RESPONSE OF AN INVERTEBRATE COMMUNITY TO
PATCH-SPECIFIC BED DISTURBANCE

by

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Date 10/10/2000
Abstract

Geometric bedform structures promote physical stability in streams. They occur in gravel beds in varying degrees of development, and hence may control the spatial distribution of bed disturbance, and the corresponding distribution of invertebrates.

Partial stone cell structures and line clusters formed the principal structural elements in East Creek. Bed stabilisation as parameterised by Shields number was at least one and a half times greater where structures existed. They reduced event averaged transport rates by half and resulted in a patchy distribution of bed disturbance. Limited evidence suggests there could be a scaling relation between partial stone cell diameter and area of patch disturbance.

Structure development in East Creek took place in an artificially loosened bed. Development was maximised during two moderate floods. These floods were of sufficient magnitude to mobilise only loose sediment. Evidence from this study suggests structural development in a natural system is dependent upon the history of recent flows and external sediment supply.

The response of the macroinvertebrate community to bed disturbance was varied. Disturbance mechanisms are taxon specific, and may be related to scour, abrasion from fine bedload and movement of surficial particles. Paradoxically, stabilised areas of the stream bed, such as stone structures, whilst remaining stable during a flood, may not uniformly act as refugia. Population maintenance on stabilised structures during a flood may depend on shear forces and turbulent velocities, and amount of fine bedload.
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Chapter One. Introduction

Bedload is sediment that is entrained and transported downstream in contact with the stream bed. While it generally constitutes a small proportion of the total sediment load in a river it nonetheless may include a substantial portion of bed material moved. Bedload transport is therefore closely associated with channel stability and morphological form in alluvial rivers. It has significance not only for engineers but also the instream biota.

The stream bed, through its interaction with water flow, provides oxygen, space, food and other resources for benthic life, and acts as the template on which communities exist. Particle movement therefore represents an obvious challenge to organisms. The winnowing of fine sand can potentially cause abrasion and burial, and the entrainment and movement of larger particles may crush and damage sessile organisms and initiate dispersal of mobile ones. Longer term impacts may include reduction in food sources and alteration of the physical habitat. Bedload is therefore a potentially dominant organizing factor in lotic ecosystems.

Prediction and measurement of bedload in streams and rivers however is inherently difficult. Variability occurs across a range of spatial scales and is controlled by both internal processes, such as particle imbrication, and external processes, such as bank erosion. It can vary markedly both between events (e.g. see Powell and Ashworth 1995) and within events (e.g. see Warburton 1992) over small spatial scales. This not only represents a major problem for the computation of transport rates for engineers and geomorphologists, but it also represents a major problem for ecologists in predicting the impact of bedload on lotic invertebrate communities.
The Impact of Bedload on the Invertebrate Community

Natural physical disturbance has been recognized as an important factor in regulating the structure of invertebrate communities, and disturbance by flooding is seen as the dominant form in rivers and streams (Resh et al. 1988). Furthermore there is a general acceptance that disturbance of the stream bed may represent the prime source of variation in faunal diversity and abundance in flooded streams (Downes et al. 1997).

Recently several models have been produced based on disturbance of the stream bed that aim to predict river to river variation in community composition and or species richness (e.g., Death and Winterbourn 1994; Townsend and Hildrew 1994; Townsend et al. 1997a&b). The success of such models therefore relies heavily on our ability to predict the effect of bed movement on the invertebrate community. At the moment however we lack the required knowledge.

One of the major problems that has hindered the development and testing of such disturbance models has been the appropriate scale at which to define and measure bed movement (Downes et al. 1998). For example, if a flood mobilizes every particle on the stream bed, then focusing at the scale of the individual particle will serve only to increase the precision of estimates of disturbance effects on invertebrate populations. In this situation one may appropriately describe and model the effects of disturbance at the reach or site scale. However, if a flood overturns only individual rocks or patches of rocks then continuing to focus at the reach scale may result in loss of precision, causing large confidence intervals around estimates of bed disturbance, and potentially large errors around estimates of invertebrate population means. The application and ultimate success of disturbance models is therefore contingent upon a very good understanding of the spatial scales of natural bed disturbance (Downes et al. 1998). However, we currently have little understanding at all.
The majority of recent field studies on disturbance of the stream bed have focused at the reach scale (e.g. Townsend et al. 1997a). Inherent in this approach is the assumption that most variation in bedload is set by reach scale processes, and the bed is correspondingly disturbed evenly. This contrasts with the recent suggestion that the dominant form of bedload transport in gravel bed streams is in fact one of partial transport (Wilcock and McArdell 1997), whereby only a portion of the bed is mobile at once.

To appropriately address disturbance models in streams ecologists must understand how a potentially patchy movement of bed material during a flood affects invertebrate populations, and at what scales. Does patchy movement of the bed produce corresponding patches of invertebrates? What are the scales of these patches? Can they be linked to the geomorphological character of the stream bed? These are questions that we should be attempting to address.

A Brief Review

A first step is to identify the spatial scales of bed movement. Some information can be gained from geomorphological studies (e.g. Warburton 1992), however most of these focus on bedload transport rates. Of primary interest to ecologists is the disturbance of surficial particles, a slightly different measure.

Three studies on the spatial scales of surficial particle movement exist in the ecological literature. Two studies focused on the individual particle (Downes et al. 1997 & 1998) and the other on micro bed form clusters (Biggs et al. 1997). The latter study was purely descriptive and related the occurrence of micro bed form clusters to general stream characteristics. It did not attempt to study their maintenance during flooding. The main outcome from these papers was that significant variation in surficial rock movement can exist at small spatial scales and potentially represents an important source of community variation. Correspondingly, Downes et
al. (1998) suggested that disturbance models should at least be keyed to the scale of the particle, as well as larger scales, to ensure an adequate level of precision.

None of the above studies however attempted to relate the effects of variation in particle movement with invertebrate populations. Indeed to the best of my knowledge only two studies have, Matthaei et al. (2000), who focused on the movement of individual bed particles, and Strayer (1999), who focused on disturbance of the stream bed at the patch scale and the corresponding distribution of Unionid mussels. Both workers found that disturbed patches of the stream bed had significantly lower densities of organisms than stable areas after a flood. These two studies are significant as they provide the first real evidence that small scale variations in bed movement can indeed influence the distribution of invertebrates.

Neither of these workers however attempted to relate their observations of bed movement and corresponding distribution of invertebrate patches to the morphological character of the stream bed, or indeed attempted to understand the mechanisms behind the observed spatial patterns of particle movement. Furthermore, only the study by Matthaei et al. (2000) looked at the general invertebrate community, and only then on the particle itself, avoiding organisms that might inhabit the mineral interstitial spaces.

The Next Step

There is clearly a need to quantify the effects of bed movement on the general invertebrate community.

This study represents a first step towards addressing this need. It can be regarded as an exploratory study with two main aims: first, to map the spatial distribution of bed disturbance in a small gravel stream after a flood, exploring the possible mechanisms of bed stability; second, to relate the distribution of invertebrate patches after the flood to the observed distribution of bed
disturbance. The focus of this study will be on a scale larger than the particle.Geomorphologists have recently focused their attention on bed stabilizing mechanisms at the scale of multiple particles (e.g. Church et al. 1998). This provides an interesting scale at which to work. It allows invertebrate samples to be taken from multiple particles, permitting the use of standard sampling techniques and equipment, e.g. the Surber sampler. This enables the entire community to be sampled, including organisms that inhabit interstitial mineral spaces. It also potentially allows disturbance models to be keyed to a scale that is perhaps more practical than that of the individual particle.

The effect of multiple particle structures in controlling particle entrainment has been investigated by Church et al. (1998). They found the key effect of multiple particle features was to substantially reduce the mobility of the larger stones, which then effectively 'hide' the smaller particles. The overall joint effect of armoring, coarsening of the bed, and development of particle structures in the flume environment was to increase particle restraint by a factor of two (as measured by the critical Shields number) substantially stabilizing the bed. Variation in particle entrainment has also been ascribed to the effects of other multiple particle features such as particle clusters (Brayshaw et al. 1983; Brayshaw 1984). In the natural environment such particle clusters are typically distributed around larger particles (Brayshaw 1984), creating distinct cluster patches of varying size. Stone lines and cells (Church et al. 1998) have also been identified in the field, and are typically incomplete, likely creating distinct stabilized patches across the stream bed.

Multiple particle features have the potential to control the distribution of bed disturbance at a scale between that of the individual particle and that of the reach, and may influence the corresponding distribution of invertebrates after a flood. They represent the focus of this study.
Overview of the Study

The study has two main objectives: first, to study the role of stabilizing bedform features in controlling substrate movement; second, to investigate the effect of bed movement on the invertebrate community. These objectives have been conceptualized into three working hypotheses, stated below.

Hypothesis 1:
Ho - Bedform grain structures have no effect on particle entrainment.
H1 - Bedform grain structures affect particle entrainment.

While the alternative hypothesis (H1) appears to be self evident, it has been rigorously investigated only in the flume environment, where Church et al. (1998) found features such as stone cells and networks substantially increase the stability of the bed. As such the aim will be to investigate the degree to which bedform structures can stabilize the bed in the natural environment. A component of this research will involve assessing the spatial distribution of bed disturbance in relation to the distribution of the structures.

Hypothesis 2:
Ho - Bed movement has no effect on the invertebrate community.
H1 - Bed movement reduces invertebrate populations and alters community structure.

The scale of interest will not be that of the individual particle (e.g. Matthaei et al. 2000), but rather a scale complimentary to that of the traditional invertebrate sampling unit, the Surber sampler (0.16 m²). The majority of stream invertebrate data originates at this scale, and yet it is a scale within which there can exist considerable variation in bed movement. Correspondingly the response of a community to variable bed movement at this scale may in itself be variable. This study will represent the first time this consideration has been addressed in the field using data...
from natural flood events, and will provide information on the degree of variability in population response to bed movement.

The third hypothesis leads on from this.

Hypothesis 3:

Ho - Spatial variation in particle entrainment does not create invertebrate patches.

H1 - Spatial variation in particle entrainment creates invertebrate patches.

In this study, a ‘patch’ is defined simply as an aggregation of individuals in a surrounding area of lower density occupation. For spatial variation in particle entrainment to create invertebrate patches two conditions have to be met. First, particle entrainment has to disturb the invertebrate community. This is addressed by hypothesis two. Second, stable areas of the bed during a flood, or those that experienced low intensity particle movement, have to experience little, if any, change in community structure. That is, they must act as refugia. Refugia are defined as those areas of the stream bed where disturbance is reduced relative to the surroundings, such that populations survive and are hence available to colonize denuded patches (Lancaster 1999).

Limited evidence so far suggests that stable areas of the bed during a flood do maintain their populations and therefore act as refugia (Strayer 1999; Matthaei et al. 2000). However, structurally stable areas of the bed, such as particle clusters, may experience shear forces far in excess of that for the critical entrainment of surrounding bed particles. Such shear forces may dislodge and / or damage organisms. The simple assumption that stable areas of the bed remain ‘undisturbed’ and act as refugia during floods requires further testing.
General Study Design

This study could not be achieved in the flume environment since, while one can scale particles and bedform features, it is difficult to appropriately scale invertebrates and their behavior. However, a certain degree of control is required to properly address the hypotheses. For example, to assess the role of bedform features in controlling particle entrainment one must control for external variables such as flow, sediment supply, river gradient and particle grain size distribution. As such a quasi-experimental approach was, as outlined in Figure 1.1.

To address hypothesis 1 the study centred on two stream reaches, Reach 1, a reach containing bedform structures and used as a control, and Reach 2, a treatment reach where the substrate was artificially loosened and all bedform structures broken apart. Flow, stream gradient and particle size distributions were constants, allowing the effect of bedform structures on bedload and spatial distribution of bed disturbance to be assessed.

Due to logistical constraints no replication was possible. Ideally one would have several replicate stream reaches, however due to the required work immediately after a flood, sampling the bedload and mapping the spatial distribution of bed disturbance, and the requirement of sampling invertebrates as soon after the flood as possible, replication at the reach scale was not possible.

The second part of the study will address hypotheses 2 and 3. Three reaches were used, Reaches 1 and 2 as described above and Reach 3, a reach with a naturally loose substrate and few bedform structures. The effect of bed movement and the ability for stable substrate to maintain invertebrate populations during flooding were assessed in these three reaches. The study was divided into two main time periods, pre-flood when replicate invertebrate samples were taken from each reach, and post-flood when replicate samples were taken from areas of the stream bed disturbed and stable areas in each reach. The pre-flood samples were used as a control and the
Pre Flood

Reach 1 - Structured reach
Reach 2 - Treatment reach
Sediment artificially loosened

Replicate invertebrate samples taken from each reach pre-flood

Post Flood

Reach 1
Reach 2

Disturbed Patches after flood

Bedload Sampled

Reach 3 - Reach with naturally loose sediment

Replicate invertebrate samples from disturbed and undisturbed areas of the bed.

Figure 1.1 General Study Design.
post-flood samples as treatments. The response in each reach was analyzed separately. Replication exists at the patch scale but not the reach scale. Therefore, any reach specific responses to flooding that may be related to stability, or other parameters that vary between reaches, must be interpreted with caution. However, this study is unique and represents the first time that the effect of particle movement on invertebrates has been studied in the field at this scale. It is in essence an exploratory study.
Chapter 2. Site Description

Study Site – East Creek

The study was conducted in East Creek, a coastal stream in the University of British Columbia’s Research Forest, approximately 60 km east of Vancouver, British Columbia (Figure 2.1). East Creek is 4 km long and drains approximately 100 ha. It is located within the Coastal Western Hemlock biogeoclimatic zone on generally shallow soils over glaciofluvial deposits. The vegetation in the catchment is dominated by coastal western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), wester redcedar (*Thuja plicata*), and red alder (*Alnus rubra*). Large waterfalls downstream from the study site prevent up-stream migration by anadromous salmonids, and resident coastal cutthroat trout (*Oncorhynchus clarki*), is the only fish species present in the creek (Young *et al.*, 1999).

Discharge records have been maintained on East Creek since 1971. Currently two gauging stations are in operation within the catchment, one approximately 500 m upstream from the study area and the other on a nearby tributary (Middle Creek). Low base flows of around 2.5 l/s occur during the summer months. The majority of annual precipitation (approximately 2100 mm) occurs during the winter months, mostly falling as rain. Rainfall intensities rarely exceed the infiltration capacity of the soils in the Research Forest, so runoff is typically dominated by subsurface storm flow and occasionally saturation overland flow (Cheng 1988). The creek is considered ideal for a study of this nature. Winter base flows are low, mostly around 12 l/s, and rain events typically produce sharp hydrographs with steep falling limbs, enabling work to be carried out within hours after a flood peak.
Figure 2.1 Location of Study Area, UBC Research Forest, near Haney, British Columbia
Study Reaches

A section of East Creek downstream of ‘F’ road, approximately 500 metres from the main gate (Figure 2.2) was chosen for the study. Three sub-reaches were selected along a three hundred meter stretch of the creek. The first two reaches (Reach 1 and Reach 2) were located in the first 50 meters. The third reach, Reach 3, was located approximately 200 metres downstream.

Reaches 1 and 2:

The channel in this part of the creek is relatively incised and more or less rectangular in cross section, and is thus flume-like. It is relatively straight and consists of a uniform riffle - run with little instream complexity (Figure 2.3a).

Within this part of the creek two 16-metre lengths of channel were chosen for the experiment. Both lengths were uniformly similar (Table 2.1). The upstream length was chosen as the control reach, and is referred to as Reach 1, while the downstream length was selected as the treatment reach, and is referred to as Reach 2. Slight variation in bed topography does exist between the two reaches (Figure 2.4). Generally the bed topography of Reach 2 is slightly variable, with a noticeably steeper section at the beginning of the reach. The corresponding water surface slope is also slightly steeper.

The reaches were approximately three-channel widths apart (8 m) (Figure 2.2).

Reach 3:

Immediately downstream from this section of East Creek the morphology is dominated by a meandering riffle / pool / bar sequence. Considerable sediment is stored throughout this section on the bars and within both the riffle and pool units (Figure 2.3b).
a) Reaches 1 (foreground) and 2 (background)

b) Reach 3

Figure 2.3  Study reaches
Figure 2.4 Bed topography and channel cross section of reaches 1 and 2. Surveyed water level corresponds to a discharge of 411 l/s.
The sediment within these units is typically loose and unconsolidated with little structural
development. A 16 m length was chosen within this part of the channel, Reach 3, to represent a
naturally loose, structureless bed. The reach consisted of a riffle / pool / bar sequence although
only information from the first riffle section will be used in the study. The selected study riffle
within this reach was approximately 4 meters long. There was no suitable riffle section of the
same length as reaches 1 and 2 within this part of East Creek due to the degree of morphological
variation.

Table 2.1 General channel and substrate characteristics of each study reach

<table>
<thead>
<tr>
<th></th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Width (m)</td>
<td>2.7</td>
<td>2.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Average Gradient (Bed)</td>
<td>0.020</td>
<td>0.021</td>
<td>0.054</td>
</tr>
<tr>
<td>D_{50subsurface} (mm)</td>
<td>25</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>D_{50surface} (mm)</td>
<td>67</td>
<td>59</td>
<td>41</td>
</tr>
<tr>
<td>D_{84surface} (mm)</td>
<td>107</td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td>D_{99surface} (mm)</td>
<td>178</td>
<td>164</td>
<td>100</td>
</tr>
</tbody>
</table>

The difference in length between the reaches should not comprise the ability to compare the
reach specific invertebrate responses to substrate movement, or indeed that on stable substrate.
The scale of the invertebrate sampling unit (0.16 m$^2$, Surber sampler) is at least two orders of
magnitude smaller than the reaches. The size difference between the reaches should not affect
the immediate response of invertebrates to substrate movement at the scale of the sampling unit.
Substrate

The substrate in Reaches 1 and 2 consists of fine to coarse gravels, with 1 or 2 isolated areas of till in both the bed and bank. The creek in this section is relatively degraded and armored with only occasional pockets of loose gravel. In Reach 3 the substrate is slightly finer with no observable till.

The surface and subsurface textures were characterized by bulk sampling at the tail of each 16 meter reach. This was completed during the installation of the bedload traps, taking advantage of the sediment excavation so as not to disrupt the experimental bed areas. The surface sediment grain size distributions were determined by removing surface particles to a depth of the largest particle from an area of 0.66 m$^2$, spanning the entire wetted channel. All particles were classified into phi increments using a template and sieve, and weighed in the field. Particles less than 16 mm were bagged in the field and sieved and weighed later in the laboratory.

All surface sediment grain size distributions (area by weight) were converted to bulk sample equivalents (sieve by weight) using the formula of Kellerhals and Bray (1971):

$$W_{\text{bulk}} = W_{\text{surface}} / D_m$$  \hspace{1cm} (1)

where $W_{\text{bulk}}$ is the converted weight of a particular size fraction, $W_{\text{surface}}$ is the weight of the size fraction on the sieve and $D_m$ is the geometric mean diameter of that material.

Subsurface sediment samples were extracted to a depth of approximately 0.2 m after the removal of the surface layer. Sediment samples were similarly classified into 1 phi increments using a template and sieve, and weighed in the field. A 5 kg portion of sediment less than 16 mm, regarded as a minimum weight to ensure representative size fractions are maintained (Church et al. 1987), was retained to be sieved and weighed in the laboratory.
Given silt and clay sized particles were not of major interest, sieving procedures in the laboratory followed a dry sediment method down to 0.063 mm. All fractions below 4 mm were classified into 0.5 phi increments.

