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The Relationship of Benthic Macroinvertebrate Assemblages to Water Surface Flow Types in British Lowland Rivers

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THE RELATIONSHIP OF BENTHIC MACROINVERTEBRATE ASSEMBLAGES TO WATER SURFACE FLOW TYPES IN BRITISH LOWLAND RIVERS

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Abstract

Surface Flow Types (SFTs), distinctive patterns of disturbance on the surface of flowing water resulting from the interaction between flow and channel shape, were used to delimit meso-scale in-channel habitats in eight British lowland rivers to determine whether SFT mesohabitats were capable of being mapped, and were physically and biologically distinct. Five different SFTs - No Perceptible (NP), Smooth (SM), Rippled (RP), Unbroken wave (UW) and Upwelling (UP) - were investigated, a further three rare types (Chute, Broken wave and Confused) were mapped but not investigated further.

Identification and mapping the extent of SFTs of was shown to be practical by estimating SFT mesohabitat extent onto large scale plans of the stream channel supported by differential Global Positioning Satellite technology. Mesohabitats were drawn as they existed, giving a large degree of variability in relation to channel shape and improving over several current rapid habitat mapping methods.

The physical distinctiveness of five SFT mesohabitats was examined using data collected from 596 mesohabitats over a wide range of discharges. Mean column velocity and substrate grain size (dominant and sub-dominant) increased from NP, through SM and RP to UW. Velocity, substrate size and embeddedness of fine particles were significantly different (ANOVA and Pair-wise) between the five SFTs investigated. Substrate size was positively associated with increasing velocity, depth and embeddedness were negatively associated with velocity. PCA showed that substrate opposes embeddedness and velocity opposes depth. The degree of distinctiveness was diminished by data ranges which encompassed several SFTs.

Macroinvertebrates were collected in 375 samples from 139 SFTs, using one-minute kick samples and identified to Biological Monitoring Working Party family level. ANOVA and Pair-wise analysis of Lotic-invertebrate Index for Flow Evaluation Velocity Group shows significant differences between 80% of SFT combinations with UP least distinct. Mean relative abundance and taxonomic richness increased from NP, through SM and RP to UW and were positively related to velocity. ANOVA showed significant differences between relative abundance and richness in SFTs, whilst Pair-wise analysis shows that adjacent SFTs, in relation to velocity, were less different than those further away. Thus NP is similar to SM and different to UW. Diversity and Equitability between SFTs were less distinct. Thirteen macroinvertebrate family groups were significantly associated (X^2 Test) with particular Surface Flow Types, *e.g.* Ancylidae with UW; Chironomidae with NP. Biological distinctiveness was not established, although general trends were identified

One mesohabitat – UP - is rare, being physically related to NP and SM in depth and substrate, and to SM and RP in velocity and embeddedness. It is biologically less distinct than the other four SFTs.

The research shows that the extents of NP, SM, RP and UW mesohabitats in British lowland rivers are capable of being mapped. There are significant trends in their physical distinctiveness which are linked to increasing downstream velocity although is not strong. The macroinvertebrate relationship is weaker, with abundance and richness increasing with velocity.

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Landowners	
Worcestershire Wildlife Trust	Access to Dowles Brook and Leigh Brook
National Trust, Sherborne Estate	Access to River Windrush
Mr and Mrs Furnival, Napley Lodge Farm, Norton-in-Hales	Access to River Tern
Severn Trent Water Ltd.	Access to River Tern
Alan Hughes, Moreton Saye, Market Drayton	Access to Bailey Brook
R A Meredith Plants Ltd., Offenham Nurseries, Evesham	Access to Badsey Brook
Drs G and K Swinburn, Rhea Court, Ledbury	Access to River Leadon
Mr P Weeks, Chatley, Droitwich	Access to Hadley Brook
Fieldworkers	
Vanda Bartosz	Field assistance
Graham Davison	Field assistance
Marie-Pierre Gosselin	Field assistance
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Environment Agency	Gauged Flow Data

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Abbreviations

ASPT	Average Score per Taxon
Bd	Badsey Brook
BFI	Base Flow Index
Bl	Bailey Brook
BMWP	Biological Monitoring Working Party
BW	Broken standing wave
Cap IV	Community Analysis Package, Version 4
CCA	Canonical Correspondence Analysis
CF	Confused flow type
CGU	Channel Geomorphic Units or Hydro-Morphological Units
CH	Chute flow type
D	Dowles Brook
DECORANA	Detrended Correspondence Analysis
EA	Environment Agency
ECM	Electromagnetic Current Meter
FDC	Flow Duration Curve
FF	Free Fall flow type
Fr	Froude Number
GIS	Geographic Information System
GPS	Global Positioning Satellite (System)
Hd	Hadley Brook
HMS	Habitat Modification Score
HQA	Habitat Quality Assessment
HSI	Habitat Suitability Index
IFIM	In-stream Flow Incremental Methodology
IQR	Inter Quartile Range
L	Leigh Brook
Ld	River Leadon
LiDAR	Light Detection and Ranging
LIFE	Lotic-invertebrate Index for Flow Evaluation
MesoCASiMiR	Meso-scale Computer-Aided Simulation System for In-stream Flow Requirements
MesoHABSIM	Meso-Habitat Simulation
MI	Macroinvertebrate
MiTG	Macroinvertebrate Taxonomic Group
NGR	National Grid Reference
NMCM	Norwegian Mesohabitat Classification Method
NOXY	No X (co-ordinate) No Y (co-ordinate)
NP	No Perceptible flow type
PCA	Principle Component Analysis
PHABSIM	Physical Habitat Simulation
Q	Discharge
RCC	River Continuum Concept
RHM	Rapid Habitat Mapping
RHS	River Habitat Survey
RIVPACS	River InVertebrate Prediction and Classification System
RP	Rippled flow type
SDR IV	Species Diversity and Richness, Version 4
SFT	Surface Flow Type

SFTM	Surface Flow Type Mapping
SM	Smooth flow type
SPSS	Statistical Package for the Social Sciences
T	River Tern
TWINSPAN	Two Way Indicator Species Analysis
UK	United Kingdom
UP	Upwelling flow type
UW	Unbroken Standing Wave flow type
W	River Windrush

1 INTRODUCTION

"A robust, empirical and practical channel typology / taxonomy needs to be developed to allow rapid characterisation of reaches in the field" (Newson and Newson, 2000, p.211).

Worldwide, rivers and streams have played a defining role in the evolution of mankind and development of civilisation; providing basic needs - water for drinking and washing, a source of food and a means of transport (Dingman, 1994; Poff, 2004). As civilisation developed, rivers were manipulated for navigation, crop irrigation and, following industrialisation, for power generation, as a raw material and a repository for waste (Hey, 1992; Harper *et al*., 1995). Consequently, rivers close to human habitation have been modified by urbanisation or agriculture although the ecological interest persists, and provides a focus for novel areas of research. In the latter part of the 20th century such damage was recognised and steps have been taken to improve river quality. River restoration and conservation has developed from the need to improve habitat for valued fish species, to the wider management of rivers (King, 2004; Vaughan *et al*., 2009).

In modern times there have been, essentially, two approaches to scientific studies of rivers, the physical and the biological. Two books, Fluvial processes in Geomorphology (Leopold *et al*., 1964) and The Ecology of Running Waters (Hynes, 1970), provided the foundation of modern river science. From these two sources research followed separate courses (Figure 1:1), although as time progressed researchers in the two disciplines produced, at first, inter-disciplinary then cross-disciplinary studies.

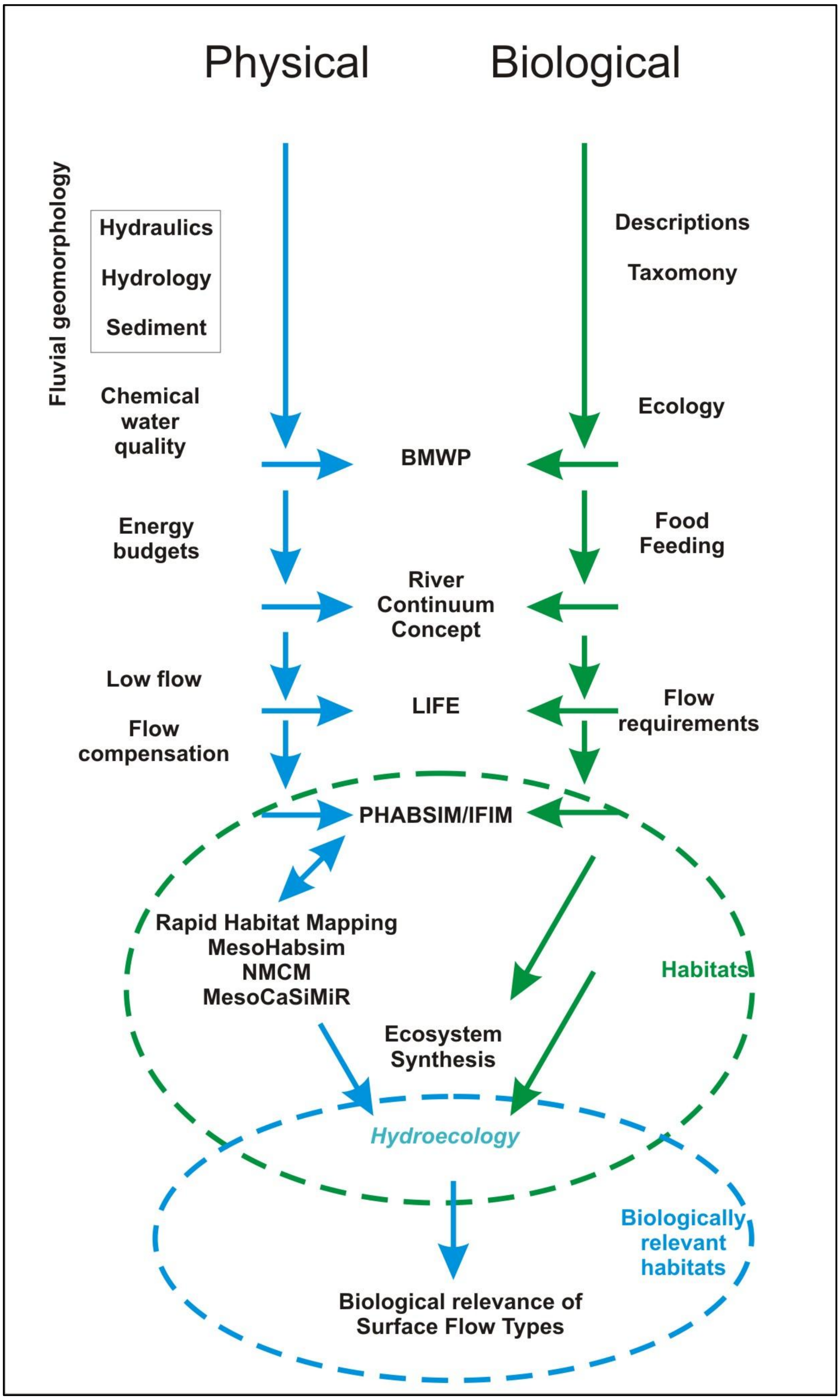


Figure 1:1 Flow diagram showing development of Hydroecology from physical and biological sources. Key: BMWP - Biological Monitoring Working Party; LIFE - Lotic-invertebrate Index for Flow Evaluation; PHABSIM Physical Habitat Simulation; IFIM In-stream Flow Incremental Methodology; MesoHabism - Meso- Habitat Simulation; NMCM - Norwegian Mesohabitat Classification Method.

The two approaches have co-existed for some time and a new discipline of Hydroecology, combining both physical and biological research is emerging (Thoms and Parsons, 2002; Wood *et al*., 2007; Reid and Thoms, 2008; Lancaster and Downes, 2010). The physical and biological disciplines meet in the habitat – “*the natural home or environment of an animal* …” (Soanes and Stevenson, 2003). However, it is important to recognise that “*the term habitat implies some biological significance, and that it is not just an identifiable physical feature*” (Maddock, 1999, p375). Therefore, whilst this research started with the premise that in-stream habitats defined by their Surface Flow Type (SFT) were visually distinct, the distinctiveness of their physical and biological characteristics required validation through rigorous investigation. If the physical and biological character of a stream can be determined from its SFT then habitat identification could be simplified and perhaps remotely sensed and automated.

1.1 Why A New Method?

River managers need effective tools that will assist them to identify river condition for monitoring purposes. In Europe, the Water Framework Directive is driving towards good ecological and good hydromorphological status (European Union, 2000; Large, 2009; Newson, 2009). Many rivers do not meet these standards and since 2000 interest in restoring degraded rivers has increased, requiring some way of predicting the outcomes of management proposals. Surveying river habitats is traditionally undertaken from the banks and several methods are in use: all can be time consuming. Remotely sensing the planet surface has been shown to be practical and, relatively, cheap. For example, Google Earth provides a low-resolution three dimensional view of the earth at no additional cost to the user. However, more detailed surveys would be required to identify river habitats. A viable system to remotely sense river habitats and to identify their hydromorphology and predict their ecology would be useful to river managers. Identification of in-stream habitats from hyperspectral imagery (Legleiter *et al*., 2002; Marcus, 2002; Marcus *et al*., 2003) and Terrestrial Laser Scanning (Milan *et al*., 2010) have been demonstrated. In her concluding remarks, Zavadil (2009, p9-9) suggests that ‘*Biotopes [alias SFTs] have direct links to ecology, and have the potential of advancing flow-ecology relationships’* and have the potential to support collaborative work between geomorphic and ecological disciplines.

1.2 Key Terms

Specific terms have been used by researchers when referring to particular areas of interest. In-stream habitats are referred to as Channel Geomorphic Units (CGU) or hydro-morphological units, both based on the shaping of channel sediments by stream flow, whereas biotopes are regions with a similar ecological community. Within the biological approach Harper *et al.* (2000) defined functional habitats by associating groups of macroinvertebrates with the physical habitat, whereas Armitage *et al.* (1995) and Armitage and Cannan (2000) defined mesohabitats based on substrate type or vegetation and established some degree of correspondence between them and macroinvertebrate communities supported. The association proved to be weaker in spring when discharge was high than in summer when discharge was lower. Table 1.1 identifies terms of interest within this research; SFT extents and their physical nature will be investigated at the mesohabitat scale, whilst biological relevance and associated physical conditions were determined at the microhabitat scale.

Table 1.1 Definition of key terms used when referring to in-stream habitats. Key: NP - No perceptible; SM - Smooth; RP – Rippled; UW - Unbroken standing wave; SFT - Surface Flow Type.

Term	**Definition**	**Examples**
Microhabitat	Homogeneous in-stream area extending to a few m^2, of particular interest to benthic macroinvertebrates.	Principe *et al*., 2007 Jähnig *et al*., 2009
Mesohabitat	An in-stream area between one and several channel widths long, perhaps comprising several microhabitat types.	Armitage *et al*., 1995 Principe *et al*., 2007 Jähnig *et al*., 2009
Reach	An in-stream habitat comprising several mesohabitats.	Common use
Sector	An in-stream habitat comprising several reaches.	Common use
Catchment	In-stream habitat extending to the watershed of the stream.	Common use
Channel Geomorphic Unit	A mesohabitat defined by its geomorphological characteristics – pool, glide, run, riffle *etc*.	Tickner *et al*., 2000 Maddock and Hill. 2005
Hydraulic Biotope	A mesohabitat defined by the water surface patterns – NP, SM, RP, UW *etc*. SFT.	Wadeson, 1994 Wadeson and Rowntree, 1998
Physical Biotope	A mesohabitat defined by physical properties of relevance to lotic macroinvertebrates, substrate type, underwater roots, submerged bryophytes *etc*.	Padmore, 1998
Functional habitat	Mesohabitats defined by substrate size, vegetation, bryophyte and macroalgae.	Harper *et al*., 1992 Kemp *et al*., 2000

Newson and Newson (2000) consider that whilst the microhabitat is of particular interest to macroinvertebrates and the basin scale is of increasing interest to river managers, future research should be focused at the meso-scale because this potentially provides a linking mechanism between these two scales of interest. Further, they recommend that research encompasses both physical and biological fields.

This research focuses on the distinctiveness of the physical characteristics of meso-scale habitats and their biological relevance. The first five terms in Table 1:1 have the following meaning in this thesis:

- Microhabitat. The location of the macroinvertebrate sample, a rectangle c. 0.23 x c. 0.35m (c. 0.08m^2).
- Mesohabitat. A contiguous area of channel with one SFT.
- Reach. A length of channel containing several examples of SFT mesohabitats, here extending from 110m to 346m.
- Sector. A length of channel containing several reaches and extending from several hundred metres to several kilometres.
- Catchment. The area of land from which surface water drains through the site investigated.

The term ‘SFT mesohabitat’ is used here to refer to in-stream habitats, ranging from several m^2 to several hundred m^2, defined by their SFT.

1.3 Surface Flow Types

Surface flow types are the result of interactions between channel form, bed shape, bed roughness and flow, which in some cases cause turbulent flow in the water column and interaction with the water surface to create patterns of disturbance. Whilst the nature of flow structures is complex (Harvey and Clifford, 2009), lower water velocity generates less turbulence than does higher velocity. At low velocity the turbulent structures can be so insignificant that the water surface remains smooth, whilst at higher velocities, the water surface becomes progressively more disturbed. Bed roughness is one source of turbulent structures (Harvey and Clifford, 2009) and whilst a viscous sub-layer is associated with flow through the substrate, clasts projecting into the water column above this layer can generate turbulence. Thus, slow flowing areas, which are often deep and with fine substrate, are likely to have little turbulence and a smooth surface, whereas shallow areas with higher velocities and coarser substrate are likely to have more turbulence and a disturbed water surface. Turbulence also results from increased bed-roughness from other in-stream structures, *e.g.* aquatic plants (Sand-Jensen and Pederson, 1999; Franklin *et al*., 2004) and tree roots (Harvey and Clifford, 2009).

Wadeson and Rowntree (1998) proposed that hydraulic biotopes defined by their surface flow type and substrate class provided a useful tool for assessing their hydraulic character, an adaptation of which was subsequently adopted by the United Kingdom's (UK) Environment Agency (EA) in the River Habitat Survey (RHS) (Newson *et al*., 1998; Environment Agency, 2003). The RHS has had wide application in the UK and has been modified for use in other countries (Szoszkiewicz *et al.*, 2006). Identification of SFTs is effective (Raven *et al*., 1997; Newson and Newson, 2000), Padmore (1997, 1998) showed that SFT mapping could identify geomorphological changes resulting from high flows, suggesting that SFTs could be capable of identifying the spatial extents of in-stream habitat.

Surface flow types are widely recognised and are often used within the description of in-stream habitats, however the relationship between SFTs and near-bed hydraulics is complex (Lancaster and Belyea, 2006; Reid and Thoms, 2008). Their physical distinctiveness has been investigated in upland rivers (Padmore, 1998; Dyer and Thoms, 2006); Reid and Thoms, 2008) their lowland character is less well known and their biological relevance even less so (Newson and Newson, 2000). In lowland rivers a limited range of SFTs occur, Figure 1:2 shows a reach of the River Tern at Ternhill, Shropshire, UK and the extents of five SFTs (the boundaries are shown by coloured lines). The extent of the SFTs varies; some extend completely across the channel others are close to the bank and some in the centre of the channel.

In this research SFTs were adopted as mesohabitat descriptors because of an interest in potentially identifying in-stream habitats remotely and issues associated with water turbidity in lowland streams preventing identification of depth and substrate size. Whilst schemes have been devised for classifying in-stream habitats (Section 2.4), many rely on descriptions of water depth and substrate size, whereas SFTs do not. Further, European researchers have adopted hydraulic biotope classification schemes (e.g. Padmore, 1997; Padmore 1998 Harvey *et al*., 2008; Szoszkiewicz *et al*., 2006), and a set of SFT descriptions was available from the RHS which, having been developed in the UK was appropriate for this research.

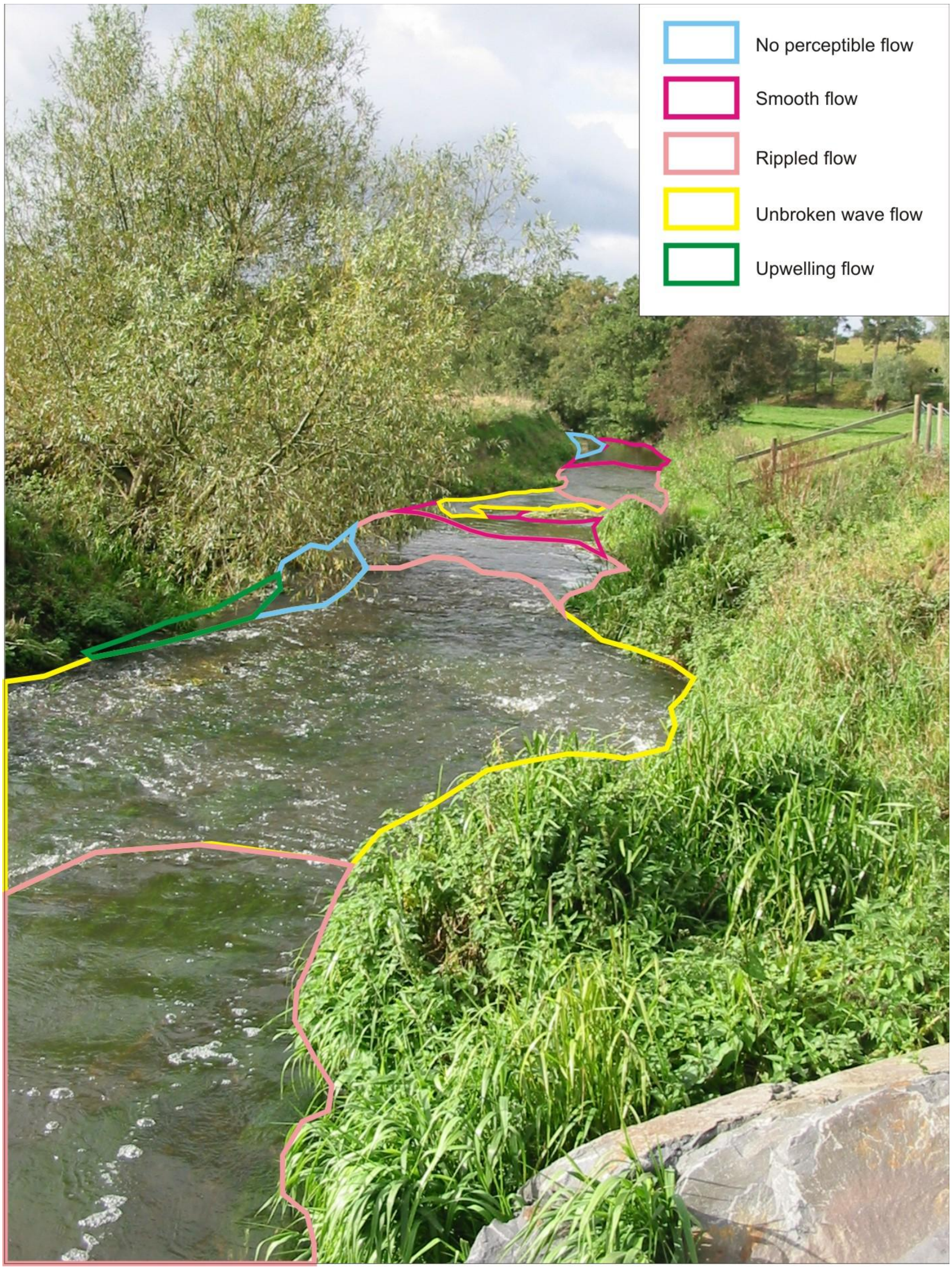


Figure 1:2 The River Tern, Tern Hill, Shropshire, United Kingdom.

1.4 Primary Research Questions

The questions to be investigated and answered within this research project are:

Primary Research Question 1:

Can Surface Flow Type mesohabitats in British lowland rivers be identified and recorded effectively?

- Can the extent of Surface Flow Type mesohabitats be accurately recorded?

Primary Research Question 2:

Which hydraulic variables best characterise No perceptible, Smooth, Ripple, Unbroken wave and Upwelling Surface Flow Type mesohabitats found in British lowland rivers?

- How distinct are the physical characteristics of each of the Surface Flow Type mesohabitats in British lowland rivers across a range of sites and discharges?

Primary Research Question 3:

What is the relationship between benthic macroinvertebrate communities and No perceptible, Smooth, Ripple, Unbroken wave and Upwelling Surface Flow Type mesohabitats in British lowland rivers?

- What is the nature of benthic macroinvertebrate communities in No perceptible, Smooth, Ripple, Unbroken wave and Upwelling Surface Flow Type mesohabitats in British lowland rivers?

1.5 Thesis Structure

The structure of this thesis is shown in Figure 1:3. CHAPTER 2 reviews the literature related to this research. CHAPTER 3 describes the sites used to investigate SFT mesohabitats and CHAPTER 4 explains and discusses the methods used. Identification of SFT mesohabitats and their physical distinctiveness is examined in CHAPTER 5, a discussion of the elements and conclusions from this part of the research are presented at the end of the chapter. The biological relevance of SFT mesohabitats is examined in CHAPTER 6, followed by a discussion and some conclusions. Conclusions relating to the primary research questions and practical applications of the method are presented in Chapter 7.

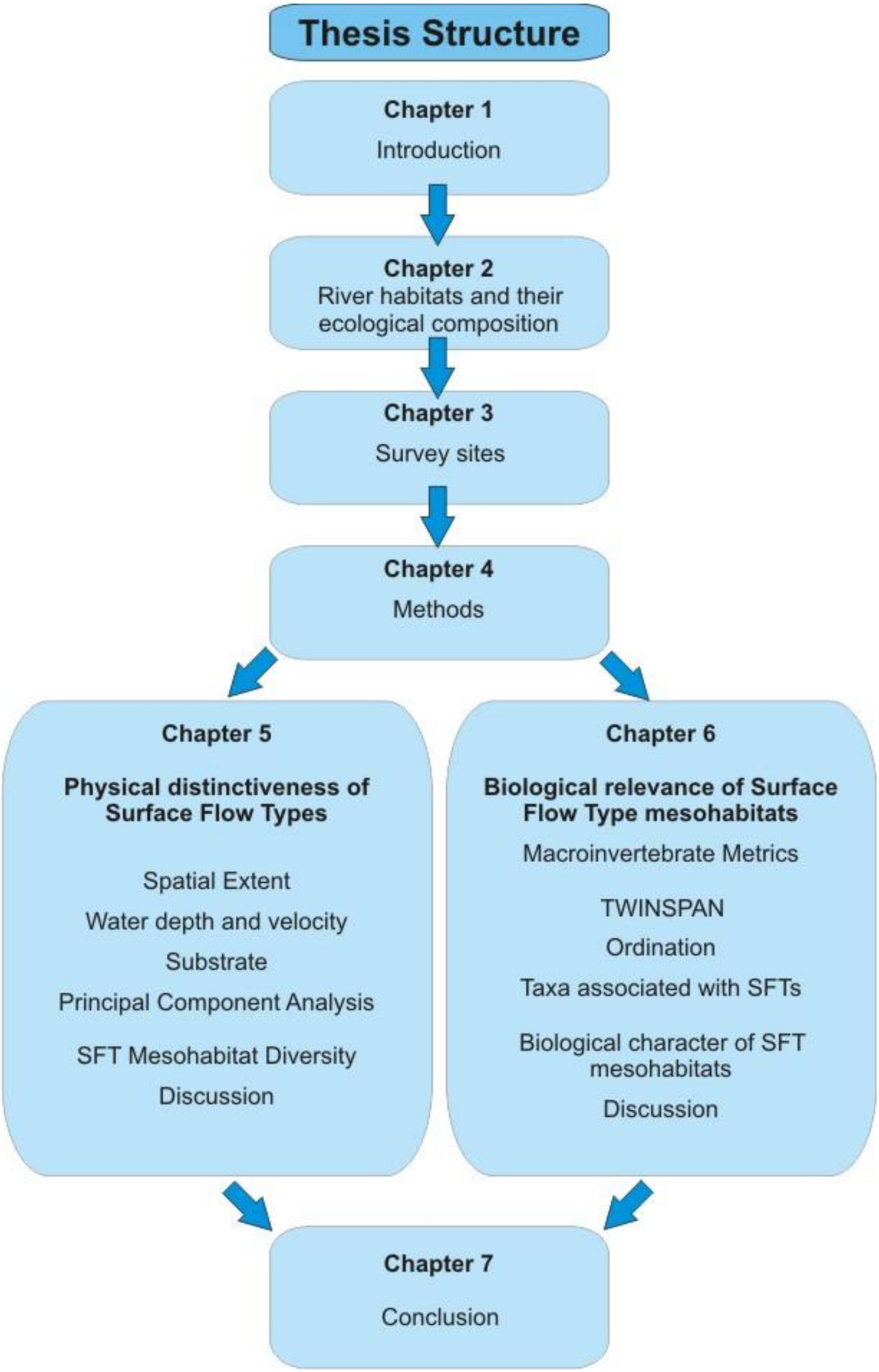


Figure 1:3 Thesis structure.

2 RIVER HABITATS AND THEIR ECOLOGICAL COMPOSITION: CURRENT UNDERSTANDING

2.1 Introduction

CHAPTER 2 reviews the current understanding of river science from the physical and biological perspectives and describes how this research project adds to that knowledge. The principles of hydrology, geomorphology and biology are reviewed within the discipline of Hydroecology and this research is placed into that wider context.

2.2 Surface Flow Types

Surface Flow Types form a key part of this research, being the method by which meso-scale in-stream habitats were defined. Rivers contain habitats at a wide range of scales, ranging from the microscopic to several hundreds of m^2, whilst each habitat has relevance for both natural and man-made interests, the meso-scale habitat is currently of considerable interest to river managers and researchers (Newson and Newson, 2000). Defining the extent of habitats at the mesohabitat scale has been subject to a great deal of research over recent years (Maddock and Bird, 1996; Paraseiwicz, 2001; Harby *et al*., 2004; Eisner *et al*., 2005; Maddock and Hill, 2005), several methods have been developed to describe and map mesohabitats.

The interaction between riverbed morphology, bed roughness and local hydraulics produces a series of distinct patterns on the water surface – Surface Flow Types. Photographs of a range of SFTs are shown in Figure 2:1. It should be noted that three SFTs (BW, CH and FF) are not commonly associated with British lowland rivers and were, therefore, not investigated in detail further.

(a) No perceptible flow type (NP).

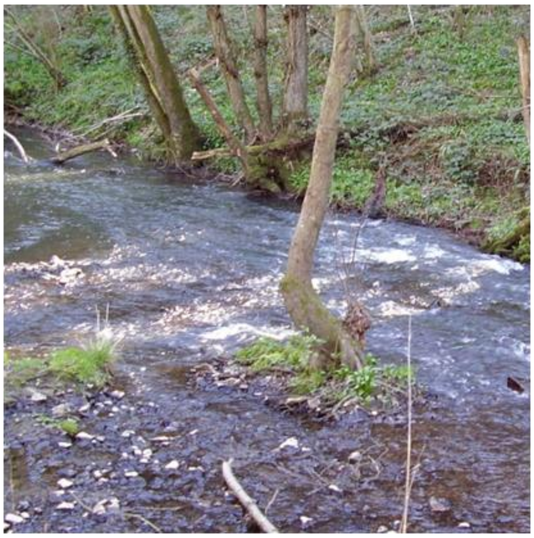
(b) Smooth flow type (SM).

(c) Rippled flow type (RP).

(d) Unbroken wave flow type (UW).

Figure 2:1 Photographs showing Surface Flow Types. Grey backgrounds show Surface Flow Types not investigated in detail.

(e) Upwelling flow type (UP), within the yellow circle.



(f) Broken wave flow type (BW).

(g) Chute flow type (CH).

(h) Free fall flow type (FF).

Figure 2:1 (cont.) Photographs showing Surface Flow Types. Grey backgrounds show Surface Flow Types not investigated in detail.

Surface flow patterns were classified by Wadeson (1994) and Wadeson and Rowntree (1998), and have been used to define mesohabitats in several studies. Padmore (1997) developed detailed descriptions of SFTs and advocated that they could provide a standard description of in-stream habitats that was visually identifiable, the descriptions were reproduced in Newson and Newson (2000). Surface Flow Types were adopted by the UK EA as surrogates for CGUs in the RHS (2003 version) (Raven *et al*., 1997; Environment Agency, 2003). Dyer and Thoms, (2006) and Reid and Thoms (2008) used SFTs in a study of hydraulic diversity and the distribution of benthic macroinvertebrates in the Cotter River, Australia.

2.2.1 Hydraulic Character of Surface Flow Type Mesohabitats

River flow is both non-uniform and unsteady and in natural channels is almost always turbulent above a thin viscous layer (Gordon *et al*., 2004). The hydraulic character of SFT mesohabitats is driven by large and small scale factors. At the larger scale, the distribution of currents within SFT mesohabitats is complex. In-channel flow is constrained by channel shape, which directs flow around curves with the greater flow directed to the outside of the bend. Flow through bends, therefore, is three dimensional with secondary flow cells occurring. Thorne and Hey (1979) showed that in meander bends a large flow cell directs fast-flowing water at the surface of a bend to the outer bank, with a corresponding movement of bed flow towards the inside of the bend. This transports eroded material from the outer bank and carries it to the inner bank creating a ‘cut-bank’ on the outer part of the bend and point bar on the inner bank. Further, small cells of upwelling flow were identified in the upper parts of the outer bank. Therefore, the nature of channel flow, driven by channel shape will determine the presence of certain SFTs (e.g. upwelling SFTs on the outside of meander bends).

At a smaller scale, both turbulent and laminar flow is present in the water column, although laminar flow is rare. Turbulent flow is considered likely to be present in any natural channel (Wadeson, 1994) and forms the upper part of the column whilst a viscous boundary layer exists close to the bed caused by friction with the bed. It is within this viscous layer that many macroinvertebrates live most of their lives. The physical nature of hydraulic biotopes is complex; Wadeson (1994) suggests that ecologists require more detail than can be provided by geomorphologists, and that hydraulics of flow, integrating flow dynamics and geomorphological variables provides a possible solution.

Hydraulic indices fall into two groups, those in the water column and those near the bed. In the water column, the existence of laminar flow or turbulent flow is determined by the ratio of inertial forces to viscous forces described by the Reynolds number (Re) = $(V \times D)/v$ where V is velocity at 0.4 depth; D is depth; v is kinematic viscosity (Gilvear and Bravard, 1996). Tranquil and rapid turbulent flow is determined by the relationship between inertia and gravity described by the Froude number (Fr) = $v/\sqrt{gD}$, where v is velocity; g is acceleration due to gravity and D is depth Gilvear and Bravard, 1996), this dimensionless number has been used to characterise local habitat (Jowett, 1993) although Clifford *et al.* (2006) caution that Froude numbers can relate to very different depth/velocity combinations.

