10^{-2}$	2	$4.271*10^{-2}$	21.120	0.017
	Within Groups	$6.067*10^{-3}$	3	$2.022*10^{-3}$		
	Total	$9.148*10^{-2}$	5			
D_{50}	Between Groups	87.865	2	43.932	1.230	**0.407**
	Within Groups	107.170	3	35.723		
	Total	195.035	5			
D_{95}	Between Groups	479.891	2	239.946	6.151	0.087
	Within Groups	117.0.35	3	39.012		
	Total	569.927	5			

Results for Hydrograph 8 Reach 2.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.162*10^{-2}$	2	$5.808*10^{-3}$	1.530	**0.303**
	Within Groups	$1.898*10^{-2}$	5	$3.797*10^{-3}$		
	Total	$3.060*10^{-2}$	7			
D_{50}	Between Groups	0.309	2	0.155	0.976	**0.439**
	Within Groups	0.792	5	0.158		
	Total	1.101	7			
D_{95}	Between Groups	6.458	2	3.229	0.169	**0.849**
	Within Groups	95.584	5	19.117		
	Total	102.042	7			

Results for Hydrograph 8, Reach 3.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$8.810*10^{-3}$	2	$4.405*10^{-3}$	1.502	**0.326**
	Within Groups	$1.173*10^{-2}$	4	$2.933*10^{-3}$		
	Total	$2.054*10^{-3}$	6			
D_{50}	Between Groups	0.790	2	0.395	0.616	**0.584**
	Within Groups	2.564	4	0.641		
	Total	3.354	6			
D_{95}	Between Groups	23.962	2	11.981	2.473	0.200
	Within Groups	19.381	4	4.845		
	Total	43.343	6			

Results for Hydrograph 10, Reach 1.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$5.121*10^{-3}$	2	$2.560*10^{-3}$	2.259	0.200
	Within Groups	$5.667*10^{-3}$	5	$1.133*10^{-3}$		
	Total	$1.079*10^{-2}$	7			
D_{50}	Between Groups	0.788	2	0.394	1.314	**0.348**
	Within Groups	1.499	5	0.300		
	Total	2.288	7			
D_{95}	Between Groups	281.641	2	140.820	3.297	0.122
	Within Groups	213.560	5	42.712		
	Total	495.201	7			

Results for Hydrograph 10, Reach 2.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.754*10^{-3}$	2	$8.771*10^{-4}$	0.433	**0.671**
	Within Groups	$1.013*10^{-2}$	5	$2.027*10^{-3}$		
	Total	$1.189*10^{-2}$	7			
D_{50}	Between Groups	0.189	2	$9.463*10^{-2}$	0.293	**0.758**
	Within Groups	1.614	5	0.323		
	Total	1.803	7			
D_{95}	Between Groups	6.499	2	3.249	0.192	**0.831**
	Within Groups	84.650	5	16.930		
	Total	91.149	7			

Results for Hydrograph 10, Reach 3.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$8.762*10^{-4}$	2	$4.381*10^{-4}$	0.223	**0.810**
	Within Groups	$7.867*10^{-3}$	4	$1.967*10^{-3}$		
	Total	$8.743*10^{-3}$	6			
D_{50}	Between Groups	$8.437*10^{-2}$	2	$4.218*10^{-2}$	0.520	**0.630**
	Within Groups	0.325	4	$8.118*10^{-2}$		
	Total	0.409	6			
D_{95}	Between Groups	62.125	2	31.063	11.020	<u>0.024</u>
	Within Groups	11.275	4	2.819		
	Total	73.400	6			

Results for Hydrograph 13, Reach 1.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.697*10^{-2}$	2	$8.483*10^{-3}$	6.848	0.076
	Within Groups	$3.717*10^{-3}$	3	$1.239*10^{-3}$		
	Total	$2.068*10^{-2}$	5			
D_{50}	Between Groups	1.923	2	0.961	1.479	**0.357**
	Within Groups	1.951	3	0.650		
	Total	3.873	5			
D_{95}	Between Groups	83.512	2	41.756	0.512	**0.644**
	Within Groups	244.699	3	81.566		
	Total	328.211	5			

Results for Hydrograph 13, Reach 2.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$2.167*10^{-3}$	2	$1.083*10^{-3}$	1.946	0.237
	Within Groups	$2.783*10^{-3}$	5	$5.567*10^{-4}$		
	Total	$4.950*10^{-3}$	7			
D_{50}	Between Groups	0.447	2	0.224	2.536	0.174
	Within Groups	0.441	5	$8.813*10^{-2}$		
	Total	0.888	7			
D_{95}	Between Groups	132.455	2	66.227	2.152	0.212
	Within Groups	153.840	5	30.768		
	Total	286.294	7			

Results for Hydrograph 13, Reach 3.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	0.000	1	0.000	0.000	1.000
	Within Groups	$8.000*10^{-4}$	4	$2.000*10^{-4}$		
	Total	$8.000*10^{-4}$	5			
D_{50}	Between Groups	$2.940*10^{-2}$	1	$2.940*10^{-2}$	2.502	0.189
	Within Groups	$4.700*10^{-2}$	4	$1.175*10^{-2}$		
	Total	$7.640*10^{-2}$	5			
D_{95}	Between Groups	2.548	1	2.548	0.961	**0.383**
	Within Groups	10.609	4	2.652		
	Total	13.157	5			

Results for Hydrograph 18, Reach 1.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$7.921*10^{-3}$	2	$3.960*10^{-3}$	1.892	0.244
	Within Groups	$1.047*10^{-2}$	5	$2.093*10^{-3}$		
	Total	$1.839*10^{-2}$	7			
D_{50}	Between Groups	2.334	2	1.167	1.114	**0.398**
	Within Groups	5.239	5	1.048		
	Total	7.574	7			
D_{95}	Between Groups	177.922	2	88.961	0.781	**0.507**
	Within Groups	569.475	5	113.895		
	Total	747.397	7			

Results for Hydrograph 18, Reach 2.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.825*10^{-3}$	2	$9.127*10^{-4}$	0.088	**0.918**
	Within Groups	$3.118*10^{-2}$	3	$1.039*10^{-2}$		
	Total	$3.300*10^{-2}$	5			
D_{50}	Between Groups	0.879	2	0.440	0.974	**0.472**
	Within Groups	1.354	3	0.451		
	Total	2.233	5			
D_{95}	Between Groups	24.275	2	12.138	0.315	**0.751**
	Within Groups	115.559	3	38.520		
	Total	139.834	5			

Results for Hydrograph 18, Reach 3.

		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
D_5	Between Groups	$1.537*10^{-3}$	2	$7.687*10^{-4}$	0.336	**0.730**
	Within Groups	$1.145*10^{-2}$	5	$2.290*10^{-3}$		
	Total	$1.299*10^{-2}$	7			
D_{50}	Between Groups	1.208	2	0.604	0.945	**0.449**
	Within Groups	3.197	5	0.639		
	Total	4.406	7			
D_{95}	Between Groups	39.404	2	19.702	12.729	0.011
	Within Groups	7.739	5	1.548		
	Total	47.143	7			