Surface particles ranged in size up to a maximum of 185 mm. Surface sediment size distributions were similar in Reaches 1 and 2 (Figure 2.5), although slightly coarser in Reach 1 (Table 2.1). Subsurface sediment size distributions were once again similar in both reaches, however with slightly greater sand to fine gravel content in Reach 1. The sediment in Reach 3 was finer than that in Reaches 1 and 2 (Table 2.1) with limited surface armouring.

**Bedform Characteristics**

Bedform structures were identified and mapped using aerial photographs in reaches 1 and 2. A series of stereo photographs were taken of the substrate in both reaches during summer low flow, after surface sediment manipulation in Reach 2. The approach was two-fold; first, to identify and map bedform structures in Reach 1 and, second, to assess the effectiveness of sediment manipulation in breaking apart the stone structures in Reach 2. A camera with a 55mm lens suspended 3 m above the streambed was used to take the photographs. The camera was mounted on the end of a 2.4 m pole which was hoisted and held over the stream bed from the bank. A 3 m plumb line attached to the camera was used to ensure photographs were taken at the correct height. This was swung out of the way before the photograph was taken.

Photographs of the bed were aligned and emergent rocks were traced onto transparencies and later digitized. Each photograph covered an area of stream bed roughly 2 by 1 m.

Figure 2.6 illustrates the surface pattern of bed material in Reach 1 of East Creek. Immediately obvious is the butting and closely neighboring nature of many clasts, forming identifiable grain clusters. Field observations indicated that the majority of these clasts are in point contact with
Figure 2.5 Cumulative grain size distribution curves for each reach
one another, with only minor imbrication. These clusters form the principal structural element in East Creek, a pervasive feature that has been described elsewhere (e.g. Brayshaw 1984; Biggs et al. 1997). They generally form either compact rounded clusters or line clusters orientated either streamwise or transverse across the channel. Some of these line features have one or two particles at the end abutting at an acute angle, forming partial circular structures. Church et al. (1998) noted similar structures in Harris Creek. At their fullest development they form closed cells linked together forming a reticulate network, demonstrated by Church et al. (1998) in the flume environment. A map of the bed constructed after one of their flume runs illustrates the formation of a closed cell network (Figure 2.7). Two features are of interest, first not all cells are composed of tightly abutting or imbricated particles. This was also noted in East Creek. Second, the distribution of the finer particles is mostly confined to the interior of the fully formed cells. The effect of such features is to stabilize the larger particle fraction which then effectively 'hides' the smaller fraction (Church et al. 1998).

As a comparison a partial stone cell feature from East Creek is also shown in Figure 2.7. The criterion for bedform structure identification in East Creek differs from that used by Church et al. (1998) in their flume experiments. They used particle size as the main criterion. Particles $D_{84}$ or larger, or those particles that were members of a chain of large stones were shaded dark gray (Figure 2.7a). Bedform structures are composed of this larger particle fraction. In this study, size was not used as a criterion for defining bedform structure as any attempt to size the particles would have resulted in considerable disturbance. Definition of the structures therefore was based only on the pattern of bed material; that is, on the position of one stone in relation to its neighbour. As structures typically are composed of imbricated or abutting clasts, bedform structures are defined in this study as chains or aggregates of three or more clasts in contact with one another. These clasts are shaded grey in Figures 2.6 and 2.7. However, if an obvious chain
Figure 2.6 Map of surface stones that stand proud during summer low flows. Rock structures and clusters are shown by shaded stones. Streambed from transects 20 to 28 is shown in Figure 2.7.
Figure 2.7  a) Surface pattern of bed material from flume experiments showing a fully developed closed cell network, darkly shaded stones (after Church et al 1988). b) Surface pattern of bed material in East Creek illustrating partial stone cell development.
was formed then not all stones had to be in contact.

The stone cells in East Creek illustrated in Figure 2.7b represent the most fully formed feature in Reach 1. Generally structural development throughout the reach is sporadic and incomplete. Most partial stone cells and line features are separate with no evident linking or network development. Most large particles were emergent during the low flows when the photographs were taken. The clear areas therefore more than likely represent areas of the bed with a higher percentage of the small gravel fraction, although it is possible that some larger key particles remained submerged during low flows, embedded in the bed.

In Harris Creek Church et al (1998) noted that the constituent particles in stone cells are typically $D_{84}$ or larger and the ratio of cell structure diameter and constituent clast diameter is of the order of 10:1. The partial stone cells in East Creek do not entirely comply with this ratio, having an estimated diameter of between 40 and 85 cm ($D_{84} = 107$ mm, for Reach 1).

Figure 2.6 illustrates the pattern of bed material in Reach 2 after all bedform structures and imbricated rocks had been broken up. Figure 2.7 therefore represents the patterning of a loose, structureless bed. Even so, some particle clusters are evident. These clusters may be bedforms that were overlooked or the outcome of random particle placement during manipulation. Whether these clusters are inherently stable remains to be seen.

Figure 2.6 further illustrates what appears to be a variation in the number of large, emergent particles, with fewer in Reach 2 and in Reach 1. This should not, however, affect the ability to test Hypothesis 1, 'bedform grain structures have no effect on particle entrainment', as the actual sediment size distribution in both reaches is similar. The variation in numbers of emergent particles is more than likely an artefact of the manipulation in Reach 2.
Chapter Three  Field and Laboratory Methods

Introduction

A major deterrent to investigating flow refugia and disturbance of the stream bed within the natural environment is the difficulty in obtaining field observations and reliable data. Invertebrates typically function within spatial and temporal scales much smaller than ourselves, the observer. In order to identify a response to bed movement, samples must be taken as soon as possible after the disturbance and at spatial scales appropriate to the organism of interest.

The limiting factor in a study such as this is the identification and mapping of bed disturbance and corresponding potential sites of refugia, i.e. stable areas of the bed. Three problems arise. First, to identify and map disturbance of the stream bed and relate such disturbances to the invertebrate community, one must first wait until flood waters have receded so as to be able to view the bed, and then sample. A problem arises when invertebrate response times to recovery are shorter than the time from peak discharge to time of sampling, a problem compounded in this study due to the time required to detail bed movement. Second, one must map the disturbance of the bed at a spatial scale at least as fine as that of the invertebrate sampling unit, otherwise samples may be taken from areas of the bed with an unknown disturbance history. Third one must also overcome the confounding problem of adequately identifying and mapping bed disturbance at reasonably high resolution, without disrupting the invertebrate community.

Conversely, there also exists a problem of sampling the invertebrate community without significantly increasing bed disturbance and altering the potential for particle entrainment. However due to the difference in scale between that of the sampling unit and that of the experimental reach, invertebrate sampling should have minimal effect on both reach averaged bedload and the spatial distribution of bed disturbance.
The methodologies employed in this study attempt to overcome these difficulties. East Creek was chosen for this field study for two important reasons: first, due to its flashy nature, allowing work to be carried out soon after peak discharge. However, when working outside a controlled environment one can not control for all contingencies and occasionally extended periods of rainfall and rapid succession of storm events disrupted field work. Second, East Creek was chosen for its relatively steep banks and narrow stream bed. This enabled all work to be completed from a ladder suspended across the channel. Disturbance of the stream bed could be mapped, tracers reset and invertebrate samples taken without unnecessary disruption of the stream bed and invertebrate community. This was considered essential in a study of this nature to reduce any confounding disturbances.

**Study Period**

The field component of the study was undertaken from early August 1999 until late March 2000. It was composed of two stages, a summer stage during which river levels were at their lowest, and an early autumn / winter stage during which episodic flooding took place.

During the low flows of summer the substrate in Reach 2 was manipulated and the stream surveyed, photographed and mapped. Early autumn, two months after sediment manipulation, baseline invertebrate samples were collected. This period served to establish pre-flood conditions.

The flooding season extended from October 30th, the date of the first flood, until late March. During this time 11 floods occurred on East Creek, ranging in discharge from 179.73 l/s to 1385.4 l/s (Figure 3.1). However, due to time constraints, not all floods were monitored. Bedload transport from Reaches 1 and 2 was sampled from nine events, and the spatial distribution of bed disturbance was correspondingly mapped from seven of them. Due to time constraints on
Figure 3.1 Peak discharge events and invertebrate and bedload sampling times over the study period. Invertebrate flood sampling was carried out 33 hours after the October 31 flood. Winter base flow was approximately 12 l/s.
resetting tracers after each flood, disturbance mapping could not be achieved for every individual event. Invertebrate samples were taken immediately after the first major flood on October 31st.

**Surface Sediment Manipulation in Reach 2**

During July 1999 all rock clusters and structures in Reach 2 were broken up by turning over large rocks and breaking apart imbricated and interlocking clasts. Care was taken to ensure that only the surface layer was disturbed, and minimally so, so as not to change the overall character of the size distributions of surface and subsurface sediment. This was completed during low flows of only 2.5 l/s. Some surface coarsening may have taken place during the artificial disturbance as a result of disturbance of fines into the water column, although it is assumed to have been minimal due to the extreme low flows. The bedform structures in Reach 1 were left untouched.

**Spatial mapping of bed disturbance**

The main objective of the study required event-based mapping of small scale spatial variations in bed movement. This is difficult to achieve during peak discharges when turbid high flows make it almost impossible to observe and record substrate movement. Furthermore, detection and mapping had to be achieved in a non-invasive manner, so as not to disrupt the invertebrate community.

Recent ecological studies attempting to characterize aspects of substrate disturbance have used tracers seeded artificially within the stream bed (e.g. Death 1995; Townsend et al. 1997a). If placed in a natural position, they can be used effectively to identify areas of the bed mobilized during a flood without directly disrupting the invertebrate community. Strayer (1999) successfully seeded tracers within a grid pattern across the stream bed to assess the influence of bed disturbance on unionid mussel populations. Tracers have also been used effectively to
determine travel distances of individual particles (e.g. Hassan *et al.* 1991), estimates of bed material transport (e.g. Haschenburger 1996), influence of clast shape, size and density on entrainment (Schmidt and Gintz 1995), and burial depths of transported material (e.g. Hassan and Church 1994). They represent the only effective means of mapping disturbance of the bed without considerably disrupting the invertebrate community.

Tracers were employed in this study along the same lines as Strayer (1999), placed systematically across the entire stream bed in a grid pattern, although in far greater densities than Strayer (1999) and therefore providing better resolution.

*Tracer Characteristics:*

A total of 1200 rocks between 32 and 45 mm of a lithology and shape similar to those found in East Creek were collected from a neighboring stream. Four hundred rocks were then painted blue, another 400 red and the rest yellow, after which a black dot was then painted on the high point of each tracer. As only surface disturbance was to be assessed, magnetic tracers recoverable from beneath the surface were not required.

The choice of tracer size was somewhat arbitrary, although limits were provided by two conditions. First, they could not be too large in comparison with the natural bed material (<D₅₀ of natural surface material). If so, bed movement affecting the invertebrate community might go undetected. Second, if too small, movement of the tracer particles might not represent a significant disturbance to the invertebrate community, as they might be winnowed out from around the main framework of the bed (i.e., fine gravel or sand). In Reach 1 the tracers represented a particle fraction between D₁₈ and D₂₈, in Reach 2 they corresponded to a fraction between D₁₆ and D₃₃, and in Reach 3, between D₃₄ and D₅₄.
Positioning and Location of Tracers:

To accurately locate, identify and map the disturbance of tracers a grid was established over the stream bed, with two tracers positioned within each cell of the grid. The grid was established by erecting numbered transects across the stream at 40 cm intervals along the three study reaches. On each bank wooden stakes were driven to mark each transect. To define position across the stream, the distance along each transect from a reference stake on the bank to the edge of the stream channel was measured and recorded (Figure 3.2a). From the channel edge at this location a standard distance of 40 cm along each transect was used to establish position over the stream bed, allowing each 40 by 40 cm (0.16 m$^2$) cell to be positioned and identified over the bed in a non invasive manner. The ladder suspended across the stream bed enabled work to be carried out within the channel without disturbing the substrate.

Thirty nine transects were established in each of Reaches 1 and 2, with between three and seven cells established along each transect, depending on the width of the channel. A simple system was used to locate oneself within the grid, a number from 1 to 39 designating the transect, and a letter from A to G designating location of the cell across the stream. A total of 219 cells was established across Reach 1 and 189 across Reach 2. Eight transects were established across the riffle section in Reach 3, with a total of 36 cells.

Justification of Cell Size:

A minimum area of 0.16 m$^2$ was required for each invertebrate sample. One sample was to be taken per cell, therefore 0.16 m$^2$ represented a minimum area. This area was regarded as sufficiently small to permit detailed mapping of bed disturbance in relation to bedform structures, as initial observations of the stream bed showed structures such as partial stone cells and pockets of loose gravel to be no smaller than 0.16m$^2$. 
**Deployment of Tracers:**

Two tracers of the same color were placed within each cell either by removing a rock of similar size and replacing it, or by nestling the tracer into the bed. Every stream-wise neighboring cell was assigned a different color, reducing the likelihood of misidentification of disturbance, i.e. when a tracer rolled into a cell immediately downstream. All deployment was carried out from the ladder suspended across the stream. Tracers were positioned with the black dot facing skyward, clearly visible. Ideally one would have allowed for natural seeding of tracers, however it would have been difficult to subsequently define and control bias in the location of each cell, as positioning would ultimately be random.

A total of 438 tracers was planted in reach 1, 378 in reach 2, and 72 in Reach 3 at a density of slightly over 12 tracers per square meter of stream bed (Figure 3.2b).

**Tracer Disturbance:**

Three categories of tracer disturbance were recognized:

- Both tracers disturbed (maximum disturbance)
- One tracer disturbed (minimum disturbance)
- Tracers undisturbed (no disturbance)

The streambed in all reaches was typically examined within 12 hours after a peak discharge using the ladder suspended across the stream. Each cell was examined and a disturbance category assigned to each tracer. Movement of the tracer within the cell was determined by the position of the black dot. While there is a slight probability of a tracer flipping 360 degrees and realigning itself with the black dot in the same position, the probability of both tracers flipping and realigning is considered to be negligible. As such, for this study a cell was considered
a) Grid set-up

b) Tracers and rocks marked *in situ* along Reach 2

**Figure 3.2** Study reaches: measurement arrangements
'disturbed' only if both tracers had moved. The probability of misidentifying a 'disturbed' cell is therefore assumed to be negligible. This convention represents an operational definition only. It is adopted to identify those cells that experienced near-complete bed disturbance, from which macroinvertebrate samples were taken (see later this chapter, page 40).

After mapping of tracer disturbance had been carried out all disturbed tracers were carefully collected using the ladder, and reset in their appropriate cells. Lost tracers were replaced. During the study period close to 25% of the tracers were lost. The majority of losses occurred during the major December 15 flood and most from Reach 3.

**Rocks Marked In situ**

To assess the movement of large key stones, emergent rocks in reaches 1 and 2 were marked *in situ* with white glue during summer low flows. No size criterion was used to define which emergent clasts were to be marked. However, if a particle moved slightly while attempting to mark, then it was considered unstable and either not marked at all or disregarded. Marked particles were therefore considered to be key stones as they tended to represent the stable portion of emergent clasts. The procedure of marking *in situ* was used in conjunction with the tracers to acquire a clear picture of the spatial extent of bed disturbance and the maintenance of bedform structures and clusters. Many of the marked rocks in Reach 1 represented key constituent particles within the rock structures and clusters (Figures 2.6). In all, 122 rocks were marked within Reach 1 and 100 within reach 2.

**Mapping Disturbance:**

The disturbance of the large rocks was noted and recorded after every flood event (except the November 10 event) by carefully viewing the streambed from the suspended ladder and noting the position of the rocks relative to detailed maps of the stream bed and photographs. An attempt
was made to map the new position of disturbed rocks, however this was only partially successful as the rocks, marked only with a white dot, could often not be distinguished from one another. This was attempted only after the October 31st flood. No attempt was made to remark rocks or relocate them, so as not to disturb developing bedform structures.

**Bedload**

The measurement of bedload transport from Reaches 1 and 2 represents a key aspect in examining the structural effect on bed disturbance. While it provides little indication as to the spatial distribution of bed disturbance, important in identifying potential invertebrate refugia, it does provide an indication of the overall effect of bedform structures in restraining particles, and provides some idea of disturbance intensity. It therefore complements the spatial mapping of bed disturbance.

**Installation of Pit Traps:**

Bedload transport was measured by pit traps installed in the channel bed. These collected the total mass of bedload moved over a given event, thus providing gross yields rather than instantaneous transport rates. While data can not be used to investigate small-scale temporal variations in transport rates, samples will give estimates of total transport loads and grain size distributions per event, hence an index of total disturbance.

Two bedload traps were installed across the full width of the streambed, one each at the downstream end of both Reaches 1 and 2 (Figure 2.2) where the bulk sediment samples were taken from. Each trap consisted of a 220cm by 25cm by 25cm steel compartment sunk into the bed with the top flush with the surface. Two slightly smaller, removable steel compartments were placed inside to collect the bed load. Each of these compartments were further subdivided
into two, giving a total of four samples across the width of the stream (Figure 3.3a). Such a
design enabled the traps to be emptied easily and replaced after each event with no loss of
sediment. Each trap had a volume of 0.1375 m$^3$, and over-filling occurred only once in Reach 1,
after the December 15 event, and twice in Reach 2 after the events on October 31 and December
15.

**Sampling:**

The bedload from nine flood events was collected and analyzed. During the study period the
traps were inspected within 12 hours after most events larger than 150 l/s. This discharge served
as the flow threshold defined in the study as a ‘flood’, below which no detectable bedload was
produced. On only two occasions was it not possible to empty the traps immediately after an
event. On both these occasions the load consisted of the yield of two separate events of varying
magnitude (December 2 and 6, and December 13 and 15, see Figure 3.1 and Table 4.2).

The load from each of the four compartments of each trap was removed, sieved and weighed
separately from all events except those on November 8 and November 22. As very little
sediment was produced from these events, the load from each compartment was pooled before
analysis. Sediment was weighed and sieved in the field at 1 phi intervals to a size fraction of 16
mm. The gravel fraction less than 16 mm was then weighed and subsampled to between 5 and 6
kg, as per bulk sampling. This fraction was taken back to the laboratory to be sieved and
weighed following the dry sediment method at 1 phi class intervals to 4 mm, and 0.5 phi class
intervals from 4 mm to 0.063 mm.

**Hydraulic Measurements**

Discharge as recorded from the two gauging stations was not used directly in the analysis. While
no significant surface inputs are evident within the 500 m section of creek from the study reaches
a) Channel spanning pit trap, Reach 1 (turn sideways for cross-channel view)

b) Sampling invertebrates from ladder suspended across the creek

Figure 3.3 Sediment transport after the 31 October flood and invertebrate sampling. Flow in both photographs is from the bottom to the top. The white strip across the upstream edge of the pit trap was to stop sand penetrating between the moveable compartments and the casing.
to the main gauges on the creek, subsurface inputs may result in different discharges at the two
catchment locations. However, discharge as calculated from the gauges does provide a good
relative estimate of the magnitude and return interval of the floods experienced during the study
period.