Near to the bed, Shear velocity (V*) = *v*/[5.75<log(12.3 *d/k*) (where *v* is velocity; *d* is depth, *k* is substrate height) and Roughness Reynolds Number (Re*) = V*k/v (where V* is shear velocity; k is roughness height; v is mean velocity) have been used to characterise near-bed hydraulic conditions, although Wadeson and Rowntree (1998) consider that Roughness Reynolds Number is ecologically useful because it combines elements of both substrate and flow.

Wadeson and Rowntree (1998) examined Froude number, Reynolds number, Shear Velocity and Roughness Reynolds number in respect of several South African rivers, encompassing a wide range of hydraulic biotopes at several discharges. They show that there is considerable overlap of index values between the several hydraulic biotopes although they consider that the hydraulic biotope has potential as a habitat unit descriptor. Usefully their study included surface flow type within the hydraulic unit descriptions. Figure 2:2 shows the general homogeneity of backwater pool and pool in relation to other habitats, and the variability of higher energy biotopes (Wadeson and Rowntree, 1998, p150). There is an increase in index value through Pool (NP SFT), Run, (RP) and Riffle (UW) these appear to follow the increasing energy gradient, although Glide (SM SFT) is shown as ‘concentrated data’ with the highest values. They conclude that, apart from rapid and cascade which can be grouped together, the hydraulic biotopes can be considered hydraulically distinct. Note that Backwater Pool, Pool (both NP SFTs) and Glide (SM SFT) biotopes contain data which are highly concentrated, suggesting similarities with these low energy biotopes.

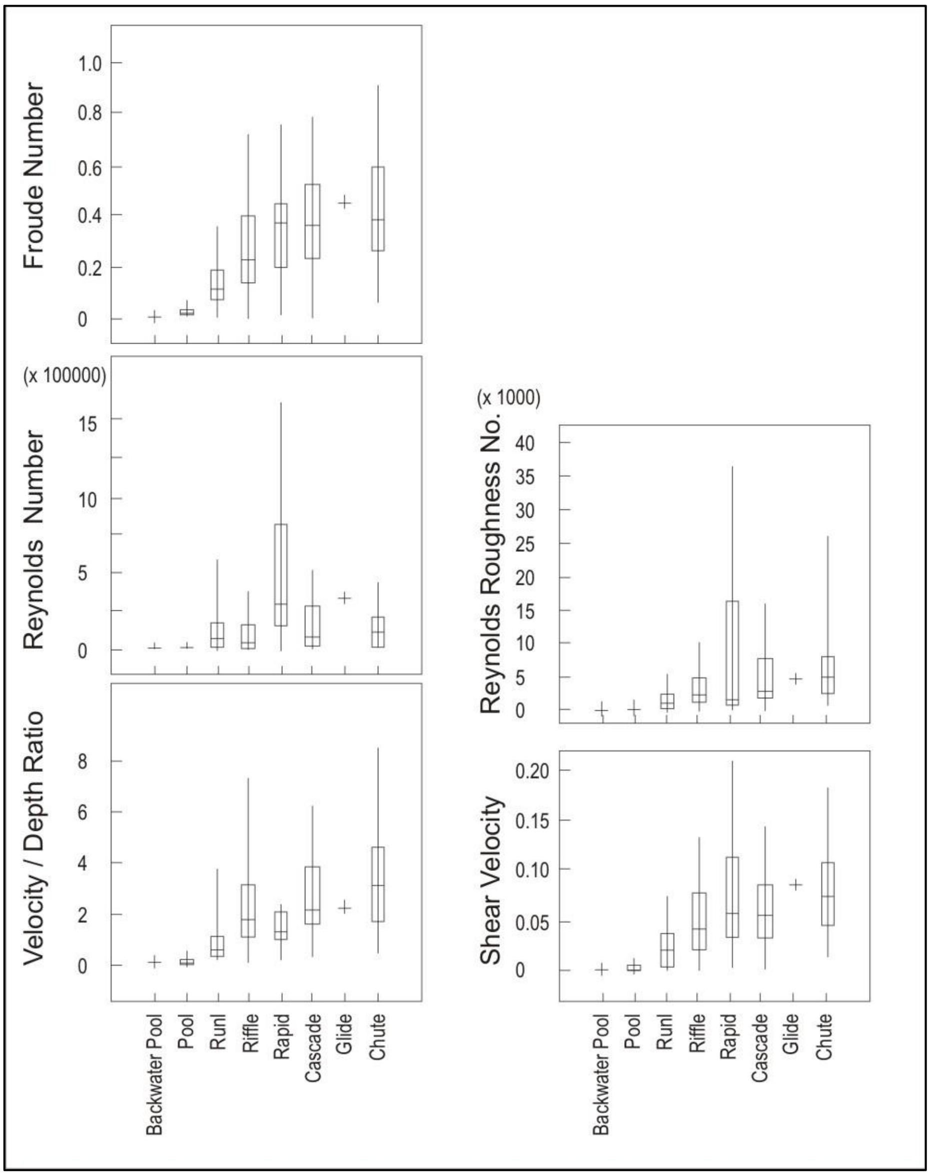


Figure 2:2 Box plots showing variability of selected hydraulic indices for hydraulic biotope classes in the Buffalo River. Box indicates median and interquartile range, whisker indicates total range, + indicates highly concentrated data. (Re-drawn from Wadeson and Rowntree, 1998, p 150.)

Figure 2:3 presents a conceptual diagram showing how turbulence increases with increasing substrate size and velocity and decreasing depth in relation to several hydraulic biotope classes. The SFT for each class is also shown. Apart from chute and upwelling flow, turbulence in the water column generates a series of distinct water surface patterns. Upwelling flow might be considered as a plume of water directed to the surface by a sufficiently large feature, a large bed or bank form. Chute flow is more laminar in nature and occurs over flat surfaces (*e.g.* bedrock) or through narrow gaps between large substrate and is found primarily in upland areas.

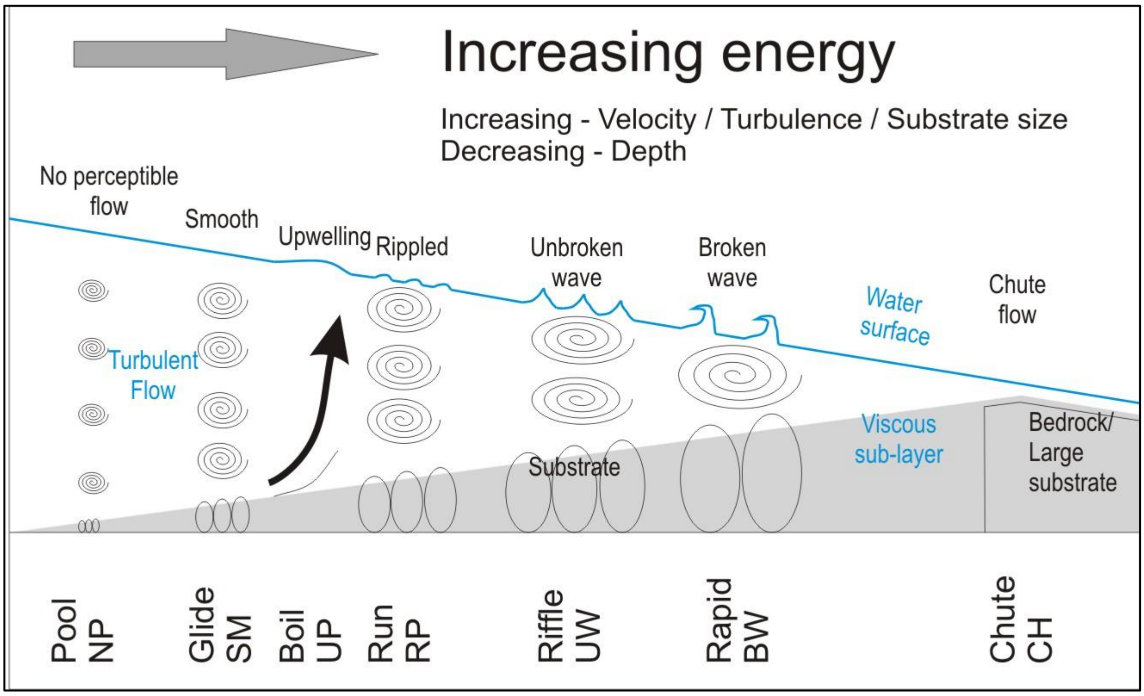


Figure 2:3 Conceptual diagram showing the interaction of substrate and water column hydraulics producing distinct patterns on the water surface - surface flow types.

The nature of flow within hydraulic biotopes is complex. Harvey and Clifford (2009) investigated flow structures in pools, glides, and riffles in the River Tern, Shropshire. Recordings were taken from points in a cruciform shape consisting of five points spaced at 1m intervals along the centre of the channel a further and five points at 1m intervals across the channel at the central point of the sample area. The velocity components in both stream-wise and vertical vectors at 0.2 and 0.8 water depth were recorded for 30s at 16hz. The data were subjected to a range of analytical techniques, intended to quantify turbulence. They conclude that burst-sweep turbulence generation, shedding of vortices from individual clasts and bed micro-topography, and larger structures associated with tree roots and larger-scale forms are responsible for the internal flow patterns in each hydraulic biotope. Glide (SM SFT) is considered to have the simplest flow structure possibly related to burst – sweep structures, reflecting the flume like nature of the channel. Riffle (UW SFT) has a more complex form with vortices being shed from microform roughness, whilst pool (NP SFT) is the most hydraulically complex biotope, characterised by burst-sweep structures and vortex shedding from small scale grain roughness and larger scale forms. The relationship of pool to glide and riffle is at odds with Wadeson and Rowntree (1998).

Because lowland rivers have shallow angle beds, water velocity is lower and at a given discharge the less energetic SFTs (NP, SM, RP, UW, UP) are likely to occur more often than the more energetic SFTs (BW, CH, CF and FF). High energy SFTs are also more likely at higher discharges and at bank-full may dominate the channel.

The biological relevance of in-stream habitats defined by SFTs is not well understood, although some research has been published. Reid and Thoms (2008) investigated the relationship between SFTs and macroinvertebrates in an upland Australian river (Section 2.5.4). The biological relevance of SFT mesohabitats in British lowland rivers is not known and will be established in this research using benthic macroinvertebrates.

2.3 Background to the Research

This research focuses on British lowland rivers, and was instigated during the later stages of the Lowland Catchment Research Programme (LOCAR) which addressed the bias of British hydrological research towards small upland catchments (Wheater and Peach, 2004). The programme expanded hydrological research into lowland catchments as part of the move towards integrated catchment management. The nature of the research and site selection dictated that sites should be <200m AOD which resulted in a reduction in the range of SFTs encountered.

Modern river science has its foundation in two works: *Fluvial Processes in Geomorphology* (Leopold *et al*., 1964) and *The Ecology of Running Waters* (Hynes, 1970) both of which stimulated scientific endeavours during the later part of the 20th Century. Research initially took two routes, one based upon physical properties and the other on biological properties. Hydraulics, hydrology and sediments were the focus of physical research with efforts made to explain the processes by which rivers are formed and maintained. In parallel, biologists were researching plants, fish and macroinvertebrates, describing the organisms and understanding their life strategies. During the late 1980s the work of the two scientific communities began to move closer together and during the 1990s a new discipline of Hydroecology emerged.

Developing understanding of river processes led to a quest for integrated process understanding. The River Continuum Concept (RCC) (Vannote *et al*., 1980) was developed to predict the downstream relationship between aquatic macroinvertebrates grouped by functional feeding types. Walker (2006) considers that, although the RCC provided a platform for further understanding of lotic environments, it failed to link science and resource management. Newson and Newson, (2000) consider that the RCC is the principal conceptualisation of downstream pattern and control in biota, although Hydraulic Stream Ecology (Statzner *et al*., 1988) and Patch Dynamics (Townsend, 1989) emphasise the temporal aspect of stream ecology, and also provide an important contribution to the issue of lateral and longitudinal variability in hydraulic habitats.

Traditionally the ecology of rivers and their surroundings have been studied separately, although rivers are inexorably linked with their floodplains. The Flood Pulse Concept (Junk *et al*., 1989) was proposed as a way of integrating understanding of the river and its floodplain. More recently interest in restoration of channel and floodplain connectivity is being developed (Thoms *et al*., 2006; Reid *et al*., 2006; Tetzlaff *et al*., 2007) and new survey methods created (*e.g.* GeoRHS – Environment Agency, 2005). Temporal flow variability was recognised as necessary for biotic diversity in the Natural Flow Regime (Poff *et al*., 1997), which has been suggested as a solution to many catchment management issues (Stanford *et al*., 2006; Tockner *et al*., 2006), although Thorp *et al*., (2006a, 2006b) consider that the biological links to habitats are over-simplified and proposed the Riverine Ecosystem Synthesis model to describe whole catchments from an eco-geomorphological perspective.

An interdisciplinary (or multidisciplinary as some would suggest) approach to river science, involving hydrology, ecology and geomorphology is widely advocated (*e.g.* Newson and Newson, 2000; Thoms and Parsons, 2002; Hannah *et al.*, 2004; Hannah *et al*., 2007; Vaughan *et al*., 2009). Such an approach allows investigation of the whole of the river to provide a broader understanding of lotic habitat. The new discipline is still evolving, and has several aliases. As a fusion of ecology, hydrology and geomorphology several combinations of the root names of these core disciplines have been used, *i.e.* Eco-hydraulics (Pardo and Armitage, 1997); Eco-geomorphology (Thoms and Parsons, 2002; Thorp *et al*., 2006a, 2006b), Biogeomorphology (Viles *et al*., 2008) and Eco-hydromorphology (Vaughan *et al*., 2009). Currently both Ecohydrology and Hydroecology are widely used, although Hannah *et al*. (2004) consider that ecohydrology is more closely associated with aquatic plants. Hydroecology usefully combines both hydraulics and hydrology with ecology, which are major themes in this thesis and is, adopted henceforth (Figure 2:4).

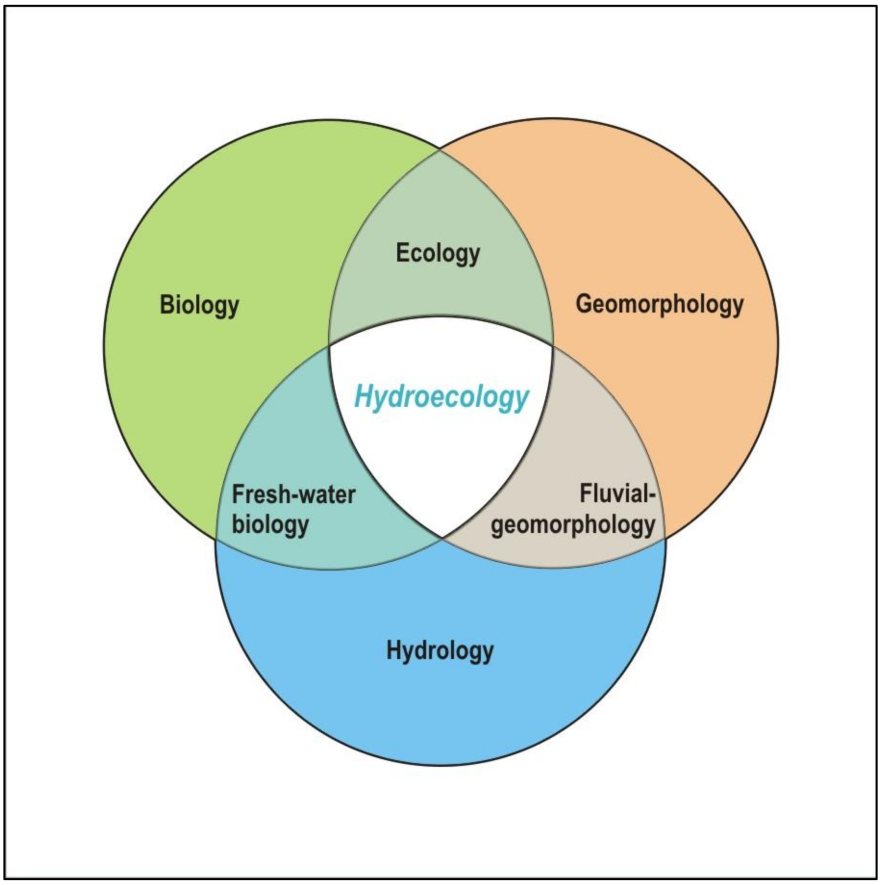


Figure 2:4 Hydroecology at the interface of biology, geomorphology and hydrology.

2.4 In-Stream Habitats

2.4.1 Habitats

Habitats are where the physical and biological disciplines meet. However, the term is often used (in the popular media) in the context of the physical environment without reference to the biological significance. A wide range of physical conditions exist in a range of habitats. For example, increasing substrate size increases bed roughness, and steeper bed slope increases velocity, which has to be overcome by resident biota. Greater water depth is associated with lower velocity and a smoother water surface. Macroinvertebrates have evolved strategies to cope with these conditions, including locomotion, attachment and concealment (Cummins, 1992). For example, the burrowing mayfly (Ephemeridae) has a cylindrical form and is frequently found in soft substrates and slow moving water whilst the mayfly (Heptageniidae) has a flattened form, with powerful feet and legs to cope with fast flowing water (Elliott *et al*., 1988) although Lancaster and Belyea (2006) contend that this body shape also allows access to interstitial spaces.

Several habitat classification schemes have been developed. Some are based on their physical characteristics, and include ‘channel geomorphic units’ (Hawkins *et al*., 1993), ‘mesohabitats’ (Tickner *et al*., 2000), ‘physical biotopes’ (Padmore, 1997) and ‘hydraulic biotopes’ (*e.g.* Wadeson, 1994; Wadeson and Rowntree, 1998). Other schemes are based on biotic variables; Functional Feeding Groups (Cummings, 1974) uses the feeding adaptations of macroinvertebrates to classify habitat, patch dynamics and lateral diversity. Models predicting the biological relevance of the physically based classification schemes followed, *e.g.* Physical Habitat Simulation Model (PHABSIM) and In-stream Flow Incremental Method (IFIM) (Bovee, 1982) where suitable habitat for fish was predicted. Thus, the habitat became the focus of hydroecological research.

2.4.2 Issues of Scale

River processes operate at a range of scales from microhabitats occupying a few square metres to catchments extending to thousands of square kilometres. At the micro- or meso-scale, geomorphologists and biologists have devised classification schemes (Bovee, 1982; Maddock and Bird, 1996; Extence *at al*., 1999; Eisner *et al.,* 2005). Although the schemes have similar goals the two disciplines have produced different solutions. Geomorphologists have favoured an approach starting with the habitat and exploring the nature of the biota, whilst biologists have taken an approach starting with biological needs (Figure 2:5) Newson and Newson (2000) consider that, at this point, there was an opportunity for geomorphologists and biologists to merge understanding and SFTs may be a method to carry this forward.

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Figure 2:5 A comparison of physical biotopes and functional biotopes. (Newson and Newson 2000, p200).

The small size of benthic macroinvertebrates suggests that the habitat of most relevance to them is also very small, perhaps a single stone, or a small area of gravelly sand – the patch or microhabitat. At this scale near-bed turbulence can vary in magnitude and direction over short time periods (Statzner *et al*., 1988). Water velocity is closely correlated with macroinvertebrate family distribution (Extance *et al*., 1999) and may be responsible for family presence/absence influencing community composition.

Physical conditions in adjacent microhabitats are likely to be different, sometimes subtly, sometimes not. Beisel *et al*., (2000) concluded that substrate heterogeneity was a key factor in determining macroinvertebrate community, MiTG richness increased with substrate heterogeneity, providing a wide range of niches for different taxa and short distances between them to allow colonisation. Townsend (1989, p47) argues that in-stream (microhabitats) conform reasonably well to the patch dynamics concept. He asserts that "*every section of every stream bed is patchy on some scale and has its own kinds of disturbances, colonisers, colonial sources and species interactions*". The patch dynamics concept predicts that, at the patch level, species interact where some are pioneer species, whilst some arrive later and may out-compete the original pioneer inhabitants. Therefore, the time interval between disturbances (high flow events) is a driver of microhabitat macroinvertebrate community in flashy streams. Where high flows occur more frequently, the community may not have the opportunity to reach its natural peak. Clearly microhabitat scale conditions are important to macroinvertebrates; however, using patch dynamics to model in-stream conditions at basin scale is unrealistic, especially when coupled with the downstream zonation advocated by Vannote *et al*. (1980) in the RCC. Meso-scale habitats are seen by Newson and Newson (2000) as a solution to the problem of selecting an appropriate scale that allows both integration with and movement between, other scales of interest.

Effective sampling in mesohabitats is an issue, because samples are collected from a series of microhabitats. Heino *et al*. (2004) examined patchiness of benthic macroinvertebrate abundance at three nested scales: ten samples were obtained from three riffles at two sites within three tributaries. Mean macroinvertebrates abundance in one sample varied considerably Figure 2:6. They concluded that overall, most of the variation was at the small (microhabitat) scale and appeared to be linked to the extent of bryophyte within the sample area, although they are not conclusive on this point, and caution that many replicate samples are required to identify macroinvertebrate assemblages. Similarly, Lancaster and Beylea (2006) found a wide range of near-bed velocities in 99 macroinvertebrate sample points in one riffle.

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Figure 2:6 Mean (±1 SE) number of individuals and taxa per sample in each riffle. Capital letters (A, B, C) refer to different tributaries, small letters (a, b) to upstream versus downstream sections within each tributary, and numbers (1, 2, 3) to riffles within each section (Heino *et al.,* 2004, 1234).

Recently, Principe *et al*. (2007) examined four upland Argentinean streams in two flow periods (high flow and low flow): identifying habitats by SFT and substrate. Three benthic samples were taken from each hydraulic unit. Diverse grain size was found to be positively related to macroinvertebrate richness, diversity and evenness whilst

Canonical Correspondence Analysis (CCA) grouped samples and taxa mainly in relation to hydraulic units.

Catchment-scale understanding based on small units (microhabitats) is impracticable. At the meso-scale, several microhabitats are grouped together to form a larger unit – the mesohabitat - which may consist of several microhabitats with similar water depth and velocity but, perhaps, with a range of substrate sizes. Newson and Newson (2000, p211) argue that mesohabitats are an appropriate scale at which to develop '*a robust, empirical and practical channel typology/taxonomy … to allow rapid characterisation of reaches in the field'*. It is implicit that research at the meso-scale will result in some generalisation of habitat conditions Clifford *et al.,* 2006).

If a mesohabitat consists of several microhabitats, the reach consists of several mesohabitats linked together with several reaches forming the sector which group together to form a catchment (Figure 2:7). With the catchment increasingly becoming the scale of interest, the challenge is to translate microhabitat scale dynamics into meaningful catchment models (Parasiewcz, 2007).

Rivers are unidirectional systems with progressive changes from headwaters to mouth. Flow and sediment (size and availability) largely determine the nature of in-stream habitats (Charlton, 2007). Simplistically, headwater channels are narrow, steep and shallow, with highly variable water velocity and coarse bed substrate leading to high turbulence; oxygen levels are high and turbidity low. In contrast, in the lower reaches channels are wider and deeper; the bed less steep leading to less variation in water velocity. Although gradients generally decline downstream, average flow velocity typically increases due to increasing water depth and declining influence of boundary roughness (Schumm, 1977), bed and bank substrates are finer, there is less turbulence and oxygen levels are lower (Petts and Amoros, 1996). Schumm identified three catchment zones (Petts and Amoros, 1996, p7).

- Zone 1 - Production Zone in the headwaters where water, sediment, organic matter and solutes pass from the hill slopes into the channel,
- Zone 2 – Transfer Zone to where these materials are transported,
- Zone 3 - Storage Zone where sediment is stored for long periods of time.

Within the catchment, zones are delimited by changes in valley width and gradient, changes in water quality from different sub-catchments and within these zones different types of SFT will dominate.

In steep, coarse bedded reaches SFT mesohabitats are likely to be small and energetic (FF, CH, BW and UW) as coarse substrate disturbs the water column causing turbulence. In the middle reaches SFT mesohabitats are likely to be of intermediate energy (BW, UW, CH and RP) as slope and substrate size diminishes (resulting in less turbulence), SFT mesohabitats are likely to be larger than in the upper reaches. In the lower graded sectors larger and less energetic SFTs (RP, SM and NP) are likely to dominate as fine sediments cause less turbulence in the water column, although other structures, e.g. tree roots, may cause local disturbance.

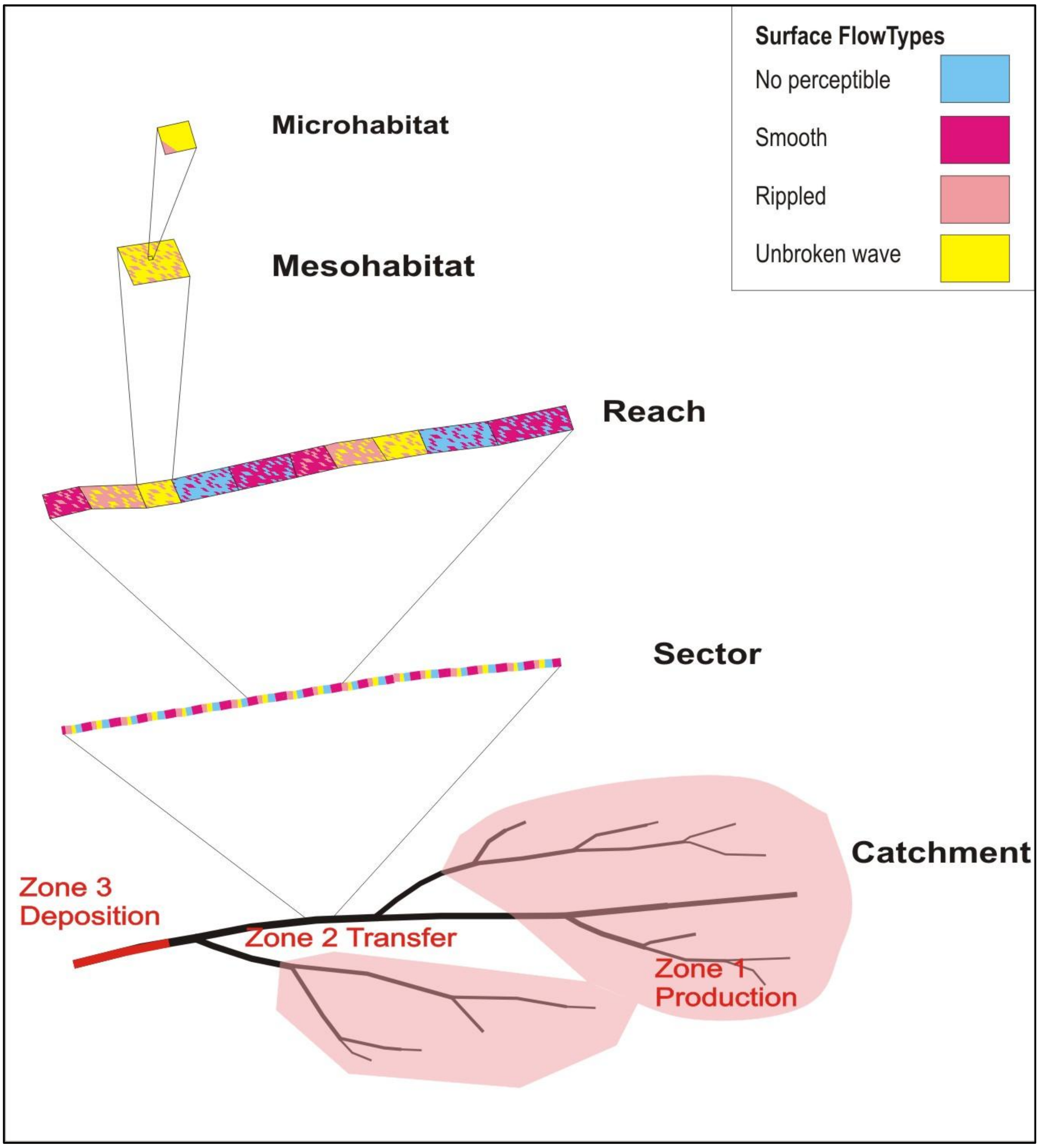

Figure 2:7 Nested habitats at the patch, meso, reach, sector and catchment scale (with Schumm's (1977) Zones shown).

In dynamic river systems, not only does the hydraulics of individual microhabitats change over time, but they do so at different rates. At the microhabitat scale, hydraulic variation (turbulence and eddies) operate over short temporal scales, seconds and minutes (Table 2.1), whilst increases in discharge from a storm may operate at the day to week level, with some catchments responding more quickly to inputs than others. Seasonal variation may be driven by higher rainfall in winter and climate change may be responsible for variation over many years. It is suggested (Effenberger *et al*., 2006) that more frequent high flows, found in flashy systems, favour pioneer species, whilst stable rivers allow communities to reach maturity.

Table 2.1 Spatial and temporal scales of river processes.

	Patch/ Microhabitat	**Reach/ Mesohabitat**	**Sector**	**Catchment**
Area	1x10-1 – 1x101m^2	1x102 – 1x103 m^2	1x103 – 1x104 m^2	1x104 – 1x106 m^2
Time	1 sec – 1 min	1 hr – 1 week	1 month – 1 year	1 year – 1000 years
	Turbulence	Storm event	Season	Inter-annual

2.4.3 Habitat Characterisation

Rivers compose a highly variable chain of hydraulic microhabitats with varying water depth, velocity and substrate; these can be grouped into areas with similar characteristics based on geomorphic and hydraulic properties (mesohabitats) which are repeated along a river, although the sequence varies. Researchers have sought to classify these areas into types with similar characteristics, leading to many habitat classifications. Schemes include 'Channel Geomorphic Units (CGUs)' (Hawkins *et al*., 1993), 'mesohabitats' (Tickner *et al*., 2000), 'physical biotopes' (Padmore, 1997; Orr *et al*., 2008; Harvey *et al*., 2008) and 'hydraulic biotopes' (Wadeson, 1994; Wadeson and Rowntree, 1998).

A hierarchical scheme based on increasingly fine descriptions of morphological and hydraulic properties of CGUs (Figure 2:8) were devised by Hawkins *et al*. (1993). Hawkins' original classification has been amended to reflect individual circumstances. Using Rapid Habitat Mapping (RHM) (Maddock and Bird, 1996), Maddock and Hill (2005) used a reduced number of CGUs in a trial of several mesohabitat mapping systems on the River Windrush, UK (Table 2.2).

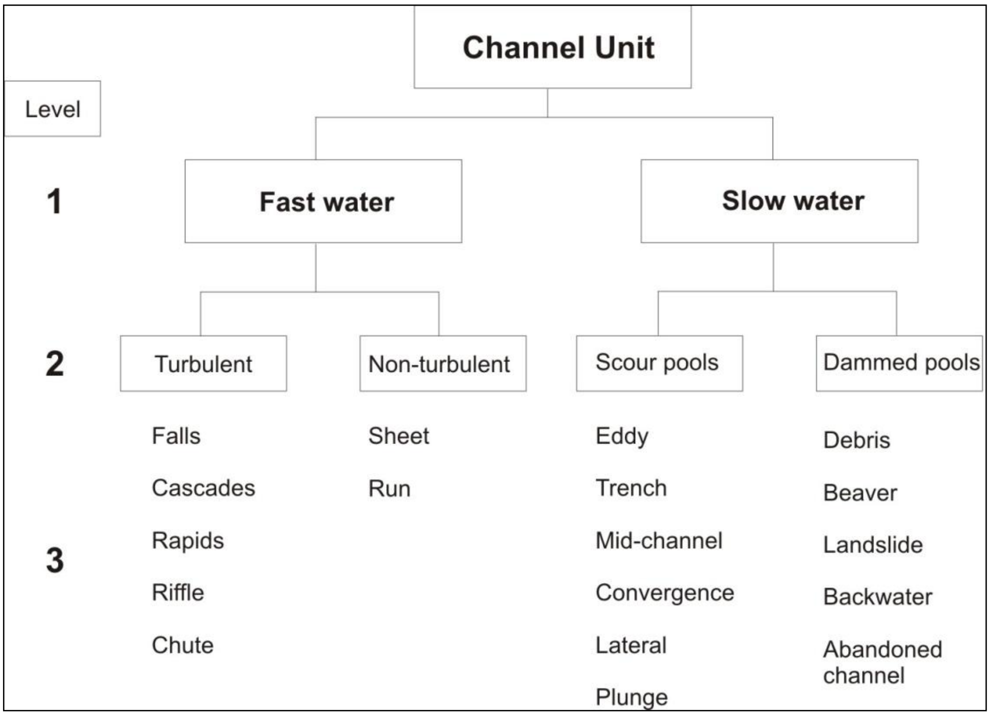

Figure 2:8 Channel Geomorphic Unit classification used by Hawkins *et al*., 1993. (Re-drawn from Bisson and Montgomery, 1996).

Comparisons of habitat descriptions from four habitat identification schemes are presented in Table 2.2. These demonstrate that naming schemes are based on either description of the physical properties (*e. g.* Bisson *et al*., 1982 and Hawkins *et al*., 1993) or surface flow patterns (Padmore, 1997 and RHS, 2003). Within this set of schemes the same word is used to describe habitats with more than one set of characteristics – *e. g.* pool, which in Hawkins *et al*. (1993) is low energy whilst under Bisson *et al*. (1982) it may have higher energy with coarse substrate and high velocity. Similar physical conditions are described as a Rapid in Hawkins *et al*. (1993) and a High Gradient Riffle in Bisson *et al*. (1982) These issues can cause confusion between researchers and are a possible cause of errors of identification (Maddock and Hill, 2005), compounded by the geographic divide inherent in the widespread use of Bisson in the USA and hydraulic biotopes in Europe (Milan *et al*., 2010).

Table 2.2 Comparisons of meso-habitat descriptions: Bisson *et al*. (1982), Hawkins *et al.* (1993) amended by Maddock and Hill, (2005), Padmore (1998) and River Habitat Survey (EA, 2003).