Stage Recorders:

Three stage gauges were installed along the length of the study reach comprising reaches 1 and 2
prior to the first flood (Figure 2.2). Two more gauges were placed in Reach 3, one each at the top
and bottom of the riffle section. Each gauge consisted of a wooden stake driven into the substrate
with a hollow perspex tube open at both ends attached to the outside. One end was buried
slightly in the substrate with a series of holes near the bottom to allow water to enter the tube.
The other end was fixed above the water line. Ground cork was placed inside the tube to mark
the maximum water height obtained from a peak discharge, which was then recorded against a
graded tape fixed to the outside of each stake. The height of each gauge above a standard datum
point was established using a theodolite and stadia, enabling relative water heights for a given
flood peak to be estimated. The relative position of each gauge permitted water surface slopes
for each flood event to be calculated for all study reaches.

As a measure of confidence the water surface height at each stage gauge from a peak discharge
of 411 l/s was surveyed using a theodolite and stadia during the November 10 flood. Good
correspondence was observed between water surface slope as calculated using stage gauges and
that surveyed (Table 3.1). The difference in slope estimates takes into account both an error
associated with reading the gauge (correspondence between water level inside the tube and true
water level outside), an error associated with water surface position measurements during the
flood, and an error associated with estimates of the relative heights between the gauges.
Table 3.1 Water surface slope as estimated from stage gauges and detailed surveying using a theodolite and stadia. Estimated during a moderate flood of 411 l/s.

<table>
<thead>
<tr>
<th></th>
<th>Estimate from Stage</th>
<th>Estimate from Theodolite and Stadia</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach 1</td>
<td>0.019</td>
<td>0.020</td>
<td>0.001</td>
</tr>
<tr>
<td>Reach 2</td>
<td>0.026</td>
<td>0.024</td>
<td>0.002</td>
</tr>
<tr>
<td>Reach 3</td>
<td>0.029</td>
<td>0.024</td>
<td>0.005</td>
</tr>
</tbody>
</table>

**Velocity Profiles:**

Velocity profiles were measured in the field during a flood peak on October 30th. This flood represented a minor peak preceding the first large flood on October 31st. During the time in which profiles were taken between Reaches 1, and 2 and 3 a small rise in discharge was recorded. Profiles from each reach were therefore taken at slightly different discharges, corresponding approximately to 330 l/s over Reach 1 and 390 l/s over Reaches 2 and 3. Discharge was checked both at the start and completion of measurements from each reach. Measurements were generally taken during periods of constant discharge, although a slight rise was recorded during measurements from Reach 1.

While this flood was considered moderate, peak discharge was close to that for particle entrainment from Reaches 2 and 3. Tracers from several cells within Reach 2 and the majority from the riffle section in Reach 3 were mobilized. Profiles were taken using an electromagnetic meter housed in a streamlined epoxy molding, mounted on to a wading rod. The instrument was moved up and down the wading rod to the desired depth and oriented in the streamwise direction before reading. Generally five measurements were taken in each profile, with the majority taken.
in the lower 60% of flow. A five-second average at each point height was used for all field readings. This average was taken four times at each point for 20 seconds total record. While the recording period is short, it was considered necessary given the spatially intensive sampling.

A total of 20 profiles were taken across four transects in Reach 1, 17 across five transects in Reach 2 and 7 profiles across three transects in Reach 3 (for location see Figure 4.2). Velocity profiles were taken over both disturbed and undisturbed cells from reaches 2 and 3. No cells were disturbed in Reach 1.

**Macroinvertebrate Sampling**

All benthic samples were taken from a ladder suspended across the stream (Figure 3.3b), allowing access to the substrate without disturbing nearby particles, structures or clusters. Samples were taken using a standard Surber sampler with a 500 μm mesh net. The sampler had an area of 0.16 m$^2$, allowing one sample per cell. The substrate was disturbed by hand to a depth of 10 cm for a standard 30 seconds. All samples were preserved in the field in 5% formalin.

**Baseline Sampling:**

Five grid cells were randomly chosen from each of Reaches 1 and 2 on October 6 and sampled. However, if a nominated cell fell across constituent particles from an obvious cluster or bedform structure, or marked rock, it was discarded and another cell was selected for sampling. This might have introduced some bias as large constituent particles, typically D$_{84}$ or larger, were avoided. Indeed at small scales invertebrates can display microhabitat preferences for particular substrate sizes (Jowett et al. 1991). However, as such bias was maintained on all sampling occasions and within all reaches it is not considered to be of concern in this study. Prior to baseline sampling no flooding had occurred, as such these samples reflected summer base flow communities.
Five baseline samples were collected from the riffle within Reach 3 on October 18. Due to the small number of total cells within this reach these samples were taken just above the first transect, but still within the same riffle. Due to the proximity of the grid, less than 1 metre from the first transect, I believe the invertebrate populations were no different than those under the grid (location of post-flood samples).

**Disturbance Sampling**

Macroinvertebrate samples were taken 33 hours after peak discharge from the first flood event, on October 31\textsuperscript{st}. Five disturbed cells and five undisturbed cells were chosen randomly and sampled from all reaches. For the purpose of macroinvertebrate sampling, a cell in which both tracers remained intact was defined as 'undisturbed' and a cell in which both tracers had been disturbed, either moving completely out of or remaining within the cell, was defined as 'disturbed'. If a selected cell had already been sampled during baseline sampling, a different cell was chosen. Exactly the same sampling methodology and equipment was employed as for baseline sampling.

**Sample Processing and Identification:**

Invertebrate samples were washed and sieved in the laboratory before sorting. The size fraction >2 mm completely sorted for all samples. Large 0.5 mm – 2 mm fractions were sub-sampled to 25% or 50%. Sub-0.5 mm material was not processed since the sampling net had an 0.5 mm mesh, so that smaller specimens would have been only capriciously sampled. When sub-sampled, a minimum requirement of 100 individuals was maintained to ensure adequate representation of the common taxa. If this was not achieved another portion of the sample was sorted. All small samples between 0.5 and 2 mm and all sample fractions > 2 mm were completely sorted. Specimens were preserved in 80% alcohol.
All common taxa and those easily identified were identified to family using the keys in Merritt and Cummins (1984). This was a necessary compromise between the value of data obtained and the time involved to identify taxa to lower levels. However, most major resistance and resilience traits considered important for maintenance in a frequently disturbed environment, such as basic body form and mobility (Townsend and Hildrew 1994), appear to be expressed reasonably well at the family level (e.g. see Rader 1997; Usseglo-Polatera and Tachet 1994). Three other taxa groupings were formed: unidentified cased Trichoptera, unidentified free living Trichoptera and Oligochaeta.
Chapter 4. Structural Restraint and Bed Disturbance in a Small Stream

Introduction

This chapter analyses the effect of structural restraint provided by particle clusters and bed form structures in East Creek on bed load transport and on the spatial distribution of bed disturbance. The first part of the chapter focuses on the analysis and description of the basic hydraulic parameters associated with each flood event. The second part centers on the analysis and description of the effect of particle restraint on the bedload and spatial distribution of bed disturbance.

Velocity Structure in the Study Reaches

The velocity profiles taken on October 30th provide an opportunity to assess the structure of the velocity field during a moderate flood. The profiles along each of Reaches 1, 2 and 3 were taken at slightly different discharges, approximately 330 l/s for Reach 1 and 390 l/s for Reaches 2 and 3. In Reaches 2 and 3 the discharge corresponded to slight bed mobility, as indicated by the disturbance of several tracers.

The flow near the bank in Reaches 1 and 2 was influenced by occasional bank roughness elements. This section of East Creek is relatively narrow and incised and large cobbles and root wads protrude from the bank in several places and distort the velocity field. Low velocity zones are created mid depth immediately downstream from the protrusions, although such effects are mainly limited to within 20 to 30 cm of the bank.

In mid channel, the vertical profile of velocity (u) appears to exhibit logarithmic form through the lower 60 - 80% of flow (e.g. Figure 4.1b) throughout the study reach. Due to the low
resolution provided from only 4 to 5 measurements per profile, identification of the logarithmic region (that portion of the profile that appears as a straight line on the $u/ln z$ plot) and its height ($z$) is only approximate.

In Reach 3 velocity structure was much the same, logarithmic profiles being evident throughout much of the flow depth in mid-channel.

**Bed Shear Stress**

**Local Shear Stress Estimates:**

Boundary shear stress in rivers cannot easily be measured directly, but can be estimated from observations of velocity profile geometry (Wilcock 1996). The velocity profiles taken on October 30th can be used to describe the variation of local bed shear stress throughout Reaches 1, 2 and 3.

The vertical variation of velocity with depth is used to provide an estimate of bed shear stress imposed on an area immediately upstream containing a few dozen of the coarser grains. From the von Karman-Prandtl law of vertical variation in horizontal velocity:

$$u = u^*/k \ln(z/z_0)$$  \hspace{1cm} (2)

where $u$ is the time averaged streamwise velocity at elevation $z$ above the bed, $k$ is von Karman's constant (typically taken to be 0.4), $u^*$ is the shear velocity and $z_0$ is the roughness height. Rearrangement of (2) shows that the slope of a least squares fitted line from the derivative $du/dlnz$ is equal to $u^*/k$. The bed shear stress, $\tau$, can then be estimated from the shear velocity as

$$\tau = \rho u^*^2$$  \hspace{1cm} (3)

where $\rho$ is the density of water.
Figure 4.1 Example of velocity structure a) near bank b) mid channel. Depth measurements are centimetres.
The von Karman-Prandtl equation can only be applied to the logarithmic portion of flow, which is typically observed to occur in the bottom 20 to 30% of the boundary layer (Biron et al 1998). In most field studies however, it is difficult to obtain multiple flow measurements close to the bed, i.e. within the bottom portion of the boundary layer, due to the minimum measurement height of velocity above the bed. This problem was accentuated in East Creek by relatively shallow depths, the mean being approximately 0.22 m (Table 4.1), while the velocity meter used in this study had a minimum practical height of velocity measurement of 0.038 m above the support base platform. As such, a profile-specific approach was taken whereby the portion of depth considered to be semi logarithmic in each profile was used in the calculation of bed shear stress. In the majority of cases this meant applying the von Karman-Prandtl law to between 60 and 70 percent of the flow, incorporating most measurement points. Those points obviously outside the logarithmic region were omitted from the calculation.

Roughness Height, $z_0$, is defined by:

$$z_0 = \exp(-a / b)$$  \hspace{1cm} (4)

where $a$ and $b$ are the regression coefficients obtained from the least squares line fitted to the relation $u(z)$, taking the form:

$$u = a + b \ln z$$ \hspace{1cm} (5)

Data from only those profiles that exhibited a logarithmic velocity distribution are shown in Table 4.1.

Considerable variation in local shear stress estimates exists in Reaches 1 and 2. Some variation can be attributed to channel morphology. The slightly elevated values through transects 5 to 11 in Reach 2 may be a result of a slightly higher energy gradient in this section of the reach (see
Figure 2.4). Localized flow turbulence may also result in locally variable shear stress. Indeed, the flow entering Reach 1 may not be totally uniform, influenced by the culvert and the slight channel constriction just downstream of the plunge pool (Figure 2.2).

The resultant error terms (Err $\tau$) for most estimates of shear stress are reasonable (Table 4.1). This error incorporates error terms associated with measurement of depth and estimates of mean horizontal velocity in so far as they contribute to the variance about the regression from which $u^*$ was determined. Estimates of shear stress however may also be affected by the minimum height of velocity measurement (Biron et al 1998). As this was fixed, varying the position of the meter relative to a clast effectively varies the relative height of the first velocity measurement. Biron et al (1998) demonstrated that increasing the first point of measurement was to decrease the estimated shear stress, as determined from the velocity profiles.

A further check on the reliability of bed shear stress estimates can be made by considering the relation between $z_0$ and $D_{50}$ of the surface material. Ferguson and Ashworth (1992) considered values of $z_0/D_{50}$ outside the range of 0.1-0.5 as suspicious. An attempt was made to estimate the local $D_{50}$ at each velocity profile location from the detailed photographs of the bed used to identify the bedform structures. However particle resolution below the water surface was generally very poor. As such a local estimate was not obtainable.

For all reaches the value of $D_{50}$ surface as obtained from bulk sampling (see Table 2.1) was therefore used. While this is not particularly desirable it does allow for a rough indication of bed shear estimate reliability. In considering the approximate nature of the data, only those shear stress estimates with a $z_0/D_{50}$ ratio considerably outside the range proposed by Ferguson and Ashworth (1992) are identified as unreliable. In all cases such estimates fall below the 0.1$D_{50}$ threshold by a factor of two or more (Table 4.1). These profiles may well have been taken over
Table 4.1 Velocity profile characteristics and estimated bed shear stress and roughness height. For profile locations see Figure 4.2.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Location</th>
<th>z max (m)</th>
<th>u* (m/s)</th>
<th>( \tau ) (N/m²)</th>
<th>( z_0 ) (mm)</th>
<th>Err (( \tau ))</th>
<th># Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td>a</td>
<td>0.20</td>
<td>0.437</td>
<td>188.2</td>
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<td>13.2</td>
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<td>0.218</td>
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<td>9.9</td>
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</tr>
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<td></td>
<td>c</td>
<td>0.22</td>
<td>0.214</td>
<td>45.5</td>
<td>12.3</td>
<td>8.4</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>a</td>
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<td>0.097</td>
<td>9.2</td>
<td>1.2</td>
<td>5.3</td>
<td>5</td>
</tr>
<tr>
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<td>8.5</td>
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<tr>
<td></td>
<td>c</td>
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<td>0.155</td>
<td>23.8</td>
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<td>7.8</td>
<td>4</td>
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<tr>
<td></td>
<td>d</td>
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<td>52.5</td>
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<td>0.080</td>
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<td>0.3</td>
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<td>5</td>
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<tr>
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<td>18.7</td>
<td>6.5</td>
<td>5</td>
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<tr>
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<td>8.7</td>
<td>5</td>
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<tr>
<td></td>
<td>b</td>
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<td>0.156</td>
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<td>7.3</td>
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<td>5</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.22</td>
<td>0.196</td>
<td>53.2 (±51.3)</td>
<td>15.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reach 2</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>5</td>
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<td>32</td>
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<td>5</td>
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<tr>
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<td>0.129</td>
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<td>2.5</td>
<td>8.4</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
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<td>4.6</td>
<td>4</td>
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<tr>
<td></td>
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<td>8.5</td>
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</tr>
<tr>
<td>11</td>
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<td>0.380</td>
<td>142.7 *</td>
<td>21.9</td>
<td>11.9</td>
<td>5</td>
</tr>
<tr>
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<td>a</td>
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<td>0.147</td>
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<td>6.4</td>
<td>4</td>
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<td>5</td>
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<tr>
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<td>a</td>
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<td>6.8</td>
<td>4</td>
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<tr>
<td></td>
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<td>0.151</td>
<td>22.6</td>
<td>4.1</td>
<td>3.4</td>
<td>5</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.23</td>
<td>0.21</td>
<td>68.8 (±46.1)</td>
<td>17.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reach 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>a</td>
<td>0.18</td>
<td>0.178</td>
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<td>5.4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>0.21</td>
<td>0.198</td>
<td>38.7 *</td>
<td>7.2</td>
<td>7.4</td>
<td>5</td>
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<tr>
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<td>0.202</td>
<td>40.9 *</td>
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<td>5</td>
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<tr>
<td>5</td>
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<td>0.092</td>
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<td>4</td>
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<tr>
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<td>4</td>
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<tr>
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<td>8</td>
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<td>5.1</td>
<td>5</td>
</tr>
<tr>
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<td></td>
<td>0.19</td>
<td>0.155</td>
<td>30.1 (±10.6)</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- * - Profiles over disturbed cells
- # - \( z_0/D_{50} \) outside the range of 0.1-0.5, considered as suspicious (Ferguson and Ashworth, 1992).

\[
\text{Err (}\tau\text{)} = \sqrt{2\text{err }u^*}, \quad \text{where err } u^* \text{ is the error estimate from the slope of the regression } u / ln z
\]
the top of large clasts. Biron et al (1998) demonstrated that increasing the height of first point of measurement was to decrease estimated shear stress, with roughness heights falling below the 0.1D_{50} threshold.

Profile locations for Reaches 1 and 2 are shown in Figure 4.2, along with the spatial distribution of bed disturbance generated from the October 31\textsuperscript{st} flood. In Reach 1 there appears to be little correspondence between the distribution of bed disturbance along each transect and local shear stress values. This comparison is very coarse due to limited data, however it does indicate that the spatial distribution of bed disturbance in this reach maybe controlled by parameters other than simply localized velocity. This matter is discussed later in the chapter. In Reach 2 the slightly elevated shear stress values across transects 5 to 11 may be a result of the slightly higher energy gradient in this section of the reach (Figure 2.4). The higher average bed shear stress in this section of the reach also appears to correspond with the distribution of maximum bed disturbance (see Figure 4.2).

In Reach 3 shear stress corresponds reasonably well with bed topography. Measurement ‘a’ (lower estimated shear stress values) taken along transects 2 and 5 (see Table 4.1) were taken over a small bar emergent only during low summer flows. The slightly reduced depths and velocities over the bar resulted in lower estimates of shear stress. Measurement ‘c’ along transects 2 and 5 were taken from the thalweg which was located close to the left bank. Correspondingly estimates of local shear stress in this region are greater.

*Reach Averaged Bed Shear Stress:*

An estimate of mean bed shear stress for each reach can be obtained from the du Boys formula

\[ \tau_0 = \rho g R S \]  

(6)
where $\rho$ is the density of water, $g$ is the acceleration due to gravity, $R$ is the hydraulic radius, and $S$ is the energy slope. Du Boys formula is strictly applicable only for uniform flow. Its use inappropriate for channels with marked variations in bed topography. Both Reaches 1 and 2 show only minor variations in bed topography and, despite the presence of occasional large bed elements, flow can be considered uniform. During high flows, depths exceeded all particle diameters and flow in the mid channel can be regarded as semi-logarithmic. In Reach 3 the small bar near the right bank, emergent only during low flow, resulted in a small redirection of flow towards the right bank. Local shear stress estimates vary across the channel in correspondence with the general bed topography and dominant flow thread.

Ideally hydraulic radius ($R$) should be corrected for the sidewall. However, this was not possible for every event as real time velocity measurements were taken during only two peak discharges (November 10 and December 15, when only one transect in Reach 1 was taken).

To therefore maintain consistency between calculations, hydraulic radius ($R$) as defined by:

$$R = \frac{wd}{2d+w}$$

was used in equation (6) where, $w$ is the wetted width and $d$ is the average cross-sectional depth. Stream wetted width and average cross-sectional depth were estimated from detailed cross sections at each stage gauge.

As a measure of confidence a test calculation of reach averaged bed shear correcting for sidewall effects was undertaken using the deepest flow, occurring on December 15. This can then be compared with that calculated using $R$ as defined by equation (7). This calculation is detailed below.
Figure 4.2 Surface sediment disturbance after October 31 flood. Small arrows (→) indicate locations of velocity transects. Letters (a,b,c,d) indicate locations of measurement. (see Table 4.1 for details).
Using the velocity measurements in Reach 1 from the peak discharge on December 15 hydraulic radius of the bed, corrected for sidewall effects, $R_b$, can be estimated using the Manning equation following the Einstein (1942) method,

$$ n = (R^{2/3}S^{1/2})/V $$  \hspace{1cm} (8)

where $n$ is the Mannings number and $V$ is the mean velocity.

Now

$$ R_b = (A - 2dR_w) / (2d + w) $$  \hspace{1cm} (9)

where the term $(A - 2dR_w)$ is the proportion of the cross sectional area occupied by the bed, $A$ is the cross sectional area, $d$ is the depth, $w$ is the width and $R_w$ is the hydraulic radius for the sidewalls.

Following the Einstein method, $V$ (velocity) and $S$ (slope) are assumed to be the same for the wall and the rest of the flow. Therefore rearranging the Manning equation (8),

$$ R_w = (Vn_w/S^{1/2})^{3/2} $$  \hspace{1cm} (10)

where $n_w$ is the Manning number for the wall.

From equation (8) the Manning number for the bed was calculated to be 0.1005 ($V = 0.77 \text{ m/s}, S = 0.02$ and $R = 0.405$, using $w = 3.67 \text{ m}$ and $d = 0.520 \text{ m}$). Assuming the same Manning $n$ for the wall as for the bed, we calculate $R_w = 0.405$ from equation (10). Substituting this into equation (8) we calculate $R_b$ to be 0.316, where $A = 1.91 \text{ m}^2$.

Substituting $R_b$ for $R$ in equation (6) we see that $\tau$ during peak discharge on December 15 corrected for sidewall effects for Reach 1 is approximately 77.42 $(\pm 7.3)$ N/m$^2$. Using the value for $R$ as calculated in equation (7), $\tau$ is calculated to be 109.2 $(\pm 7.3)$ N/m$^2$. Due to this large
discrepancy reach averaged shear stress as calculated using R (not corrected for sidewall effects), should therefore be interpreted with caution. However, as bank roughness did not appear to differ substantially between Reaches 1 and 2, a comparative basis is still maintained.

**Bed Shear Estimates**

Reach averaged bed shear stress and total bedload from Reaches 1 and 2, and reach averaged bed shear stress for Reach 3, for each flood peak are shown in Table 4.2.

The averaged bed shear stress values obtained from the velocity profiles for Reaches 1, 2 and 3 are 53.2 (± 51.3) N/m², 68.8 (± 46.1) N/m² and 30.1 (± 10.6) N/m² respectively. One standard deviation is shown in parenthesis (Table 4.1). Reasonable correspondence exists between the estimate from the velocity profiles and that calculated from equation (5) for Reach 1 (Table 4.2). The mean value obtained from the velocity profiles for Reach 2 however is comparatively high (Figure 4.3), due in part to the outlying values in transects 5 and 11. The average value of 30.1 ± 10.6 N/m² for Reach 3 obtained from the velocity profiles is slightly under the reach averaged bed shear from equation (5), at 35.0 ± N/m². This may be due to the presence of the small bar, possibly creating form drag. The mean bed shear as calculated from equation (5) includes a component corresponding to larger scale form drag, whereas bed shear as calculated from near-bed velocity profiles does not.

A reasonably linear relation between discharge and reach averaged bed shear stress (equation 5) for Reaches 1 and 2 is illustrated in Figure 4.3. This corresponds with the flume-like nature of these reaches. The steep banks contain the flow during most flood events. It is clear that the mean bed shear stress estimated from the velocity profiles for Reach 2 falls outside the range of that expected from the linear relationship.
Table 4.2 Reach averaged bed shear stress estimates and total bedload for each flood event monitored.

<table>
<thead>
<tr>
<th>Date</th>
<th>Q (l/s)</th>
<th>Slope</th>
<th>( \tau_0 ) (N/m²)</th>
<th>b (kg)</th>
<th>Slope</th>
<th>( \tau ) (N/m²)</th>
<th>b (kg)</th>
<th>Slope</th>
<th>( \tau ) (N/m²)</th>
<th>b (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 31</td>
<td>674</td>
<td>0.02</td>
<td>65.1 (± 7.1)</td>
<td>133.21</td>
<td>0.023</td>
<td>68.3 (± 8.3)</td>
<td>230.93</td>
<td>0.029</td>
<td>83.3 (± 9.5)</td>
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<tr>
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<td>237</td>
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<td>47.3 (± 7.3)</td>
<td>0.62</td>
<td>0.024</td>
<td>45.0 (± 7.6)</td>
<td>2.26</td>
<td>0.024</td>
<td>35.2 (± 5.6)</td>
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<tr>
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<td>51.8 (± 7.2)</td>
<td>6.99</td>
<td>0.024</td>
<td>56.4 (± 8.2)</td>
<td>16.97</td>
<td>0.024</td>
<td>49.0 (± 6.9)</td>
<td>N/A</td>
</tr>
<tr>
<td>Nov 12</td>
<td>396*</td>
<td>0.02</td>
<td>51.2 (± 7.2)</td>
<td>12.41</td>
<td>0.023</td>
<td>55.5 (± 8.0)</td>
<td>11.54</td>
<td>0.024</td>
<td>48.8 (± 6.9)</td>
<td>N/A</td>
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<tr>
<td>Nov 22</td>
<td>179</td>
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<td>31.7 (± 6.0)</td>
<td>0.68</td>
<td>0.024</td>
<td>39.3 (± 8.1)</td>
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<td>0.034</td>
<td>31.2 (± 5.7)</td>
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<tr>
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<td>49.5 (± 7.2)</td>
<td>4569</td>
<td>0.023</td>
<td>46.8 (± 7.4)</td>
<td>1.05</td>
<td>0.023</td>
<td>37.3 (± 5.4)</td>
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</tr>
<tr>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
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<td>55.5 (± 8.0)</td>
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<tr>
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<td>0.023</td>
<td>106.2 (± 9.5)</td>
<td>360.87</td>
<td>0.051</td>
<td>312.3 (± 34.3)</td>
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</tr>
<tr>
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<td>49.5 (± 7.2)</td>
<td>4.77</td>
<td>0.023</td>
<td>46.8 (± 7.4)</td>
<td>3.47</td>
<td>0.023</td>
<td>37.3 (± 5.4)</td>
<td>N/A</td>
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</tbody>
</table>

\( \tau \) error, shown in parenthesis, was calculated from \( \sqrt{(\text{depth error})^2 + (\text{slope error})^2} \). Error associated with depth was due to placement of the measuring staff on a variable substrate. An error of 0.5D for each reach was accepted. The main error associated with calculation of water slope was due to an error associated with reading peak discharge heights from the stage gauges due to fluctuating flow. This was accepted to be ± 1 cm, a conservative value from experience in reading the gauges during peak flow. Note, no bedload measurements available for Reach 3.

* Discharge during which velocity profiles were taken in Reaches 2 and 3.
# Discharge during which velocity profiles were taken in Reach 1.
Figure 4.3 Relation between Discharge and bed shear stress for Reaches 1 and 2. One deviation is shown for reach averaged shear as estimated from velocity profiles (see Table 4.1)
**Bedload**

The results presented here are for bedload from reaches 1 and 2, compiled over eight flood events.

During the study period a total of 427 kg of sediment was sampled from trap 1 (at the base of Reach 1), and 630 kg from trap 2 (at the base of Reach 2) (Table 4.2). The bulk of the sediment in both reaches was mobilized from just two events, the first flood of the season on October 31\textsuperscript{st} and a large flood with a return interval of 4.5 years, occurring on December 15\textsuperscript{th}. Generally a greater amount of sediment in each event was sampled from Reach 2, although on both November 24 and December 6 almost 4 times the weight of sediment was sampled from Reach 1. These floods may have accessed a sediment source outside that of the immediate bed, such as a collapsed bank, resulting in a sediment pulse through Reach 1.

Except for the flood on December 15\textsuperscript{th}, bedload distributions from Reach 1 have a typical unimodal grain size distribution dominated by the fine sand fraction (e.g. Figure 4.4). The load resulting from the large flood on December 15 however was clearly bimodal, composed of both a fine sand fraction and a coarse gravel fraction approximately 90 to 128 mm, similar to D\textsubscript{84} of the surface material. The distributions from Reach 2 are complicated by the possible development of bed form structures over the study period, described later. However, the distributions from the floods on October 31\textsuperscript{st} and December 15 both show a slight bimodal distribution similar to that from Reach 1 on December 15 (Figure 4.4), although not as pronounced possibly due to a partial loss of the sand fraction trapped at the base of Reach 1. The coarse gravel fraction from both of these floods corresponds to a fraction similar to D\textsubscript{84} of the surface material in Reach 2, approximately 90 mm to 128 mm (Figure 4.4).
October 31

Figure 4.4 Bedload grain size distributions (absolute scale).

Reach 1

Reach 2
November 10

![Graph showing weight distribution for Reach 1 and Reach 2 on November 10.](image)

November 12

![Graph showing weight distribution for Reach 1 and Reach 2 on November 12.](image)

December 6

![Graph showing weight distribution for Reach 1 and Reach 2 on December 6.](image)

**Figure 4.4 cont’d.**
The loads on both December 6 and December 15 are each composed of two separate events. While this may have considerably elevated the total load on December 6, as the two events were of a similar magnitude (Table 4.2), it more than likely did not significantly alter the sediment size distribution. Similarly one would not expect the load from the December 15 flood to have been significantly influenced by the preceding flood on December 12. While the flood of December 12th was the third highest flow recorded during the study period it was still well under half the magnitude of that on December 15. In the following analyses the transported grain size distributions from the combined loads are therefore associated with the reach averaged bed shear stress estimates corresponding to the flood peaks on December 6 and 15 respectively.

**Bedload Transport Rates:**

An event-averaged transport rate was obtained from an estimate of the time of competent flow from each hydrograph (estimated to be the time during which flow exceeded 150 l/s) and the known total weight of bedload from each event (Table 4.3). For the total loads collected on December 6 and 15 the time of competent flow includes the preceding flows.

**Table 4.3** Estimated bedload transport rates for events with peak flow larger than 170 l/s.

<table>
<thead>
<tr>
<th></th>
<th>Reach 1 $q_b$ (kg/hr)</th>
<th>Reach 2 $q_b$ (kg/hr)</th>
<th>$q_b1/q_b2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 31</td>
<td>674</td>
<td>3.42</td>
<td>5.92</td>
</tr>
<tr>
<td>Nov 8</td>
<td>237</td>
<td>0.10</td>
<td>0.37</td>
</tr>
<tr>
<td>Nov 10</td>
<td>411</td>
<td>0.22</td>
<td>0.53</td>
</tr>
<tr>
<td>Nov 12</td>
<td>396</td>
<td>0.33</td>
<td>0.3</td>
</tr>
<tr>
<td>Nov 24</td>
<td>328</td>
<td>0.25</td>
<td>0.06</td>
</tr>
<tr>
<td>Dec 06</td>
<td>394</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>Dec 15</td>
<td>1385</td>
<td>4.24</td>
<td>6.12</td>
</tr>
<tr>
<td>Mar 03</td>
<td>328</td>
<td>0.15</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Transport rates were clearly higher in Reach 2 during the first three floods. During subsequent floods the event based transport rate declines rapidly. This was due to a combination of sample dependence, described below, and the development of particle restraint in Reach 2, discussed later in this chapter.

**Sample Dependence:**

Towards the end of November Reach 2 was starved of a fine sediment input. The majority of sediment transported through Reach 1 during November was dominated by the fine sand fraction. This fraction was trapped and contributed to the load from Reach 1, but did not replenish Reach 2. The large reduction in transport rate observed in Reach 2 is partly a result of this (Table 4.3). This is well illustrated in considering the three floods of similar magnitude, occurring on November 10, 12 and December 6 (Table 4.2). Little change in the distribution of the sand fraction from Reach 2 occurred over the first two floods but, by December 6, there was a noticeable reduction compared with Reach 1 (Figure 4.4). Indeed on December 6 Reach 1 yielded slightly over seven times as much sand as Reach 2 (Table 4.4). During this flood, the event averaged transport rate was five times higher in Reach 1.

A possible sample dependence of the fine sediment fraction however does not affect our ability to study rates of structural development in Reach 2 subsequent to the October 31 flood. While a reduction in fine sediment would likely serve to decrease the total load in this reach relative to Reach 1, the dominant effect of structural development is actually one of limiting all size fractions, including the coarse fractions (Church *et al* 1998). As coarse gravel does not represent a significant fraction of the load emanating from Reach 1 during most events (e.g. Figure 4.3), the samples of this fraction can be considered as roughly independent. Indeed, for fractions coarser than 4 mm yields from Reach 2 are far greater than those from Reach 1, at least for the first three gravel mobilizing floods, October 31 and November 10 and 12 (Table 4.4).
Table 4.4 Total yield (kg) from major sediment classes for Reaches 1 (R 1) and 2 (R 2) from the first flood of the season on October 31st, and three subsequent events of similar magnitude.

<table>
<thead>
<tr>
<th></th>
<th>October 31st (675 l/s)</th>
<th>November 10 (410 l/s)</th>
<th>November 12 (395 l/s)</th>
<th>December 6 (395 l/s)</th>
<th>Events of a similar magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R 2</td>
<td>R 1</td>
<td>Ratio</td>
<td>R 2</td>
<td>R 1</td>
</tr>
<tr>
<td>Sand (&lt; 2mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.6</td>
<td>71.1</td>
<td>1.3</td>
<td>2.38</td>
<td>5.4</td>
</tr>
<tr>
<td>Granules (2-4 mm)</td>
<td>17.0</td>
<td>30.6</td>
<td>1.2</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>&gt; 4mm (&gt; granules)</td>
<td>193.5</td>
<td>42.72</td>
<td>4.5:1</td>
<td>27.8</td>
<td>1.2</td>
</tr>
<tr>
<td>&gt; 32 mm (&gt; Pebbles)</td>
<td>138.6</td>
<td>7.7</td>
<td>18:1</td>
<td>8.7</td>
<td>0.2</td>
</tr>
<tr>
<td>&gt; D50 surface</td>
<td>99.3</td>
<td>2.93</td>
<td>33:1</td>
<td>5.9</td>
<td>0</td>
</tr>
<tr>
<td>&gt; D84 surface</td>
<td>45.9</td>
<td>1.9</td>
<td>24:1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&gt; D99 surface</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

D50 surface
Reach 1 = 67 mm
Reach 2 = 59 mm

D99 surface
Reach 1 = 178 mm
Reach 2 = 164 mm

D84 surface
Reach 1 = 107 mm
Reach 2 = 100 mm
For the coarser fraction of the bedload (>4mm) the culvert above Reach 1 (Figure 2.2) likely acts as a sediment sink during most flood events, trapping coarse material. But for floods of a magnitude similar to or larger than that on December 15, coarse gravel is more than likely mobilized through the culvert into Reach 1. However for the majority of floods during the study period it is reasonable to assume that the sediment transport of the coarser fraction into Reach 1 was actually no different to that of Reach 2. For this fraction both reaches 1 and 2 can be considered to be like non re-circulating flumes. This fortunate characteristic allows the effect of structural development in Reach 2 to be investigated.

**Effect of Surface Structure on Bed load**

No bed load measurements were taken prior to the artificial break up of clusters and structures in Reach 2. One therefore has to assume a similar bed load for each reach prior to the experimental manipulation. This is justified given the similar bed material grain size distributions (Figure 2.5), water surface slopes and mean bed shear values (Table 4.2), and the absence of any notable indication of differential degradation or aggradation between the two reaches.

The design of the study is such that a direct assessment of the effect of surface structure on bedload and spatial distribution of disturbance can be undertaken using information only from the first major flood, as structural development in both reaches immediately prior to the first event is known in detail (see Figures 2.6). Observations through the rest of the study period do permit some comment upon the rate of structural development in Reach 2 (described in the following section).

The first major flood occurred on October 31 at a discharge of 674.17 L/s, with an estimated return interval of 1.8 years. This flood resulted in a considerably greater bed load yield from Reach 2 as compared with Reach 1 (Table 4.2). The bed load grain size distribution from Reach
2 was strongly skewed, dominated by coarse gravels with a $D_{50}$ of 47 mm whereas the
distribution from Reach 1 is unimodal, dominated by the sand fraction with a $D_{50}$ of 2.4 mm.

For fractions larger than granules (4 mm) Reach 2 yielded a considerably greater amount (Table 4.4). Indeed for fractions coarser than $D_{50surf}$ this reach yielded 33 times that yielded from Reach 1. For particles $D_{84surf}$ or larger, regarded as the typical size of constituent particles in bedform structures (Church et al 1998), the ratio is slightly lower at 24:1. However only one particle of this size fraction was mobilized from Reach 1. No particles $D_{99surf}$ or larger were mobilized from either reach during this flood (Table 4.4).

A pattern emerges whereby the ratio of grain size bedload yielded from Reach 2 compared with
that from Reach 1 increases rapidly with grain size. As the culvert upstream of Reach 1 likely
acted as a blockage point for grains $>$4 mm, the observed difference in the larger mobilized
fractions is likely to be a direct consequence of particle restraint in Reach 1.

As both reaches experienced a similar mean bed shear stress (Table 4.2) the difference in
mobilized grain size distributions between the two reaches can be parameterised by forming the
ratio of median surface grain size ($D_{50s}$) to median transported grain size ($D_{50t}$). A ratio of
$D_{50s}/D_{50t}$ of 40 was found for Reach 1, compared with 1.25 for Reach 2. A value close to one
indicates that almost every size fraction on the stream bed was mobilized, suggesting a much
lower mobility of coarse particles in Reach 1.

**Shields Criterion: Parameterising Structural Restraint**

An analysis of bed shear stress and sediment entrainment can provide information on particle
restraint and bed stability. Shields (1936) expressed the force balance at particle entrainment as a
critical threshold number, a ratio of the fluid shear stress exerted on the bed to resisting force,
assumed as particle weight by Shields. The Shields number can be calculated from the function:
\[ \tau^* = \frac{\tau}{(\rho_s)gD_{50}} \]  

(10)

where \( \tau \) is the threshold shear stress for particle entrainment, \( \rho_s \) is the submerged density of the particles (taken here to be 1650 kg \( \text{m}^{-3} \)), and \( D_{50} \) is the median surface grain size. It has been suggested that using \( D_{50} \) of the surface material in the Shields number equation reliably determines the ratio of forces at the bed for sediment transport (Wilcock and McArdell 1993). When fluid shear becomes too great, stone clusters and bedform structures are destroyed. The Shields number at the point at which this occurs provides some indication of the degree of restraint imposed by the structures. Typical values of Shields numbers for natural rivers and streams are generally accepted to be between 0.045 and 0.06. However a large range in values has been observed from natural rivers, from 0.03 (Andrews 1983) to well over 0.1 (Reid et al 1985). A value of 0.045 is generally accepted for loose heterogeneous sediments, whereas a value approaching 0.1 indicates a constrained bed. In the flume experiments of Church \textit{et al} (1998) the joint effect of armouring and structural development increased the critical Shields number to a value around 0.09.