Bisson et al. (1982)	Hawkins et al. (1993)	Padmore (1998)	RHS (EA, 2003)
	Fall - Vertical drops of water	Free Fall - Vertically falling water, generally >1m high	Free Fall - Vertically falling water
	Cascade – Highly turbulent series of short falls and small scour basins		
	Chute – Narrow steep slots or slides in bedrock	Chute – Fast smooth flow over boulders/ bedrock	Chute - Low curving flow hugging the water surface
High Gradient Riffle – Steeper slope (than low gradient riffle) shallow with fast flowing white water	Rapid – Moderately steep channel units with coarse substrate, with planar profile	Broken standing wave - White water tumbling wave facing upstream	Broken Standing Wave - White water tumbling wave must be present
Low Gradient Riffle – Less slope than (High gradient riffle)shallow with less turbulence and no white water	Riffle – Shallow fast flow with some substrate breaking the surface	Unbroken Standing Wave - Undular standing waves, upstream facing unbroken crest	Unbroken Standing Wave - Upstream facing wavelets (dragons back)
Run – Strong focused current with deeper water	Run – Moderately fast and shallow gradient with ripples on the water surface	Rippled – Surface turbulence produces symmetrical ripples moving downstream	Rippled - Small symmetrical ripples (1cm high) move downstream
	Boil - Strong vertical flow producing a characteristic ‘boil’ at the surface		Upwelling - Strong upward flow producing a ‘boil’ effect
Glide – Similar to runs but with less depth, velocity and turbulence	Glide – Smooth ‘glass-like’ surface, with visible flow movement along the surface	Smooth Boundary Turbulent - Little surface turbulence, reflections distorted	Smooth - Laminar flow with a smooth surface
Pool – Deepest with little surface turbulence but often with coarse substrate and high velocity	Pool – Deep and slow flowing with fine substrate. Usually little surface water movement visible	Scarcely Perceptible Flow – Surface stationary and reflections not distorted	No Perceptible Flow - Smooth surface with possible eddy flow
Standing Water – Occurs in abandoned channels	Ponded - Water held behind an obstruction		
Eddy drop zone – Re-circulation flow where fine sediments are deposited			

Water depth and velocity are widely used in mesohabitat description (Maddock and Bird, 1996; Paraseiwicz, 2001; Harby *et al*., 2004; Eisner *et al*., 2005) and are also key variables used by ecologists (Elliott *et al*., 1988; Extence *et al*., 1999; Lancaster, 1999), because velocity is used as a surrogate for forces acting on animals (Mérigoux and Schneider, 2005).

Habitat identification by operator observations using methods described above is subjective. Without rigorous training and assessment, repeatability, precision and transferability is compromised (Poole *et al*., 1997). Whilst using hyperspectral imaging, Marcus *et al*. (2003) suggest that overall classification accuracy, between observers and remote sensing, was between 69% and 86% in 3rd and 5th order streams respectively. They consider that the results are scale dependent, with small streams having a greater proportion of the area as transitional zones between units. However, these figures may be 'misleadingly low' because the field workers did not record the fine-scale variations recorded by 1m resolution imagery.

An objective approach was taken by Jowett (1993) to identify pool, run and riffle habitats by using Froude number. Jowett (1993) concluded that pool habitat <0.18Fr, run habitat >0.18Fr and < 0.41Fr, and riffle >0.41Fr. Padmore (1997) used Froude number to differentiate between the hydraulic characteristics of habitats with different SFTs and concluded that it was the best discriminator and Kemp *et al*. (2000) established a link between functional habitats and 'biotypes' using Froude number. However, Clifford *et al*. (2006) conclude that Froude number requires careful interpretation as similar values can occur at very different velocities and depths and suggest that surveys involving cross sectional transects may be misleading, they consider that further research to identify associations between flow types and functional habitats would be profitable. Subjectivity remains an issue in the location and density of depth/velocity measurements, although replication and random selection reduces the impact.

PHABSIM (Bovee, 1982) is applied principally at the mesohabitat scale to determine the amount of suitable habitat (Weighted Usable Area) for target species, but has been criticised for its lack of biological realism (Newson and Newson, 2000; Booker *et al*., 2006; Goodwin *et al*., 2006). Dedual (2007) reports that mesohabitat use by fish is uneven, because fish often prefer particular parts of a habitat – *e.g.* the upper reaches of runs below riffles (Gosselin, 2007).

2.4.4 Mesohabitat Mapping

The variety of methods and the time required to complete a survey provide the user with a choice of methods, some are relatively simple and therefore less expensive others more complex and expensive. All survey methods assume that habitats are distinctive, although this is an anthropocentric view of river habitat and may be at odds with the view of the aquatic inhabitants.

Habitat mapping at the meso-scale does not itself provide an indication of habitat use by target species. However, it provides the opportunity to select representative examples of each type of habitat for further investigation, the results of which can be extrapolated to the reach as a whole. Rapid Habitat Mapping (Maddock and Bird, 1996), Meso-Habitat Simulation (MesoHABSIM) (Parasiewicz, 2001) and the Norwegian Mesohabitat Classification Method (NMCM) (Borsányi, 2004; Harby *et al*., 2004) adopt a two stage approach, and require further investigation, often PHABSIM/IFIM, following the initial mesohabitat identification.

In August 2005 the author attended a workshop on the River Windrush, at Sherborne Park, organised by the Centre for Ecology and Hydrology, Wallingford, where four habitat mapping methods were compared. Whilst some operators were experienced in some methods, not all were experienced in all methods trialled. Habitat maps of the RHM, MesoHABSIM and NMCM surveys were drawn from data recorded during the workshop and drawn into a GIS (MapInfo 6). The MesoCASiMiR map was provided by A. Eisner, (Personal communication, 2005). These outputs were reported in Maddock and Hill (2005).

At the meso-scale several habitat classification schemes, *e.g.* MesoHABSIM and RHM use habitat description, based on Hawkins *et al*., (1993) CGU classification, although definitions vary. Both MesoHABSIM and RHM record the dominant habitat type across the whole channel width without allowing for lateral variation, this approach was criticised by Clifford *et al*. (2006) as channel edge areas often differ in hydraulic character from channel centre areas. Figure 2:9 shows the same reach of the River Windrush surveyed in 2005 (Extract from Maddock and Hill (2005, 10 and 13) mapped using RHM and MesoHABSIM.

Images removed River Habitat Mapping	MesoHABSIM

Figure 2:9 A reach of the River Windrush mapped using Rapid Habitat Mapping and MesoHABSIM showing Channel Geomorphic Units extending across the whole channel. From Maddock and Hill (2005, 10 and 13).

Mesohabitats comprise a range of microhabitats and are often not homogeneous across the channel width. The NMCM uses a classification based on a decision tree (Table 2:3) and allows up to three CGUs laterally. Figure 2:9 left shows a reach of the River Windrush surveyed in 2005 (Extract from Maddock and Hill, 2005, p12) each homogeneous area is coded based on surface gradient, surface velocity and water depth. The NMCM uses mesohabitat codes which do not necessarily relate to derivatives of Hawkins' CGUs. In a Norwegian context, some types of flow do not physically exist and have been shown in grey. NMCM was developed in steep Norwegian salmon rivers, posing problems transferring the system directly to British lowland rivers.

Table 2:3 Norwegian Mesohabitat Classification Method decision tree. Grey areas show combinations that do not occur in practice.

Surface Pattern	**Surface Gradient**	**Surface Velocity**	**Water Depth**	**Code**	**Name**
Smooth/rippled (wave height <0.05m)	Steep	Fast (>0.5m/s)	Deep (>0.7m)	A	Run
			Shallow (<0.7m)		
		Slow (<0.5m/s)	Deep (>0.7m)		
			Shallow (<0.7m)		
	Moderate	Fast (>0.5m/s)	Deep (>0.7m)	B1	Deep glide
			Shallow (<0.7m)	B2	Shallow glide
		Slow (<0.5m/s)	Deep (>0.7m)	C	Pool
			Shallow (<0.7m)	D	Walk
Broken/unbroken (wave height >0.05m)	Steep	Fast (>0.5m/s)	Deep (>0.7m)	E	Rapid
			Shallow (<0.7m)	F	Cascade
		Slow (<0.5m/s)	Deep (>0.7m)		
			Shallow (<0.7m)		
	Moderate	Fast (>0.5m/s)	Deep (>0.7m)	G1	Deep splash
			Shallow (<0.7m)	G2	Shallow splash
		Slow (<0.5m/s)	Deep (>0.7m)		
			Shallow (<0.7m)	H	Rill

MesoCASiMiR (Eisner *et al*., 2005) uses a single stage approach that simply requires operators to identify and map areas that are different from each other, lateral variability is allowed. Water depth and velocity are then estimated for each mesohabitat identified and habitat suitability for target species is assessed using HSIs. Figure 2:10 (right) shows a MesoCASiMiR output colour coded for fish habitat suitability in a reach of the River Windrush surveyed in 2005 (Extract from Maddock and Hill (2005, 9).

Images removed Norwegian Mesohabitat Classification Method	MesoCASiMiR (colour coded to show habitat suitability for target species)

Figure 2:10 Examples of Norwegian Mesohabitat Classification Method and MesoCASiMiR showing lateral diversity allowed. From Maddock and Hill (2005).

Hydraulic habitat location and extent is variable. Dyer and Thoms (2006) showed that SFT extent and location in the Cotter River, Australia, were sensitive to small changes in discharge over time. In the context of this research the approach to lateral variability taken in MesoCASiMiR has much to commend it. In times of high flow macroinvertebrates make use of refugia (Lancaster, 1999) which are often within the substrate (Lancaster and Belyea, 2006), sheltered by larger stones perhaps, or located at channel edges, the location of these important habitats can be lost if only the dominant mesohabitat across the channel width is recorded.

Remotely sensing ecologically relevant mesohabitats could have benefits (Cummins, 1992). Gilvear *et al.* (1995) used digitised aerial photographs to identify three habitat types based on water depth in Alaska, whilst more recently multi-spectral and hyperspectral techniques have been adopted to identify water depth and grain-size in a range of habitat types (Legleiter *et al*., 2002; Marcus, 2002; Marcus *et al*., 2003).

Carbonneau *et al*. (2006a) developed the remotely sensed pixel colour / water depth relationship, used to produce bathymetric maps, by use of feature based image processing, producing 4m^2 spatial resolution with a precision of ± 15 cm. However, this process requires the water to be at least semi-transparent. British lowland rivers are often turbid and can be obscured by trees preventing calibration of depth, velocity or substrate from aerial photography (Carbonneau *et al*., 2004, 2006b). It is probable, therefore, that remote sensing will only see the river surface and perhaps the distinctive surface flow patterns controlled by hydraulics and bed morphology *i.e.* SFTs.

Airborne LiDAR (Laser-induced Direction and Ranging) has been used to map UK rivers, (Charlton *et al*., 2003; Feurer *et al*., 2008; Notebaert *et al*., 2009), although its ability to survey the river bed is limited (Bailly *et al*., 2010). LiDAR has also been used successfully to identify archaeology below the tree canopy in the Wyre Forest (Forestry Commission, 2008) suggesting that remote sensing of SFTs as mesohabitats could be possible.

2.4.5 Hydrological Characterisation

The hydrologic regime has multiple impacts on physical and chemical properties of the stream (Richards, 1990), and on its biota (Di Maio and Corkum, 1995; Baker *et al*., 2004). Benthic macroinvertebrate density is negatively related to increasing discharge during high flows (Basaguren *et al*., 1996), although many species are resilient and recover. Not only are mesohabitats spatially variable, they are also temporally variable. This is driven by changes in throughput linked to the hydrological cycle. Discharge variation changes the nature of habitat hydraulics: higher discharge increases depth and velocity. The frequency of high flow events and the rate at which changes occur is thought to have an impact on benthic macroinvertebrate communities (Effenberger *et al*., 2006) as communities subjected to a flashy regime are 'reset' more frequently. The Intermediate Disturbance Hypothesis (Connell, 1978) suggests that stability provides opportunities for species to outcompete others, so reducing diversity, whilst frequent disturbance could eradicate communities. Disturbance at intermediate frequency produces maximum diversity, however this should be seen in the context that conditions in streams vary over very short time-scales and are very disturbed places.

Monk *et al*. (2006) investigated a series of hydrological and ecological indices from examples of rivers with three different flow regimes in the UK looking for redundancy between hydrologic data sets. They concluded that flashy regimes produced weaker results and advised caution be exercised when seeking wide ranging explanatory variables. This suggests that the ecological character of, otherwise similar, habitats differ between stable and flashy regimes.

Two hydrographs, from the same year, for two rivers in the UK Midlands with differing hydrological regimes are shown in Figure 2:11. Dowles Brook has a flashy hydrological regime with many spiky peaks, characterised by rapid rise and fall of stage, whilst the River Windrush has a smoother trace.

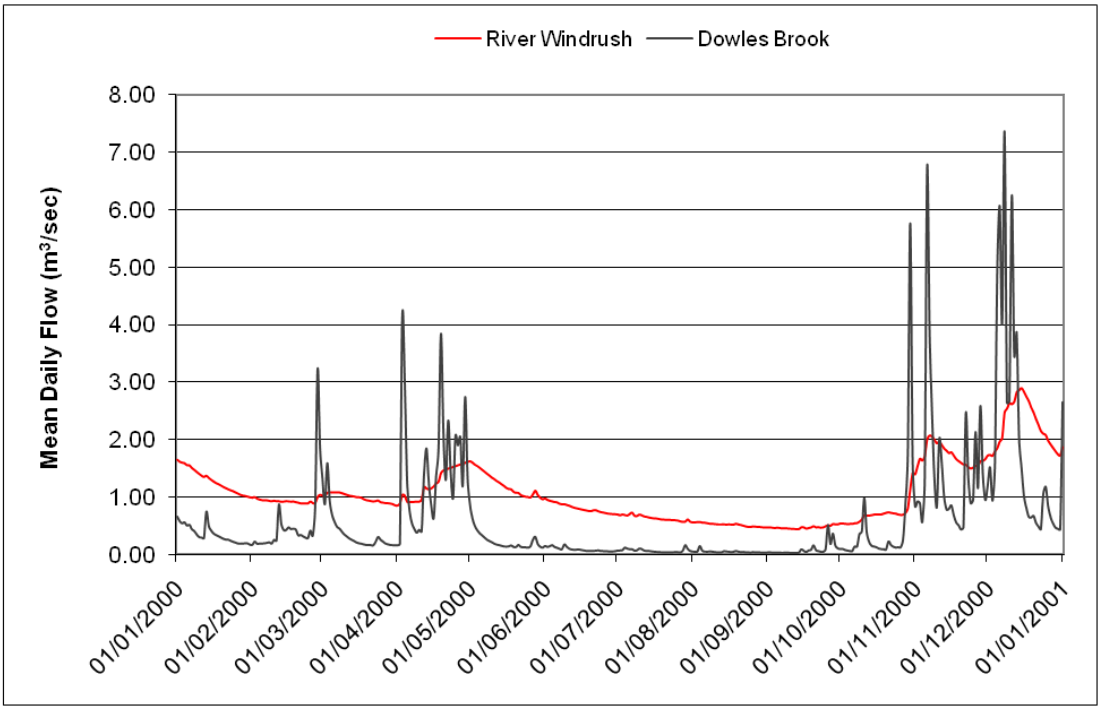

Figure 2:11 Hydrographs of River Windrush and Dowles Brook recorded in 2000. (Data Source: Environment Agency, B. Taylor, Personal Communication, 2006).

Hydrograph shape is determined by the relative proportions of overland flow plus quick through-flow, versus baseflow in discharge. Base-flow is of interest because groundwater sustains streamflow during periods without rainfall and is a major influence on the flashiness of the hydrological regime (Davie, 2003; Marsh and Lees, 2003). The hydrological regime of rivers with higher proportions of baseflow is generally more stable than rivers with lower proportions of baseflow (Gordon *et al*., 2004). An index of baseflow was developed by Beran and Gustard (1977) (Figure 2:12) (Institute of Hydrology, 1979 a, b, c, d). The Base Flow Index (BFI) describes the ratio of baseflow within total discharge in a given catchment. Separating runoff from baseflow is complex and measuring the proportion of baseflow is still surprisingly subjective (Shaw, 1988; Davie, 2003; Gordon *et al*., 2004), although computer software (*e.g.* Wallingford HydroSolutions, 2007) is now used in these calculations. The BFI is used here to characterise the hydrological regime of the rivers investigated.

Image removed

Figure 2:12 Hydrograph separation scheme for calculation of the Base Flow Index. (Source: Institute of Hydrology, 1979a, p21).

Monk *et al*., (2006) examined the relationship between flow regime and macroinvertebrate community in a range of UK rivers. They concluded that metrics related to the magnitude of flow produced the strongest relationship with macroinvertebrate community structure and proposed a classification based on these. Flashy regimes, generally, have higher and more frequent high flow events than stable regimes.

2.5 Ecological Characterisation

2.5.1 Macroinvertebrates

Streams are a special case in ecology; they are long narrow ribbons of water, with a perpetual overall movement down slope (Hynes, 1970). Within this matrix many plants and animals live, their existence dependant on the nature of their surroundings, where physical stresses imposed on them, *e.g*. effects of water moving past them can be considerable. Aquatic species live in an environment that is subjected to constant change, driven by flowing water and the changes in flow that result from hydraulic inputs. These variations are considerably greater in magnitude than found in terrestrial habitats. Additionally there are important and complex interactions between macroinvertebrate individuals, e.g. competition and, prey-predicator interactions. In-stream habitats are subjected to m a wide range of stresses, at the meso-scale the relationships between macroinvertebrates and in-stream habitats are often simplified in order to assist river managers with tools, the level of that simplification has been criticised recently (Lancaster and Downes, 2009) although that is not to suggest that established ideas and methods are inappropriate.

In order to deal with these stresses macroinvertebrate families/species have evolved strategies to which allow them exploit niches within their environment (Hynes, 1970, p116). Some burrow into fine substrates whilst others cling onto larger substrate found in higher velocity habitats. Many fish require running freshwater, however, habitat quality must be suitable for their needs. In the case of salmon, they require fast flowing water and open gravel (often found in riffles) in which to spawn but also require habitats with slower velocities in which to rest and feed. Dedual (2007) observes that fish do not use the whole of a habitat equally, rather they favour some places more than others. Macroinvertebrates in streams have received a great deal of attention because they are large enough to be seen unaided, sufficiently abundant to allow collection and link the primary producers (algae) with fish and other macroinvertebrates for which they are prey (Cummins, 1992). Identification of larvae to family level is relatively straightforward (Giller and Malmqvist, 1998). Macroinvertebrates make good indicators of river health; consequently their life histories and ecology are well understood.

It is widely accepted that physical habitats differ, and that distributions of macroinvertebrates will be fundamentally different between major (meso) habitats *e.g*. pools and riffles (Cummins, 1992). It is also widely assumed that habitat quality determines species richness (Harper and Everard, 1998) which provides a convenient link between the physical environment and the biological structure. This suggests that higher habitat heterogeneity will support higher biodiversity (Harper and Everard, 1998, Tickner *et al*., 2000).

Much inter-disciplinary work involving the physical nature of in-stream habitats and macroinvertebrate communities has been reported. Harper and Everard (1998) reviewed the link between physical habitat and biodiversity inherent in the RHS. Broad in-stream flow requirements of macroinvertebrates have been evaluated (Gore, 1978; Extence *et al*., 1999) River Habitat Survey data were used by Hastie *et al*. (2003) to investigate habitat requirements of the freshwater pearl mussel in Scotland. Suren and Jowett (2006) found that macroinvertebrate community change in New Zealand was proportional to flood magnitude. Discharge pattern and temperature were found to be drivers of macroinvertebrate communities in two Scottish rivers (Jackson *et al*., 2007).

2.5.2 Ecological Requirements of Macroinvertebrate Taxonomic Groups

Macroinvertebrates were used in this study because they are sufficiently large, numerous and well studied, providing the background to the research whilst being less mobile than other species, e.g. fish. Table 2.3 summarises the ecological requirements of MiTGs encountered during this research. It is clear that a wide range of flow and substrate conditions are utilised by macroinvertebrates and that within each MiTG there are species that have different requirements and that many groups have similar needs.

Both body shape and life style help to determine particular niche/s exploited by MiTGs. Overcoming the hydraulic forces present on and near the stream bed is important if MiTGs are to remain in the appropriate niche (Hynes, 1970). Adaptations of MiTGs found in running water are many. Heptageniidae have a flattened dorso-ventral form which may be an adaptation limiting the effects of high velocity by presenting a 'streamlined' shape to the water, but this shape also allows it to squeeze between stones to avoid the current altogether (Hynes, 1970, Lancaster and Belyea, 2006). Baetidae also have a 'streamlined' form, although more cylindrical. Hynes (1970) observes that they place the body into the stream flow, by extending their legs, to absorb oxygen from the faster flowing water. However, in fast flowing conditions they bend their legs and rest on the stream bed.

Adult Elmidae use their strong claws to cling to the substrate, whilst the larvae of some species have a flattened form with spines around the outer edges which engage with substrate roughness to prevent dislodgement (Hynes, 1970). Suckers are employed by some MiTGs, leeches can use them to move in high velocities although they are more often found in low velocities. Snails have large, soft contact areas which attach them to the substratum; Ancylidae also has the benefit of a ‘streamlined’ shell to prevent dislodgment in the high velocities where it is often found.

Amongst the Trichoptera, those adapted to life in fast flowing water frequently build cases from stones, although this may also be due to the local availability of building materials, *e.g*. Goeridae incorporate large stones into the lateral edges of the case, which acts as ballast. Limnephiliidae, which are more common in slow flowing waters often construct their cases from vegetation which may be more abundant in those areas, but is likely to be less resilient in fast flow. Another important consideration for these animals is camouflage and by using ‘local’ materials they are less susceptible to predation (Wallace *et al*., 2003).

A number of feeding groups are present within macroinvertebrate communities, with each group occupying a niche. Many MiTGs associated with this research are collectors, grazers, gatherers or shredders relying on algal or detritus. Several are predators, of which some are surface dwellers (Veliidae and Gyrinidae) and others benthic (Sialidae, Rhyacophilidae and Polycentropodidae), other MiTGs (Hydropsychidae) have species which both predate and filter.

Table 2.3 Summary of the ecology of 41 Macroinvertebrate Taxonomic Groups identified in samples within this research in both 2006 and in 2007.

(a) Elliot *et al.* (1988); (b) Savage (1989); (c) Wallace *et al*. (2003); (d) Edington and Hildrew (1995); (e) Cranston (1982); (f) Elliott and Mann (1979), (g) Elliott (1996); (h) Macan (1977); (i) Concholigical Society of Britain (2010a); (j) Concholigical Society of Britain (2010b); (k) Concholigical Society of Britain (1010b); (l) Fitter and Manuel (1994); (m) Hynes (1977), (n) Bass (1998) and Hynes (1970), (p) Elliott (2008).

	No. of species	LIFE Class	Habit	Substrate	Functional feeding group	Overview
Hydrobiidae (j)	5	IV			Grazer	Abundant in rivers, canals and streams throughout England and Wales.
Lymnaeidae (k)	2	IV		Soft	Gatherer	Found in slow-flowing rivers, canals, ponds and lakes, throughout the British Isles. It is a carrion eater, feeding upon dead animal matter.
Planorbidae (h)	4	IV			Gatherer	Widespread, not found in fast flowing water
Ancylidae (i)	2	IV	Crawler	clear hard surface	Grazer	Found in rivers, canals and lakes, throughout the British Isles, adhering to any suitable clean, hard substrate. It prefers those areas where the turbulence of the water is sufficient to keep the substrate clean, such as shallow rippling water of streams
Sphaeriidae (h)	Many	IV	Burrowing	soft	Grazer	Adults burrow into substrate
Oligochaeta (l)	Many	N/A	Soft substrates	Soft sediments	Gatherer	Live in soft substrates, swallowing large quantities and digesting the organic nutrients.
Glossiphoniidae (f)	8	IV	Parasitic		Predator	Parents brood the eggs in cocoons attached to the substratum
Erpobdellidae (f)	5	IV				Cocoons attached to the substratum
Hydracarina (l)	17	N/A	Wide range	Wide range	Predator	Wide range of habitats, partly parasitic predator
Ostracoda(l)	Many	N/A	Crawler	On substrate surface	Filter	Scuttles around on top of the bed substrate
Asellidae (l)	1	IV	Crawler		Gatherer	Common in permanent stagnant or slow flowing water

	No. of species	LIFE Class	Habit	Substrate	Functional feeding group	Overview
Gammaridae (l)	3	II	in or under substrate	coarse	Gatherer	Common in clean rivers or lakes
Baetidae (a, l,o)	11	II	Swimmer-climber		Grazer	Streamlined and common in running waters
Heptageniidae (a,l)	7	I	Clinger	coarse	Gatherer	Common in fast flowing rivers with coarse substrate, flattened body
Leptophlebiidae (a,l)	6	II	Sprawler -climber	burrower	Collector gatherers	Common in still or slow flowing waters
Ephemeridae (a,l)	3	II	Burrower	soft	Collector filterer	Burrowers in mud or stones
Ephemerellidae (a,l)	2	II	Clinger sprawler		Gatherer	Use running water
Caenidae (a,l)	6	IV	sprawler		Gatherer	Common in mud, detritus and under stones, tolerate silt well because of gill covers
Leuctridae (m)	6	II	wide range	stony	Shredder	Mostly in stony streams, L. geniculata in lowland rivers. Widespread
Veliidae (b)	0	IV	Water surface		Predator	Surface dwellers, usually of lentic habitats
Corixidae (b)	0	IV	Water surface		Predator	Surface dwellers, usually of lentic habitats
Gyrinidae (l)	Several	IV	Water surface		Predator	Adults are surface dwellers, larvae live on the substratum
Elmidae (l,p)	4	II	Clinger	Coarse	Grazer (uncertain)	Both adults and larvae are aquatic, in fast flowing streams, probably eating algae and detritus.
Sialidae (g, l)	1	IV	Sluggish water	silt/decaying vegetation	Predator	Predates on Chironomidae larvae, Oligochaeta, Crustaceans, Plecoptera larvae.
Rhyacophilidae (d)	4	I	High flow	coarse	Predator	Found on mossy stones
Glossosomatidae (c,l)	6	II	Fast stony streams		Shredder	found in fast running stony streams
Hydroptilidae (c)	31	IV	Instar V – uses pouch type case		Shredder	Found in all waters except small pools and ephemeral bodies
Philopotamidae (d)	5	I	High flow		Shredder	
Polycentropodidae (d)	13	IV	Low flow		Predator	Territorial

	No. of species	LIFE Class	Habit	Substrate	Functional feeding group	Overview
Hydropsychidae (d)	11	II	Ubiquitous		Predator/ Filterer	Territorial
Brachycentridae (c)	1	II	Attached to substratum		Shredder	Can move case if current become too strong
Lepidostomatidae (c)	3	II			Shredder	Change from sand to plant cases during growth
Limnephilidae (c)	58	IV	Mobile		Shredder	Largest group in Britain.
Goeridae (c,l)	3	I	Ballasted case		Shredder	Common in small streams and occasionally in still waters
Sericostomatidae (c,l)	2	II			Shredder	Occurs in streams
Odontoceridae (c,l)	1	I	Under stones	coarse	Shredder	Occurs in fast running streams
Diptera(l)	Many		Varied		Varied	Many wet habitats although few species inhabit rivers and ponds.
Tipulidae (l)	Many	IV	All water types	Buried in sediment/ vegetation	Carnivore	Common in a wide range of aquatic (and terrestrial) habitats
Ceratopogonidae (l)	Several		Pools and ditches	Filamentous algae	Filterer	Common in slow flowing water, often at the surface
Simuliidae (n)	32	II	Flowing water	clean substratum	Filterer	Microhabitat partitioning between species on same site. Anchored to substratum, will drift if dislodged.
Chironomidae (e)	>450		Wide range	Largely fine	Gatherer	Widespread , a range of habitats and feeding traits

Based on the habitat requirements in Table 2.3, it might be expected that Heptageniidae, Rhyacophilidae, Philopotamidae, Goeridae and Odontoceridae, for example, which all require rapid flow, might be associated with UW SFT, whilst Gammaridae, Baetidae, Ephemerellidae, Elmidae and Simuliidae, for example, which prefer moderate to fast flows might be associated with RP SFT. Hydrobiidae, Planorbidae, Caenidae and Hydroptilidae, for example, which prefer standing or slow flowing water, might be associated with NP SFT.

2.5.3 Microhabitat Conditions

Many aquatic macroinvertebrates live most of their lives on or near the river bed. Frequently this is confined to the larval stage(s) with adults emerging into the terrestrial environment to complete the life-cycle; a considerable amount of research has focused on taxonomy and life histories (*e.g.* Elliott *et al*., 1988; Wallace *et al.,* 2003). Because of their small size, much research into benthic macroinvertebrates occurs at the microhabitat scale (Lancaster, 1999; Effenberger *et al*., 2006). Understanding the relationship between microhabitat and mesohabitat is crucial (Thoms and Reid, 2007). Some work has investigated links between the micro- and meso-habitat scales (Pardo and Armitage, 1997; Hastie, 2003; Mérigoux *et al*., 2005; Principie *et al*., 2007) although rarely are mesohabitats defined by SFTs (Reid and Thoms, 2008).

Many physical variables determine lotic habitat quality; *e.g.* water depth and velocity, dissolved oxygen, temperature, turbidity, substrate and acidity. Living on or near the bed, macroinvertebrates are subject to hydraulic stress from the effects of water flowing over the bed (Statzner, *et al*., 1988). Roughness of the river bed, at the patch scale, causes friction within that zone, resulting in lower downstream velocities near the bed, the highest velocities in the mid to upper section and a small lowering of velocity at the surface (due to friction with the air) (Gordon *et al*., 2004). Velocities through the water column are complex, Thorne and Hey (1979 showed the complexity of secondary currents through bends in a river channel. They found that flow cells in the upper part of the water column skew towards the outer bank when entering a bend, driving water in the lower column away from the bank, creating a spiralling effect which can be responsible for some types of upwelling flow.

Figure 2:13 shows the bowed trace of downstream velocities in a hypothetical channel, with low velocity near the bed. Bed roughness influences the shape of the curve, with greater bed roughness increasing friction between the water and the bed, slowing water velocity further than in channels with smoother boundaries (Gordon *et al.*, 2004). Downstream velocities are expected to vary between SFT mesohabitats, for example, water velocities in NP SFT mesohabitats are likely to be lower than in UW SFT mesohabitats. Figure 2:14 hypothesises velocity profiles from five SFT mesohabitats: NP, SM, RP, UW, UP. If it is possible to relate surface flow conditions (particularly velocity) to near-bed conditions in this research, a strong relationship will be required between surface and bed velocities.

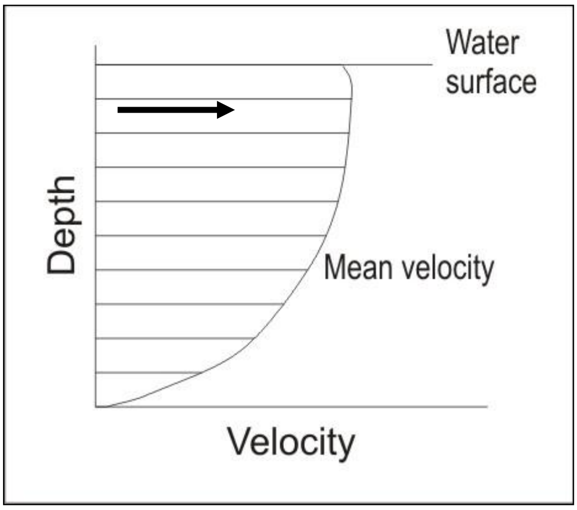

Figure 2:13 A hypothetical velocity profile within a stream channel, showing the decrease in stream velocity near the bed. Redrawn from Gordon *et al*., 2004.

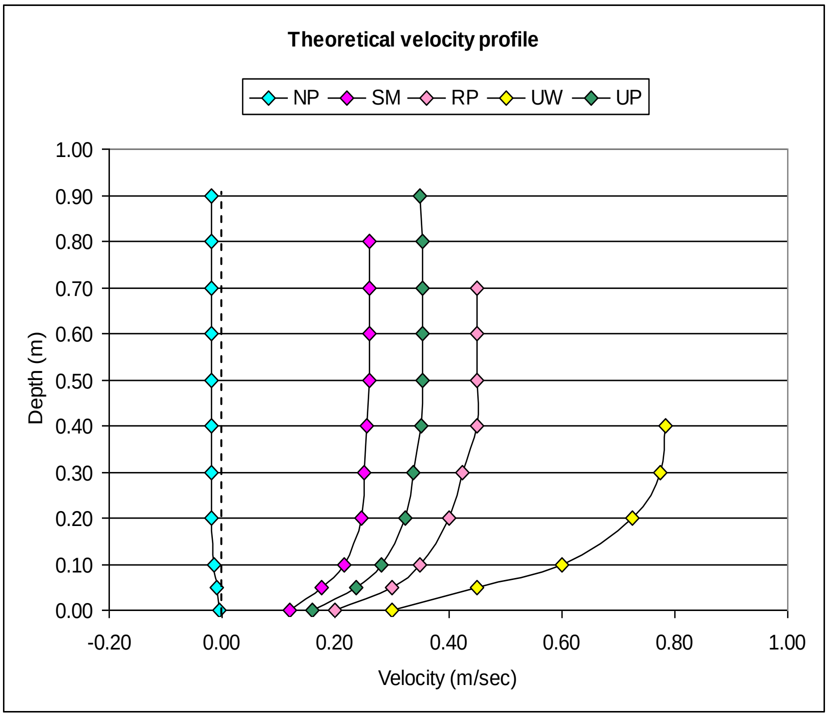

Figure 2:14 Hypothesised velocity profiles for downstream velocities in five Surface Flow Types. Key: NP – No Perceptible; SM – Smooth; RP – Ripple; UW- Unbroken wave and UP – Upwelling Surface Flow Types.

High discharges may be sufficient to mobilise substrate together with macroinvertebrates on or within it. Gibbins *et al*. (2007) found that shear stress >9 dynes cm^2 in a small flume resulted in bed-load transport which triggered a rapid increase in drifting macroinvertebrates. Whilst the bed-load transport was small, it is considered typical of small frequent floods, indicating that disruption to benthic macroinvertebrate communities occur at flows below that required for the bed armour to be disrupted.

Larger and therefore more stable substrates have been shown to support a greater range of invertebrates (Allan, 1995; Principie *et al*., 2007); whilst sand is particularly mobile and difficult for macroinvertebrates to colonise. Parker (2007) described sand bedded streams as 'biological deserts'.

The presence of fine material is linked to stream hydraulics because at higher discharges, greater velocity and turbulence in or near the bed has the effect of flushing fine material from high energy areas and depositing it in low energy areas. Lisle and Hilton (1992) show that fine material (in their case sand) was winnowed from riffles and deposited into pools as discharge fell below bank-full although the precise effects depend upon local upstream sediment supply being adequate. Fine material in low energy environments is capable of infilling the interstitial spaces between larger bed substrate, in some cases preventing macroinvertebrates accessing these areas. Eastman (2004) produced a scale of embeddedness for use with MesoCaSiMiR, in which the degree of infilling coarse substrate with fine material is quantified. Figure 2:15 shows increasing levels of fine material (dashed lines) in a coarse matrix with degree of embeddedness code used in this research. This index works best in rivers with evenly sized substrate of gravel, pebble or cobble in the rivers investigated by Eastman (Danube and Eyach in southern Germany) the infilling material was generally sand. This index was considered useful in this research as it held the potential to relate lack of interstitial habitat.

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Figure 2:15 Fine materials, depicted by the horizontal lines, and shown ‘clogging-up’ the interstitial spaces in a coarse matrix (Source: Eastman, 2004, p88.).

High water velocity over coarse substrate produces turbulence, in turn increasing oxygen saturation. Although water depth, downstream velocity and substrate type are routinely measured, measuring turbulence for hydraulic microhabitat characterisation is challenging, requiring instruments that work in three dimensions and at a fine scale. This research concerns the complex relationship between water surface and the near-bed conditions, as Thoms and Reid (2007) put it – “*Is what you see what you get?”* Therefore, understanding the relationship between downstream surface velocity and near bed velocity is crucial (Young 1992; Newson and Newson, 2000).

2.5.4 Surface Flow Types, Hydraulic and Macroinvertebrate Distributions

Reid and Thoms (2008) investigated the relationship between SFTs, near-bed hydraulics and stream macroinvertebrates in the Cotter River, Australia. They addressed three research questions:

- Do surface flow types provide a characterisation of physical habitat that is relevant to macroinvertebrates?
- How well do near-bed hydraulics conditions explain macroinvertebrate distributions?
- What components of near-bed hydraulic conditions exert the strongest influence on macroinvertebrate distributions?

Whilst there are a number of similarities between the research of Reid and Thoms (2008) and this research, there are differences which are summarised in Table 2.4. Key differences between the two bodies of research include the setting; the range of SFTs examined; discharge range, flow regime and velocity measurement method. Also, the macroinvertebrate sampling method differs although identification was taken to a similar level.

Table 2.4 Comparison of research approaches between Reid and Thoms (2008) and this research. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Variable	Reid and Thoms, 2008	Research presented in this thesis
Location	Eastern Australia	England
Setting	Upland	Lowland
Altitude	500 - 700m above sea level (asl)	25 - 114 m asl
Geology	Granite, limestone, siltstone and shale	Sandstone, limestone, mudstone. Superficial deposits of sand, gravel and alluvium
Catchment topography	Steep with rocky outcrops in upland areas	Low to moderate relief in lowland setting
Surface Flow Types investigated	NP, SM, RP, UW, BW, CH	NP, SM, RP, UW, UP
Discharge	Low flows, 0.21 - 0.51m^3	Variable - Q_1 to Q_{99}
Flow regime	Regulated (dams)	Natural
Hydraulic variables	3D near-bed velocity	Velocity Profile
SFT area	Estimated	Estimated and mapped
Substratum characterisation	% cover of silt/clay combined, sand, gravel, cobble, boulder, bedrock	Dominant (>50%), sub-dominant (<50%) and other present
Macroinvertebrate sampling strategy	5 replicate patches of each SFT, 3 macroinvertebrate samples from each	139 SFTs sampled, three macroinvertebrate samples per SFT mesohabitat investigated
Sampling method	Surber sampler	Kick sample
Taxon identification	Generally family level	Generally family level

In their analysis Reid and Thoms (2008) used ANOVA to test for between flow type differences in hydraulic variables and macroinvertebrate measures of abundance, taxon richness and diversity. ANOSIM was used to examine differences in physical and macroinvertebrate data. Canonical Correspondence Analysis was used to investigate macroinvertebrate assemblages.

Reid and Thoms (2008) found that the SFTs examined by them have distinct hydraulic, substratum and macroinvertebrate character, although the distinction of the macroinvertebrate community between some SFTs is not strongly separated. They show that these less strongly separated SFTs are adjacent to each other in an energy gradient: NP – SM; RP – UW; UW – BW and BW – CH, although NP and SM differ from RP, UW, BW and CH. In terms of near-bed hydraulics and substratum character, they contend that the two are closely interlinked and together have the strongest relationship with macroinvertebrate community. Near-bed velocity was measured in three dimensions and the variance in each reading used as a surrogate for turbulence. They found that downstream velocity is the most important variable influencing macroinvertebrate assemblage composition and taxa richness. Turbulence is also shown to have a strong relationship with macroinvertebrate community structure, although the reasons are unclear.

In conclusion Reid and Thoms (2008, p1054) consider that the relationships between SFTs, near-bed hydraulics and substrate character are sufficient to support the idea that mapping SFTs is an *'effective way of characterising the physical habitat template controlling macroinvertebrate distributions.'*

Reid and Thoms (2008) suggest that there is merit in considering the biological relevance of using SFTs to map rivers and that SFTs can provide spatially important information about habitat diversity at different flows. Dyer and Thoms, (2006) indicate that SFTs could provide an important tool for river managers. Similar questions are addressed in this research in a different context – lowland rivers – and using a different approach.

2.5.5 Macroinvertebrate Relationship to Flow

A strong relationship between benthic macroinvertebrates and flow has been identified by Extence *et al*. (1999) in the Lotic-invertebrate Index for Flow Evaluation (LIFE) technique. The LIFE technique assigns macroinvertebrates to one of six flow groups, (Table 2.5) three groups are defined by mean current velocity Group 1 - >1.0m/s, Group 2 – >0.2 – <1.0m/s and Group 3 - <0.2m/s. Group 4 is assigned to slowing flowing and standing waters, Groups 5 and 6 relate to standing and intermittent water bodies. Column three has been added to show predicted associations between LIFE flow group and SFTs velocities.

Table 2.5 Flow categories from Lotic-invertebrate Index for Flow Evaluation (LIFE). Source: Extence *et al*. (1999).

LIFE Scores	LIFE Flow Category	SFT mesohabitat
1	Rapid	BW/CH
2	Moderate/Fast	RP/UW
3	Slow/Sluggish	SM/RP
4	Flowing/Standing	NP/SM
5	Standing	NP
6	Intermittent	N/A

2.5.6 Modelling Habitat Suitability

Habitat suitability modelling determines the area of habitat suitable for the target species, by assessing the physical habitat conditions, and comparing them to habitat suitability indices. This represents the functional relationship between physical conditions and the response of the target species (Conallin *et al.,* 2010). PHABSIM/IFIM (Bovee, 1982) is widely used although other methods with similar characteristics have been developed: EVHA (Pouilly *et al.,* 1995) for French streams, RHYHABSIM (Jowett, 1989) for New Zealand Streams.

The In-stream Flow Incremental Methodology (IFIM) (Bovee, 1982) has been applied worldwide in respect of both fish (Maddock and Bird, 1996: Maddock *et al.,* 2004) and macroinvertebrates (Jowett *et al*., 1991; Gore *et al*., 2001; Maddock *et al*., 2001). The IFIM model uses a one-dimensional (1-D) hydraulic model and incorporates macrohabitat (longitudinal stream sectors) and microhabitat (the location where target species are found) scales, with the Weighted Usable Area (WUA) output calculated using the Physical Habitat Simulation (PHABSIM) model.

IFIM/PHABSIM is based on river segments, with similar geomorphology, hydrology and water quality, the segment is sub-divided into reaches with differing channel morphology and/or bankside vegetation. Transect measurements are taken in representative reaches at a minimum of three flows; these describe the microhabitat conditions (Bovee, 1982). Habitat suitability criteria – water depth, velocity and substrate size - for the target species is incorporated into the model which produces a flow / habitat relationship (Figure 2:16). Incorporation of flow time series produces a habitat time series which can be reduced to a habitat duration curve (Maddock, 1999).

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Figure 2:16 The basis of PHABSIM showing the integration of hydraulic measurements and habitat suitability criteria to define the flow/habitat relationship and subsequent combinations with flow time series to produce habitat time series and habitat duration curves (Maddock, 1999, p382).

PHABSIM, has been in use for nearly 30 years and during that time understanding of the complexity of the hydraulics of in-stream habitats has improved, as has the computing ability to calculate more complex models. Traditionally PHABSIM uses a 1-D hydraulic model which potentially underestimates microhabitat complexity. 2-D and

3-D models are more sensitive hydraulically (Leclerc *et al.*, 1995; Crowder and Diplas, 2000; Crowder and Diplas, 2002) and are, perhaps, more appropriate to complex situations. However 1-D models may be adequate for lowland streams where microhabitat is less variable (Gan and McMahon, 1990, cited in Gordon *et al.,* 2004, p298). PHABSIM assumes that habitat availability is the limiting factor, ignoring others such as food, competition etc. (Deudal, 2007).

Habitat Suitability Indices (HSIs) are the biological basis for habitat suitability modelling, the index varies between 0 (unsuitable) and 1 (most suitable), both univariate and multivariate HSIs have been developed (Miller and Giese, 2007; Conallin *et al.*, 2010) (Figure 2:17).

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Figure 2:17 Examples showing (a) univariate HSI curve for the habitat variable 'depth' and (b) a multivariate HSI showing the species response to the cumulative effects of both habitat variables depth and velocity (Source: Conallin *et al.,* 2010, p94).

Univariate HSIs are the most common form, and have been developed for a wide range of biota often fish, but also aquatic macroinvertebrates (Jowett *et al*., 1991; Gore *et al*., 2001) and hippopotamus (Gore *et al*., 1990). Although developed at the micro-scale, generalised criteria have been used at wider spatial scales (Raleigh, 1986; Conallin *et al.*, 2010). HSIs commonly use water depth and velocity but other variables are also used *e.g.* substrate, temperature and water quality (Raleigh, 1986). HSIs are developed in three ways:

- Category I – expert opinion indices are derived from professional judgement and life history literature;

- Category II – habitat use indices are based on the frequency of occurrence from *in situ* studies of habitat use; and
- Category III – preference indices are category II indices adjusted for *in situ* habitat availability showing use relative to availability.

Connalin *et al*. (2010) consider that Category II and III HSIs are the most ecologically defensible. Category II HSIs can be considered to describe macrohabitat *use* as a function of its availability. Category III HSIs are indices of *preference,* although the term *association* is preferred by Lancaster and Downes (2010). Category III HSIs may be developed from index of selection techniques. The forage ratio is often used to determine habitat utilisation, this being a measure of use of the available habitat although the more complex Jacobs Selectivity Index is favoured by some because it provides a measure of selection (positive values) and avoidance (negative values). However, determining Category III HSIs is extraordinarily difficult and requires experimental manipulation, rather than simple survey to determine (Lancaster and Downes, 2010).

Modelling habitat suitability is problematic; the assumption is that each species/group has a range of conditions in which they can live although within that range there are some conditions in which they are more commonly found. In Figure 2:18, which shows depth and velocity Category III HSIs (*preference*) for three life-stages of the two-spined blackfish (*Gadopsis bispinosus),* juvenile depth *preference* peaks at c.45cm, immature at c.20cm and adult at 55cm, there is little difference in velocity *preference* between the life-stages.

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Figure 2:18 Category III Habitat Suitability Curves for two-spined blackfish (*Gadopsis bispinosus*) in the Cotter River (Maddock *et al*., 2004, p178)

PHABSIM, and other similar models, work at the microhabitat scale, whereas the meso-scale is a focus of interest. Parasiewicz and Walker (2007) compared outputs from PHABSIM using univariate HSIs; HARPHA (which uses multivariate HSIs) and MesoHABSIM (a meso-scale habitat model using multivariate habitat criteria). They found that only MesoHABSIM predictions correlated with fish observations. The variation within the micro-scale models (PHABSIM and HARPHA) was greater than between micro-and meso-scale models (HARPHA and MesoHABSIM); and simple univariate habitat-use criteria provided the largest source of discrepancies among the models (Parasiewicz and Walker, 2007). They conclude that full account should be taken of all habitat variables when undertaking habitat suitability studies.

Determining the availability of suitable habitat in areas of river channel is a form of spatial analysis. Development of GIS, which is designed to undertake spatial analysis, has allowed other types of habitat rating methods to be developed. CASiMiR (CASiMiR, 2010) and MesoCASiMiR (Eisner *et al*., 2005) use fuzzy rules describing physical conditions and HSIs to generate habitat suitability for both fish (Peter *et al*.,

2004) and macroinvertebrates - *Baetis rhodani* (Mouton, *et al.,* 2005). Further, GIS is a method whereby remotely sensed topographical data, hydraulic and biotic data could be analysed to predict habitat utilisation.

Relationships between macroinvertebrates and the physical nature of their environment are complex, and traditional methods used by ecologists to model the relationship between them using single dominant factor may be inappropriate. Lancaster and Belyea (2006) argue that the widely used identification of the central response (using Ordinary Least Squares Regression - OLS) is inappropriate and that the limiting factors are more appropriate. They suggest that the spread of data provides more effective insights into the relationship between macroinvertebrate abundance and near-bed velocity and that Quantile Regression performs better OLS. This recent work challenges, but does not necessarily replace, the view that relationships exist between mesohabitats and macroinvertebrate communities, although some of the tried and trusted methods may have greater limitations that have been hitherto accepted.

2.5.7 Criticisms of habitat models

Lancaster and Downes (2010) raise some fundamental concerns about abundance-environment relationships, believing that habitat modelling takes a rather simplistic view of aquatic invertebrate ecology with a detailed understanding of macroinvertebrate biology lacking in many studies. They consider that ‘habitat preference’ means individuals select habitats over others that are available which is difficult to demonstrate even using controlled experiments, They also advocate species level identification and use of limiting responses rather than using central tendencies or means.

Generalized Linear Models (GLMs) provide the opportunity for variables with different distributions to be used, and may be a suitable way of investigating biota – physical relationships. Conallin *et al.* (2010) conclude that, whilst GLMs have been little used in biota – hydraulic studies, they have the ability to identify relationships where the assumptions of other methods cannot be met. Generalized Additive Models (GAMs) are a non-parametric extension of GLMs (Conallin *et al*., 2010, p97). Because GAMs are able to deal with curvilinear and non-monotonic relationships they, perhaps, have more flexibility in dealing with and explaining the biota – physical relationship.

The transfer of HSIs from river to river has been criticised (Gibbins *et al*., 2007) and found problematic (Moir *et al*., 2005). Some of these issues were investigated by Moir *et al*. (2005) in the River Dee catchment, Scotland. Category II and III HSIs were used to examine Atlantic salmon breeding sites and compared with a Category II HSI developed for a Dorset, England river. Category II HSIs were developed from empirical data collected from three streams in the River Dee catchment, they were converted to Category III HSIs by relating the amount of habitat used in relation to that available. Figure 2:19 shows the HSIs developed, together with percent habitat availability in the River Dee.

Images removed

Figure 2:19 Depth and Velocity Habitat Suitability Indices for the River Dee and a river in Dorset, UK (Moir et al., 2005)

Figure 2:19 shows that the Dorset HSI uses depths greater than those from the Dee catchment, although velocity from the Dorset HSI occupies a narrower range than those of the Dee. The results of the PHABSIM modelling showed the Dee HSIs, performed better than the Dorset HSI in identifying locations where spawning occurred. However, there was little difference between the predictions using the Dee Category II and Category III HSIs, this attributed to small differences in the availability / use ratio. Moir *et al*. (2005) conclude that PHABSIM is an appropriate tool for predicting salmon spawning areas and that *ex-situ* HSIs should be used with caution.

Habitat use is patchy, Deudal (2007) notes that fish do not use the whole of an available habitat area, which is the assumption of many habitat models (Heggenes, 1996). This suggests that habitat preference (Category III) HSIs should be more meaningful than Category I or II HSIs. Habitat preference, however, implies a choice of habitat where in reality many factors influence the use of habitats and the organism may, in fact, not be able to choose its preferred habitat. The term ‘habitat utilisation’ is preferred to by Lancaster and Downes (2010) as being more meaningful.

2.5.8 Diversity of in-stream habitats

Use of habitats by macroinvertebrates is complex. However, there is a general expectation that greater habitat diversity leads to greater biological diversity (Tickner *at al*., 2000; Dunbar, 2009).

Not all organisms occur in all environments, they perform best in particular niches, neither are different kinds of organism distributed randomly throughout different habitats, there is a correspondence between habitats and occupants (Begon *et al.,* 2006). Odum and Barrett (2005) explain that habitat diversity can be seen as a basis for metapopulation dynamics it follows, therefore, that provision of a range of environments (habitats) will suit a greater number of organisms and lead to greater biological diversity, which, if SFT mesohabitats are biologically relevant, habitat diversity could be linked to biodiversity, a principle considered by Harper and Everard (1998) to underpin the RHS. Diversity of in-stream habitat has been examined with the Shannon Wiener’s Diversity Index (Yarnell *et al*., 2006), which is a measure of diversity widely used in landscape ecology (Magurran, 2004).

The restoration of rivers is of increasing concern, being driven by the desire to improve the negative effects of anthropogenic manipulation. One goal is to increase the mosaic of (meso) habitats in the belief that this will lead to increases in species abundance and diversity. These changes may be driven by legislation *e.g.* the European Water Framework Directive (European Union, 2000) or by the desire to improve habitat for target species. Many objectives can be identified; these include the restoration of near-natural hydromorphology and enhancement of ecosystem function (Jähnig *et al*., 2009). Whilst it may be impossible to improve biodiversity directly, improving physical habitats promotes biodiversity indirectly (Padmore, 1997, 1998; Newson and Newson, 2000) and helps to achieve good ecological status without the need to install dedicated water quality improvement facilities (Bolton, 2009; Richardson, 2009). Jähnig *et al*. (2009) showed that restoration on several rivers in Germany increased habitat diversity. However, Palmer *et al*. (2010) investigated restoration of habitat heterogeneity in severely impacted streams. They conclude that whilst restoration increased the habitat heterogeneity there were few statistically significant cases of increases in macroinvertebrate diversity.

Channel morphology is controlled by bank-full discharges that disturb bed sediments, at those discharges most of the channel becomes 'run' mesohabitat (Leopold *et al.,* 1964) *i.e*. RP SFT mesohabitat, it is at lower discharge that bed morphology exerts controls over mesohabitats extent. High velocity increases water column turbulence in NP and SM mesohabitats and reduces the influences of bed roughness associated with UW mesohabitats. With little mesohabitat diversity at high discharge, one might conclude that at lower discharge mesohabitat diversity would be greater.

Flashy rivers are characterised by a wider range of flows, with both low and high flows more extreme than in their stable counterparts. With extremely low flows, bed morphology is likely to exert a greater influence on the water surface in flashy streams and therefore also on mesohabitat structure.

2.6 Summary

River habitats are diverse. The relationship between near-bed hydraulic conditions and the water column is complex. Near-bed hydraulics are controlled, largely, by bed roughness which has the effect of lowering velocities near to the bed. Turbulence in the water column is common, it's magnitude dependant on stream velocity, manifesting itself as patterns on the water surface. At higher discharges the impact of bed form and roughness on surface flow types changes with whole channels becoming RP at bank-full (Leopold *et al*., 1964). Nevertheless research has found correspondence between benthic conditions and macroinvertebrate communities (Reid and Thoms, 2008).

Surface Flow Types are discrete hydraulic habitats, and at the meso-scale are capable of identification, although this identification is subjective, particularly in the areas of transition from adjacent mesohabitats. It is considered that with adequate operator training/experience that this method can be at least as good as other current mesohabitat identification methods; however, their biological relevance is uncertain. Research into in-stream habitats is focused at the meso-scale, with a need to demonstrate the biological relevance of those habitats. Macroinvertebrates are an appropriate group to investigate because they are sufficiently large, numerous and well known to provide the background to the research and are less mobile than fish.

This research project will develop our understanding of the biological relevance of SFT mesohabitats in understudied lowland rivers and is crucial to validate any method that defines in-stream habitat areas by their physical properties. The sites used to undertake this research on the relationship of benthic macroinvertebrate assemblages to water surface flow types in British lowland rivers are described in detail in CHAPTER 3.

Ch 3: STUDY SITES

3 STUDY SITES

3.1 Introduction

CHAPTER 3 describes the study sites used during this research. Data describing the physical properties of Surface Flow Type mesohabitats and the macroinvertebrate communities contained within them were collected from twelve sites in two successive years. The range of inter-site variables was minimised, although not completely eliminated as this is practically impossible in natural conditions.

3.2 Site Locations

There were a total of twelve study sites on eight British lowland rivers (Figure 3:1).

Six study sites were selected for investigation in 2006: there was one site on each of the River Windrush (Figure 3:2), Badsey Brook (Figure 3:3), Leigh Brook (Figure 3:4), Dowles Brook (Figure 3:5), Bailey Brook (Figure 3:6) and the River Tern (Figure 3:7).

In 2007 adjacent sites on the River Windrush, Leigh Brook, Bailey Brook and River Tern were investigated, whilst the River Leadon (Figure 3:8) and Hadley Brook (Figure 3:9) replaced sites on Badsey Brook and Dowles Brook.

Sites were selected using the following criteria:

- Diversity of SFTs present within a workable channel length,
- <200m AOD,
- Rural lowland setting, and
- Safely accessible channel.

The actual locations chosen were based on access permission, personal knowledge and because some had been used as research sites recently.

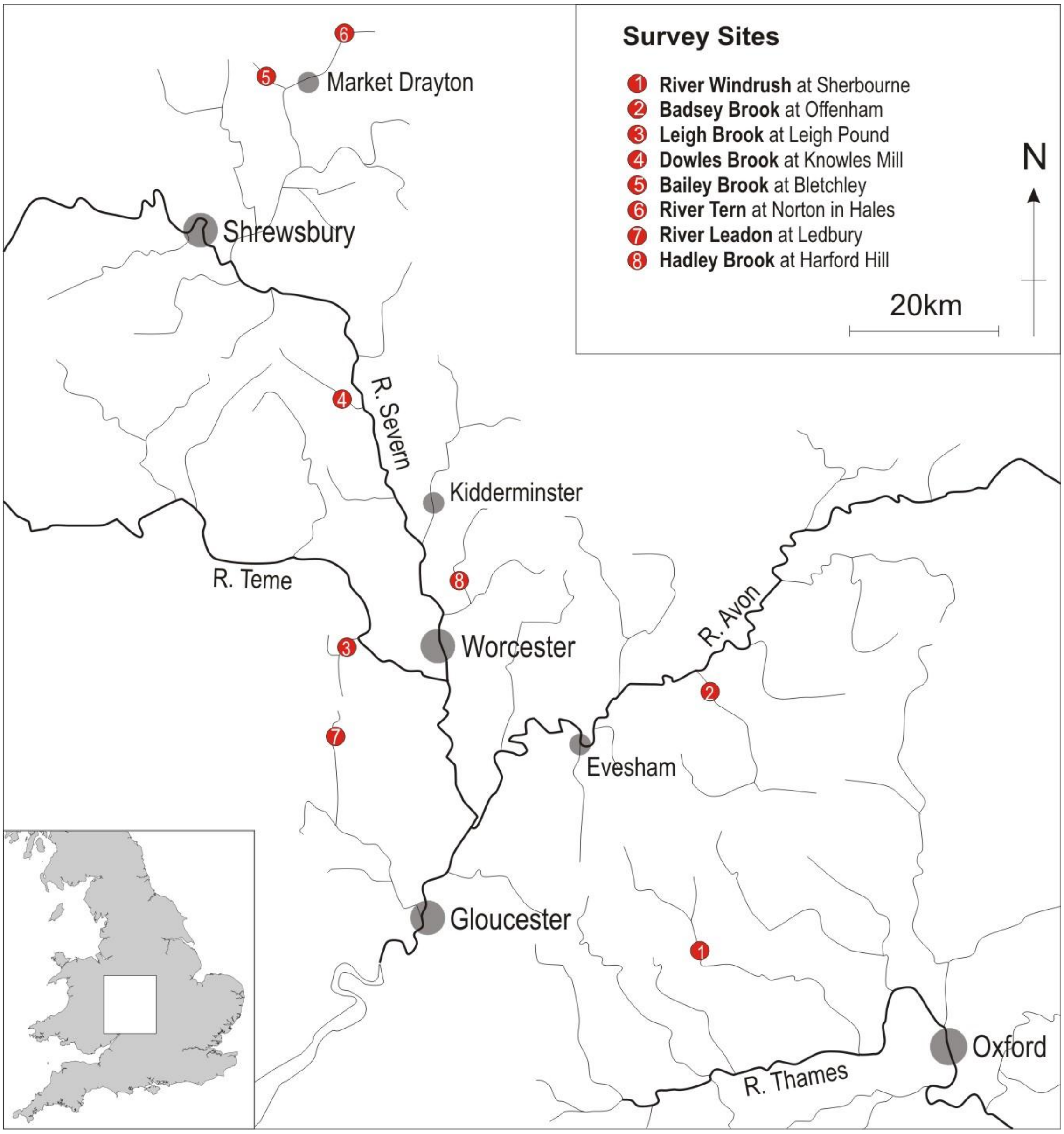

Figure 3:1 Location of eight British lowland rivers investigated in 2006 and 2007.

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Figure 3:2 Location and typical view of the River Windrush near Sherborne, Gloucestershire. NGR SP 187 156 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 25/10/2007.)

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Figure 3:3 Location and typical view of Badsey Brook (marked Broadway Brook) near Offenham, Worcestershire. NGR SP 057 452 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 25/10/2007.)

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Figure 3:4 Location and typical view of Leigh Brook near Alfrick Pound, Worcestershire. NGR SO 746 513 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 25/10/2007.)

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Figure 3:5 Location and typical view of Dowles Brook near Bewdley, Worcestershire.NGR 763 764 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 25/10/2007.)

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Figure 3:6 Location and typical view of Bailey Brook at Bletchley, Shropshire. NGR SJ 625 328 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 25/10/2007.)

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Figure 3:7 Location and typical view of the River Tern at Norton-in-Hales, Shropshire. NGR SJ 706383 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 25/10/2007.)

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Figure 3:8 Location and typical view of the River Leadon at Ledbury, Herefordshire. NGR SO 697 394 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 03/10/2008.)

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Figure 3:9 Location and typical view of Hadley Brook at Harford Hill, Worcestershire. NGR SO 868 622 (Map source: www.ordnancesurvey.co.uk/oswebsite/getamap/, 03/10/2008.)

3.3 Site Characteristics

Physical variables between sites were minimised (Table 3.1). Mean annual discharge ranges from 0.34m^3/sec to 0.84m^3/sec (mean: 0.58m^3/sec), whilst catchment sizes range from 33.75km^2 to 171.53km^2 (mean: 75.125km^2). Site altitudes range from 25m to 114m Above Ordnance Datum (AOD), mean catchment altitudes 78m to 210m AOD. All catchments have low urbanisation, ranging from 0% to 3.1%.

Empirical studies of natural sites are constrained by variation in the physical conditions amongst those sites. Although every effort was made to reduce the range of variation between sites selected they differed physically, to a small degree. The use of adjacent reaches was adopted, where possible, because it allowed for predictions or expectations to be made and tested with two groups of physically similar sites. Each site had broadly similar discharge, channel size, stream order and land use, meeting the following criteria: altitude <200m, with a low percentage of built-up area within the catchment, channel modification low to moderate, accessible by wading, and discharge data available.

Mudstones and sandstones underlie the catchments of both Bailey Brook and the River Tern, with glacio-fluvial deposits, superficial deposits of Alluvium, and head. The catchment of Dowles Brook is underlain by sandstones and coal measures, with superficial deposits of alluvium. Hadley Brook flows over Bromsgrove sandstone and Mercia Mudstones with superficial deposits of alluvium and sands and gravel. Leigh Brook flows over a complex area of mudstones, sandstones and siltstones overlain with alluvium and head, whilst the River Leadon catchment lies over mudstones overlain by alluvium, sand, gravel and head. The catchment of Badsey Brook overlies mudstones with some limestone in the upper part; superficial deposits consist of alluvium, sand, gravel and head. The catchment of the River Windrush lies over limestone with some mudstone overlain with superficial deposits of alluvium, head and gravel (BGS, 2010).

Site length ranged from 110m on the River Leadon in 2007 to 346m on the River Windrush in 2007 and mean channel width from 3.5m at Badsey Brook in 2006 and Hadley Brook in 2007 to 8.9m at Leigh Brook in 2006. In this study it was considered more important for sites to have lowland SFT mesohabitats well represented than to be of similar overall length. Therefore, the channel length of each site was determined by the number and range of SFT mesohabitats. Lowland SFT mesohabitats generally comprise those with less energy, *i.e.* NP, SM, RP, UW and UP. Other SFT mesohabitats – Broken Wave, Chute, Free Fall and Confused were mapped, but not investigated further because they were rare and more closely associated with upland rivers.

The RHS (Environment Agency, 2003) allows the degree of habitat quality and modification to be determined; this was used as a surrogate for the degree of 'naturalness' at the site. River Habitat Surveys were conducted at each site. A low RHS Habitat Modification Score (HMS) indicates a high degree of naturalness (Table 3:1). Badsey Brook is the most modified (over deepening) whilst Leigh Brook and River Windrush are largely unmodified. Low RHS Habitat Quality Assessment (HQA) scores indicate poor habitat quality, values range from 35 at Badsey Brook to 60 on the River Tern (maximum 100).

Table 3.1 Physical characteristics of eight British lowland rivers investigated in 2006 and 2007. Sources - (a) CEH, 2007; (b) Marsh and Lees, 2003; (c) Wallingford HydroSolutions, Personal Communication 24/6/06. Substrate: Be – Bedrock; Cl – Clay; Sa – Sand; Gr – Gravel and Co – Cobble.

Ordnance Survey grid reference	Mean annual discharge (m^3/sec)/ Strahler order	Stream power per unit length (watts/m)	Bed slope (m/m)	Mean channel width (m)	Catchment area (km^2) (a)	Longest drainage path (km) (a)	Dom. Substrate class	Bryophyte cover (%)	Over-head cover (%)	Site altitude (m) (a)	Mean catchment altitude (m) (a)	Base flow index (b) (c)	Urban extent in 2000 (%) (a)	RHS HMS (score)	RHS HMI (class)	RHS HQA (score)
River Windrush: Sherborne Gloucestershire, with a sinuous planform and active meander bends. The largest catchment, with high habitat quality lies on the Cotswold Oolitic limestone creating a very stable hydrological regime Agricultural land use dominates with little urbanisation. Channel length - 346m (2006) and 170m (2007) (Figure 3.2).																
SP 1875	0.73 / 4	10.5	0.0015	7.5	172	30	Gr	<1	6	114	210	0.95	0.7	0	1	45
Badsey Brook: At Offenham, Evesham, moderately sinuous with modified habitats. The second largest catchment, land use is horticultural, arable, grassland and woodland over low permeability geology with low BFI value. Flow regime is impacted by agricultural abstraction, urban extent is greatest although still low, 287m (2006) (Figure 3.2).																
SP 0576	0.65 / 4	10.6	0.0017	4.5	95	17	Cl	5	26	25	78	0.43	3.1	32	4	35
Leigh Brook: Within the Knapp and Papermill Nature Reserve at Alfrick, Worcestershire, with moderately sinuous channel and wooded banks. The site is little modified. The third largest catchment, land use is a mosaic of woodland, grassland, and arable with impervious geology and a flashy regime. 341m (2006) and 150m (2007) (Figure 3.3).																
SO 7460	0.41 / 3	2.5	0.0063	8.0	70	19	Co	6	40	45	124	0.5	1.1	0	1	54
Dowles Brook: A moderately sinuous, shaded 224m reach within the Wyre Forest near Bewdley with little habitat modification. The fourth largest catchment with a mosaic of woodland, grassland and arable, over mixed or very low permeability geology resulting in a flashy catchment. There is little urbanisation (Figure 3.4).																
SO 7637	0.39 / 3	10.1	0.0033	7.8	42	14	Be	3	43	25	129	0.4	1.2	4	2	54
Bailey Brook: Bletchley, Shropshire, moderately sinuous at with semi-continuous bankside trees and moderate habitat modification. Habitat quality is good. The smallest catchment consisting of grassland, arable, little woodland, over variable geology producing a high BFI value with a stable regime. 280m (2006) 170m (2007) (Figure 3.5).																
SJ 6251	0.44 / 3	11.3	0.0026	3.8	34	13	Sa	0	20	62	93	0.72	1.5	10	3	52
River Tern: A moderately sinuous reach at Norton-in-Hales, within wet woodland, habitat modification is low and habitat quality high. The catchment is small with grassland, arable and woodland, over glacial till with both high and very low permeability. Groundwater dominated with little urbanisation. 284m (2006) 200m (2007) (Figure 3.6).																
SJ 7067	0.84 / 3	27.4	0.0033	5.5	38	11	Gr	<1	10	100	136	0.76	0.8	6	2	60
Hadley Brook: A 210m reach in an agricultural landscape, moderately sinuous with some shading. The catchment comprises low to moderate relief on Mercia Mudstone, split between highly impervious geology and highly pervious geology. Land use is arable and grassland with little urbanisation. Habitat modification is low (Figure 3.7).																
SO 8683	0.46 / 3	3.8	0.0008	3.5	55	22	Cl	<1	25	25	68	0.55	0.0	20	3	43
River Leadon: A moderately sinuous 110m tree lined reach set in an agricultural landscape at Rhea Court, Ledbury. A small catchment with low permeability geology resulting in a flashy regime. Land use is dominated by arable and grassland, urbanisation is low (Figure 3.8).																
SO 6974	0.34 / 3	6.4	0.0019	5.0	52	14	Gr	<1	39	53	102	0.56	0.0	0	1	40

3.4 Site Water Quality

Poor water quality is a potentially limiting factor in macroinvertebrate studies. Biological water quality data for the sites investigated in both 2006 and 2007 were obtained from the EA. Only in the case of Hadley Brook did the EA monitoring site coincide with the site surveyed, in the other cases data from the closest monitoring site were used. Table 3.2 shows the variation in water quality between sites, and shows that biological water quality in the River Windrush declined from Grade A in 2006 to Grade B in 2007. Table 3.3 explains the EA grades (Environment Agency, 2009). Although water quality data for Bailey Brook was not available for 2006 and 2007, in 2003 it was rated as Grade C. This grade is likely to be as a result of sewage outfall discharging approximately 1km upstream of the site, causing low dissolved oxygen levels.

Table 3.2 Environment Agency biological water quality during 2006 and 2007 in relation to eight British lowland rivers, ranked according to water quality. Source: Environment Agency, 2009. BMWP is Biological Monitoring Working Party; ASPT is Average Score per Taxon.

River	Environment Agency Monitoring Site in Relation to Study Reach	EA Grade 2006	EA Grade 2007	Study BMWP Rank	Study ASPT Rank
Leigh Brook	2.5 km upstream	A	A	1	2
Hadley Brook	EA reach encompasses site	A	A	4	5
River Leadon	2.8 km upstream	A	A	6	7
River Tern	6 downstream	B	A	3	4
River Windrush	3.2 km upstream	A	B	2	1
Dowles Brook	1.2 km downstream	B	B	5	3
Badsey Brook	870 m downstream	C	C	8	8
Bailey Brook	Not available	N/A	N/A	7	6

Table 3.3 Environment Agency water quality classifications. Source: Environment Agency, 2009.