\textit{Local Estimates of Critical Shields Number:}

From estimates of local bed shear stress taken over disturbed cells in Reach 2 (Table 4.1), a rough estimate of the critical Shields number for local areas of this reach can be obtained. Only two cells in this reach were disturbed, one corresponding with a shear stress of 128 ± 6.7 N/m\(^2\), the other with a shear stress of 142 ± 11.9 N/m\(^2\). At 82 ± 8.5 N/m\(^2\) no tracers were mobilized. If we therefore consider values for \( \tau \) of 82 ± 8.5 N/m\(^2\) and 128 ± 6.7 N/m\(^2\) in equation (10), we see that the Shields number for critical entrainment falls somewhere between 0.086 ± 0.013 and 0.134 ± 0.010. The estimates of critical Shields number above are based on the reach averaged
D₅₀. As a more conservative measure one could use D of the disturbed tracers (taken here to be 42 mm). This gives a corresponding estimate of critical Shields number between 0.125 ± 0.012 and 0.189 ± 0.01.

These values are exceedingly high, which brings into question the reliability of bed shear estimates derived from the velocity profiles. However, while the majority of structures and clusters in Reach 2 were broken apart, some may have been overlooked (see chapter two). It is possible that locally high levels of particle restraint may exist in this reach.

The maximum shear stress experienced in Reach 1 was 188 ± 13.2 N/m², corresponding to a Shields number of 0.17 ± 0.012, from equation (10). This value is also exceedingly high. As no sediment was mobilized in Reach 1, any local value of τ* represents a minimum for the critical entrainment of particles in this reach.

In Reach 3 if we consider that the majority of profiles were taken over disturbed cells, we can obtain some sort of reach averaged upper estimate to the critical Shields number. In considering an averaged bed shear value from the velocity profiles across all disturbed cells (τ = 35 ± 10.6 N/m²) we obtain a maximum critical Shields number of 0.052 ± 0.016. This seems within reason, given 0.045 is regarded as typical for loose heterogeneous sediments.

*Reach Averaged Estimates of the Critical Shields Number:

Further analysis can be carried out using estimates of mean bed shear stress as calculated from equation (5). During the first flood on October 31st, almost complete bed mobilization was experienced in Reach 2, illustrated by the map of bed disturbance (Figure 4.2) and a ratio of D₅₀ᵣ/D₅₀ᵣ close to 1. In considering the mean peak shear stress for this flood, 68.3 ± 8.3 N/m², an upper limit for critical particle entrainment in Reach 2 can be established, corresponding to a
critical Shields number of 0.072 ± 0.009. However, this calculation is based on an estimate of reach averaged shear stress that has not been corrected for sidewall effects. The corresponding estimate of critical Shields number may therefore be elevated. Nonetheless, it is considerably higher than the critical Shields value for loose heterogeneous sediment (0.045), indicating that indeed some form of particle restraint may well exist in Reach 2 over that provided by a simple hiding effect. The effect of this flood on Reach 1 however was to produce only partial bed entrainment, with only a limited number of cells disturbed (Figure 4.4), and a bedload derived mostly of sand sized particles. The corresponding reach averaged Shields number for Reach 1 was 0.060 ± 0.006.

Evidence suggests that the flood on December 15, with a peak discharge of 1385 l/s, was close to the critical shear for full bed mobility and indeed structural breakup in Reach 1. The extent of bed disturbance illustrated in Figure 4.5, and the movement of key structural rocks (Figure 4.6) indicate this. Nevertheless, not all clusters and structures were destroyed. In fact 74 % of all rocks marked in situ remained immobile during this flood (discussed later this chapter). Therefore, from equation (10) we can obtain a conservative estimate of the critical Shields number for Reach 1, at 0.1 ± 0.070, approaching that for a highly restrained bed.

In comparing the critical Shields number for a structureless loose bed with that of a well structured bed in the flume environment, Church et al. (1998) noted a two fold difference. This compares with a rather modest estimated increase in East Creek of approximately 1.4. However, it is evident that some structures may have persisted after the artificial break up during summer (see Figure 2.6). The stream bed as such can not be regarded as totally structureless and loose. Correspondingly bedform structures in Reach 1 are not fully developed, indeed development is partial and relatively sporadic in comparison to that observed by Church et al. (1998) in the flume (see Figure 2.7). Finally, the ratio of 1.4 is regarded as conservative, as the estimated
critical Shields values for Reaches 1 and 2 represent lower and upper estimated limits respectively.

Development of Particle Restraint in Reach 2

This following section is an analysis of three events of equal magnitude occurring on November 10, 12 and December 6, subsequent to the first major flood on October 31st.

In considering the forces associated with these three floods, from equation (10) we see that the corresponding critical Shields numbers are between $0.058 \pm 0.009$ and $0.059 \pm 0.009$ (Table 4.5), under the reach-averaged critical threshold of $0.071 \pm 0.009$ estimated for this reach. However, the values are still greater than 0.045, a critical entrainment value considered appropriate for loose heterogeneous sediment. Therefore one would expect ‘loose’ areas of the bed exposed to the flow to have been mobilized during these floods, with particles possibly coming to rest against stable particles or clusters. The patchy movement of tracers and key rocks marked in situ during these floods (e.g. see Figures 4.6 and 4.7) demonstrates the existence of partial sediment transport during these floods, whereby a proportion of a given size fraction is mobilized at any one time (Wilcock and McArdell 1997). It is within the realm of partial transport that structural development takes place (Church et al. 1998), whereby larger particles knock and jostle together to come to rest in stable positions.

It is evident that some form of particle restraint developed in Reach 2 during the study period. This is illustrated by a gradual change in bedload grain size distribution, eventually approaching that from Reach 1 (Figure 4.8). The change is mostly due to loss of the larger gravel portion (Table 4.4).
Figure 4.5 Surface sediment disturbance after December 15 flood.
Figure 4.6 Movement of particles marked in situ. The new location of mobilized particles was assessed after the October 31 event and is shown by a dotted outline and ‘x’. Where identified, original location is shown by an arrow. ‘#’ indicates location where mobilised particles have come to rest against stable particles.
Table 4.5 Shields parameter based on $D_{50}$ surface and $D_{50}$ bedload for each reach and each flood event. Standard error is in parenthesis.

<table>
<thead>
<tr>
<th>Date</th>
<th>$\tau$ (N/m$^2$)</th>
<th>$D_{50\text{er}}$ (mm)</th>
<th>$\tau^*_{\text{surface}}$</th>
<th>$\tau^*_{\text{transport}}$</th>
<th>$\tau$ (N/m$^2$)</th>
<th>$D_{50\text{er}}$ (mm)</th>
<th>$\tau^*_{\text{surface}}$</th>
<th>$\tau^*_{\text{transport}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 31</td>
<td>65.1 (± 7.1)</td>
<td>2.4</td>
<td>0.06</td>
<td>1.68</td>
<td>68.3 (± 8.3)</td>
<td>47.0</td>
<td>0.071</td>
<td>0.098</td>
</tr>
<tr>
<td>Nov 8</td>
<td>47.3 (± 7.3)</td>
<td>1.0</td>
<td>(± 0.006)</td>
<td>(± 0.181)</td>
<td>45.0 (± 7.6)</td>
<td>2.8</td>
<td>0.047</td>
<td>(± 0.009)</td>
</tr>
<tr>
<td>Nov 10</td>
<td>51.8 (± 7.2)</td>
<td>1.4</td>
<td>0.048</td>
<td>2.29</td>
<td>56.4 (± 8.2)</td>
<td>35.0</td>
<td>0.059</td>
<td>(± 0.168)</td>
</tr>
<tr>
<td>Nov 12</td>
<td>51.2 (± 7.2)</td>
<td>1.2</td>
<td>(± 0.007)</td>
<td>(± 0.327)</td>
<td>55.5 (± 8.0)</td>
<td>5.5</td>
<td>0.078</td>
<td>(± 0.014)</td>
</tr>
<tr>
<td>Nov 22</td>
<td>31.7 (± 6.0)</td>
<td>0.8</td>
<td>0.029</td>
<td>2.45</td>
<td>39.3 (± 8.1)</td>
<td>2.8</td>
<td>0.041</td>
<td>0.868</td>
</tr>
<tr>
<td>Nov 24</td>
<td>49.5 (± 7.2)</td>
<td>0.7</td>
<td>0.046</td>
<td>4.08</td>
<td>46.8 (± 7.4)</td>
<td>1.7</td>
<td>0.049</td>
<td>1.703</td>
</tr>
</tbody>
</table>
Table 4.5 Cont’d

<table>
<thead>
<tr>
<th>Date</th>
<th>( \tau ) (N/m²)</th>
<th>Reach 1</th>
<th>Reach 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( D_{50} ) (mm)</td>
<td>( \tau^*_{\text{surface}} )</td>
<td>( \tau^*_{\text{transport}} )</td>
</tr>
<tr>
<td>Dec 2</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Dec 6</td>
<td>51.2 (± 7.2)</td>
<td>0.047 (± 0.007)</td>
<td>2.63 (± 0.372)</td>
</tr>
<tr>
<td>Dec 12</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Dec 15</td>
<td>109.2 (± 7.3)</td>
<td>0.100 (± 0.007)</td>
<td>1.67 (± 0.113)</td>
</tr>
<tr>
<td>Mar 3</td>
<td>49.5 (± 7.2)</td>
<td>0.046 (± 0.007)</td>
<td>3.51 (± 0.495)</td>
</tr>
</tbody>
</table>

\( \tau^*_{\text{surface}} \) calculated from equation (10), where \( \tau^* = \tau / (\rho g D_{50\text{surface}}) \).

\( D_{50\text{surface}} = 67 \text{ mm in Reach 1 and 59 mm in Reach 2. Surface grain size distributions were measured only once in both reaches before the flooding season. It is likely some level of surface coarsening took place during the study period, as such estimated } \tau^*_{\text{surface}} \text{ values can be regarded as only approximate. Further, sidewall effects were not taken into account in the calculation of } \tau. \text{ It was demonstrated (see pp 51) that such effects may be large and values of } \tau \text{ overestimated when not taken into account. Values of } \tau^* \text{ may therefore be overestimated. For example, for the flood on December 15, } \tau^* \text{ was estimated to be } 0.100 \text{ (} \tau = 109.2 \text{ N/m}^2). \text{ Taking into account the sidewall effects (i.e. using } \tau = 77.4 \text{ N/m}^2 \text{, see pp 51) } \tau^* \text{ is now estimated to be approximately 0.072. Note, as flow depth decreases the overall effects of bank roughness on estimates of } \tau \text{ also decrease. The sidewall effects are therefore greatest for the flood on December 15.}

\( \tau^*_{\text{transport}} \) was similarly calculated from equation (10), but based on } D_{50} \text{ of the transported load, where, } \tau^* = \tau / (\rho g D_{50u}). \text{ } D_{50u} \text{ is the median size of the transported load.}
The stability of a channel can be enhanced by two mechanisms, textural coarsening of the surface, usually described as ‘armouring’, and structural modification of the bed. While partitioning the effect of surface armouring from that of structural development is difficult, it is likely the latter mechanism was responsible for the majority of stabilization observed in the reach during these floods. While crudely expressed, the partial development of rock clusters in Reach 2 is illustrated in Figure 4.6. During the flood on October 31 key rocks marked in situ came to rest against stable particles. Subsequent flooding during November 10 and 12 mobilized a slightly smaller grain size fraction that may have contributed to the development of the limited particle clusters observed after the October 31 flood. Further, the change in bedload grain size distribution during these floods is solely due to the loss of the gravel portion (Table 4.4). Indeed very little change in the sand fraction was observed. During development of structures and clusters it is assumed that the larger gravel portion would be incorporated into the structures, effectively reducing the transportable portion of this size fraction. In their flume experiments Church et al. (1998) found that the key effect of structural development was a substantial reduction in the mobility of the larger particles.

Quantifying the development of Particle Restraint:

The effect of particle restraint in Reach 2 can be quantified following Church et al. (1998) by considering the $D_{50}$ of the surface material (Reach 2) and $D_{50}$ of the transported material, and comparing the critical Shields number based on the transported material with that expected for the surface material (Table 4.5). First, in just considering the floods on November 10 and 12, the effect is illustrated in Figure 4.9 by a substantial increase in the Shields number based on the transported load, of up to 6 fold. This increase is much larger than that reported by Church et al. (1998) from their flume experiments. It appears evident that the flood on November 10, and at least the early stages of the flood on November 12, produced a considerable change in particle
Figure 4.7 Surface sediment disturbance after November 12 flood.
Figure 4.8 Cumulative transported grain size distribution from the November 10, 12 and December 6 floods. All floods were of similar magnitude.
restraint. These two floods were therefore instrumental in the development of particle restraint and overall stabilization of Reach 2. Indeed, by December 6 the reach appears to have reached a maximum level of restraint, some 16 to 17 times that indicated from the November 10 flood (Figure 4.9).

A Further Comment on Particle Restraint:
The variable flows experienced during the study period provide for a unique study on of the history of particle restraint in Reach 2.

The first flood of the season on October 31st resulted in only a minor increase in particle restraint (Figure 4.9). However through subsequent floods on November 10 and 12 particle restraint was notably increased, possibly through the development of particle structures and clusters. The bedload grain size distribution from the following floods on November 24 and December 6 indicate a high level of particle restraint for the stream bed, actually approaching that of Reach 1 (Figure 4.9).

The large flood on December 15 resulted in almost complete mobilization in both Reaches 1 and 2. Particles marked in situ were mobilized in both reaches and some clusters and structures in Reach 1 were destroyed. The effect on particle restraint in Reach 2 was considerable. It resulted in a substantial reduction in particle restraint in Reach 2, up to 13 fold as indicated by the bedload from the flood on March 3 (Figure 4.9). A clear difference exists when compared with the maximized level of particle restraint as indicated from the flood on November 24, of a similar magnitude. Two mechanisms are likely responsible for the change in particle restraint, a break up of the structures developed in Reach 2 during November, releasing sediment, and a replenishment of sediment into Reach 2, as trap 1 overfilled during the flood on December 15.
Critical Shields Number Based on $D_{50}$ of Surface Sediment

**Figure 4.9** Shields number based on $D_{50}$ of the surface sediment versus Shields number based on $D_{50}$ of the Bedload for Reach 2. Error bars show maximum and minimum values.
While estimates of critical Shields number are approximate, the series of floods during the study period in East Creek illustrates the dynamic nature of reach averaged particle restraint. Foremost, restraint is governed by the history of recent flows. It is also strongly dependant on local external sediment supply. Structural development in a natural system may well be rather dynamic, changing along a continuum punctuated by rapid changes. This itself may have consequences for the biotic life and represent a disturbance regime on the scale of months, seasons or years.

**Effect of Structures on the Spatial Disturbance of the Stream Bed**

The flood on October 31 provided an ideal opportunity to assess the effect of clusters and bedform structures on the spatial distribution of bed disturbance, as it was sufficient to mobilize loose, unconstrained material, but not to mobilize clusters and structures.

In Reach 2 the distribution of bed disturbance is almost continuous along the entire length of the channel (Figure 4.2), with a greater amount concentrated in the first third, possibly corresponding to the slightly higher energy gradient in this section (Figure 2.4). Downstream from this, maximum disturbance, as defined in chapter 3, is generally limited to a narrow continuous thread that appears almost to meander. Along this section disturbance is mostly limited to mid channel, except for a few areas. Towards the very end of the reach disturbance is once again almost complete across the entire channel. In comparison, bed disturbance in Reach 1 is discrete and patchy, and almost totally confined to mid channel (Figure 4.2).

Two mechanisms could be responsible for the observed pattern in Reach 1. First, it is possible the effect of impinging turbulent forces could have resulted in the spatially discrete and patchy disturbance pattern. Two independent lines of evidence tentatively support this. First, local estimates of bed shear stress varied considerably throughout the reach (Table 4.1), at least demonstrating the possibility of locally variable forces. Second, the pattern of mobilized rocks
marked *in situ* is also somewhat patchy (Figure 4.6). Furthermore the patches from the October 31 and December 15 floods generally correspond with one another, perhaps indicating some consistency in disturbance mechanisms between floods.

However, if spatially variable turbulent forces were the dominant mechanism responsible for the observed pattern, one would expect a similarly patchy distribution of bed disturbance in Reach 2. This was not observed though, indeed the pattern of spatial disturbance was much more pervasive in Reach 2 than Reach 1. Given the uniform nature of East Creek in this reach it is unrealistic to consider that general flow conditions differed greatly from Reach 1 to Reach 2. This leads one to suggest that, if indeed variability in turbulent forces did affect the distribution of bed disturbance, it was not the overriding mechanism responsible at the reach scale.

Second, and more plausibly, the pattern of disturbance could have been created by spatially differential susceptibilities in the critical threshold for particle entrainment. Indeed, examination of the substrate in Reach 1 during late summer before flooding revealed isolated pockets of loose gravel amongst particle clusters and presumably more stable areas of the bed. These pockets may represent the fraction of stream bed that is easily transportable, and may correspond to the distribution of bed disturbance observed from this reach. In comparison the substrate in Reach 2 was presumably uniformly loose after the artificial manipulation. One would therefore not expect such a spatially patchy distribution of bed disturbance.

The effect of bedform structures and clusters on the spatial distribution of bed disturbance appears to be one of both reducing total bed disturbance, and also its continuous nature, forming distinct separate patches. This may have important implications for both total area of refugia within a stream bed, and also refugium parameters such as refugium perimeter length to area
ratios, considered potentially important attributes for the persistence of some invertebrate populations (Lancaster, 2000).

Spatial Correspondence of Bed Disturbance with Bedform Structures:

Scale of Disturbance in Reach 1:

Seven patches of maximum disturbance were created in Reach 1 after the October 31 flood (Figure 4.2). Each patch is composed of two to five neighboring cells. Eight isolated single cells of maximum disturbance also occur within this reach. In considering the area of each cell, this corresponds approximately to scales of maximum disturbance in this reach of between $0.16 \, \text{m}^2$ and $0.8 \, \text{m}^2$. Now considering estimates of partial stone cell diameters in Reach 1 range from 0.4 m to 0.95 m (e.g. see Figure 2.7), we obtain corresponding areas of $0.13 \, \text{m}^2$ and $0.70 \, \text{m}^2$ for fully formed stone cells, or approximately $0.07$ to $0.35 \, \text{m}^2$ for partially developed cells. This very rough calculation illustrates a consistent scaling factor of two exists between that for the partial stone area and that for bed disturbance area. This may or may not be coincidental.

In their flume experiments Church et al (1998) found the key effect of bedform structures such as stone cells was to substantially reduce the mobility of the larger stones, which then effectively ‘hide’ the smaller particles. On inspection of their particle map illustrating full stone cell development (Figure 2.7), the smaller particles mostly reside in the middle of the cells. These particles are ‘hidden’ by the formation of a closed cell. In East Creek however stone cells were only partially developed (e.g. Figure 2.7). Such features may not adequately ‘hide’ smaller particles that reside inside them. They may however control the scale of disturbance to a certain extent. The larger constituent particles may remain stable around the outside of the partial cell, but provide little protection for the smaller particles inside, which may be more readily mobilized. As the partial cells have only three confining limbs the size of disturbance patch may
be greater than the area within the cell itself. However the cell may control the scale ranges of patch disturbance.

On close examination of the disturbance map from Reach 1 some patches of maximum disturbance do lie within the bounds of partial stone cells; for example, along transects 9 and 23 and 24. In general most patches of maximum disturbance are located away from clusters of larger particles (Figure 4.2). Most large particles were emergent during the time when the bed was photographed, so one can assume that clear areas in Figure 2.6 mostly represent that portion of the bed composed of smaller particles. The location of patches of the stream bed composed of the smaller gravel portion may have been an important factor in controlling the distribution of bed disturbance in Reach 1. Further, partial cell structures and stone clusters may control or influence the distribution of the smaller gravel portion.

While the effect of partial cell structures in controlling the scale of disturbance is conjecture, it does have important implications for disturbance ecology, and therefore warrants brief discussion. It is possible that the scale of bedform features such as stone cells may provide an indication of the dominant scale of disturbance. If disturbed patches of the stream bed do indeed represent a significant disturbance for the invertebrate community (see chapter 5), then such features may provide an indication of the appropriate scale at which to address disturbance studies in rivers and streams.

**Disturbance of Particles Marked In Situ:**

A total 32 of the 122 particles marked in situ from Reach 1, and 79 of the 100 from Reach 2 were mobilized during the study period (Table 4.6). After the flood on October 31 it was possible to map the new positions of 7 of the 8 mobilized particles from Reach 1, and 22 of the 29 mobilized particles from Reach 2. Where the origin of the particles could be determined
(using detailed maps and photographs of the bed showing the particle shape), the movement is shown by an arrow in Figure 4.6.

**Table 4.6** Number and cumulative percent of marked rocks mobilized during the October 31, November 12 and December 15 floods.

<table>
<thead>
<tr>
<th>Reach 1</th>
<th>Reach 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood</td>
<td># Mobilized</td>
</tr>
<tr>
<td>October 31</td>
<td>8</td>
</tr>
<tr>
<td>November 12*</td>
<td>0</td>
</tr>
<tr>
<td>December 15</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
</tr>
</tbody>
</table>

* - Combined movement from two floods of equal magnitude, on November 10 and 12.

There is evidence to suggest that some of the mobilized particles in both Reaches 1 and 2 may have come to rest in stable positions. This is illustrated in Reach 1 by the turning of a particle to form what appears to be a tight cluster of rocks (see Figure 4.6). This cluster was later mobilized by the flood on December 15. In Reach 2 several mobilized particles came to rest either against one another or against other stable particles (see Figure 4.6), illustrating the early development of particle clusters. This was also observed in the flume experiments of Church *et al.* (1998) during bedform development.

In examining the pattern of disturbed particles marked *in situ* from Reach 1 the majority appear to be confined to mid channel, similar to the pattern of disturbed cells after the October 31*st* flood (see Figure 4.2). The mobilization in this reach also appears to occur in clumps or patches, illustrated by the disturbance from the December 15 flood.
Area of Bed Disturbed vs Bedload:

The overall effect of bedform structures is to reduce bedload. This has been shown experimentally in flumes by Church et al. (1998), and now within this study under natural flooding conditions.

As expected, the reduction in bedload appears to equate to a similar reduction in area of bed disturbed. In considering the number of tracers mobilized in each of Reaches 1 and 2, one can estimate the percent area of bed disturbed in each event by assigning each tracer an area of 800 cm$^2$, one half a cell. While this is only an approximation, it does provide a rather good comparative measure. Once again in firstly considering the October 31 flood, almost twice as much area of bed was disturbed in Reach 2 (Table 4.7) compared with Reach 1. This observation corresponded directly to a total bedload almost twice as great from Reach 2.

The effect of developing particle restraint in Reach 2 subsequent to the October 31 flood, evident from the bedload, is not particularly clear in Table 4.7 due to limited data. However a general trend does appear whereby the area of stream bed disturbed in both Reaches 1 and 2 subsequent to this flood is similar (Table 4.7). The anomaly resulting from the December 6 flood is hard to explain, except in that it results from very limited data and is therefore greatly influenced by the chance disturbance of one or two tracers.

It is likely that a greater intensity of disturbance was experienced in Reach 2 than Reach 1 during the October 31st flood. The ratios of bedload and area disturbed from both reaches during this flood are equivalent (Table 4.7). However if one considers that some bedload trapped from Reach 1 may well have originated from upstream then there remains the possibility that a greater amount of bedload per unit area was produced from Reach 2 than Reach 1. This trend was also observed from the flood on December 15 (Table 4.7), comparing $b_1/b_2$ with $A_1/A_2$.
Table 4.7 Area of stream bed disturbed

<table>
<thead>
<tr>
<th>Date</th>
<th>Reach 1 Q (l/s)</th>
<th>Max</th>
<th>Min</th>
<th>% area Dist.</th>
<th>Reach 1 Max</th>
<th>Min</th>
<th>% area Dist.</th>
<th>Reach 2 b1/b2</th>
<th>A1/A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 31</td>
<td>674</td>
<td>33</td>
<td>89</td>
<td>35.4</td>
<td>88</td>
<td>56</td>
<td>61.5</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>Nov 8</td>
<td>237</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>0.28</td>
<td>0*</td>
</tr>
<tr>
<td>Nov 12</td>
<td>396</td>
<td>3</td>
<td>48</td>
<td>12.3</td>
<td>7</td>
<td>35</td>
<td>13</td>
<td>1.08</td>
<td>0.95</td>
</tr>
<tr>
<td>Nov 22</td>
<td>179</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.91</td>
<td>0*</td>
</tr>
<tr>
<td>Nov 24</td>
<td>328</td>
<td>0</td>
<td>3</td>
<td>0.6</td>
<td>0</td>
<td>2</td>
<td>0.5</td>
<td>4.34</td>
<td>1.2</td>
</tr>
<tr>
<td>Dec 6</td>
<td>394</td>
<td>0</td>
<td>1</td>
<td>0.2</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>4.94</td>
<td>0.2</td>
</tr>
<tr>
<td>Dec 15</td>
<td>1385</td>
<td>167</td>
<td>34</td>
<td>84.1</td>
<td>175</td>
<td>12</td>
<td>95.9</td>
<td>0.7</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Max Dist. = number of cells in which both tracers were disturbed
Min Dist. = number of cells in which only one tracer was disturbed
% area Dist. = total percentage of bed area disturbed
b1/b2 = bedload from reach 1/ bedload from reach 2
A1/A2 = Area disturbed in reach 1/ Area disturbed in reach 2
* - Reach 1 stable.

Two mechanisms could possibly be responsible for the apparent increase in bed movement intensity: first, that indeed a greater amount of bedload was produced per unit area from Reach 2 than Reach 1; second, particles once mobilized traveled further in Reach 2, therefore effectively increasing the area of bed from which particles were sampled at the trap. More than likely a combination of the two factors was in play. It should be noted that on close observation of the bed immediately after the flood on October 31st several deep scour patches were observed in Reach 2. Such scour was not observed in Reach 1. It therefore appears that the greater event averaged transport rate during this flood in Reach 2 may not have been solely due to an increase in area of bed disturbed.
Concluding Remarks

The effect of bedform structures in East Creek was to stabilize the bed and reduce overall disturbance. While the estimated increase in reach averaged particle restraint imposed by the structures in Reach 1 was not great, it was enough to produce significant differences in bed disturbance. Two important effects were noted. First, bedform structures reduced event based transport rates and total bedload by a factor of 2. The dominant effect was to produce a considerable reduction, up to 33 fold, in the mobilization of the larger particle fraction, a feature also noted by Church et al. (1998). Second, they reduced the overall spatial distribution of bed disturbance, producing discrete disturbance patches. The ability of bedform structures to produce a patchy distribution of disturbance has been noted before by Francoeur et al. (1998). Further, they demonstrated that the effects of flooding on the periphyton community are mediated by the presence of bedform structures, as they remained stable during a flood and acted as refugia.

Indeed the prime significance of bedform structures to the invertebrate community may lie in their ability to produce a patchy distribution of bed disturbance. The significance is two fold. First they may act as refugia, potentially allowing for population persistence. Lancaster and Belyea (1997) produced simple mathematical models to illustrate the potential importance of spatially patchy refugia for population persistence in a frequently disturbed environment. However, the ability for bedform structures to act as refugia for invertebrates remains to be tested. This represents the next part of the thesis (Chapter 5).

Second, if bedform structures do act as refugia they may provide a useful scale at which to address studies of disturbance in streams. Tentative evidence here suggests that partial stone cells may control the scale of disturbance. This is significant as they may provide a means of establishing dominant scales of disturbance a priori, potentially allowing some form of
generality in spatial disturbance between riffles, study sites and rivers. A next logical step would be to investigate potential relationships between scales of bedform structure and corresponding scales of bed disturbance in the flume environment.

Due to the nature of the experiment and the reliance on natural events I was unable to replicate any findings. Much of what has been presented is therefore exploratory and somewhat speculative. However, the results provide a basis from which to explore potentially interesting and important aspects related to bedform structures and disturbance ecology.
Chapter Five. Macroinvertebrate Response to Bedload - Results

Introduction

This chapter describes the analysis and results from the invertebrate sampling program. The first part of the chapter deals with a description of the analysis, data and general community structure. This is followed by an analysis of the taxa specific response to bed movement, as defined in this study by the movement of two tracers per cell. The final part will focus on stable substratum and the potential role this has in providing refugia for invertebrates in the face of a bed mobilizing event.

Analysis

The general aim of this section of the study was to assess the response of invertebrate communities to flooding on both stable and disturbed substrate.

The design of the study was to allow for analysis by fixed factor ANOVA, with two treatment types, post-flood disturbed substrate and undisturbed, or hereby referred to as stable substrate. Pre-flood baseline samples represent a control. ‘Disturbed’ corresponds to the movement of both tracers within a cell, as defined earlier in Chapter 3. ANOVA was carried out on the abundance of the common taxa (average greater than 10 per sample in all reaches). This analysis was completed separately for each study reach as the reaches were not considered to be true replicates. After exploratory analysis, all invertebrate data were log(x+1) transformed to meet the assumption of normality and reduce heteroscedasticity. After transformation the data were essentially normal. Tukey’s HSD a posteriori test (see Day and Quinn 1989 for review) was used to determine significance between the two treatments and pre-flood data. As this study is in essence exploratory, any relation indicated by a significance at 10% or lower will be reported.
General community responses on stable and disturbed substrate after the flood were studied using an ordination procedure in PATN (Belbin, 1993), semi-strong Hybrid Multi Dimensional Scaling (SSH). By reducing the multidimensional nature of the data to only a few dimensions, 'natural' sample clusters and trends if they exist are more easily identified. In this sense the procedure was used as a descriptive tool to assess the overall community variation between pre- and post-floods samples. The Bray Curtis dissimilarity measure was used in each procedure.

SSH is considered to be a robust ordination method (Faith et al. 1987), able to cope with the typical situation in which invertebrate responses are noisy and skewed (Marchant et al. 1994). SSH ordination requires the number of dimensions to be specified *a priori*, of which three were used in all procedures. As such the SSH ordination procedure produces a stress index as a measure of confidence in maintaining the 'natural' characteristics of the data. In all procedures this index was within the recognized limits (Belbin 1993).

An assessment of sample variability within treatments has particular ecological relevance in this study. In comparing the variance of pre-flood and post-flood samples one can gain an idea of the degree of invertebrate patchiness created by the flood. Also, in comparing the variance of disturbed and undisturbed samples with those from pre-flood samples one can assess whether or not the spatial scale of disturbance as defined by the movement of the two tracers was appropriate. A coefficient of variation defined by standard deviation / mean was used to quantify sample variability. This scales the sample variance by the mean and thus is a better comparative measure of variability than sample variance alone (e.g. see Palmer et al. 1997). Generally, if the two treatment means (disturbed and stable substrate) are not significantly different from baseline pre-flood means then two possibilities exist. First, that it is a truth, and the null hypothesis (see chapter one) is accepted. Second, a type II error exists whereby the power of the analysis is reduced by large sample variation in one or more of the treatments. If such variation exists...
within the disturbed or stable substrate samples and is considerably greater than base line pre-
flood levels then the definition of disturbance and/or refugium as defined by the tracers may not
be at a scale appropriate to that organism or, indeed, may not address the actual mechanisms
involved.

**General Community Description**

A total of 10,573 individuals was collected and identified over the sampling period from all
reaches. The density of invertebrates varied slightly between reaches and appeared to be
correlated with distance from culvert, and hence pre-flood substrate 'looseness' (see Chapter 4).
The density of invertebrates identified in Reach 1 was approximately 1996 m$^{-2}$, in Reach 2 it was
2415 m$^{-2}$, and in Reach 3, 2915 m$^{-2}$. Due to time constraints not every individual in the sample
was identified, hence these densities are only estimates. All abundant taxa were identified to
family level, as well as those taxa that were easily recognizable. In total nine families were
identified (Table 5.1). Three other taxa groupings were formed, Oligochaeta, unidentified cased
caddis and unidentified free living caddis. Taxa with an average of at least 10 individuals per
sample (i.e., $\geq 10\%$) in all three reaches were regarded as common and used in the analysis.

There was no significant difference ($p > 0.1$) in mean pre-flood abundances between the study
reaches for all common taxa except Leptophlebiidae and Chironomidae (Table 5.1). As the study
reaches are not regarded as replicates differences between pre-flood community populations are
not of major concern. Data from each study reach are analyzed separately.

The seven common taxa used in the analysis, Baetidae, Heptageniidae, Leptophlebiidae,
Nemouridae, Chloroperlidae, Chironomidae, and Oligochaeta represent a good cross section of
the community. They exhibit a range of basic morphologies and mobility traits that are
Table 5.1 Average abundance (n = 5) per baseline pre-flood sample. 1 standard deviation is shown in parentheses.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ephemeroptera</td>
<td>* Baetidae</td>
<td>58.6 (± 23.8)</td>
<td>43.4 (± 9.7)</td>
</tr>
<tr>
<td></td>
<td>* Heptageniida</td>
<td>11.2 (± 8.5)</td>
<td>23.2 (± 20.7)</td>
</tr>
<tr>
<td></td>
<td>* Leptophlebiidae</td>
<td>86.6 (± 43.7)</td>
<td>72.8 (± 23.1)</td>
</tr>
<tr>
<td>Plecoptera</td>
<td>* Nemouridae</td>
<td>25.6 (± 11.0)</td>
<td>43.4 (± 24.1)</td>
</tr>
<tr>
<td></td>
<td>* Chloroperlidae</td>
<td>16.6 (± 8.4)</td>
<td>24.8 (± 9.0)</td>
</tr>
<tr>
<td>Trichoptera</td>
<td>Glossosomatidae</td>
<td>2.4 (± 1.5)</td>
<td>8.2 (± 7.0)</td>
</tr>
<tr>
<td>Diptera</td>
<td>* Chironomidae #</td>
<td>62.4 (± 20.6)</td>
<td>91.2 (± 23.3)</td>
</tr>
<tr>
<td></td>
<td>Ceratopogonidae</td>
<td>6 (± 0.6)</td>
<td>7.8 (± 4.4)</td>
</tr>
<tr>
<td>Coleoptera</td>
<td>Elmidae</td>
<td>2.4 (± 1.3)</td>
<td>5 (± 2.5)</td>
</tr>
<tr>
<td></td>
<td>* Oligochaeta</td>
<td>20.4 (± 15.1)</td>
<td>46.4 (± 28.7)</td>
</tr>
<tr>
<td>Cased caddis</td>
<td></td>
<td>9.2 (± 0.5)</td>
<td>11 (± 6.0)</td>
</tr>
<tr>
<td>Free living caddis</td>
<td></td>
<td>18 (± 0.5)</td>
<td>9.2 (± 8.1)</td>
</tr>
</tbody>
</table>

* - Taxa used in ANOVA analysis.

# - Significant (p < 0.1) difference in pre-flood abundance between reaches.
potentially important in allowing for population resistance and or resilience during flooding, such as streamlined body shape and swimming ability. Morphologies such as streamlining and flattened body shape may allow individuals to maintain body position during high flows, and hence confer resistance. High mobility permits an organism to actively leave an area if the environment becomes too harsh or unsuitable, and potentially enable rapid recolonisation after the event and therefore confer resilience. Table 5.2 lists the basic traits and morphologies for each of the taxa used in the analysis.

General Mobility Traits:
The classification of taxa mobility is at the family level (see Table 5.2), and hence very general. However, in the context of an exploratory study it may provide a useful framework from which to address disturbance responses.

Swimmers:
Both Baetidae and Leptophlebiidae have been classified as ‘swimmers’, capable of directional “porpoise-like” swimming undulations (Wilzbach et al 1988). Chironomidae have also been described as ‘swimmers’, although weak, using a side-to-side thrashing movement to produce weak directional locomotion (Rader 1996). Taxa in this category are considered very mobile.

Crawlers:
This classification refers to taxa that are not generally regarded as swimmers, but are able to actively crawl around the substrate. This includes Nemouridae, Chloroperlidae and to a certain extent Heptageniidae (see Rader 1996), although this taxon is regarded as a 'sluggish mover' (Edmunds et al 1986).
Table 5.2 Mobility and basic body morphology of the common invertebrate taxa in East Creek. See text for explanation and references.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Streamlined</th>
<th>Flattened</th>
<th>Swim</th>
<th>Crawl</th>
<th>Cling</th>
<th>Burrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baetidae</td>
<td>***</td>
<td></td>
<td>***</td>
<td></td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>Leptophlebiidae</td>
<td>**</td>
<td>*</td>
<td>**</td>
<td>*</td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>Heptageniidae</td>
<td></td>
<td>***</td>
<td></td>
<td></td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>Nemouridae</td>
<td></td>
<td></td>
<td>***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroperlidae</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td></td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>Chironomidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oligochaeta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** strongly expressed ** moderately expressed * expressed
Clingers:

The category of ‘clinger’ refers to an organism that expresses some form of morphological trait adaptive to clinging on to substrate, but is not sessile and hence able to move. Heptageniidae are classified as ‘clingers’ as they are dorso-ventrally flattened and able to use tarsal claws to ‘cling’ on to the substrate and maintain a body position with low resistance to the flow.

Burrowers:

Some species of Chloroperlidae are regarded to be ‘burrowers’, able to utilize the interstitial spaces in the sediment (Kenneth and Stark 1993), and hence may be able to avoid surficial disturbances.

Mobility and Disturbance response:

Rader (1996) made the general assumption that greater mobility, defined by swimming > crawling > attached > sessile, increases the likelihood of avoidance of or dislodgment by high flow. He reasoned this was due to a tradeoff between mobility and attachment. Accordingly one would therefore expect a greater disturbance response to high flows with increasing mobility. One could also reason that a taxon’s flight response from an unsuitable habitat is linked to their mobility. This may result in a differential response to disturbance at the scale of the Surber sampler. For example, a ‘swimmer’ may instinctively enter the water column and ‘swim’ in response to a threat from a potential disturbance, i.e., damage due to moving particles or high shear forces. Hence they would likely be carried out of the bounds of the sample cell. A 'crawler' on the other hand may respond by crawling from an unstable particle or one under high shear forces to another particle that may still lie within the bounds of the sample cell. While both represent distinctive responses, at the scale employed in this study one would be detected, the other not.
The taxa used in this analysis (Table 5.2) fall into the first two categories as defined by Rader (1996). He defined ‘attached’ taxa as those that are typically fastened in one position for days at a time. In this study ‘crawlers’ and ‘clingers’ are therefore subsets of Rader’s category of ‘crawling’. They are not ‘attached’.

Following the assumptions regarding general mobility and the likelihood of dislodgment, and or the assumption of flight response under the disturbance of moving substrate, one would perhaps expect the following disturbance response in order of greatest to least;

Swimmer > Crawler > Clinger > (Burrower ?)