Classification	Description
A - very good	Biology similar to that expected for an unpolluted river.
B - good	Biology is a little short of an unpolluted river.
C - fairly good	Biology worse than expected for unpolluted river.
D - fair	A range of pollution tolerant species present
E - poor	Biology restricted to pollution tolerant species.
F - bad	Biology limited to a small number of species very tolerant of pollution.

In the natural environment it is almost inevitable that that water quality will vary between sites and over time at a site. That said, the range of variation can be minimised by careful site selection. Water qualities at all sites except Badsey Brook were either ‘very good’ or ‘good’ and Badsey Brook was ‘fairly good’, no sites appeared in the poorer three categories. Whilst water quality is variable between sites it does not seriously restrict the range of macroinvertebrate able to colonise suitable habitat, and is adequate for this type of research.

3.5 Summary

Efforts were made to reduce the range of variation between sites selected although physically they differed to a small degree. Stream order, channel size and mean annual discharge have a smaller range of values than substrate. Considerable exposures of bedrock, with gravel/pebble features were present at Dowles Brook whilst sand dominated both reaches of Bailey Brook. Leigh Brook had some bedrock exposures, but mostly loose substrate. Badsey Brook was cut into a clay substrate with gravel/sand features and concrete blocks in places. Despite being located in an intensively farmed setting, Hadley Brook had many natural features; hydro-geomorphology was enhanced by coarse woody debris dams. The Rivers Tern and Windrush both benefited from a natural setting where erosion and deposition was largely unconstrained.

CHAPTER 3 has shown that although there are differences between the sites, they remain broadly comparable. Any differences in physical characteristics will be considered in analysing and interpreting the findings in subsequent chapters. The methods used to characterise the twelve study sites are described in CHAPTER 4.

4 METHODS

4.1 Introduction

CHAPTER 4 describes the methods adopted to investigate the physical and biological characteristics of mesohabitats, as defined by Surface Flow Type, and the character of the macroinvertebrate community within those mesohabitats. A range of data was collected from the physical environment. Survey work was completed in the early summer period (May, June and July) because it is a period when many macroinvertebrates are sufficiently well developed to allow rapid identification. Macroinvertebrate life stages are seasonal, with growth linked to water temperature. During the chosen survey season many macroinvertebrates will grow, making identification simpler although many insects will also mature into adults and move into the terrestrial environment.

4.2 Physical and Biological Data

4.2.1 Site Variables

The variables recorded or calculated for each of the twelve study sites are: BFI, catchment area, days since last Q_{10}, discharge exceedence, RHS HMS, RHS HQA, visit – seasonality, water conductivity, water dissolved oxygen, water pH and water temperature.

4.2.2 Surface Flow Type Mesohabitat Variables

Within each of the Surface Flow Type mesohabitats identified five sets of point data were recorded or assessed. The variables recorded were: mean column velocity, biofilm cover, bryophyte cover; dominant substrate, embeddedness, filamentous algae cover, macrophyte cover, overhead cover, Surface Flow Type, sub-dominant substrate, substrate present, surface velocity and water depth. Data from each of the 2 335 points were recorded from points arranged in a cruciform pattern similar to that used by Harvey and Clifford (2009, 163); see section 4.3. These measurements were not made at the location of the macroinvertebrate sample points and to circumvent pseudoreplication issues (Hurlbert, 1984) a further set of data were collected from the macroinvertebrate sample points to represent the microhabitat characteristics.

4.2.3 Microhabitat Variables

Microhabitat variables were recorded for each of the 375 macroinvertebrate samples. The variables recorded were: bed velocity, bed +0.05m velocity, bed +0.10m velocity, bed

+0.20m, velocity at 0.10m intervals to and including the surface, biofilm cover, bryophyte cover; dominant substrate, embeddedness, filamentous algae, macrophyte cover, overhead cover, Surface Flow Type, sub-dominant substrate, substrate present, surface velocity and water depth.

4.2.4 Surface Flow Type

A SFT mesohabitat survey was undertaken of each of the twelve study sites. Descriptions of SFTs follow the RHS (Environment Agency, 2003, p3.19) and are described below (Table 4.1), those SFTs not investigated in detail are shown with grey backgrounds. The eight SFT mesohabitats identified and mapped were NP, SM, RP, UW, UP, BW, CH and CF. Three SFT mesohabitats, BW, CH and CF, were not investigated further because they are rare in British lowland rivers, FF SFT was not encountered. Although the identification of SFTs is subjective, at the meso-scale it is adequately robust with sufficient operator training and experience (Section 2.6).

Table 4.1 Surface Flow Type descriptions. Grey backgrounds show Surface Flow Types not investigated in detail.

Surface Flow Type	**Description of Water Surface**
No perceptible	Areas with no detectable net downstream flow, may have upstream (eddy) flow.
Smooth	Laminar flow with a ‘glassy’ surface.
Rippled	Small symmetrical surface ripples generally <1cm high moving downstream or laterally.
Unbroken standing wave	Stationary waves with upstream facing wavelets that have not broken, may resemble ‘dragon-backs’.
Upwelling	Strong upward flow resulting in ‘boils’ on the water surface.
Broken standing wave	Distinct stationary waves with tumbling tops trying to flow upstream.
Chute	Low curving flow with substantial water contact ‘hugging’ the substrate.
Free Fall	Vertically-falling water clearly separating from the back wall of a distinct vertical rock face.
Confused	A chaotic mixture of several flow types.

4.2.5 Water Conductivity, Dissolved Oxygen, pH and Temperature

Water conductivity, dissolved oxygen, pH and temperature were recorded, during each of the 39 field-based surveys, using a YSI multi-parameter water quality meter. Data were collected from one location on each survey. This approach limited the ability of subsequent analysis (Canonical Correspondence Analysis) to remove the effect of water quality. These data would have been better recorded at each macroinvertebrate sample location.

4.2.6 Water Depth

Water depth was measured at each of the data points in the SFT mesohabitats using a wading rod marked in cm graduations.

4.2.7 Mean Column Velocity

Mean column velocity (at 0.6 depth) was measured at each of the data points in the SFT mesohabitats using a Valeport 601 Electromagnetic Current Meter (ECM). Velocity at 0.6 depth is, perhaps, of little relevance to benthic macroinvertebrates, although depth and velocity at 0.6 depth are widely used to give an approximation of average velocity in the vertical for discharge measurements (World Meteorology Organisation, 1980).

4.2.8 Near-Bed Velocity

Because benthic macroinvertebrates live most of their lives in close proximity to the riverbed, water velocity in this zone is particularly important. Water velocity was measured in one dimension – downstream, although it is actually three dimensional and, at the micro-scale, variable viz. turbulent. Downstream velocity was measured, on the bed, at 0.05m above the bed and then at 0.10m intervals up to and including the surface at each of the macroinvertebrate sample locations using a Valeport 601 ECM. This protocol provided the opportunity to construct a velocity profile and provided a means of examining the correlation between downstream water velocity on and near the bed and at the water surface.

4.2.9 Substrate

Visual estimates were made of substrate class in an area c. 0.30m in diameter around the wading rod, based on Wentworth particle size classifications (Wentworth, 1922) (Table 4.2). Measurements were recorded at each of the data points in the SFT mesohabitats and at each of the macroinvertebrate sample locations. Three categories of abundance were used -

dominant (>50% of substrate surface composition), sub-dominant (<50%) and 'present' (other notable substrate). Embeddedness was estimated using Eastman (2004).

Table 4.2 Substrate class sizes (based on Wentworth, 1922).

Variable	Size (mm)	Code
Detritus	Fine particulate matter	DE
Clay	< 0.0039	CL
Silt	0.0039 -- 0.0625	SI
Sand	0.0625 --- 8	SA
Gravel	8 - 32	GR
Pebble	32 - 64	PE
Cobble	64 - 256	CO
Boulder	>256	BO
Bedrock	Solid rock	BE
Vegetation	Growing vegetation	VE

4.2.10 Vegetation cover

The percentage of in-stream channel cover of biofilm, bryophyte, filamentous algae and macrophyte and the percentage of overhead cover was estimated by the author. Measurements were recorded at each of the data points in the SFT mesohabitats and at each of the macroinvertebrate sample locations.

4.2.11 Catchment Area

Catchment area was calculated from the Flood Estimation Handbook (Centre for Ecology and Hydrology, 2007).

4.2.12 River Habitat Survey

A survey using the RHS 2003 method was conducted at each of the eight British lowland rivers (Environment Agency, 2003). The 500m RHS reach was placed so that the study site reach was in the central part. The HMS and classes and the HQA scores were calculated using the RHS database (version 3) running in Microsoft Access to provide a measure of channel modification and habitat quality at the reach scale. These data helped to determine the equitability of study sites and a measure against which site variables could be related. The author qualified as an accredited RHS Surveyor with the EA in 2006. The four-day training course is concluded with a theoretical and practical examination to ensure the high confidence levels in RHS surveys continues. Since then, the author has conducted approximately 125 RHS surveys, and re-qualified as an accredited RHS surveyor in 2009.

4.2.13 Survey Dates

Surveys were conducted in the early summer period, between 1st April and 30th June in each of 2006 and 2007. This period was chosen because river discharge usually declines steadily during this time and macroinvertebrate are abundant and of a suitably large size for capture and identification as many develop into adults and emerge during this period. The date of each survey was recorded for each of the 39 surveys.

4.2.14 Discharge Data

Discharge data for the River Windrush (Bourton-on-the Water), Badsey Brook (Offenham), Dowles Brook (Oak Cottage), Bailey Brook (Ternhill), River Tern (Ternhill), River Leadon (Wedderburn Bridge) and Hadley Brook (Wards Bridge) were provided by the EA. Stage data for Leigh Brook were obtained from an ISCO 6200 water sampler with YSI sensors operated by the University of Worcester, data were recorded at 15 minute intervals. The sensors were initially attached to a frame fixed to the streambed (NGR SO 745 513) but in September 2005 they were moved approximately 90m upstream (NGR SO 744 513). The new site provided improved access and had no discernible effect on results.

A stage/discharge rating curve for Leigh Brook was constructed using the multiple verticals method and Aquapak software (Gordon *et al*., 2004). The subsequent data sets were checked for completeness, short periods (<6 hours) of missing data were replaced with values recorded in the dataset under similar stage conditions. Periods of missing data exceeded 6 hours were ignored.

Discharge exceedence values (Q_x) were calculated for each of the 39 field-based surveys.

Flow Duration Curves (FDC) for EA data were obtained from the National River Flow Archive (National River Flow Archive, 2006). The FDC for Leigh Brook was calculated using Aquapak software (Gordon *et al*., 2004).

4.2.15 Base Flow Index

The BFI values for streams with EA Monitoring Stations were obtained from the Hydrometric Register 1996 – 2000 (Marsh and Lees, 2003). A BFI value for Leigh Brook was provided by Wallingford HydroSolutions Ltd (J. Nutter, Personal Communication 26/4/2006).

4.2.16 Velocity Profile

Using the range of depths and velocities recorded from SFT mesohabitats in 2006 and 2007 combined, vertical velocity profiles, based on Gordon *et al*. (2004, p157) were plotted using the mean velocity at each point level, to show how the velocities and depths differ between the SFT mesohabitats investigated.

4.3 Hydroecological Characterisation

4.3.1 Identification and Mapping of the Surface Flow Type Mesohabitats

The location and extent of each of the SFT mesohabitats was estimated by the surveyor and drawn on to a large scale map of the river channel based on Ordnance Survey LandLine.Plus map data (Scale – 1:2 500). Habitat extents were drawn with reference to mapped features, channel shape and visual reference points recorded onto the map. A mapping grade Global Positioning System (GPS) unit (Trimble GeoXT) with sub-metre (typically ~0.30m) accuracy was used to check the accuracy of the mapped channel edge and the location of visual reference points *e.g.* trees, in winter. Data were downloaded from the Trimble GeoXT and post-processed using Pathfinder Office 3.0 software. Dauwalter *et al*. (2006) contend that surveys using GPS receivers can be faster than traditional surveying methods although in practice poor signal strength, *e.g.* under trees, can hinder its use.

No limit was placed on the number of SFT mesohabitats that could be recorded laterally across the channel (Shoffner and Royall, 2008), although each SFT mesohabitat needed to be sufficiently large for further investigation. In practice, the smallest SFT mesohabitat mapped was approximately 0.5 m^2. Figure 4:1 shows a hypothetical river reach, dots show SFT mesohabitat data collection points.

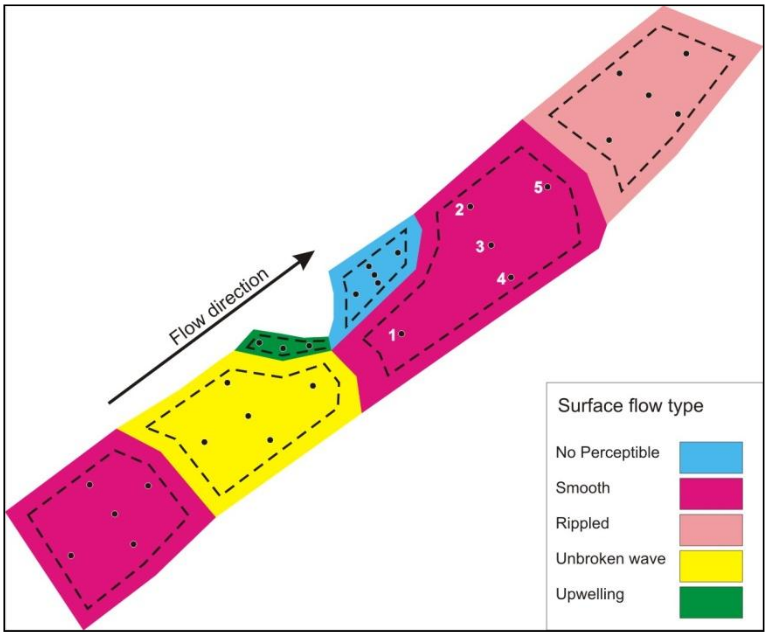


Figure 4:1 Hypothetical reach showing Surface Flow Type mesohabitats drawn onto a large scale plan. The dots represent locations where mesohabitat data were recorded.

Estimating SFT extents by eye is considerably quicker than surveying them by triangulation or dGPS, but has drawbacks because errors are more likely in the estimation process. The accuracy of using this surveying method has not been quantified, although it is considered reasonable that positional errors are unlikely to exceed 1m. A similar method for estimating the location and extent of terrestrial habitats in the UK is advocated in the environmental audit technique - Phase 1 Habitat Survey (JNCC, 1990). Inevitably selection of surveying method is a trade-off between resources available, positional accuracy, time available and extent of the river that can be assessed. This particular approach was chosen as a suitable compromise in terms of acceptable accuracy common to existing approaches (such as RHS) and the desire to map mesohabitats along reaches of several hundred metres in length. In this case adopting a broad approach allowed more rivers to be surveyed and sampled on multiple occasions which supported the aims of the research.

In natural streams, mesohabitats often have a transition zone and grade from one to another, rarely is there a distinct boundary between them. The mesohabitat boundaries are interesting, but complex and dynamic containing a variable mix of SFTs and worthy of research in their own right. This research focused on the mesohabitats defined by SFTs and therefore sampling focused on the core areas of these units to ensure these were represented by the data collected. The boundaries between mesohabitats are transitional zones and are not characterised by 'sharp' edges. The transitional zones often display the hydraulic characteristics of the two types that are merging and are not truly representative of a particular mesohabitat. By avoiding these transitional areas, this research ensured that the data collected represented the units they were collected from. In each mesohabitat mapped, only the core area was investigated in detail. An area of approximately 10% of the length/width around the edge of the mesohabitat was ignored, shown by the dotted line in Figure 4:1 in order to negate the ‘boundary’ effects. In each of the 587 SFT mesohabitats, data were recorded at five points within the core of the unit, using a cruciform pattern, similar to that used by Harvey and Clifford, (2009). This pattern was adopted because data are recorded from upstream, downstream, both edges and the centre of the SFT mesohabitat, providing sufficient data density within an acceptable time.

A photograph of each SFT mesohabitat was taken.

4.3.2 Representative Surface Flow Type Mesohabitats

During each of the field-based surveys, one representative example of each type of SFT mesohabitat present was selected for macroinvertebrate sampling and data collection. The SFT mesohabitat was selected on the basis of median depth and velocity for that SFT mesohabitat type, greatest extent of mesohabitat and safe access. Mesohabitats were selected, where possible, from non-contiguous areas.

4.3.3 Macroinvertebrate Sample Points

Within each selected SFT mesohabitat, three sample points were located diagonally (Figure 4:2 and Figure 4:3) within the core area. This pattern was adopted because data were recorded from the core of the unit, sampling upstream, downstream, edges and the centre. Although the intention was to take three macroinvertebrate samples from each SFT mesohabitat investigated, small size or unsafe access prevented this in several places.

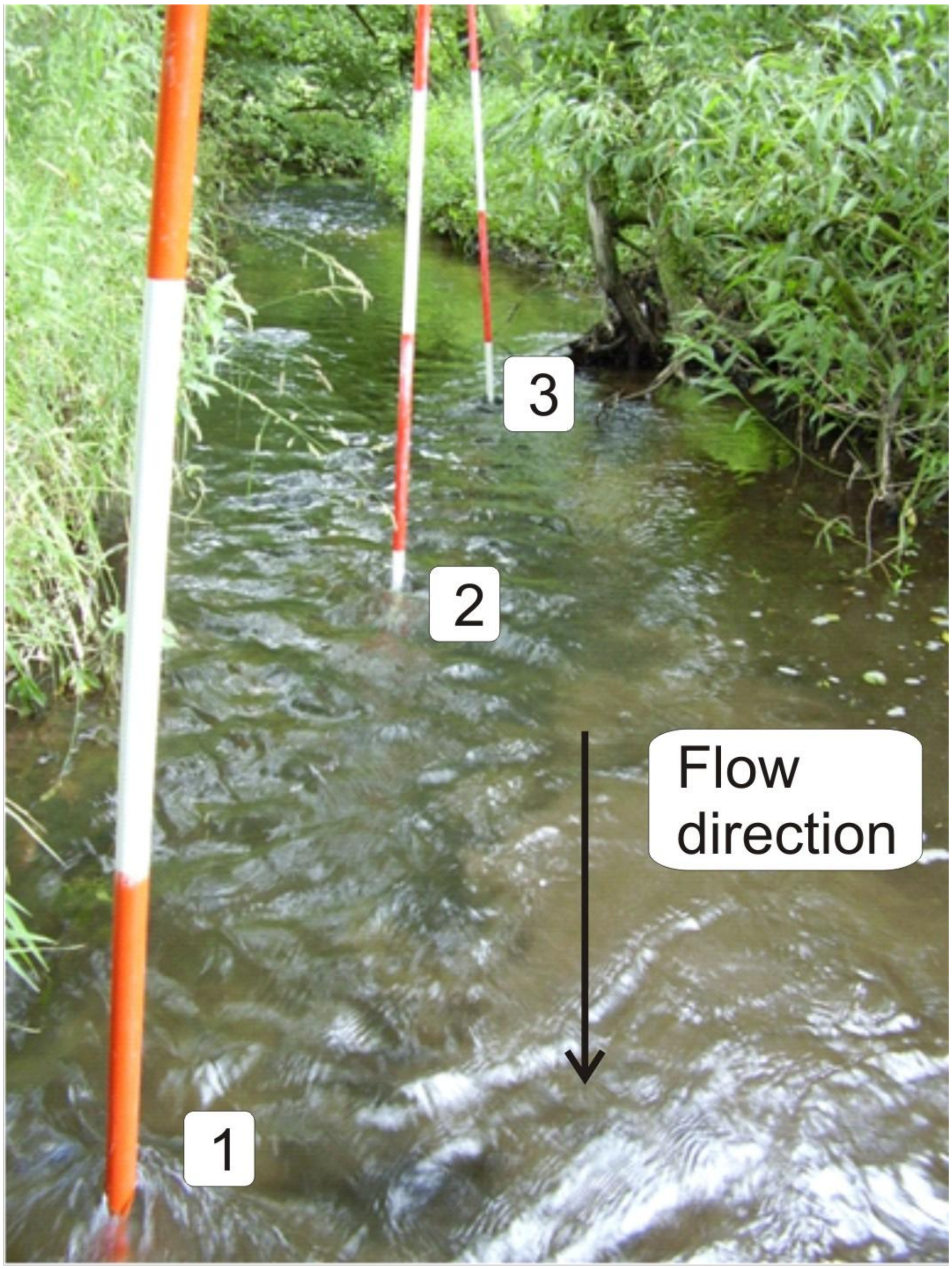


Figure 4:2 Three microhabitat sample points in an Unbroken Wave Surface Flow Type on the River Tern, Shropshire, United Kingdom. Samples were collected from the downstream point (1) first; ranging poles are for illustrative purposes only.

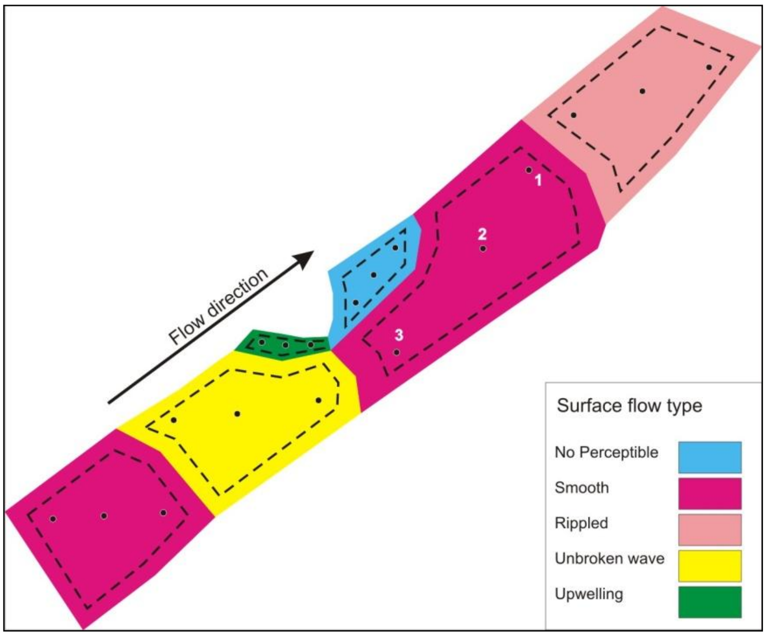


Figure 4:3 Hypothetical reach showing Surface Flow Type mesohabitats. The dots represent the locations and order in which macroinvertebrate samples were taken.

A macroinvertebrate sample was collected from each of the 375 macroinvertebrate sampling points by vigorously disturbing an area of the bed, the width of the kick-net and the length of the author’s boot (approximately 0.35m x 0.23m), with the foot and collecting the macroinvertebrates in a 500μm mesh D-net. This method does not provide true abundance data, because the sample area is not fully constrained, it does provide a relative abundance between samples, therefore *abundance* in this research refers to relative abundance. Sampling commenced at the downstream point to prevent contamination from upstream sampling (Figure 4:2). Macroinvertebrate samples were briefly examined on the bank, by-catch (*e.g.* Bullhead) was returned to the river. Samples were preserved in 80% Ethanol for later identification in the laboratory. Following Lancaster and Belyea (2006), the associated physical and biological data was also recorded afterwards from the same location.

The Biological Monitoring Working Party (BMWP) sampling protocol requires a three minute kick-sample to be collected, plus a one minute hand search of exposed stones, vegetation or debris (Freshwater Biological Association, 2009a). Adopting a protocol, in this research, where three one-minute kick samples are taken allows BMWP scoring calculations to be undertaken allowing water quality to be compared across survey sites.

4.3.4 Macroinvertebrate Identification

Macroinvertebrate samples were examined in the laboratory and broadly identified to Macroinvertebrate Taxonomic Groups (MiTGs) based on BMWP groups (Hawkes, 1997; Wright, 2000; Jackson *et al*., 2007; Freshwater Biological Association, 2009b). The term MiTG is used to refer to groups of macroinvertebrates based on families or order as appropriate. Family level identification is a widely used method (*e.g.* BMWP and LIFE protocols) and provides useful taxonomic information for a reasonable expenditure of time for broad scale studies (Hewlett, 2000). Whilst species level identification would have provided greater taxonomic resolution it is very time consuming. MiTGs that are difficult to identify to family level were identified to Order. Macroinvertebrate samples were examined using a table mounted illuminated lens and microscope assistance where necessary. The abundance of each MiTG in each sample was recorded. Large samples were sub-sampled by randomly selecting an appropriate proportion of the macroinvertebrate sample evenly spread over a white laboratory tray.

4.3.5 Water Quality

Water quality was assessed during each of the field-based surveys using revised BMWP scores (Seaby and Henderson, 2006). Data from the three macroinvertebrate samples collected from individual SFT mesohabitats were aggregated to approximate the standard BMWP sampling protocol. Mean scores for each of the eight rivers surveyed during 2006 and 2007 were derived.

4.3.6 Survey Limitations

Where water depth and/or velocity were too great and presented a risk to the surveyor, collection of in-channel data (physical and biological) were not undertaken. Where safe access to the river bank was possible, in these conditions, surface flow types were mapped.

Sampling macroinvertebrates at a wide range of water depths required compromise over the method of collection. In shallow water the Surber sampler is widely used (*e.g.* Reid and Thoms, 2008; Lancaster and Beylea, 2002), because samples are collected from a known area, abundance per unit area can be quantified. In deeper water (>c.0.30m) the Surber sampler is less convenient and the kick-net is more suitable (Frost *et al*., 1971) although kick-nets have limitations. In collection of complete macroinvertebrate communities kick-sampling is less effective, particularly of lithophilic species (Frost *et al*., 1971, 169), although the method is widely employed in the UK (Freshwater Biological Association, 2009a).

Therefore, in this research, macroinvertebrate abundance refers to the relative abundance rather than to absolute abundance.

4.4 Data Analysis

4.4.1 Data Management

All the SFT mesohabitat extents and macroinvertebrate sample points were mapped into a Geographic Information System (GIS) using MapInfo version 8 (MapInfo, 2005). After checking for completeness and accuracy, data were exported into a Microsoft Excel worksheet, where they were prepared for further analysis. Macroinvertebrate identification data were entered into an Excel worksheet and prepared for statistical analysis.

4.4.2 Community Metrics, Hydraulic Quantification and Statistical Tests

Community metrics used were Macroinvertebrate abundance, MiTG richness, Average Score per Taxon (ASPT) Lotic-invertebrate Index for Flow Evaluation Velocity Group, Shannon Weiner Diversity Index, and Shannon Wiener Equitability. HydroSignature was used to quantify the hydraulic variety of the SFTs. Kruskal Wallis ANOVA, Mann-Whitney *U* test; Spearman Rank Order Correlation, Principal Component Analysis, Chi-square, Two-way Indicator Species Analysis and Canonical Correspondence Analysis were used for statistical analysis.

4.4.3 Macroinvertebrate Diversity

Macroinvertebrate Taxonomic Group abundance, MiTG richness, Lotic-invertebrate Index for Flow Evaluation, Shannon Weiner Diversity Index and Shannon Wiener Equitability were used to describe SFT mesohabitat macroinvertebrate community (Table 4.3).

Table 4.3 Measures used to analyse macroinvertebrate samples. Key:LIFE - Lotic-invertebrate Index for Flow Evaluation; MiTG - Macroinvertebrate Taxonomic Group; SFT – Surface Flow Type.

Measure	Description	Examples of Use
Macroinvertebrate abundance	No of individuals per sample.	Extence et al., 1999; Heino et al., 2004; Principie et al., 2007; Suren and Jowett, 2007.
MiTG richness	No of MiTGs per sample.	Heino et al., 2004; Monk et al., 2006; Suren and Jowett, 2007; Jänhig et al., 2009.
Average score per taxon (ASPT)	BMWP score divided by the number of scoring taxa.	Hawkes, 1997.
LIFE score	LIFE score derived from LIFE scoring family taxa. (Three samples from one SFT mesohabitat).	Extence et al., 1999; Monk et al., 2006?
Shannon-Wiener Diversity	A measure of species diversity per sample.	Principie et al., 2007.
Shannon-Weiner Equitability	A measure of the evenness of species per sample.	Begon et al., 2006, p471.

Species Diversity and Richness IV (SDR IV) (Seaby and Henderson, 2006), is a suite of statistical routines that includes Shannon Wiener Diversity and LIFE. Shannon Weiner Diversity Index is a measure of α diversity, which takes into account both species richness and relative abundance within a sample. The value of the index, when calculated from empirical data, is usually between 1.5 and 3.5 (Magurran, 2004). Although Magurran (2004) is somewhat critical of its use she acknowledges that it is widely used and appropriate to explore diversity. The index is widely used in ecology, being used by Yarnell *et al*. (2006) to examine river habitat areal diversity. The Shannon-Weiner Index increases in response to increasing number of species/habitat types and as their proportions become more equitable (Yarnell *et al*., 2006). The Shannon-Wiener index is one of the most meaningful and robust diversity measures available, in essence it captures the variance of the species abundance distribution (Magurran, 2004).

Shannon-Weiner Equitability (*J*) (Begon *et al*., 2006, p471) was calculated from Shannon-Wiener Diversity scores, Equation 1.

Equation 1: $$J = \frac{-\sum_{i=1}^{s} P \ln P_i}{\ln S}$$

Where P is the proportion of total individuals in the *i*th species, ln is Log Normal, and S is the total number of species. This can be calculated by Equation 2:

Equation 2: $J = \frac{H}{H_{max}}$

Where H is Shannon-Weiner Diversity Index, H_{max} is the maximum value recorded.

Lotic-invertebrate Index for Flow Evaluation is a method for grouping benthic MiTGs by current velocity and prevailing flow regimes; here it is calculated at family level. Table 4.4 shows LIFE velocity groups and their associated mean current velocities, lower LIFE scores indicate a preference for higher current velocities.

Table 4.4 Lotic-invertebrate Index for Flow Evaluation velocity groups (Extence *et al*., 1999).

LIFE Group	Ecological Flow Association	Mean Column Velocity
1	Rapid flow	Typically > 1 m/sec
2	Moderate to fast flow	Typically 0. 2 to 1 m/sec
3	Slow to sluggish flow	Typically <0.2 m/sec
4	Flowing (slow) and standing waters	N/A
5	Standing waters	N/A
6	Drying/drought impacted sites	N/A

Although ASPT is based on BMWP scores and used to determine water quality, it is in-fact a measure of dissolved oxygen (Hawkes, 1997). Increasing turbulence in the water column disturbs the water surface to produce SFTs and in doing so increases the area of water surface in contact with the atmosphere, allowing greater oxygen to transfer to the water. In addition turbulent areas incorporate bubbles into the water column further enhancing the dissolved oxygen content and mixing the oxygen rich upper water with that deeper in the water column.

4.4.4 Mesohabitat Diversity

Surface Flow Type mesohabitat diversity within the reaches mapped in this research was examined with the Shannon-Weiner Diversity Index, an index widely used in landscape ecology (Magurran, 2004) and recently used in riverine habitats (Yarnell, 2006).

4.4.5 HydroSignature

HydroSignature software (Le Coarer, 2005; 2007a; 2007b; Scharl and Le Coarer, 2005) has been developed to quantify hydraulic variety for a given flow and any area of an aquatic space by calculating surface percentages of depth and current velocity in a cross-classification, this was used to analyse SFT mesohabitat depth/velocity composition. The analysis calculates the percentage of the surface area of a water body within user-defined velocity classes.

In this research the spatial location of the data points was not recorded. Collection of depth/velocity verticals from known spatial distributions (Meshes) within a defined hydraulic unit provide the best results from HydroSignature although non-spatially defined depth/velocity verticals can also be used (Le Coarer, 2005). Several processing options are available for data collected without spatial co-ordinates – termed 'No X Y' data (NOXY) - based on the method of data collection (Figure 4:4) (Le Coarer, 2007b), NOXY3_3 was considered the most appropriate method because it best fitted the pattern of data collection adopted in this research.

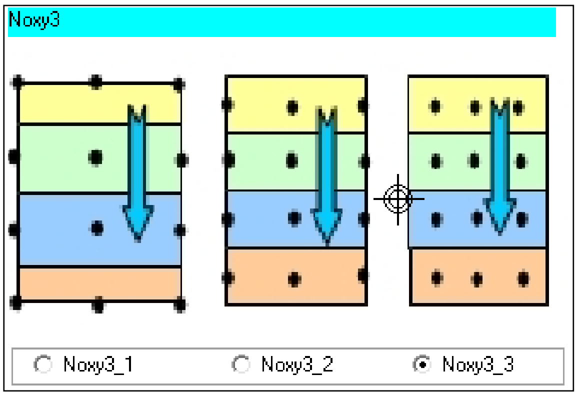


Figure 4:4 Data collection patterns from the 'No X (co-ordinate) No Y (co-ordinate)' processing set in HydroSignature.

4.4.6 Kruskal-Wallis Test

A non-parametric version of the one-way ANOVA uses ranks to determine the significance of the location of the median, it is less powerful then one-way ANOVA but is less prone to Type 1 errors (finding a significance where there is none) (Dytham, 1999). The test can be used with any number of groups and was used to test the hypothesis -

H_0: Samples from populations have the same distribution.

H_1: Samples from populations have significantly different distributions.

The Kruskal-Wallis test was used to test for significant differences between:

- Water depth recorded in SFT mesohabitats, using 2006 and 2007 data
- Mean column velocity, recorded in SFT mesohabitats, using 2006 and 2007 data

- Downstream velocities in a velocity profile recorded at macroinvertebrate sample points
- Substrate size recorded at macroinvertebrate sample points, and
- Embeddedness recorded at macroinvertebrate sample points.

The test was performed in the computer package SPSS 14 for Windows (SPSS, 2005).

4.4.7 Mann-Whitney *U* test

A non-parametric test, the Mann-Whitney *U* test makes no assumptions about data being normally distributed, and although it is considered weaker than parametric versions (Dytham, 1999) it is less likely to erroneously identify significant differences. The Mann-Witney *U* Test was used to identify significant differences between pairs of variables using the following hypotheses:

H_0: Samples from populations have the same distribution.

H_1: Samples from populations have significantly different distributions.

The Mann-Whitney *U* test was used to test for significant differences between:

- Velocity, depth, substrate size and embeddedness between data from the 2006 and 2007 field seasons.
- Macroinvertebrate abundance, MiTG richness, Lotic-invertebrate Index for Flow Evaluation, Shannon-Weiner Diversity Index and Shannon Wiener Equitability in five Surface Flow Type mesohabitat types (both 2006 data and 2007 data).

The test was performed in SPSS 14 for Windows (SPSS, 2005).

4.4.8 Spearman Rank Order Correlation

Spearman Rank Order Correlation is a non-parametric test that makes no assumptions about data being normally distributed and is useful in ecological analysis (Dytham, 1999). Spearman Rank Order Correlation was used to test the significance of correlation between dataset pairs

H_0: There is no correlation between Dataset 1 and Dataset 2; and

H_1: There is a significant correlation between Dataset 1 and Dataset 2.