A burrowing organism is possibly the least likely to be entrained as it can inhabit the interstitial mineral spaces and is able to burrow and hence possibly avoid surficial disturbances.

**Invertebrate Response to Flooding**

Two potential categories of disturbances are characterized in this study: disturbance due to the movement of surficial bed particles, defined by the movement of two tracers per cell, and disturbance from high shear stress and/or the movement of particles finer than tracer size. The latter occurs on 'stable substrate' as defined in this study. It is important to stress that the notions of stable and disturbed substrate have been constructed by the observer. Whether or not they represent an appropriate classification of disturbance as it relates to invertebrates is one of the main aims of this study.

All taxa except Chloroperlidae showed a significant reduction in population density in East Creek after the October 31 flood in at least one of the study reaches (Table 5.3). This flood had a return interval of 1.8 years and mobilized surficial particles larger than tracer size in all reaches (see Chapter 4).
Table 5.3 Results of analysis of variance of abundance for each common taxa in each reach, comparing pre-flood and post-flood stable and disturbed substrates. df = degrees of freedom, MS = mean square, F = F-statistic and p = probability.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beatidae</td>
<td>df = 2, F = 41.06, p &lt; 0.001</td>
<td>df = 2, F = 14.98, p = 0.001</td>
<td>df = 2, F = 39.73, p &lt; 0.001</td>
</tr>
<tr>
<td>Heptageniidae</td>
<td>df = 2, F = 2.02, df = 2, MS = 1.08, p = 0.173</td>
<td>df = 2, F = 2.70, df = 2, MS = 2.88, p = 0.107</td>
<td>df = 2, F = 23.92, df = 2, MS = 4.20, p &lt; 0.001</td>
</tr>
<tr>
<td>Leptophlebidae</td>
<td>df = 2, F = 28.09, MS = 6.77, p &lt; 0.001</td>
<td>df = 2, F = 27.06, df = 2, MS = 6.44, p &lt; 0.001</td>
<td>df = 2, F = 39.56, df = 2, MS = 7.80, p &lt; 0.001</td>
</tr>
<tr>
<td>Nemouridae</td>
<td>df = 2, F = 15.08, df = 2, MS = 5.86, p &lt; 0.001</td>
<td>df = 2, F = 14.81, df = 2, MS = 6.03, p = 0.001</td>
<td>df = 2, F = 48.26, df = 2, MS = 3.68, p &lt; 0.001</td>
</tr>
<tr>
<td>Chloroperlidae</td>
<td>df = 2, F = 0.26, MS = 0.11, P = 0.777</td>
<td>df = 2, F = 0.65, df = 2, MS = 0.42, P = 0.540</td>
<td>df = 2, F = 0.66, MS = 0.39, P = 0.532</td>
</tr>
<tr>
<td>Chironomidae</td>
<td>DF = 2, F = 24.11, DF = 2, MS = 8.14, p &lt; 0.001</td>
<td>DF = 2, F = 54.10, DF = 2, MS = 11.12, p &lt; 0.001</td>
<td>DF = 2, F = 31.59, DF = 2, MS = 7.79, p &lt; 0.001</td>
</tr>
<tr>
<td>Oligochaeta</td>
<td>df = 2, F = 3.91, df = 2, MS = 3.41, p = 0.047</td>
<td>df = 2, F = 18.66, df = 2, MS = 7.92, p &lt; 0.001</td>
<td>df = 2, F = 25.73, df = 2, MS = 13.16, p &lt; 0.001</td>
</tr>
</tbody>
</table>
Chloroperlidae populations remained relatively unchanged and it was the only taxon to show what truly appears to be a non-significant response to a mobilizing flood event. The response of Heptageniidae to flooding was barely significant in Reaches 1 and 2, but highly significant in Reach 3 (Table 5.3). One could hesitantly suggest that this taxon exhibited a greater amount of resistance to the general effects of flooding and bed movement than the more mobile taxa such as Baetidae, Leptophlebiidae and Chironomidae, all of which showed a highly significant response to flooding in all reaches.

The specific effects of the flood as defined by the movement of the larger framework particles, and response on stable substrate are detailed below, and represent the core of this chapter.

Response on Disturbed Substrate

The overall effect of substrate movement was to considerably reduce population abundance. As both tracers were placed in 'hidden' positions on the stream bed, i.e., 'hidden' from the flow by neighboring particles, it is fair to assume that the movement of both tracers in a cell indicated some sort of disturbance of the neighboring framework particles.

In disturbed cells, as defined in Chapter 4 by the movement of both tracers, total abundance was reduced on average by 74% in Reach 1, 85% in Reach 2 and 85% Reach 3 (Figure 5.1). Indeed, bed movement represented the dominant form of population disturbance in Reaches 2 and 3. However in Reach 1 population reductions were just as considerable on stable substrate (Figure 5.1). This is somewhat counter intuitive as one would expect movement of the larger framework particles to represent a greater disturbance than that simply associated with high shear or the mobilization of particles smaller than tracer size. However, it is clear some form of disturbance occurred on stable substrate. This was consistent across all taxa, except Chloroperlidae (Figure 5.2). This is discussed further in the next section.
Percentage of total abundance lost on Disturbed and Stable substrate compared with pre-flood population levels.

Figure 5.1 Percentage of total abundance lost on Disturbed and Stable Substrate compared with pre-flood population levels. Average number of taxa per sample pre- and post-flood (error bars show one standard deviation).
Despite large reductions in abundance on disturbed substrate, only a slight reduction in the number of taxa was recorded (Figure 5.1), and indeed no taxon was completely absent from all samples. Whether individuals remained within the cell during substrate mobilization and survived by finding small scale spatial or temporal refugia, or whether the sampled fauna represents a mobile portion of the population that colonised the disturbed substrate before samples were taken is hard to say. However, as nearly all taxa were sampled on most occasions from disturbed substrate it is likely that individuals did in fact survive 'in situ', as taxa mobilities vary considerably, and hence one would assume recolonisation rates would also vary considerably. Further, post-flood samples were taken only 33 hours after the flood peak. Matthaei et al (2000) found that even after 19 days after a flood event, disturbed particles had not been colonised, even by mobile taxa.

Taxon-Specific Response to Bed Movement:

All taxa except Chloroperlidae showed considerable population losses on disturbed substrate compared with pre-flood population levels in most reaches (Figure 5.2, and Table 5.4). Chloroperlidae however, showed some form of resistance to bed movement at the scale of the Surber sampler in all reaches with only minor population losses. This response may be due to a preference for the interstitial habitat and the ability to burrow. As disturbance was defined by the movement of surficial particles, it is possible deep interstitial spaces may have provided a refuge for this taxon. All Surber samples were taken to a depth of approximately 10 cm, so either particle disturbance during the flood was contained within the surficial layer, less than 10 cm, or this taxon utilized interstitial spaces deeper than 10 cm, moving up to the shallower sediments within 33 hours of the flood peak.

A species of Leuctridae also showed a similar resistance to bed movement in the artificial disturbance experiments of Matthaei (1996). This stonefly also inhabits the interstitial spaces and
is similarly described as a burrower (Kenneth and Stark 1993), suggesting the interstitial habitat
may indeed protect some taxa from surficial bed disturbances.

The reduction in mean population densities of four taxa on disturbed substrate, Baetidae,
Leptophlebiidae, Chironomidae and Nemouridae, was highly significant ($p < 0.01$, after Tukey's
HSD a posteriori test) in all reaches (Table 5.4). For such taxa, except Nemouridae, the mean
reduction in population was uniformly over 80%. The response of Heptageniidae to bed
movement was more varied. At the reach scale, a large reduction in mean population was
recorded in both Reaches 2 and 3 (Table 5.4, Figure 5.2). However, the power to detect a
significant response in Reach 2 was masked by large sample variance from pre-flood samples.
As such the recorded reduction in population was only significant (after Tukey's HSD a
posteriori test) in Reach 3 (Table 5.4). In Reach 1 Heptageniidae appeared to exhibit a greater
resistance to bed movement (Table 5.4 and Figure 5.2). However, this may partly be an artifact
of the low pre-flood abundances in this reach. While mean pre-flood abundances of most taxa
varied between reaches, although not significantly, the mean abundance on disturbed substrate
post-flood was consistently similar across all reaches for all taxa except Chloroperlidae (Figure
5.2). The level of significance of a detected response is therefore partly governed by the mean
pre-flood abundance.

This consistent response on disturbed substrate raises two important points. First, at the reach
scale, invertebrate response to bed movement may be independent of bed movement intensity at
the reach scale. Reach 1 experienced a lower intensity of bed movement as indicated by
sediment transport rates, total yield and spatial distribution of bed disturbance (see Chapter 4),
yet reach averaged population means on disturbed substrate were similar in all reaches. Second,
mean post-flood abundances on disturbed substrate may be independent of mean pre-flood
abundances for all affected taxa. This combined with the fact that only a slight reduction in the
Figure 5.2 Taxon specific response on disturbed and stable substrate. Error bars show 1 standard error.

- ▲ Reach 1
- ● Reach 2
- ■ Reach 3
Figure 5.2 Cont’d

- D) Nemouridae
- E) Chloroperlidae
- F) Chironomidae

Δ Reach 1  ○ Reach 2  ■ Reach 3
Figure 5.2 Cont'd

G) Oligochaeta

![Graph showing average abundance of Oligochaeta in different reaches and substrates.](image)

- Reach 1
- Reach 2
- Reach 3
Table 5.4 Average percentage loss on disturbed and stable substrate from pre-flood baseline levels. Probability is shown in parenthesis after Tukey’s HSD *a posteriori* test on mean abundance between treatments (disturbed and stable) and pre-flood control.

<table>
<thead>
<tr>
<th>Disturbed</th>
<th>Baetidae</th>
<th>Leptophlebiidae</th>
<th>Chironomidae</th>
<th>Nemouridae</th>
<th>Heptageniidae</th>
<th>Chloroperlidae</th>
<th>Oligochaeta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach 1</td>
<td>89 ***</td>
<td>87 ***</td>
<td>87 ***</td>
<td>80 **</td>
<td>61</td>
<td>25</td>
<td>80 *</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(0.003)</td>
<td>(0.373)</td>
<td>(0.763)</td>
<td>(0.054)</td>
</tr>
<tr>
<td>Reach 2</td>
<td>91 **</td>
<td>89 ***</td>
<td>95 ***</td>
<td>88 ***</td>
<td>86</td>
<td>29</td>
<td>92 ***</td>
</tr>
<tr>
<td></td>
<td>(0.005)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(0.121)</td>
<td>(0.545)</td>
<td>(p&lt;0.001)</td>
</tr>
<tr>
<td>Reach 3</td>
<td>87 ***</td>
<td>90 ***</td>
<td>92 ***</td>
<td>60 ***</td>
<td>79 ***</td>
<td>26</td>
<td>84 **</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(0.543)</td>
<td>(0.002)</td>
</tr>
<tr>
<td>Stable</td>
<td>Baetidae</td>
<td>Leptophlebiidae</td>
<td>Chironomidae</td>
<td>Nemouridae</td>
<td>Heptageniidae</td>
<td>Chloroperlidae</td>
<td>Oligochaeta</td>
</tr>
<tr>
<td>Reach 1</td>
<td>91 ***</td>
<td>88 ***</td>
<td>89 ***</td>
<td>71</td>
<td>7</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Reach 2</td>
<td>18</td>
<td>43</td>
<td>80 ***</td>
<td>54</td>
<td>4</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Reach 3</td>
<td>37</td>
<td>#</td>
<td>52</td>
<td>#</td>
<td>27</td>
<td>23</td>
<td>#</td>
</tr>
<tr>
<td>Mobility</td>
<td>Swim</td>
<td>Swim</td>
<td>Swim</td>
<td>Crawl</td>
<td>Cling</td>
<td>Burrow</td>
<td>Burrow</td>
</tr>
</tbody>
</table>

Probability in parenthesis after Tukey’s HSD *a posteriori* test.

* - significant (p < 0.1) ** - very significant (p < 0.01) *** - highly significant (p < 0.001)

# - Samples where mean post-flood abundance on stable substrate was higher than pre-flood abundance.
Note, abundances of Nemouridae were significantly highly on stable substrate in Reach 3.
number of taxa was recorded on disturbed substrate suggests that the disturbed substrate as
defined in this study may have some sort of finite low level carrying capacity. In other words, at
the scale of the Surber sampler, refugia for a limited population may exist on disturbed substrate
for most taxa.

**Response on Stable Substrate**

The ability of populations to persist on stable substrate during the flood varied considerably
between reaches (Figure 5.2) and at the sample scale. The flood resulted in only a small
reduction in total mean abundance on stable substrate in Reaches 2 and 3 (Figure 5.1). In Reach
1 however total mean abundance was considerably reduced, comparable to that found on
disturbed substrate (Figure 5.1).

For Reaches 2 and 3 no change in average taxon abundance compared with pre-flood levels was
observed (Figure 5.1). However in Reach 1 again a slight reduction in taxa abundance was
observed, similar to that on disturbed substrate.

**Taxon specific responses:**

Variation in mean abundance on stable substrate showed some degree of generality at the reach
scale. Greater populations of most taxa were maintained on stable substrate in Reach 3 than
Reach 2, which again maintained higher populations than Reach 1 (Figure 5.2, Table 5.4).

Reach 1:

Except for Chloroperlidae, large reductions in abundance of all taxa were recorded on stable
substrate after the flood (Figure 5.2). Indeed, populations of Baetidae, Heptageniidae,
Leptophlebiidae, Nemouridae and Chironomidae were on average all reduced to a level slightly
lower than that on disturbed substrate. Such reductions in population from pre-flood levels were
highly significant (p < 0.001, after Tukey's HSD *a posteriori* test) for Baetidae, Leptophlebiidae,
Nemouridae and Chironomidae (Table 5.4). For these taxa, and indeed Heptageniidae (populations reduced on average by 71%), stable substrate in Reach 1 did not constitute a refugium.

Mechanisms of disturbance on stable substrate in Reach 1 acted within an intensity governed by the entrainment of the two tracers. In Reach 1 the tracers corresponded to a size range between \(D_{18}\) and \(D_{28}\) of the surface sediment. The dominant particle fraction of the bedload from Reach 1 was considerably finer than this, indeed a considerable amount of sand was mobilized in Reach 1 during this flood, much greater than that mobilized from Reach 2. It is possible this bedload fraction may have resulted in the observed population reductions on stable substrate in Reach 1.

Reaches 2 and 3:

The response of most taxa in Reaches 2 and 3 was generally similar in that populations were typically much greater on stable substrate than disturbed substrate (Figure 5.2), the taxa therefore exhibiting at least some form of resistance on stable substrate. The response was therefore markedly different from that in Reach 1.

Chironomidae was the only taxon however to uniformly show low resistance on stable substrate in all three reaches. Populations were reduced on average by 52% in Reach 3 and 80% in Reach 2, which was in fact highly significant (\(p < 0.001\), after Tukey's HSD \textit{a posteriori} test) and comparable to the reduction on disturbed substrate in Reach 2 (Table 5.4). All taxa except Baetidae clearly showed less resistance on stable substrate in Reach 2 than Reach 3 (Figure 5.2, Table 5.4). Indeed, in Reach 2 mean reductions of over 50% on stable substrate were recorded for both Heptageniidae and Nemouridae (Table 5.4).

A key finding in the study by Matthaei \textit{et al.} (2000) was the recording of higher populations on stable post-flood particles than pre-flood control particles. This is significant in that it suggests
individuals actively sought out stable particles as refugia, rather than simply surviving *in situ*. In East Creek mean populations on stable substrate in Reaches 1 and 2 were less than mean pre-flood populations for all taxa. However, in Reach 3 the mean populations of Nemouridae, Oligochaeta and Heptageniidae were in fact greater on stable substrate after the flood than on substrate sampled pre-flood. Indeed, the mean abundance of Nemouridae on stable substrate post-flood was in fact significantly higher than pre-flood abundances (see Table 5.4). However, the response exhibited by Nemouridae may have been caused by a bias from the sampling of small early instars post-flood that were too small to be sampled pre-flood.

Invertebrates have been shown to actively crawl around the substrate seeking preferential flow environments (Lancaster 1999). It is therefore conceivable that individuals could have actively accumulated on stable substrate in Reach 3 by crawling. However, if such a mechanism is responsible for the observed post-flood distributions, one questions why only Heptageniidae and Oligochaeta show such a pattern as both have very different abilities to crawl, and indeed why only in Reach 3?

Another possibility is that individuals may have drifted on to stable substrate. As most stable substrate samples in Reach 3 were taken near the bank, it is possible organisms could have drifted or been washed towards the stream edges to accumulate on the substrate near the banks. However, once again this does not explain why only two taxa show such a post flood distribution, and once again why only in Reach 3, as a similar distribution of bed disturbance was mapped in Reach 2. Furthermore, Oligochaeta and Heptageniidae have completely different mobilities and resistance traits, such as ability to cling onto the substrate, and may therefore have differing flight responses and susceptibility to dislodgment.
Post Flood Population Patches

The key effect of the flood on October 31 was to create invertebrate patches in Reaches 2 and 3. Populations on stable substrate in these reaches were significantly higher (p < 0.1, after Tukey's HSD *a posteriori* test) than those on disturbed substrate for most taxa (Table 5.5). While no attempt was made to distinguish between and sample stable and 'unstable' substratum patches pre-flood, sample consistency between pre- and post-flood samples was maintained in part by avoiding large substratum particles. As sample cells were chosen randomly, comparing the coefficient of variation from pre-flood samples with post-flood samples may provide some indication as to the level of invertebrate patchiness pre- and post-flood. This is expressed in Figure 5.3, a plot of the coefficient of variation for pre- and post-flood samples. For most taxa in Reaches 2 and 3 the coefficient of variation is considerably greater post-flood, indicting a much higher level of sample variance and hence patchiness after the flood than pre-flood. In Reach 1 however, the coefficient of variation for most taxa post-flood is no different than that pre-flood. Disturbance was evenly distributed across both stable and disturbed substrate. While the flood significantly affected population means it did not significantly alter the level of patchiness.

The effect of the flood on Heptageniidae was slightly different to that of most taxa. The distribution of this taxon post-flood did not differ from that pre-flood in both Reaches 1 and 2 (Figure 5.3). Further, there was no significant difference in mean abundance on stable and disturbed substrate in either of these two reaches (Table 5.5). This would suggest in these reaches the forces structuring the population pre-flood are just as strong as the abiotic forces associated with the flooding, i.e., bed movement. It appears as though the overall effect of the flood on this taxon, in at least Reaches 1 and 2, was not as great as the effect on the other more mobile taxa, such as Baetidae, Leptophlebiidae and Chironomidae.
Figure 5.3 Coefficient of variation for pre-flood and post-flood samples. Post-flood samples include stable and disturbed substrate samples.
Figure 5.3 Cont'd
Heptageniidae

Figure 5.3 Cont’d
Table 5.5 Probabilities for each taxon after Tukey’s HSD \textit{a posteriori} test comparing post-flood abundances from stable and disturbed substrate.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baetidae</td>
<td>0.924</td>
<td>0.005 **</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Heptageniidae</td>
<td>0.792</td>
<td>0.199</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Leptophlebiidae</td>
<td>0.845</td>
<td>&lt; 0.001 ***</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Nemouridae</td>
<td>0.363</td>
<td>0.010 *</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Chloroperlidae</td>
<td>0.917</td>
<td>0.973</td>
<td>0.979</td>
</tr>
<tr>
<td>Chironomidae</td>
<td>0.812</td>
<td>0.002 **</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Oligochaeta</td>
<td>0.125</td>
<td>&lt; 0.001 ***</td>
<td>&lt; 0.001 ***</td>
</tr>
</tbody>
</table>

*- significant (p < 0.1) ** - very significant (p < 0.01)  
*** - highly significant (p < 0.001)

For Chloroperlidae in Reach 2 the flood produced some degree of population redistribution, despite no significant difference in population mean pre-and post-flood. This is indicated by a considerably larger post-flood coefficient of variation (Figure 5.3). The majority of post-flood variance is due to the large variance from disturbed substrate samples (Figure 5.4), considerably larger than that pre-flood, suggesting that structuring forces related to the flood, undetected by the measure of disturbance as defined by the movement of the tracers, may have influenced the distribution of this taxon. Indeed, two of the samples on disturbed substrate within this reach showed considerable reductions in Chloroperlidae populations, whereas other samples had populations matching that of the most abundant sample in pre-flood conditions.

Two important points arise from this analysis: first, a certain intensity of bed movement may indeed constitute a disturbance for this taxon, and second, habitat disturbance as defined by the
**Figure 5.4** Coefficient of variation for Chloroperlidae pre-flood, and post-flood disturbed and stable substrate samples.
movement of the two tracers did not provide sufficient resolution to detect such a disturbance. That is, the measure of disturbance as defined by the two tracers was not an appropriate measure for this taxon, and indeed may even not have addressed the appropriate disturbance mechanism.

Community Response

The formation of invertebrate patches after the flood appears mostly to be governed by the overall response on stable substrate rather than that on disturbed substrate. That is, whether or not invertebrate patches are created is dependant on whether or not stable substrate can maintain invertebrate populations. The variable ability of stable substrate to maintain populations at the reach scale is clearly shown by the general community.

There is a subtle gradational change in community structure on stable substrate from Reach 1 to Reach 3. This is illustrated in the following ordination plots (Figure 5.5). Each reach was analyzed separately and, due to a potential post-flood sample bias, Nemouridae was removed from all samples before analysis.

In Reach 3 both pre-flood and stable substrate communities generally plot close together, with some overlap, but quite distinctly separate from the disturbed substrate communities (Figure 5.5). In Reach 2 however, a subtle change in response on stable substrate has produced three almost distinct groups corresponding to each of the two post-flood treatments (stable and disturbed substrate), and the pre-flood control. Disturbed substrate communities still remain distinctly separate from both groups (Figure 5.5). Within Reach 1 however two distinct sample groups are clearly evident. The stable substrate communities now plot with the disturbed substrate communities, reflecting the inability of stable substrate in Reach 1 to maintain invertebrate populations and general community structure.
Figure 5.5 Disturbed substrate, stable substrate and pre-flood samples plotted in ordination space.

Samples  ▲ Baseline  ● Disturbed  ■ Stable
Two mechanisms could be responsible for this observed pattern; a bedload finer than the tracers, and/or high shear stress. These two possibilities are discussed in the next chapter.

**Concluding Remarks**

Three important points have arisen out of this study. First, response to bed movement appears to be taxon specific. Second, stable particles do not always act as refugia and maintain populations during a flood. Third, more than one mechanism of community disturbance appears to be associated with bedload. Simply mapping the surficial disturbance of the larger framework particles may not be sufficient if one wishes to identify areas of population disturbance and map corresponding areas of refugia.

These points are discussed in the final chapter.
Chapter Six. Invertebrate response to Bedload Movement

Movement of the stream bed has a potentially important role in regulating the diversity and biotic composition of lotic communities. However, despite numerous experiments (e.g., see Reice 1984; Brooks and Boulton 1991; Rosser and Pearson 1995; Matthaei et al. 1997) and phenomenological accounts (e.g., see Boulton et al. 1992) we still lack an understanding of even the most basic biological effects of bed disturbance (Downes et al. 1998). This is in part due to the need for natural field observations at scales that are appropriate to invertebrates, but also scales that relate directly to bedload processes, such as particle entrainment. This part of the study therefore set out to address two simple hypotheses.

Hypothesis 2
Ho - Particle movement has no effect on the invertebrate community.

Hypothesis 3
Ho - Spatial variation in particle movement does not create invertebrate patches.

Despite the simple approach, this study is unique and much of what has been presented stands alone. Indeed, only studies by Matthaei et al. (2000), Strayer (1999) and Francoeur et al. (1998), who studied the role of bedform clusters as refugia for periphyton, provide for any sort of comparison.

Effect of bed movement on invertebrate populations

The response of taxa to substrate movement as defined by the tracers, was varied. On disturbed substrate the main response appeared to be governed by the use of interstitial habitat or ability to burrow. All taxa generally exhibited large reductions on disturbed substrate except Chloroperlidae.
Chloroperlidae is a ‘burrowing’ stonefly that typically inhabits the interstitial mineral spaces (Kenneth and Stark 1993). Density of this taxon was reduced on average by only 26% on disturbed substrate compared with pre-flood population levels. All other taxa generally showed little resistance to bed movement at the scale of the Surber sampler, being reduced on average by over 75%. As the focus of the study was on movement of surficial particles, such a division in response is not surprising. It is unlikely that populations of Chloroperlidae could survive on the surface during particle disturbance. The fact that populations were essentially the same as pre-flood populations within 33 hours of the flood peak suggests that Chloroperlidae was able to utilize a nearby refugia, such as deeper interstitial spaces. In Reach 1 the majority of particle disturbance appeared to be limited to the surface layer, therefore such a habitat would have conceivably provided a suitable refugia. However, where scouring occurs deep interstitial spaces may not provide refugia.

Indeed, the effect of scouring on benthos that utilize interstitial mineral spaces during flooding was demonstrated by Dole-Olivier et al (1997). They found that scouring during large events can result in considerable organism entrainment and loss from subsurface interstitial spaces. Circumstantial evidence from this study suggests that Chloroperlidae populations may have been affected by scouring. Small scour patches were evident in Reach 2 following the flood on October 31, and it is in this reach that an observed response on disturbed substrate was detected, as indicated by the large sample variance from the disturbed substrate samples. However, no systematic sampling from scour patches was undertaken in this study, and there was no attempt to distinguish between disturbance outside that indicated by the movement of the tracers. As to whether or not scour represents a disturbance for Chloroperlidae is conjecture.
What is of prime importance is the fact that the measure of particle disturbance in this study as defined by the movement of two surficial tracers may not have appropriately addressed a mechanism of disturbance. Many studies on disturbance in streams have utilized seeded tracers in the assumption that displacement constitutes a disturbance (e.g., Death 1995). This study has shown that for many taxa this may indeed be true, but for not all. It is evidence to suggest that disturbance mechanisms are taxon specific. This needs to be taken into account if one is looking at the effects of disturbance on the whole community as defined by the movement of seeded tracers (e.g. Townsend et al 1997).

Movement of Surficial Particles - appropriate scales of disturbance.
Within each cell variation in particle movement outside that indicated by the two tracers was not directly estimated. However, such variation existed. Small scale scour patches were evident throughout Reach 2 and although not recorded, variation in tracer travel distance was observed. Further, variation in the movement of naturally positioned particles within disturbed cells was also observed, indicated by the variable entrainment of particles marked \textit{in situ} within disturbed cells. Therefore, movement of the two tracers did not always indicate complete bed mobilization within the cell.

For the majority of taxa potential variations in the intensity of surficial material scour over and above the disturbance of the two tracers did not greatly affect the overall response. Baetidae, Leptophlebiidae, and Chironomidae populations were all reduced on disturbed substrate on average by over 80% in each reach. These reductions were all highly significant. Baetidae, Leptophlebiidae and Chironomidae appeared to exhibit slightly less resistance to bed movement than other taxa, such as Heptageniidae, defined as a clinger, and Chloroperlidae. If one accepts level of significance between mean pre-flood and post-flood disturbed substrate populations (see
Table 5.4) as a measure of resistance to bed movement, then overall the more mobile taxa do show slightly less resistance to bed movement at the scale of the Surber sampler.

Note, the detection of a response on disturbed substrate is dependant on the spatial scale of the sample relative to the spatial scale of the response. For all taxa except Chloroperlidae and possibly Heptageniidae, the scale of the Surber sampler was sufficient to detect a highly significant response, even though the movement of every particle within the sample was not monitored. This is significant in that models of disturbance addressing these taxa may therefore not have to treat each individual rock as a sampling unit, a suggestion proposed by Downes et al (1998) to account for our lack of knowledge on appropriate scales of disturbance. However, for Heptageniidae, either this taxon was more resistant to individual particle movement, or the scale of the Surber sampler was not appropriate to detect a significant response. If an organism responded to particle movement by crawling to a nearby stable particle that was still within the bounds of the sampling unit, then the response will not be detected. In which case the response of the taxon to disturbance would be better modeled at the scale of the individual particle. This may be the case for Heptageniidae.

**Bedload and the Scale of Invertebrate Patches**

This study is the first to show that stable areas of the stream bed are not always suitable habitats for invertebrates, and do not always act as refugia. This finding is in direct contrast to the findings from Franceour et al. (1998), Strayer (1999) and Matthaei et al. (2000), who found that stable particles do uniformly act as refugia for lotic organisms during floods.

In Reach 1 invertebrate populations were reduced on stable substrate by an average of 75%. This was equivalent to the reduction reported on disturbed substrate. Paradoxically while the flood on October 31 created a highly patchy environment in this reach, as defined by bed movement
(Figure 4.2), few if any corresponding invertebrate patches were created. Taxa were either unaffected by bed movement, e.g. Chloroperlidae, or equally affected on both stable and disturbed substrate, e.g. Baetidae. The distributions of all taxa after the flood in Reach 1 were generally no more clumped or patchy than pre-flood distributions, but population means were significantly lower. Disturbance existed at the reach scale for most taxa independent of movement of the larger framework particles. If the mechanism(s) of disturbance on stable substrate could be identified then population disturbance for most taxa could be modeled at the scale of the reach.

In Reach 2 the flood on October 31 resulted in an almost continuous distribution of bed disturbance with only limited patch development as defined by bed movement. However, the flood did create invertebrate patches that were spatially related to the distribution of bed disturbance. For example, Baetidae populations were reduced by only 18% on stable substrate, compared with 91% on disturbed substrate (Table 5.3), creating a very clumped distribution. Correspondingly, in Reach 2 one would model the disturbance of Baetidae populations at the scale of the Surber sampler, using the density and size of tracers employed in this study. However, disturbance was taxa specific, and therefore patch formation was correspondingly taxa specific. In Reach 2 Chironomidae populations were reduced on stable substrate by an average of 80%, comparable to that reduced on disturbed substrate (Table 5.3). As such, strong Chironomidae patches were not created in this reach by the flood. It is therefore possible that disturbance of Chironomidae populations could be modeled at the reach scale in Reach 2 as well as Reach 1.

It is evident that if one simply assumes there is only one mechanism of disturbance that uniformly acts across all reaches and all taxa, then the success of any resultant models of disturbance will be greatly compromised. As the resistance of both Baetidae and Chironomidae
on stable substrate in Reach 2 differed greatly, it suggests that the mechanisms of disturbance on stable substrate for these two taxa are also different.

This study has shown that the formation of invertebrate patches after a flood is not only taxon specific, but also variable in space. Where patches are created in one reach, they are not created in another. The effect of bedload on the invertebrate community is more complex than simply the disturbance of surficial framework or larger fraction particles. Obviously the next step is to identify the taxon specific mechanisms of disturbance and the geomorphic conditions over which they operate.

**Mechanisms of Disturbance Associated with Bedload**

At least two mechanisms of disturbance were associated with the flood, the movement of surficial framework particles and a mechanism that operated within the bounds of the critical shear stress necessary to mobilize the tracers. While these two categories are based on an arbitrary classification related to the size and position of the tracer, they may represent a meaningful and important division, as the scales over which they operate may differ.

Possible Mechanisms of Disturbance on Stable Substrate:

A stable particle will normally experience higher shear forces during a flood. At high levels such forces may entrain organisms, or represent a cue to evacuate, and as such represent a disturbance to the invertebrate community. However, evidence from Reaches 2 and 3, and also that from Matthaei et al (2000), suggests that stable substrate does act as a refugium for most taxa during episodes of relatively high shear (i.e., flood), at least within the bounds of mobilizing shear forces for loose heterogeneous sediment. In East Creek reach averaged shear forces were in fact greater in Reaches 2 and 3 than Reach 1, suggesting that shear force alone may not account for the population losses observed in Reach 1.
A possible mechanism of disturbance related to high shear forces is the movement of particles smaller than tracer size. This includes both abrasion by suspended fines, suggested as a possible community disturbance by Downes et al. (1997), and abrasion and burial from a fine gravel bedload. However, the former mechanism is again unlikely to be responsible for the observed invertebrate distributions on stable substrate after the flood, as one would assume both Reaches 1 and 2 experienced similar levels of suspended fines, as suspended material was unlikely to be caught in the pit traps. Furthermore, variation in response on stable substrate also occurred at the scale of the sample unit. Indeed, populations of all taxa from at least one sample on stable substrate in Reach 2 were reduced to a level similar to that on disturbed substrate. It is unlikely, because of dispersive effects in the flow, that suspended sediment levels could vary substantially across the narrow, relatively uniform channel of East Creek at this small scale, and hence result in the observed population reduction on stable substrate.

In considering the movement of fine gravel through Reaches 1 and 2, the disturbance from a fine bedload could represent a plausible explanation. Wholesale transport of fine sediment through Reach 1 was considerably greater than that through Reach 2. This could result in the observed differences in population response on stable substrate at the reach scale. Within Reach 2 the differences observed at the sample unit scale could be due to a locally patchy distribution of fine sediment. Indeed, the movement of bedload finer than tracer particles was observed to be patchy in East Creek, at least at the scale of the sample unit. This is illustrated in Figure 6.1, which also illustrates the potential effect of burial (and presumably abrasion) by fine bedload, and the scale difference between the tracer particle and invertebrate.

As bedload was not sampled from Reach 3 it is hard to propose a solid explanation for the gradational nature of the communities on stable substrate from Reach 1 to Reach 3. However, where a source of fine sediment exists, the effect of high shear forces on taxa and abrasion due to
fine bedload are inherently linked. Without one you do not have the other. A combination of shear force and fine bedload could explain the gradational distribution of populations on stable substrate at the reach scale. Due to a lower critical Shields number, it is possible stable substrate in Reach 3 may have experienced lower shear forces than that in Reach 2, which again may have experienced lower shear forces than that in Reach 1, despite evidence to the contrary from the estimates of the reach averaged shear stress. In this study stable substrate was classified in terms of the stability of the tracer particles, which in turn was governed by the stability of the neighboring particles. Looser particles will be entrained at lower shear forces, and if entrained the substrate is accordingly classified as disturbed, and not stable. So, while less of the substrate was actually mobilized in Reaches 2 and 3, the substrate that did remain stable may well have done so because of locally reduced shear forces, due to the lower overall reach averaged critical Shields numbers. One would expect less abrasion on stable substrate from a fine bedload in areas of low shear.

The overall response of invertebrates on stable substrate is only based on one flood event with no replication at the reach scale. However, the fact that most taxa show a similar response in each reach suggests that the observed trend from Reach 1 to Reach 3 may be real, and not simply due to chance. It is evident much more work needs to be done on the possible mechanisms of disturbance associated with bedload.

**Bedform Structures as Stable Refugia**

These findings bring into question the role of stabilizing bedform structures as refugia. Biggs et al. (1997) surveyed the physical characteristics of bedform clusters in 12 headwater streams in New Zealand, prompting the suggestion that a greater percentage of these structures in high gradient headwater streams could partially account for why some streams appear to maintain rich and diverse invertebrate communities, even in the face of high frequency, high intensity floods.
Figure 6.1 The tracer on the right was buried by fine gravel bedload. This cell was classified as undisturbed as both tracers remained intact. A Glososomatidae is seen on the stone in the bottom left corner. The stone case is visible against the dark background. This photograph illustrates the scale difference between tracer and macroinvertebrate, and the potential impact by burial and abrasion of gravel bedload finer than the tracer.
Evidence from this study suggests their implication that bedform clusters act as refugia may not uniformly hold, and may be dependant on external aspects such as fine gravel source pools. To the best of my knowledge the study by Francoeur et al. (1998) on the role of bedform clusters as refugia for periphyton is the only such study attempting to assess the actual role of these structures as refugia. They found such structures did remain stable during a flood event and did confer resistance on their associated periphyton communities relative to the surrounding bed.

This leads to a potentially important point. A high degree of streamwise imbrication in structures may allow for shelter from abrasive sand and high shear forces, as well as provide stabilization. Structures such as those found in East Creek where particle contact is mostly abutting and not imbricated may equally stabilize the bed, but may not provide as much shelter from fine bedload, or indeed turbulent eddies.

Concluding Remarks - Implications for disturbance ecology in streams

The data presented in this thesis suggest some novel findings with respect to scales and mechanisms of disturbance which can have important implications for studies of disturbance ecology in streams. Ecologists have recently focused on controls of particle entrainment and the spatial scales over which they operate (e.g. Downes et al. 1997, 1998; Biggs et al. 1997) in an attempt to better apply and test models and theories of disturbance ecology. These studies, along with those attempting to test models of disturbance ecology (e.g. Townsend et al. 1997a) have assumed that particle movement is indeed a biotic disturbance, and correspondingly stable substrate acts as refugia. Furthermore, most workers have assumed that the dominant disturbance mechanism associated with bedload is the movement of the larger particles.

This study presents evidence to question many of these assumptions.
It has shown that the various disturbance mechanisms associated with bedload are more than likely taxon specific. The appropriate methodologies and scales employed in studies on disturbance may also be taxon specific. For example, for highly mobile species such as Baetidae, in situations such as those experienced in Reach 1, disturbance could be modeled at the scale of the reach. For such species, variation in particle entrainment produced no corresponding variation in response. However, in Reaches 2 and 3 disturbance would be better modeled at the particle or sample unit scale, with the appropriate density of tracers. Scale of interest and methodology employed may therefore change with geomorphic conditions as the mechanism of disturbance changes.

Perhaps the most important point to arise out of this study is that before progress is made in the field of disturbance ecology much more work needs to be done on the potential for taxon specific mechanisms of population disturbance associated with bedload. Before one can assess the appropriate scales at which to address population disturbance, one must have a good understanding of the mechanisms of disturbance. For example, if abrasion due to fine bedload was indeed the main mechanism of disturbance in Reach 1, monitoring instability of larger particles only may lead to erroneous predictions. Similarly only monitoring the entrainment of surficial particles may lead to erroneous predictions for interstitial taxa such as Chloroperlidae. A comprehensive model of disturbance in streams may need to specifically consider abrasion due to fine bedload and scour as well as entrainment of surficial particles.

Clearly the next step is to better quantify the biological effects of variable bedload and high shear stress, and the scales over which they operate. Additionally, it is apparent that the geomorphological character of the stream bed maybe of prime importance, not only for establishing controls of surficial particle entrainment, but also for the supply and routing of fine sediment and controls on scour and fill.
References