The test was used to examine the relationship between:

- Surface velocity and a) bed velocity; b) bed +0.05m velocity; and c) bed +0.10m velocity.

The test was performed using SPSS 14 for Windows (SPSS, 2005).

4.4.9 Principal Component Analysis

Principal Component Analysis (PCA) is an objective multivariate ordination technique which provides a method of condensing data (Shaw, 2003). The technique is used to identify the factors underlying a dataset and is widely used. In this research PCA was used to identify the relative strengths of sedimentary and hydraulic variables measured in each SFT mesohabitat. Although PCA shows the relative strengths of variables, it does not provide a test of significance, this must be addressed separately. Calculations were performed in Community Analysis Package IV (Seaby and Henderson, 2007).

4.4.10 Two-way Indicator Species Analysis

Two-way Indicator Species Analysis (TWINSPAN) (Hill, 1979a) is a divisive polythetic classification used to identify groups. TWINSPAN was used to classify the 375 macroinvertebrate samples into similar groups based on MiTG composition. The resultant endgroups were compared with the SFT mesohabitat from which they were collected. Originally designed for vegetation analysis, Seaby *et al*. (2007) consider it appropriate for animal communities too. TWINSPAN is widely used and was selected to classify reference sites in River InVertebrate Prediction and Classification System (RIVPACS), because of its suitability for use on large, noisy and unfamiliar datasets (Wright, 2000). Computations were undertaken using Community Analysis Package 4 (CAP 4) (Seaby *et al*., 2007).

4.4.11 Detrended Correspondence Analysis

Detrended Correspondence Analysis (DECORANA) (Hill, 1979b) is widely used in ecology, *e.g.* Extence *et al*., 1999; Principe *et al*., 2007. It is one of a family of multivariate analytical tests – Ordination. DECORANA was used to examine the length of the ordination axes prior to conducting CCA on MiTG data. Computations were undertaken using Community Analysis Package version 4 (CAP 4) (Seaby *et al*., 2007).

4.4.12 Canonical Correspondence Analysis

Canonical Correspondence Analysis (CCA) is based on ordination and is used to understand the relationship between community composition and related environmental variables

(Shaw, 2003). The technique employs two data matrices, one containing community estimations and the other describing the associated environmental factors. It is important that the data for both matrices is collected from the same place and at the same time, to avoid issues of pseudoreplication (Shaw, 2003, 180). In this research the community ordination is derived from macroinvertebrate samples and the matched environmental data collected from the same location. Calculations were performed in ECOM2 (Seaby and Harrison, 2007).

MiTGs occurring in <5 of the samples were removed from the analysis on a year by year basis. CCA was run, initially, with all environmental variables used, after each analysis the vector lengths were examined. In each case the variable with the shortest vector was removed until 10 remained. SFTs were coded using dummy coding for NP, SM, RP, UW and UP. The analyses was run using data from 2006 and 2007 separately and, to circumvent correlations errors in coding the SFTs, each analysis was run omitting UP and then NP SFTs. SFT centroids and vector lengths were extracted and combined into a single plot, this appeared to have no adverse effect on the analysis. Tests for multi-colinearity showed that the variables used were appropriate.

Vector lengths for were determined from Bi-plot scores using axes 1, 2 and 3. Vector lengths indicate the relative strength of the environmental variables (Lepš and Šmilauer, 2003).

4.4.13 Chi-square Test

The Chi-square was used to test the null hypothesis that, in using each MiTG from five different SFT mesohabitat classes, observed frequencies are equal to expected frequencies and therefore there was no significant difference. P values <0.01 indicate highly significant differences and P values between 0.01 and 0.05 have significant differences. Where P<0.05 the null hypothesis was rejected. The non-parametric nature of the test makes no assumptions as to data distribution (Dytham, 1999). Chi-square analysis was performed for each MiTG, the P value and the expected values were extracted into a table. Each result was examined, those which contained an expected value <1 or where >20% of expected values were <5 were removed from the analysis (Dytham, 1999, p148). Of the remaining MiTGs, for those with a P value <0.05, the actual number of occurrences was subtracted from the expected value. Negative values indicate that fewer samples than expected contained the MTIG; positive values indicate that MiTGs were found in more samples than expected. Data from 2006 and 2007 were examined separately. Data were structured to show the frequency of occurrence of each MiTG in each SFT mesohabitat class. The Chi-square test was performed in Microsoft Excel.

In the case of all significant associations indicated by Chi-square analyses, the proportion of animals found in SFTs was determined, Figure 4:5 shows an example of Simuliidae, from 2007 data and indicates that Simuliidae abundance was greatest in UW samples.

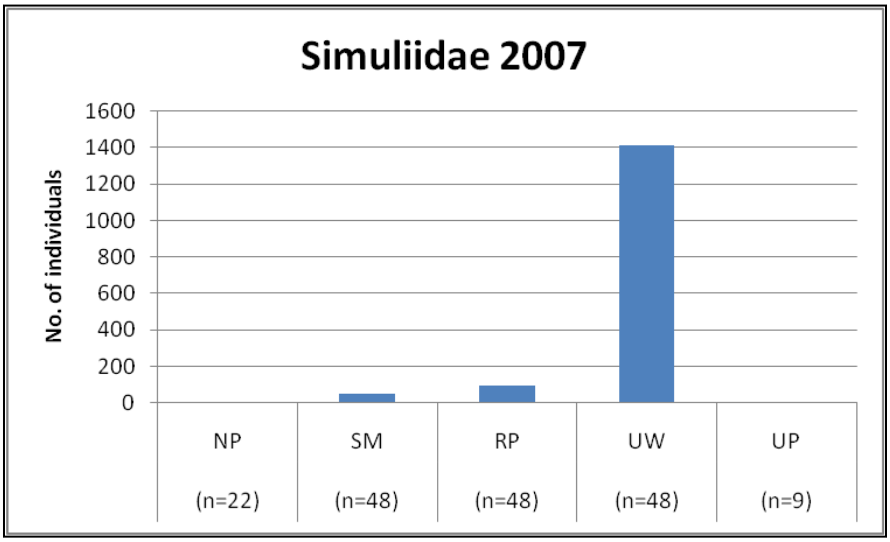


Figure 4:5 Example Macroinvertebrate Abundance chart – Simuliidae from 2007 data. Key: NP – No Perceptible; SM – Smooth; RP – Ripple; UW- Unbroken wave and UP – Upwelling SFTs.

Depth and velocity utilisation matrices were constructed for MiTGs, based on depth and velocity recorded. The matrices were constructed using the same depth/velocity classes as used in HydroSignature analysis of microhabitats.

4.5 Summary

CHAPTER 4 describes the methods selected to establish the distinctiveness of the physical and/or biological variables within SFT mesohabitats classes and the relationship of each distinctive habitat with their associated macroinvertebrate communities. The statistical analyses that follow will test the strength of the relationships and answer primary research questions (Section1.4).

In the following chapters the distinctiveness of mesohabitats described by their SFT is examined. In CHAPTER 5, SFT mesohabitat types are identified and their physical characteristics used to distinguish between the individual SFT mesohabitat types. In CHAPTER 6, the macroinvertebrate sample data are presented and described in relation to SFT mesohabitats.

5 RESULTS: IDENTIFICATION AND PHYSICAL DISTINCTIVENESS OF SURFACE FLOW TYPES

Primary Research Question 1:

Can Surface Flow Type mesohabitats in British lowland rivers be identified and recorded effectively?

- Can the extent of Surface Flow Type mesohabitats be accurately recorded?

Primary Research Question 2:

Which hydraulic variables best characterise No perceptible, Smooth, Ripple, Unbroken wave and Upwelling Surface Flow Type mesohabitats found in British lowland rivers?

- How distinct are the physical characteristics of each of the Surface Flow Type mesohabitats in British lowland rivers across a range of sites and discharges?

5.1 Introduction

CHAPTER 5 considers the physical conditions recorded in-stream during surveys in 2006 and 2007. The distinctiveness of Surface Flow Types mesohabitats are described and analysed using spatial extents, depth and velocity, substrate and embeddedness. This analysis will answer Primary Research Questions one and two.

5.2 Physical and Biological Data Collection

A range of physical and biological data were collected from six sites on six British lowland rivers between 1 April and 30 June 2006. The same range of physical and biological data was collected from six sites on six British lowland rivers between 1 April and 30 June 2007. This produced twelve sites on eight British lowland rivers that were investigated. Each of the twelve sites was surveyed on at least three occasions to give a total of 39 field-based surveys. Within the twelve sites on eight British lowland rivers a total of 587 SFT mesohabitats were identified and mapped (Table 5.1).

Table 5.1 Number of mesohabitats, listed by Surface Flow Type, identified during surveys on eight British lowland rivers in 2006 and 2007.

Year	No Perceptible	Smooth	Rippled	Unbroken wave	Upwelling	Other	Total
2006	42	97	119	55	10	18	341
2007	35	67	71	44	17	12	246

From the 587 SFT mesohabitats, a total of 557 SFT mesohabitats (NP, RP, SM, UW and UP) were investigated further. Field investigation of the 557 SFT mesohabitats gave a total of 2 335 data points for which physical and biological data were collected and recorded. Macroinvertebrate sampling and further physical and biological data collection was undertaken in 139 representative SFT mesohabitats from the 557 SFT mesohabitats.
This provided 375 macroinvertebrate samples with associated physical and biological data for desk-based analysis.

Two additional surveys in 2006, restricted to SFT extent only, were completed on Bailey Brook and River Tern at such a high discharge that water depth and velocity prevented macroinvertebrate sampling or data collection. Two planned surveys in 2007, one each on Bailey Brook and the River Tern, were confined to SFT mesohabitat extents only due to excessive water depth and velocity preventing safe access.

The field work season in 2006 generally saw discharge decreasing over time. However, during the same period in 2007 following heavy rainfall discharge increased "*Record late-spring and early-summer rainfall across much of southern Britain in 2007 produced hydrological conditions with no close modern parallel for the June - August period*"(Marsh and Hannaford, 2007, p3).

An extreme discharge (estimated at 6.8m^3/sec, Q_1) in Leigh Brook on 25/6/2007 was mapped (SFT mesohabitat data and macroinvertebrate samples/data were not collected because of safety considerations). On 26/7/2007 an even higher discharge inundated the recording equipment and data collected were lost. It was impractical to map the site at this discharge as access was too dangerous.

On 26/6/2007 SFT mesohabitats on Bailey Brook and River Tern were mapped but other data and macroinvertebrate samples were not collected due to the high discharges (2.7m^3/sec, $Q_{0.5}$ and 9.51m^3/sec, $Q_{<1}$, both measured at EA gauging stations at Tern Hill, Shropshire). These were the last two surveys planned for 2007. Due to the likelihood of bed substrate mobilisation during these extreme discharges and the subsequent disturbance of macroinvertebrate communities at these sites further surveys were not undertaken as they could be expected to be unrepresentative. The SFT mapping data from the two surveys have been used.

5.3 Surface Flow Type Spatial Extents

See Table 4.1 for descriptions of the SFTs.

5.3.1 River Windrush

Surface Flow Type mesohabitat maps of two adjacent reaches of the River Windrush (W) surveyed in 2006 and 2007 are shown in Figure 5:1 and Figure 5:2. Discharge and mesohabitat variation data recorded during three surveys is shown in Figure 5:3 and Figure 5:4 and Table 5.2, discharge exceedence range was Q_{40} – Q_{95}. Fifty seven SFT mesohabitats were recorded in 2006 and 40 SFT mesohabitats in 2007.

2006

At the highest discharge (Survey W1) nearly 70% of the channel area is RP, other SFT mesohabitat area accounts for less than 30%. As discharge decreases the proportion of RP SFT mesohabitat area reduces and SM (particularly) SFT mesohabitat area increases. At higher discharges very small areas of UW SFT mesohabitat are present, this increasing as depth declines allowing greater bed influence on the water surface.

2007

This reach is more complex than the 2006 reach. Again, RP SFT mesohabitat area decreases with discharge whilst SM SFT mesohabitat area increases. A large area of UP SFT mesohabitat is present at the two higher discharges becoming RP SFT mesohabitat at the lowest discharge. Small areas of NP SFT mesohabitat reduce with increasing discharge, being partially replaced with UP SFT mesohabitat at the lowest discharge. Unbroken wave SFT mesohabitat is confined to the upper part of the reach, expanding laterally with decreasing discharge.

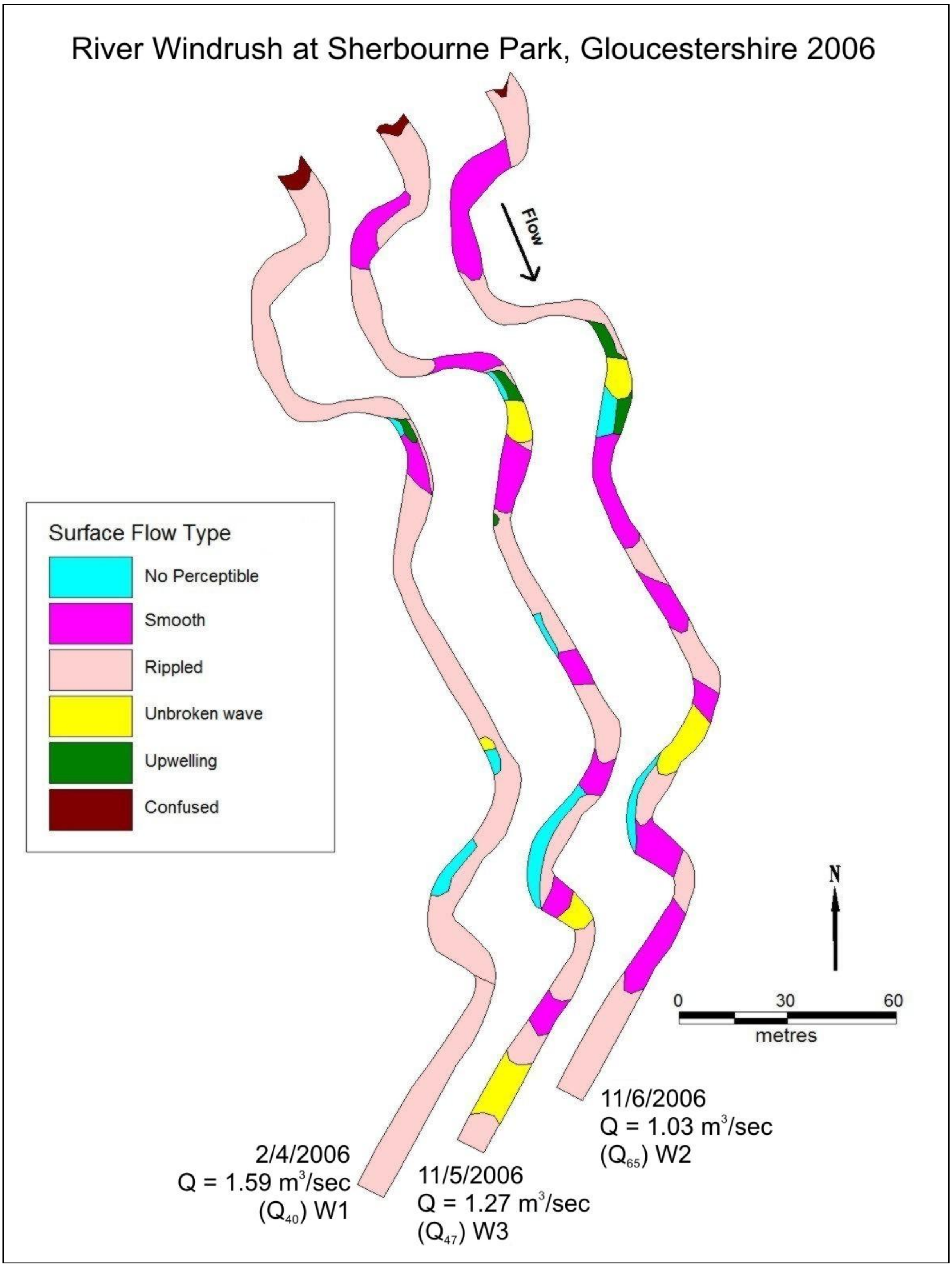


Figure 5:1 Surface Flow Type mesohabitats from three surveys of the same reach of the River Windrush, Gloucestershire during 2006. Key: W – River Windrush, Q – Discharge.

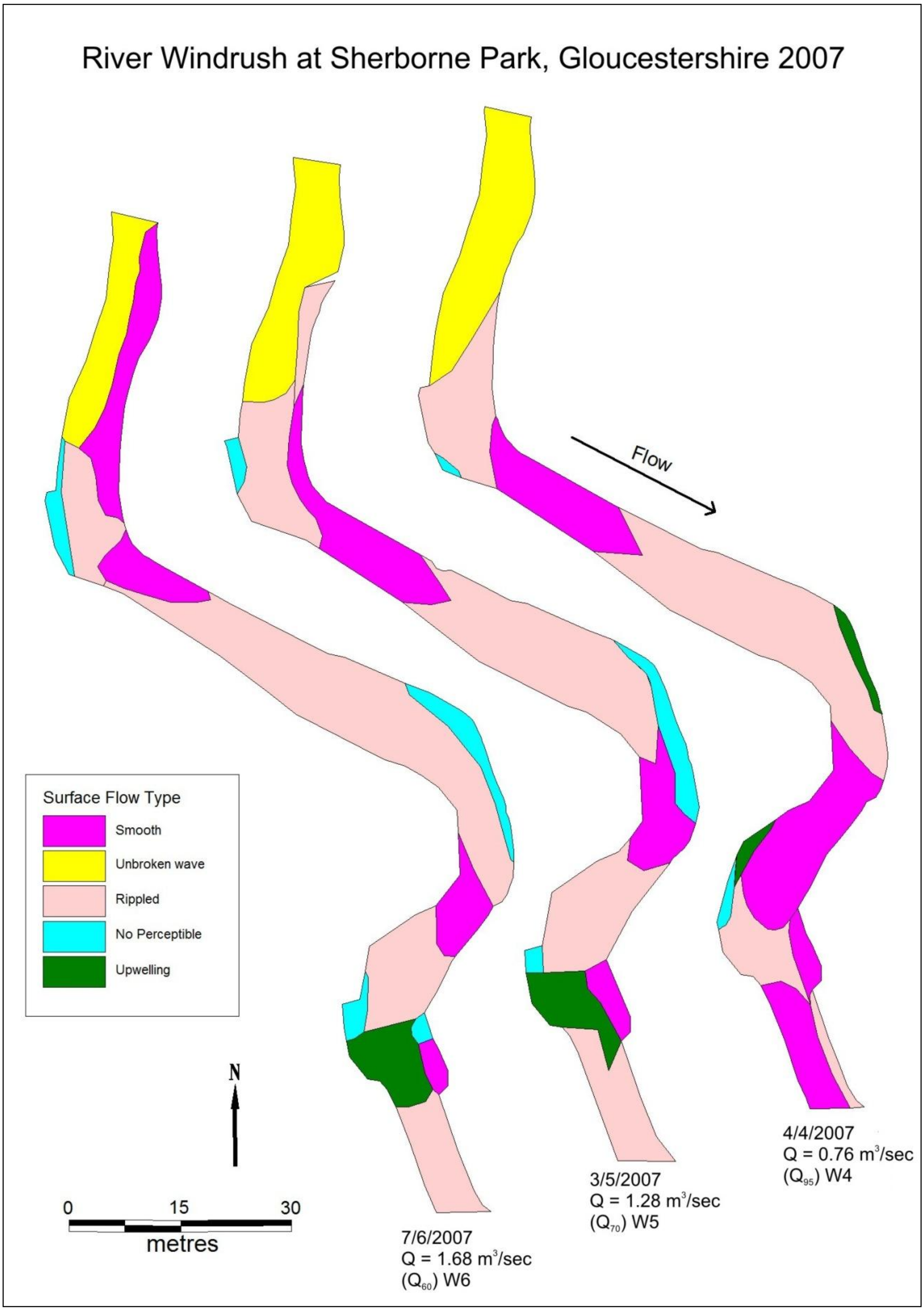


Figure 5:2 Surface Flow Type mesohabitats from three surveys of the same reach of the River Windrush, Gloucestershire during 2007. Key: W – River Windrush, Q – Discharge.

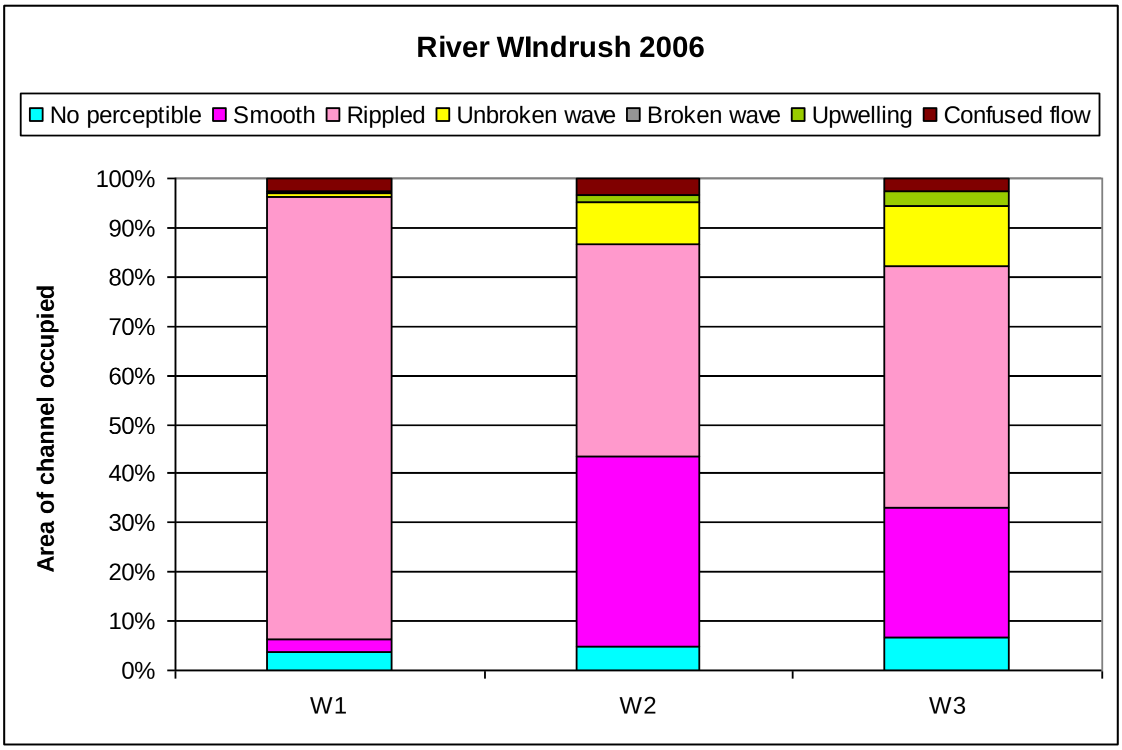


Figure 5:3 Relative proportions of the channel occupied by six Surface Flow Type mesohabitats in the River Windrush, Gloucestershire during three surveys in 2006, data derived from SFT maps drawn by eye onto channel plan. Key: W – River Windrush, Q – Discharge.

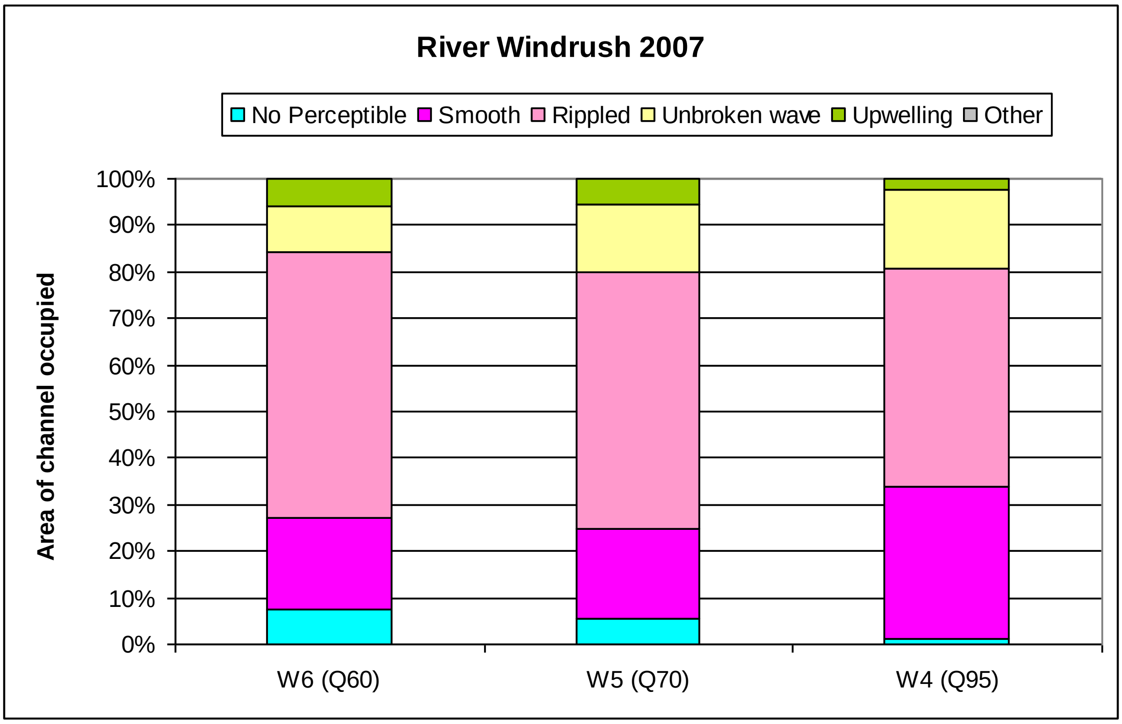


Figure 5:4 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in the River Windrush, Gloucestershire during three surveys in 2007, data derived from SFT maps drawn by eye onto channel plan. Key: W – River Windrush, Q – Discharge.

Table 5.2 Summary of Surface Flow Type mesohabitat extents, River Windrush, Gloucestershire. Key: W – River Windrush, Q – Discharge.

River Windrush	W1	W2	W3	W4	W5	W6
Q (m^3/sec)	1.593	1.026	1.273	0.764	1.281	1.686
Qx	40	65	47	95	70	60
No. of Mesohabitat units						
No perceptible	3	2	3	2	3	4
Smooth	1	6	7	4	3	4
Rippled	4	7	10	4	5	4
Unbroken wave	1	2	3	1	1	1
Upwelling	1	2	2	2	1	1
Other	1	1	1	0	0	0
Total	11	20	26	13	13	14
Mesohabitat Areas (%)						
No Perceptible	4	5	7	1	6	7
Smooth	3	39	26	33	19	20
Rippled	90	43	49	47	55	57
Unbroken wave	1	8	12	17	15	10
Upwelling	1	3	2	2	5	6
Other	2	0	1	0	0	0
Total Area (m^2)	2329	2320	2245	1354	1355	1353

5.3.2 Leigh Brook

Surface Flow Type mesohabitat maps of Leigh Brook (L) are shown in Figure 5:5 and Figure 5:6. Discharge and habitat variation data recorded during three surveys is shown in Figure 5:7, Figure 5:8 and Table 5.3, discharge exceedence range is Q_1 – Q_{75}. Eighty-four SFT mesohabitats were recorded in 2006 and 59 SFT mesohabitats in 2007.

2006

As discharge increased RP SFT mesohabitat area increased and SM SFT mesohabitat area decreased. However, it is also clear that areas of UW SFT mesohabitat expand as discharge lowers, emphasising bed controls on SFTs. At the highest discharge (Survey L1) broken wave SFT mesohabitat occupies a steep/rough area of the channel, at reduced discharge (Survey L2) this becomes UW SFT mesohabitat, but at the lowest discharge the area is a confusing mixture of chute, broken wave and UW SFT. In Survey L1, a small side channel (A) is inundated, representing a backwater SFT mesohabitat. Bed controls on features are strong; a steeper section (B) creates UW SFT mesohabitat which reduces as discharge increases.

2007

Four surveys were conducted at Leigh Brook, three were full surveys whilst Survey L7 mapped SFT mesohabitats under spate conditions (Q_1), and neither physical data nor macroinvertebrates could be safely collected. During this survey, the river was bank-full and 96% by area comprised RP SFT mesohabitat and surrounded a small area of UP SFT mesohabitat. In the three other surveys, there was little NP SFT mesohabitat in the lower discharge surveys (Surveys L5 and L6), with more at the higher discharge (Survey L4) caused by increased velocities creating spiralling flow resulting in two areas of eddy flow as water moved diagonally across the channel. Eddies have a generally small negative (upstream) velocity although they are categorised as NP. Smooth SFT mesohabitat decreased with increasing discharge. Rippled SFT mesohabitat increased from low to medium discharge, decreasing at high discharge whilst UW SFT mesohabitat increased with discharge. There was a small amount of other SFT mesohabitat recorded, comprising areas of confused and chute SFT mesohabitat.

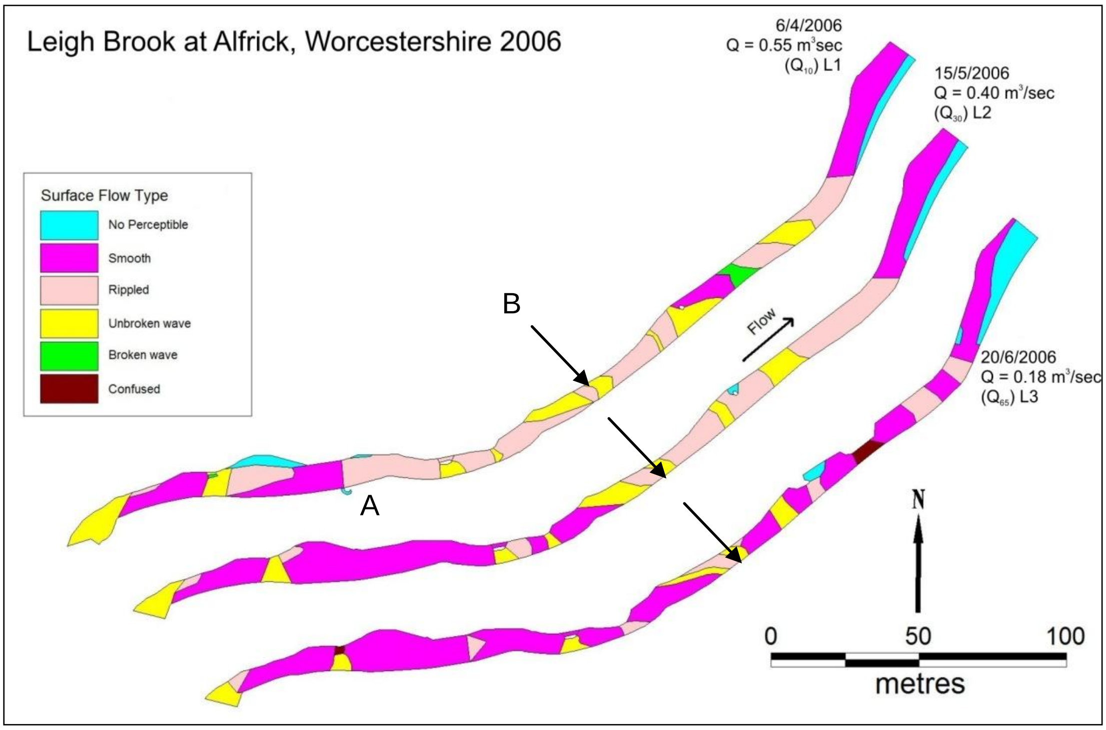


Figure 5:5 Surface Flow Type mesohabitats from three surveys of the same reach of Leigh Brook, Worcestershire in 2006. Key: L – Leigh Brook, Q – Discharge.

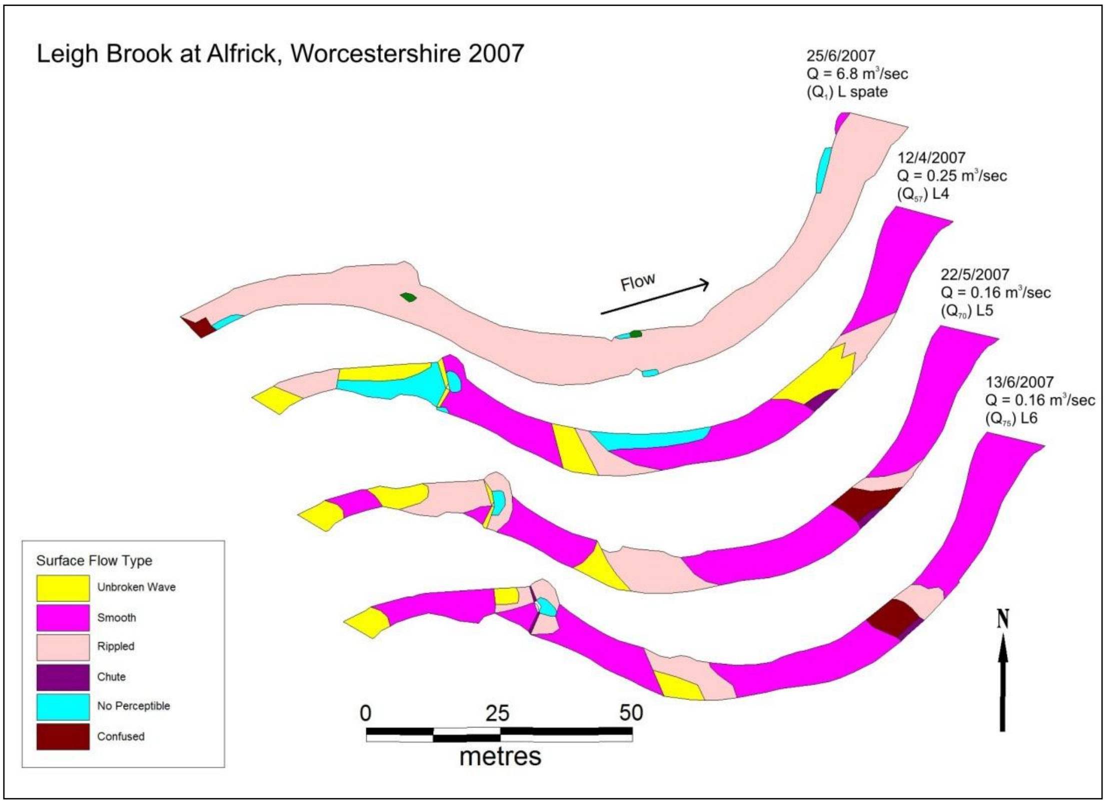


Figure 5:6 Surface Flow Type mesohabitats from four surveys of the same reach of Leigh Brook, Worcestershire in 2007. Key: L – Leigh Brook, Q – Discharge.

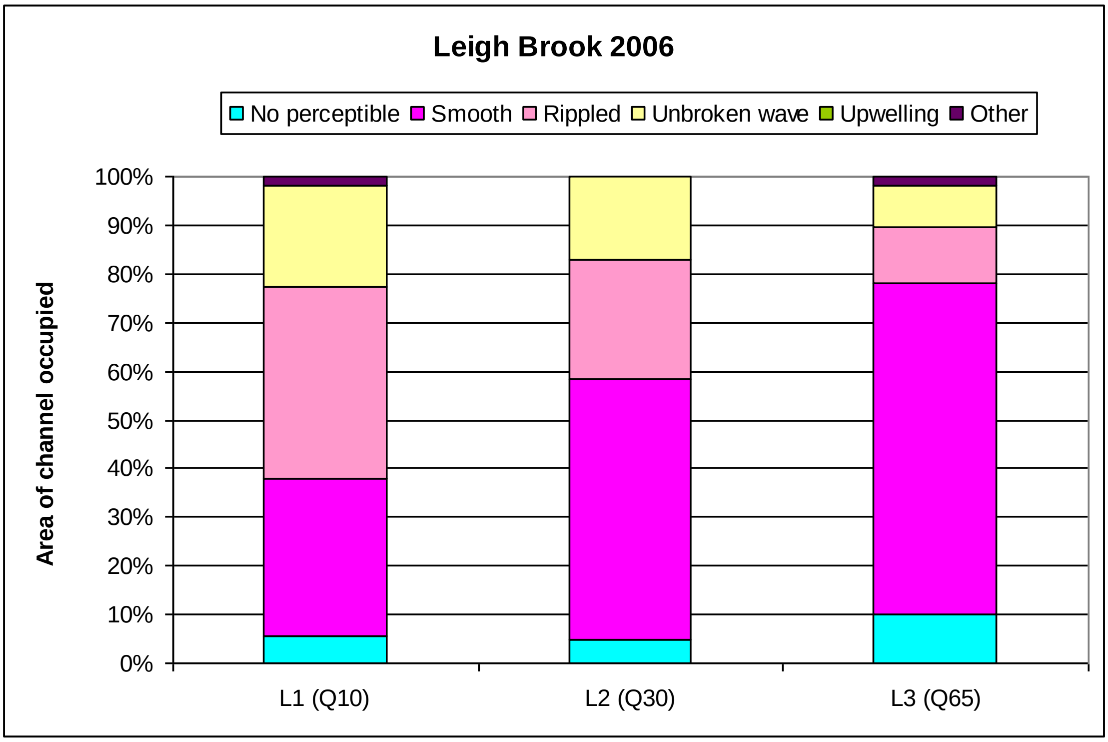


Figure 5:7 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Leigh Brook, Worcestershire during three surveys in 2006, data derived from SFT maps drawn by eye onto channel plan. Key: L – Leigh Brook, Q – Discharge.

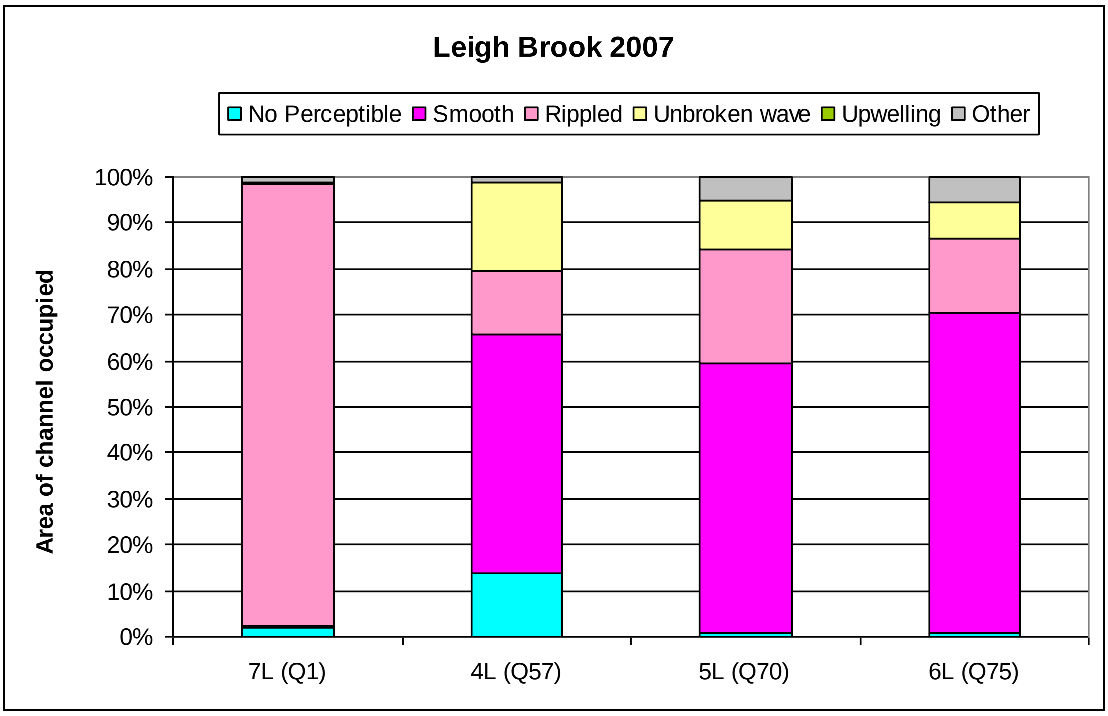


Figure 5:8 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Leigh Brook, Worcestershire during four surveys during 2007, data derived from SFT maps drawn by eye onto channel plan. Key: L – Leigh Brook, Q – Discharge.

Table 5.3 Summary of Surface Flow Type Mesohabitat Extent, Leigh Brook, Worcestershire. Key: L – Leigh Brook, Q – Discharge.

Leigh Brook	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**
Q (m^3/sec)	0.55	0.4	0.18	0.248	0.161	0.156	6.8
Qx	10	30	65	57	70	75	1
No. of Mesohabitat units							
No perceptible	4	2	3	4	1	1	4
Smooth	4	6	12	3	5	5	1
Rippled	11	7	8	3	4	5	1
Unbroken wave	9	8	6	6	4	3	0
Upwelling	0	0	0	0	0	0	2
Other	2	0	2	1	2	3	1
Total	30	23	31	17	16	17	9
Mesohabitat Areas (%)							
No Perceptible	6	5	10	14	1	1	2
Smooth	32	53	68	52	59	69	0
Rippled	39	24	11	13	25	16	96
Unbroken wave	21	17	9	20	11	8	0
Upwelling	0	0	0	0	0	0	0
Other	2	0	2	1	5	6	1
Total Area (m^2)	2869	2726	2699	1000	984	911	1162

5.3.3 Bailey Brook

Surface Flow Type mesohabitat maps of Bailey Brook (Bl) are shown in Figure 5:9 and Figure 5:10. Discharge and habitat variation data recorded during surveys is shown in Figure 5:11, Figure 5:12 and Table 5.4 discharge exceedence range is $Q_{0.05}$ – Q_{60}. Fifty four SFT mesohabitats were recorded in 2006, 37 SFT mesohabitats in 2007.

2006

Three full surveys were conducted, with an additional survey (Survey Blx) in spate conditions; this survey showed that the slightly less than bank-full discharge was c.98% ripple habitat. Surveys Bl1 – Bl3 show the reduction RP SFT mesohabitat and an increase of SM SFT mesohabitat as discharge lowers, although the survey at the lowest discharge reverses this trend due to in-channel vegetation causing surface rippling.

2007

Surveys Bl4 and Bl5 were conducted at low discharge, whilst Survey Bl6 was at a very high discharge. Although in Survey Bl6 the stream was contained within its banks, water depth and velocity prevented safe access to the channel to collect data or macroinvertebrates. At the high discharge (Bl6) 90% of the stream was RP SFT mesohabitat, with small areas of NP, SM and UW SFT mesohabitats and a larger area of UP SFT mesohabitat. Survey Bl5 had a large amount of RP SFT mesohabitat, with some UW SFT mesohabitat, slightly more SM SFT mesohabitat than the spate discharge and little NP SFT mesohabitat; tree branches submerged in the channel were probably responsible for most of the NP and UW SFT mesohabitat. In survey Bl4 SM and RP SFT mesohabitats dominates, with a small amount of UW SFT mesohabitat and very little NP SFT mesohabitat.

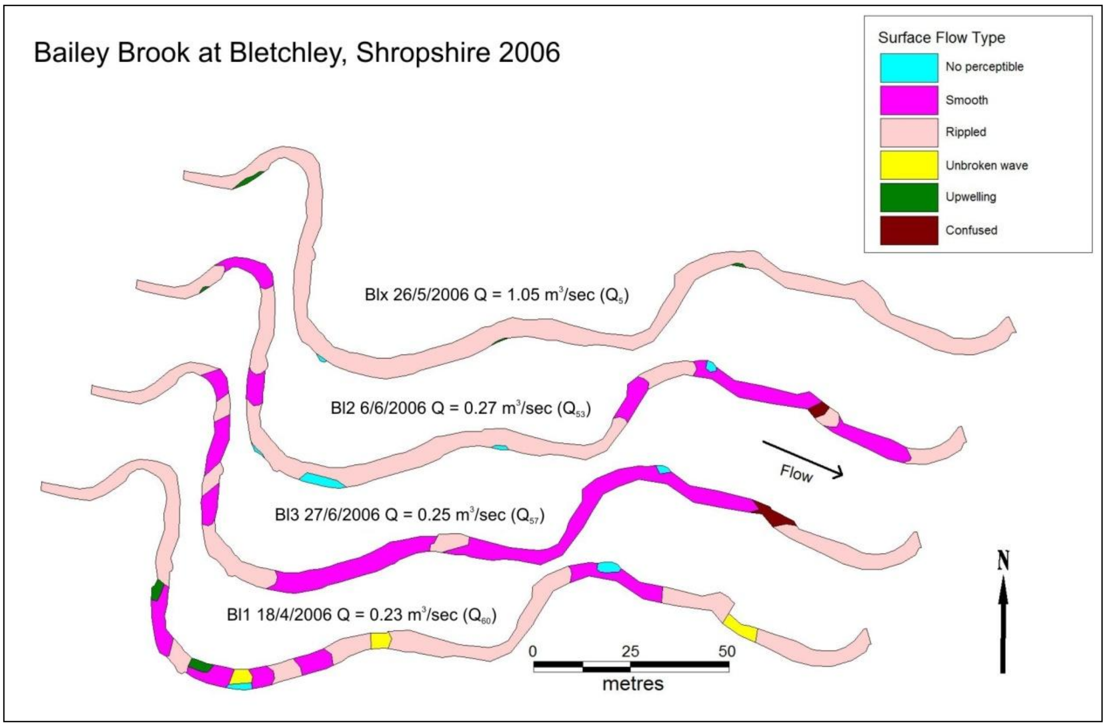


Figure 5:9 Surface Flow Type mesohabitats from four surveys of the same reach of Bailey Brook, Shropshire during 2006. Key: Bl - Bailey Brook, Q – Discharge.

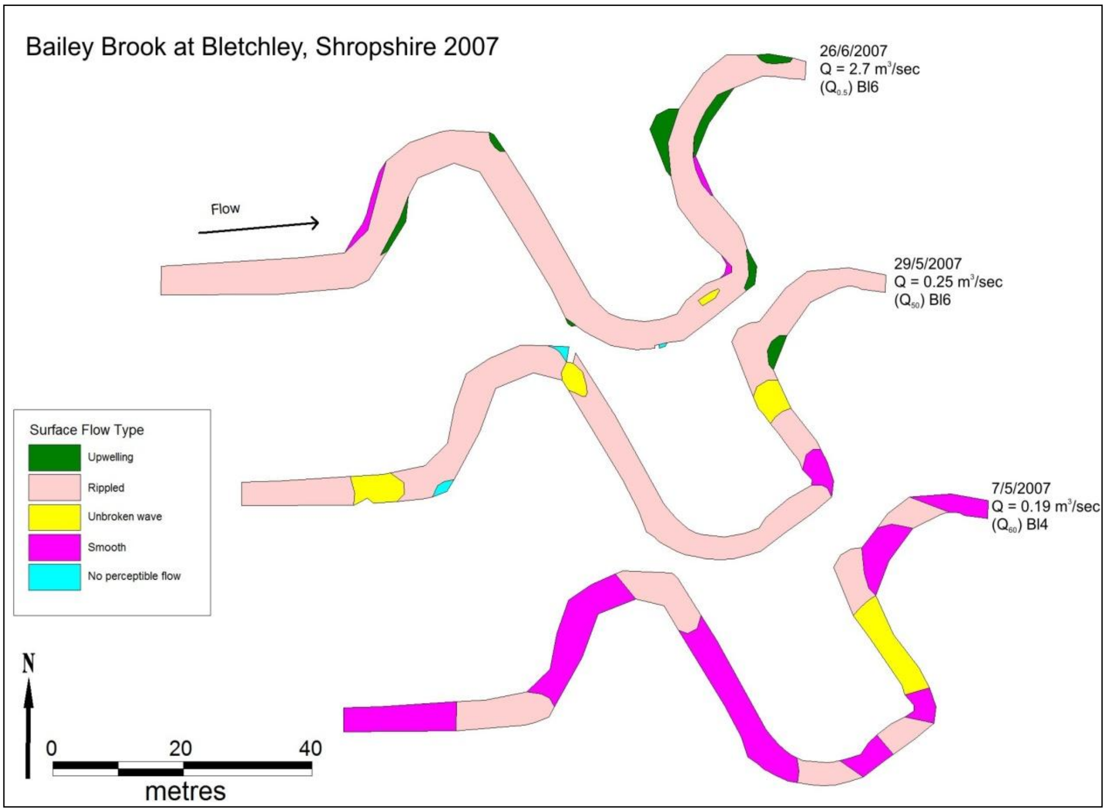


Figure 5:10 Surface Flow Type mesohabitats from three surveys of the same reach of Bailey Brook, Shropshire during 2007. Key: Bl - Bailey Brook, Q – Discharge.

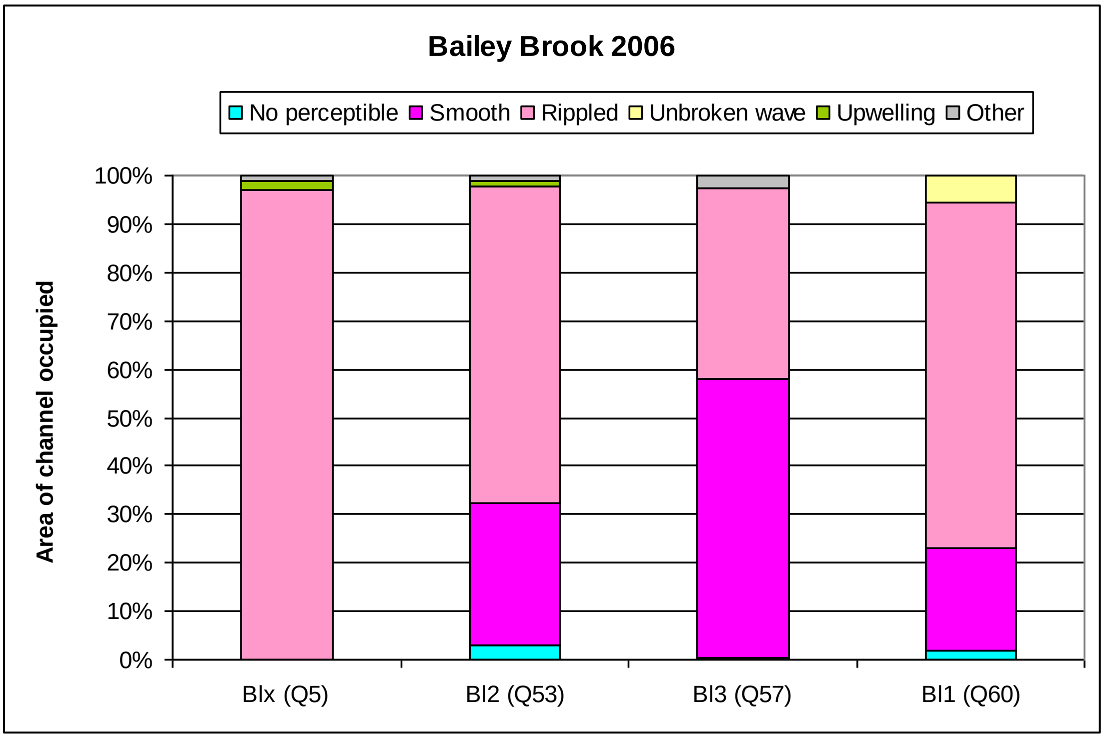


Figure 5:11 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Bailey Brook, Shropshire during four surveys during 2006, data derived from SFT maps drawn by eye onto channel plan. Key: Bl - Bailey Brook, Q – Discharge.

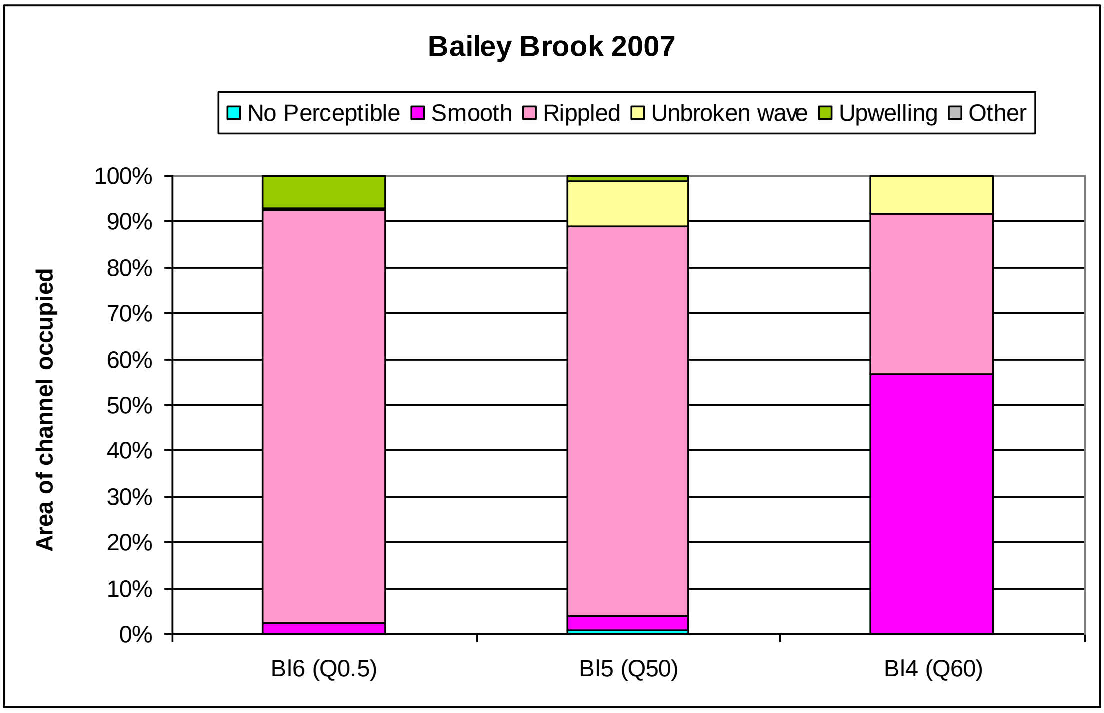


Figure 5:12 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Bailey Brook, Shropshire during three surveys during 2007, data derived from SFT maps drawn by eye onto channel plan. Key: Bl - Bailey Brook, Q – Discharge.

Table 5.4 Summary of Surface Flow Type mesohabitat extent, Bailey Brook, Shropshire. Key: Bl - Bailey Brook, Q – Discharge.

Bailey Brook	**Blxa**	**Bl2**	**Bl3**	**Bl1**	**Bl4**	**Bl5**	**Bl6**
Q (m^3/sec)	1.055	0.266	0.247	0.229	0.191	0.247	2.70
Qx	5	53	57	60	60	50	0.5
No. of Mesohabitat units							
No perceptible	1	4	1	2	0	2	1
Smooth	0	5	5	5	7	1	3
Rippled	1	6	6	7	4	5	1
Unbroken wave	0	0	0	3	1	3	1
Upwelling	3	1	0	2	0	1	7
Other	0	1	1	0	0	0	0
Total	5	17	13	19	12	12	13
Mesohabitat Areas (%)							
No Perceptible	0	3	0	2	0	0	0
Smooth	0	30	57	221	57	57	2
Rippled	99	66	39	70	35	35	90
Unbroken wave	0	0	0	5	8	8	0
Upwelling	1	0	0	2	0	0	7
Other	0	1	3	0	0	0	0
Total Area (m^2)	1154	1121	1111	1204	674	674	815

5.3.4 River Tern

Surface Flow Type mesohabitat maps of the River Tern (T) are shown in Figure 5:13 and Figure 5:14). Discharge and habitat variation data recorded during surveys is shown in Figure 5:15, Figure 5:16 and Table 5.5, discharge exceedence range is $Q_{<1}$ – Q_{99}. Sixty nine SFT mesohabitats were mapped in 2006 and 31 SFT mesohabitats in 2007.

2006

Ripple SFT mesohabitat dominates the highest discharge, and over subsequent surveys the proportion of UW and ripple decreases as SM and NP SFT mesohabitat area increases. A small area of confused SFT mesohabitat at the upstream end of the reach is caused by a fallen tree lodged in the channel. An additional SFT only survey (Survey Tx) was made when the river was in spate, discharge was estimated at 1.3m^3/sec (Q_7).This survey showed that a less than bank-full discharge was c.96% RP SFT mesohabitat with small areas of other SFT mesohabitats.

2007

One survey (Survey T6) was undertaken with the River Tern in spate conditions (discharge exceedence <Q_1 at Tern Hill, 11km downstream). On site, the river had broken its bank for c. 60% of the survey length. In-channel SFT mesohabitat was predominantly RP SFT mesohabitat, with SM SFT mesohabitat occurring on the flood-plain. Water depth and velocity prevented safe access to the channel to collect data or macroinvertebrates. At the two lower discharges NP SFT mesohabitat was absent, RP SFT mesohabitat decreased with decreasing discharge, whilst UW and SM SFT mesohabitat increased. A small amount of chute SFT mesohabitat (other) occurred over a small weir constructed from a tree trunk.

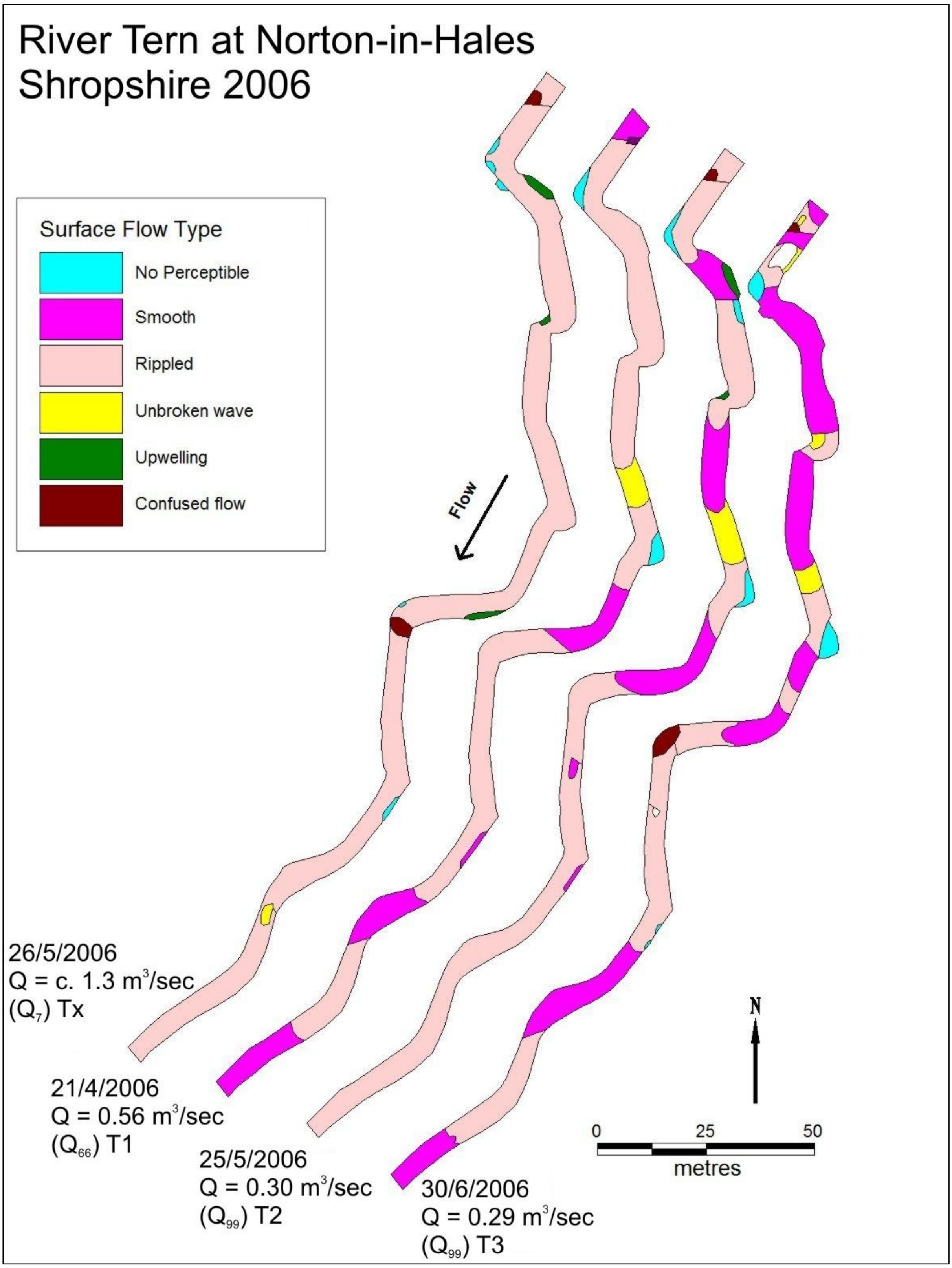


Figure 5:13 Surface Flow Type mesohabitats from four surveys of the same reach of River Tern, Shropshire during 2006. Key: T – River Tern, Q – Discharge.

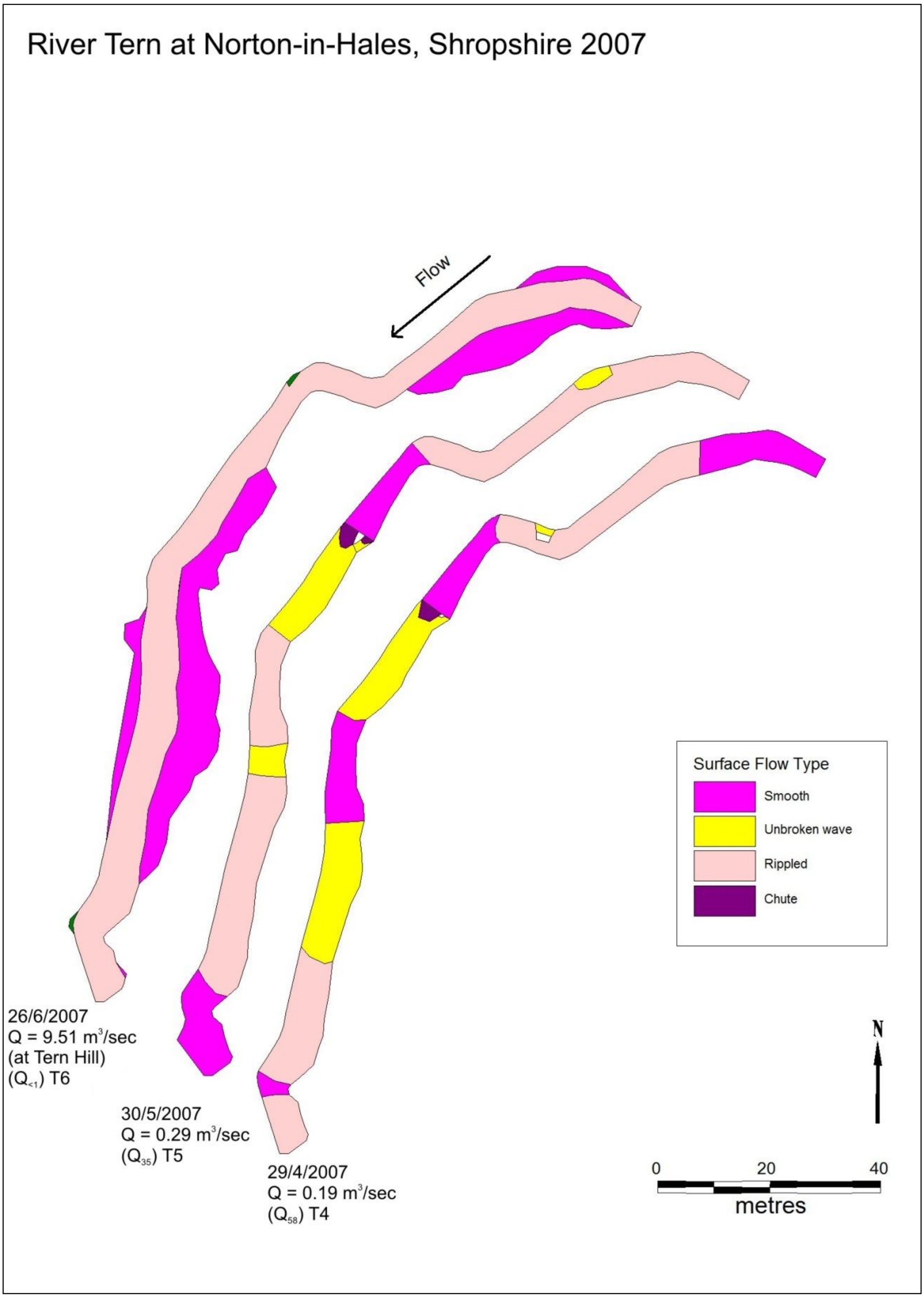


Figure 5:14 Surface Flow Type mesohabitats from three surveys of the same reach of the River Tern, Shropshire in 2007. Key: T – River Tern, Q – Discharge.

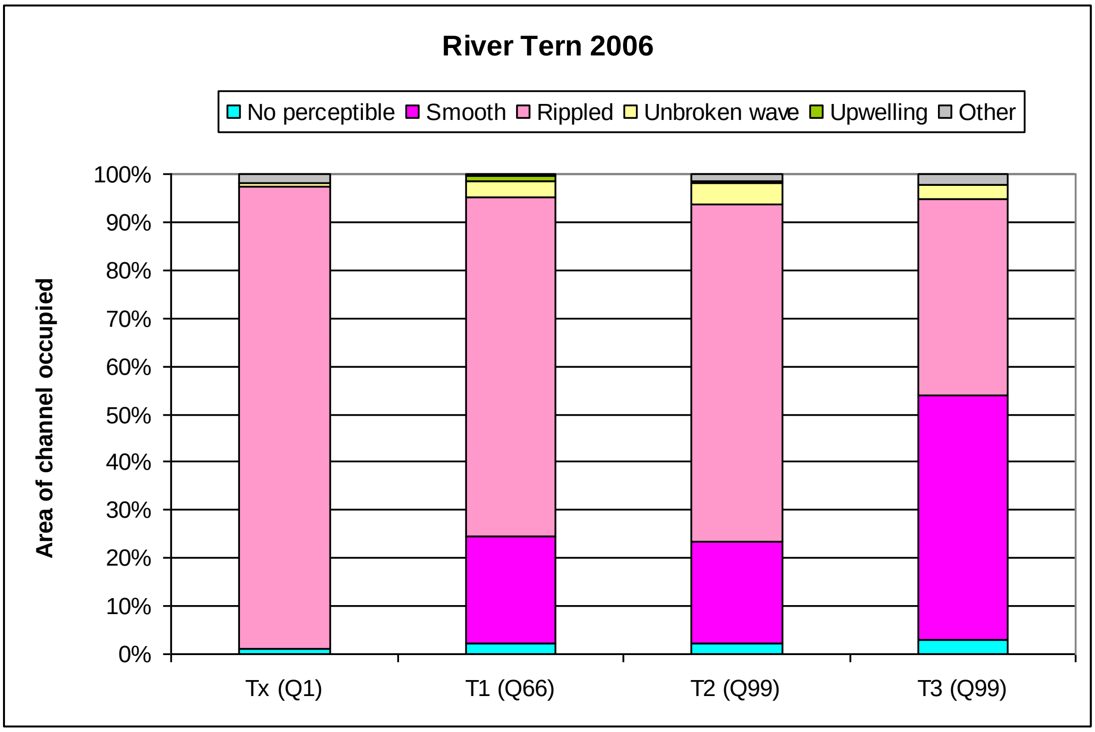


Figure 5:15 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in the River Tern, Shropshire during four surveys in 2006, data derived from SFT maps drawn by eye onto channel plan. Key: T – River Tern, Q – Discharge.

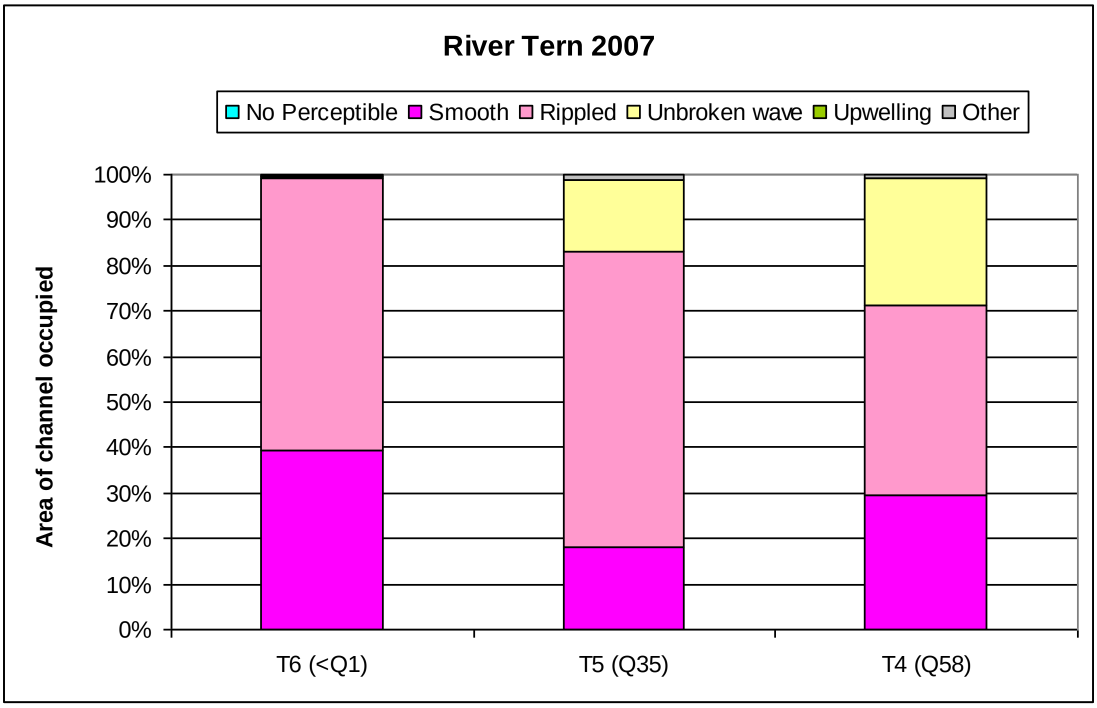


Figure 5:16 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in the River Tern, Shropshire during three surveys in 2007, data derived from SFT maps drawn by eye onto channel plan. Key: T – River Tern, Q – Discharge.

Table 5.5 Summary of Surface Flow Type mesohabitat extent, River Tern, Shropshire. Key: T – River Tern, Q – Discharge.

River Tern	**Tx**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
Q (m^3/sec)	c. 1.3	0.56	0.304	0.289	0.187	0.286	9.51
Qx	7	66	99	99	58	35	1
No. of Mesohabitat units							
No perceptible	5	2	3	4	0	0	0
Smooth	0	5	5	8	4	2	5
Rippled	2	4	5	8	3	3	1
Unbroken wave	1	1	1	4	3	4	1
Upwelling	3	0	2	0	0	0	2
Other	2	1	1	2	1	2	0
Total	13	13	17	26	11	11	9
Mesohabitat Areas (%)							
No Perceptible	1	2	2	3	0	0	0
Smooth	0	22	21	51	30	18	40
Rippled	96	71	70	41	42	65	60
Unbroken wave	1	3	5	3	28	16	1
Upwelling	0	0	1	0	0	0	0
Other	2	0	0	2	1	1	0
Total Area (m^2)	1453	1514	1507	1467	1071	1055	1772

5.3.5 Badsey Brook

2006

Surface Flow Type mesohabitat maps of Badsey Brook (Bd) are shown in Figure 5:17, stream flow is from bottom-right to top-left, and discharge is higher in the top map. Discharge range was Q_{42} – Q_{66}. Forty meso-habitats were identified; the proportions of each habitat, by area are shown in Figure 5:18 and Table 5.6 in the Surveys Bd1 and Bd3 the small area of confused SFT mesohabitat is caused by a weir. Forty SFT mesohabitats were recorded in 2006.

Rippled SFT mesohabitat reduces between Surveys Bd2 and Bd3 whilst SM and UW SFT mesohabitat increases. However, RP SFT mesohabitat decreases as discharge increases in Survey Bd1. At the lowest discharge (Survey Bd1) the slightly undulating clay bed substrate (Point A) appears to cause rippling of the water surface. Further, through the summer the channel contained increasing areas of in-stream vegetation increasing channel roughness and therefore turbulence in the water column and extending the area of RP SFT mesohabitat.

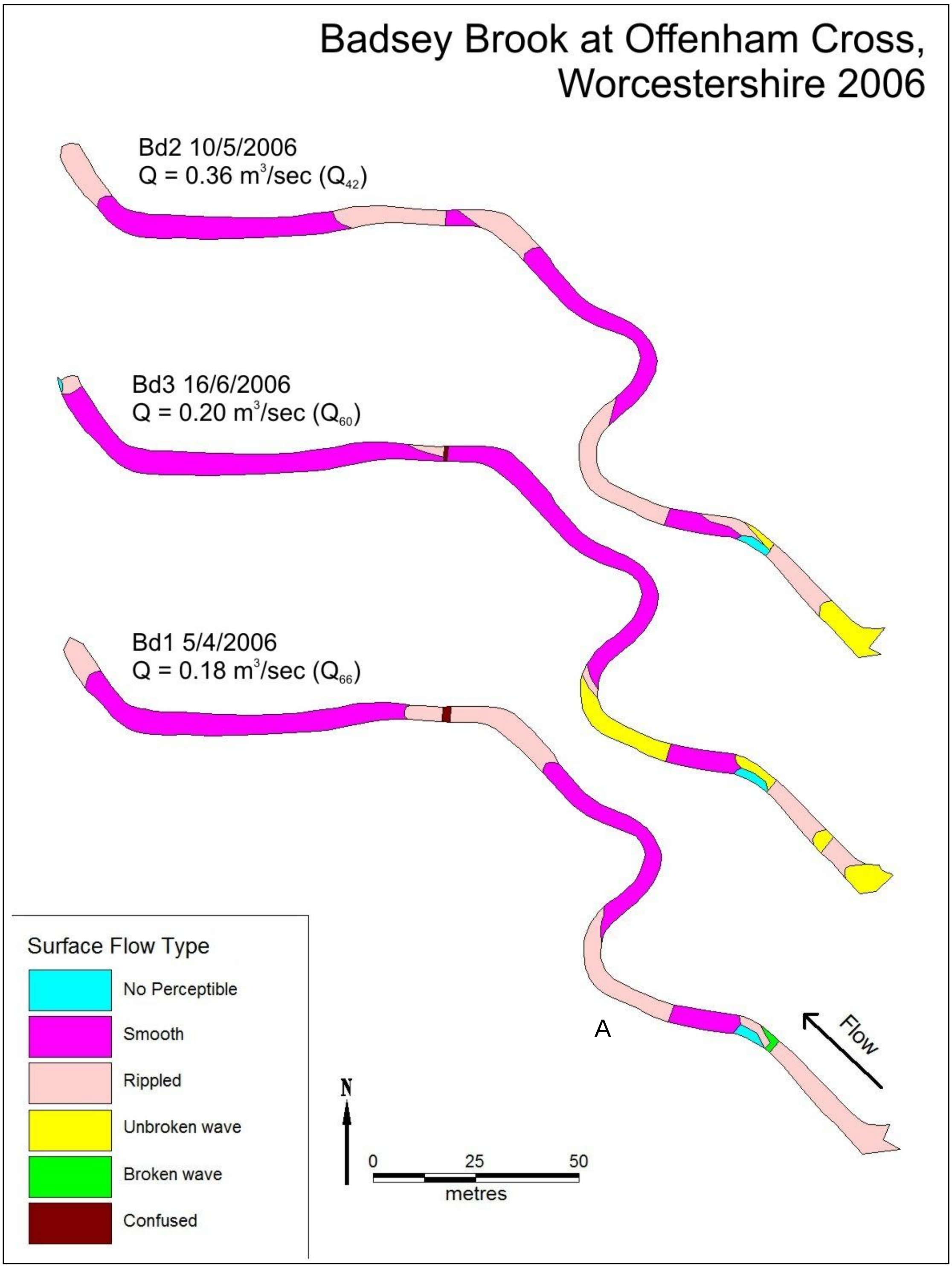


Figure 5:17 Surface Flow Type mesohabitat types from three surveys of the same reach of Badsey Brook, Worcestershire, during 2006. Key: Bd - Badsey Brook, Q – Discharge.

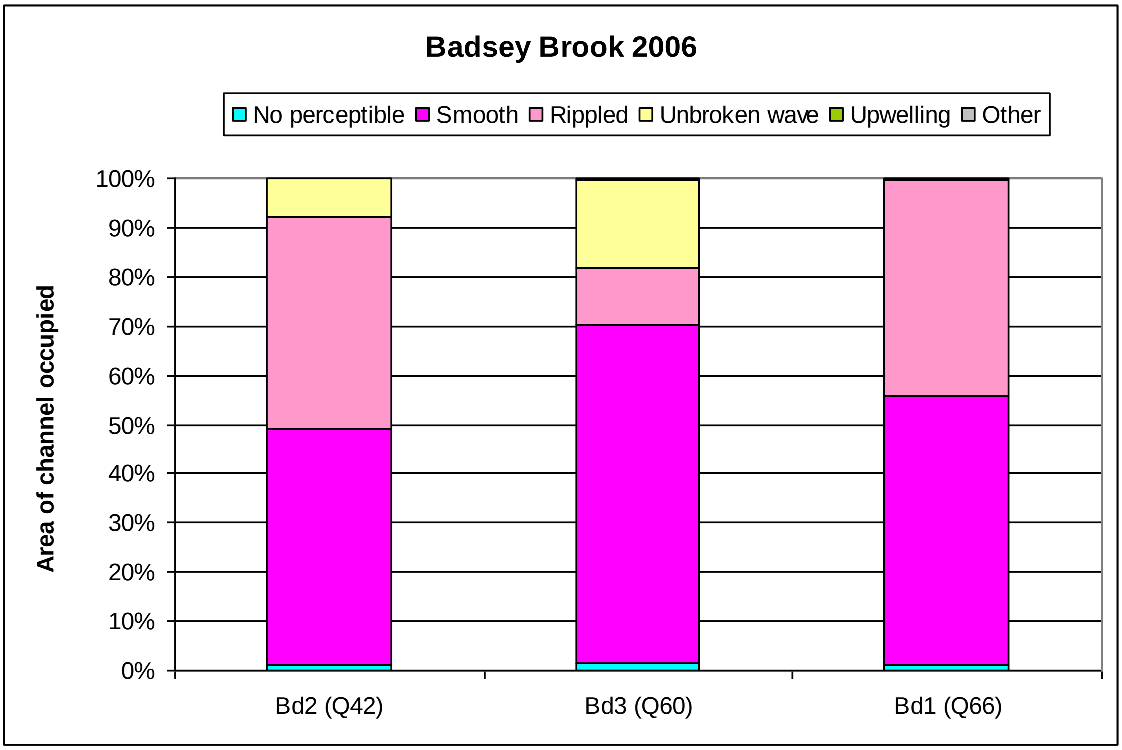


Figure 5:18 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Badsey Brook, Worcestershire during three surveys in 2006, data derived from SFT maps drawn by eye onto channel plan. Key: Bd - Badsey Brook.

Table 5.6 Summary of Surface Flow Type mesohabitat extent, Badsey Brook, Worcestershire. Key: Bd - Badsey Brook, Q – Discharge.

Badsey Brook	**Bd2**	**Bd3**	**Bd1**
Q (m^3/sec)	0.355	0.204	0.182
Qx	42	60	66
No. of Mesohabitat units			
No perceptible	1	2	1
Smooth	4	3	3
Rippled	6	5	6
Unbroken wave	2	4	0
Upwelling	0	0	0
Other	0	1	2
Total	13	15	12
Mesohabitat Areas (%)			
No Perceptible	1	1	1
Smooth	48	69	54
Rippled	43	12	44
Unbroken wave	8	18	0
Upwelling	0	0	0
Other	0	0	1
Total Area (m^2)	1281	1333	1292

5.3.6 River Leadon

2007

Surface Flow Type mesohabitat maps of the River Leadon (Ld) are shown in Figure 5:19 and stacked bar charts showing the areal proportion of SFT mesohabitat in Figure 5:20 and Table 5.7 Discharge, measured at site, ranged from 0.289m^3/sec to 0.098m^3/sec, the discharge exceedence values (Q_{30} - Q_{70}) are based on a gauging station near Gloucester and may not be representative of the site. Forty two SFT mesohabitats were recorded during 2007.

The river channel at this site contained many tree roots which trailed into the stream from the bank, and are responsible for some changes in SFT mesohabitat extent. The small amount of NP SFT mesohabitat was greatest at low discharge, and SM SFT mesohabitat decreased with increasing discharge. Unbroken wave SFT mesohabitat was small at both low and high discharges although there is an increase in the mid-discharge (Survey 4Ld). This was likely to be the result of trailing tree roots. However, if the turbulent SFT mesohabitats (RP and UW) are considered together, there is an increase in area as discharge increases. There were only small amounts of UP SFT mesohabitat and other SFT mesohabitats recorded.

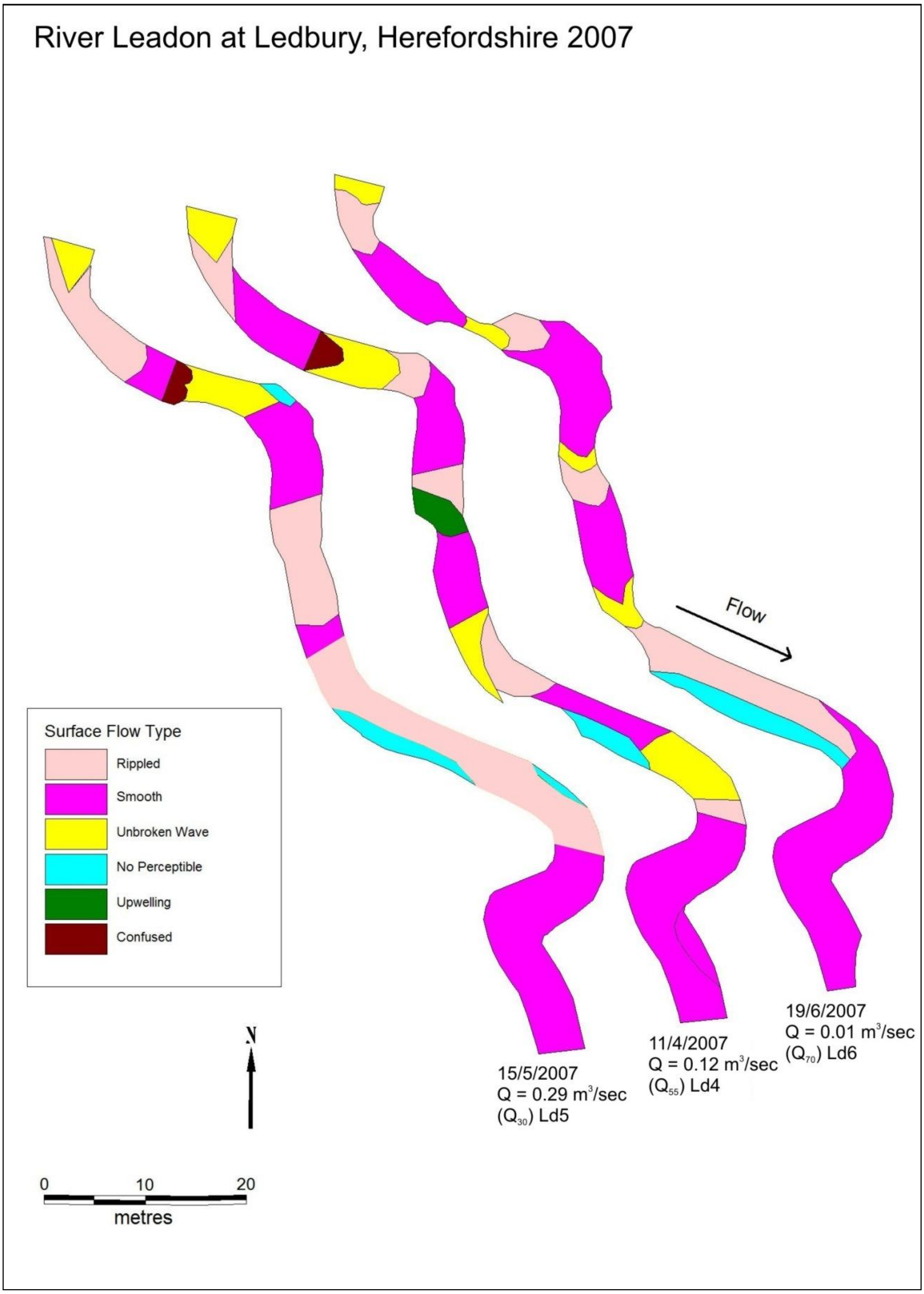


Figure 5:19 Surface Flow Type mesohabitats from three surveys of the same reach of the River Leadon, Herefordshire in 2007. Key: Ld – River Leadon, Q – Discharge.

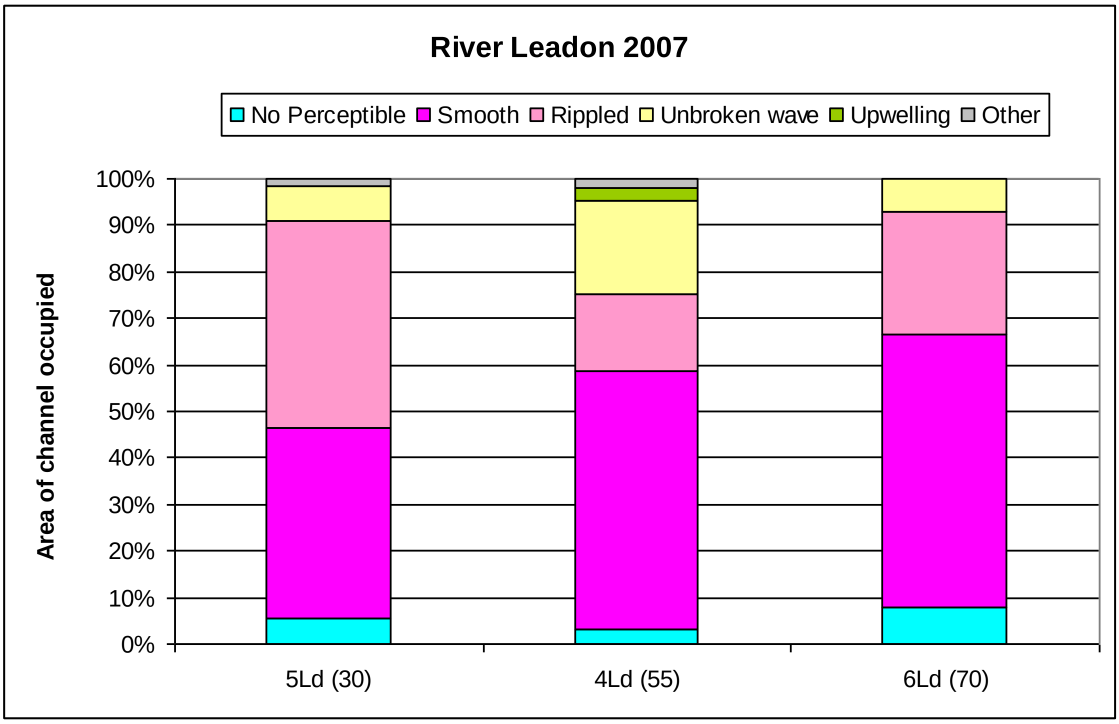


Figure 5:20 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in the River Leadon, Herefordshire during three surveys in 2007, data derived from SFT maps drawn by eye onto channel plan. Key: Ld – River Leadon.

Table 5.7 Summary of Surface Flow Type mesohabitat extent, River Leadon, Herefordshire. Key: Ld – River Leadon, Q – Discharge.

River Leadon	Ld4	Ld5	Ld6
Q (m^3/sec)	0.124	0.286	0.098
Qx	55	30	70
No. of Mesohabitat units			
No perceptible	1	3	1
Smooth	6	4	4
Rippled	5	2	4
Unbroken wave	4	1	4
Upwelling	1	0	0
Other	1	1	0
Total	18	11	13
Mesohabitat Areas (%)			
No Perceptible	3	5	8
Smooth	56	41	59
Rippled	16	44	26
Unbroken wave	20	8	7
Upwelling	3	0	0
Other	2	2	0
Total Area (m^2)	469	484	435

5.3.7 Hadley Brook

2007

Surface Flow Type mesohabitat maps of Hadley Brook (Hd) are shown in Figure 5:21 and stacked bar charts showing the areal proportion of SFT mesohabitat in Figure 5:22 and Table 1.1. Thirty three SFT mesohabitats were mapped over three surveys.

The small proportion of NP SFT mesohabitat area increased slightly at middle discharge (Hd6) due to the eddying effect of flow diagonally across the channel, RP SFT mesohabitat decreased with decreasing discharge whilst SM SFT mesohabitat increased. Unbroken wave SFT mesohabitat increased with decreasing discharge as the water surface was influenced more by the river bed in shallower areas.

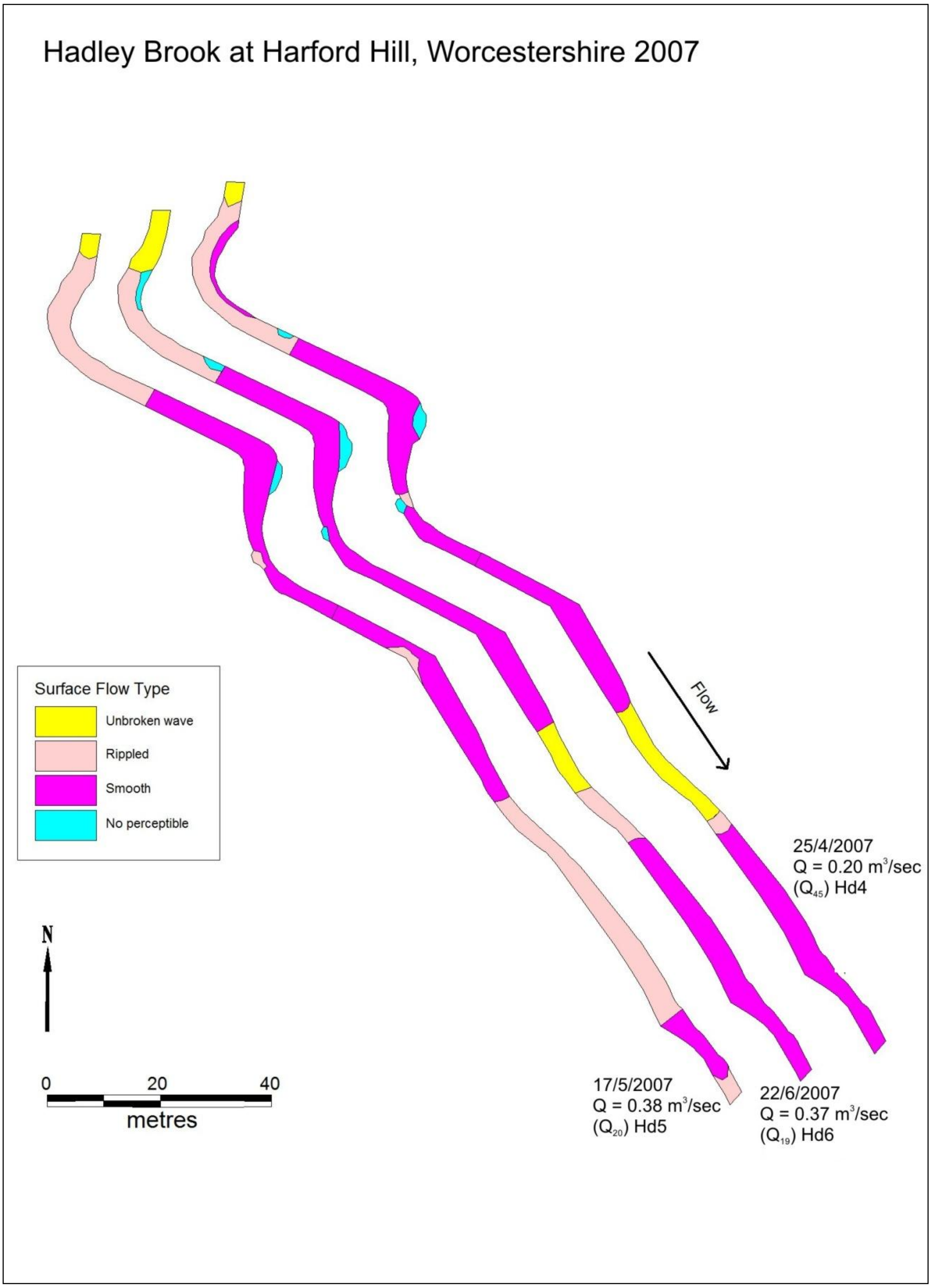


Figure 5:21 Surface Flow Type mesohabitats from three surveys of the same reach of Hadley Brook, Worcestershire in 2007. Key: Hd – Hadley brook, Q – Discharge.

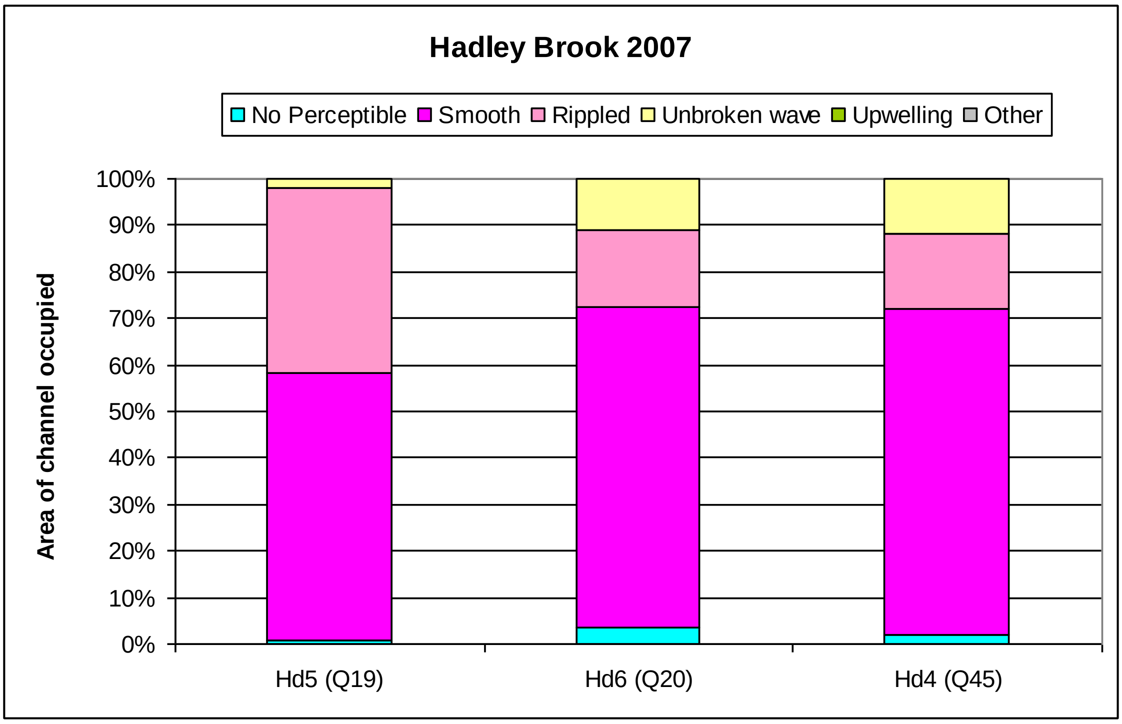


Figure 5:22 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Hadley Brook, Worcestershire during three surveys in 2007, data derived from SFT maps drawn by eye onto channel plan. Key: Hd – Hadley brook.

Table 5.8 Summary of SFT mesohabitat extent, Hadley Brook, Worcestershire. Key: Hd – Hadley Brook, Q – Discharge.

Hadley Brook	**Hd4**	**Hd5**	**Hd6**
Q (m^3/sec)	0.20	0.38	0.37
Qx	45	20	19
No. of Mesohabitat units			
No perceptible	3	1	4
Smooth	5	3	2
Rippled	3	5	2
Unbroken wave	2	1	2
Upwelling	0	0	0
Other	0	0	0
Total	13	10	10
Mesohabitat Areas (%)			
No Perceptible	2	1	4
Smooth	70	57	69
Rippled	16	40	17
Unbroken wave	12	2	11
Upwelling	0	0	0
Other	0	0	0
Total Area (m^2)	730	672	728

5.3.8 Dowles Brook

2006

Surface Flow Type mesohabitat maps of Dowles Brook (D) are shown in Figure 5:23; stream flow from left to right, discharge lowering from top to bottom. Discharge variation recorded during three surveys is shown in Figure 5:24 and Table 5.9 discharge exceedence ranges Q_{36} – Q_{60}.

Fifty-eight SFT mesohabitats were mapped. As discharge decreases, bed morphology has more influence on SFTs, proportions of turbulent flow (UW and RP SFT mesohabitats) decreases as laminar flow (SM and NP SFT mesohabitats) increase. Here, in addition to bed controls, an accumulation of coarse woody debris deflected flow directly below point A, causing a mid-channel bar to form and influence the SFT directly downstream.

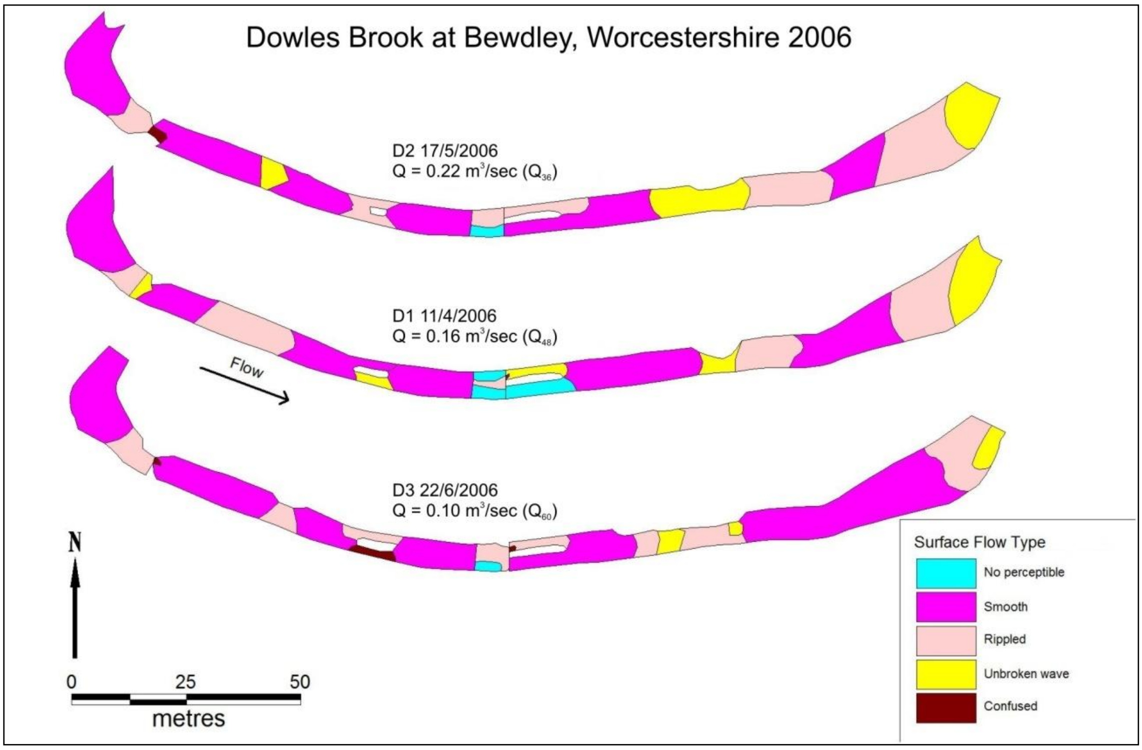


Figure 5:23 Surface Flow Type mesohabitats from three surveys of the same reach of Dowles Brook, Worcestershire during 2006. Key: D – Dowles Brook, Q – Discharge.

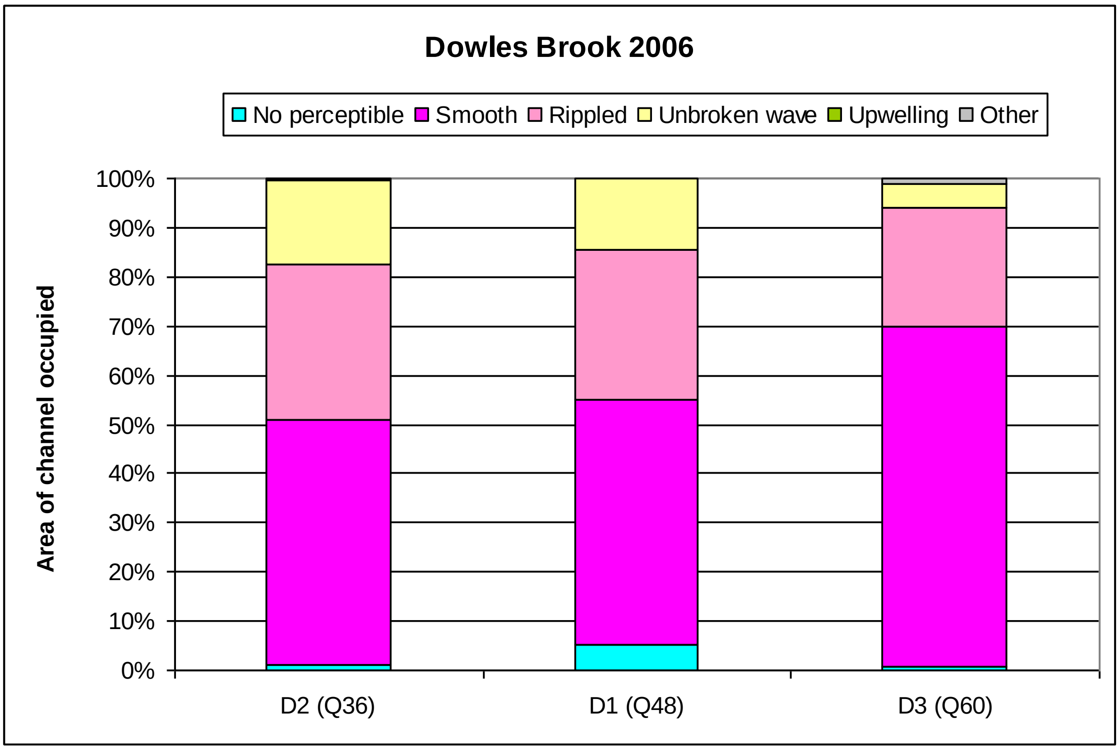


Figure 5:24 Relative proportions of the channel occupied by Surface Flow Type mesohabitats in Dowles Brook, Worcestershire during three surveys in 2006, data derived from SFT maps drawn by eye onto channel plan. Key: D – Dowles Brook.

Table 5.9 Summary of Surface Flow Type mesohabitat extent, Dowles Brook. Key: D – Dowles Brook, Q – Discharge.

Dowles Brook	D2	D1	D3
Q (m^3/sec)	0.216	0.162	0.101
Q_x	36	48	60
No. of Mesohabitat units			
No perceptible	1	3	1
Smooth	6	6	6
Rippled	6	5	8
Unbroken wave	3	5	3
Upwelling	0	0	0
Other	1	1	3
Total	17	20	21
Mesohabitat Areas (%)			
No Perceptible	1	5	1
Smooth	50	50	69
Rippled	32	30	24
Unbroken wave	17	15	5
Upwelling	0	0	0
Other	8.16	0	19.12
Total Area (m^2)	1573.52	1450.45	1524.42

5.3.9 Discharge during Surveys

A wide range of Q_x values was recorded, ranging from of $Q_{0.5}$ to of Q_{99}. In 2006 mean Q_x was 50.75 whilst in 2007mean Q_x was 45.84, suggesting that discharge was generally higher in 2007, although the differences are not statistically significant (Mann-Whitney *U* test P = 0.694). Whilst the mean Q_x value is similar in 2006 and 2007, the 25th - 75th% tile range is skewed towards higher discharge in 2007 (Figure 5:25). Therefore, although the summer of 2007 was wetter than the same period in 2006, the differences in discharge are not significant and valid comparisons can be made between the two datasets.

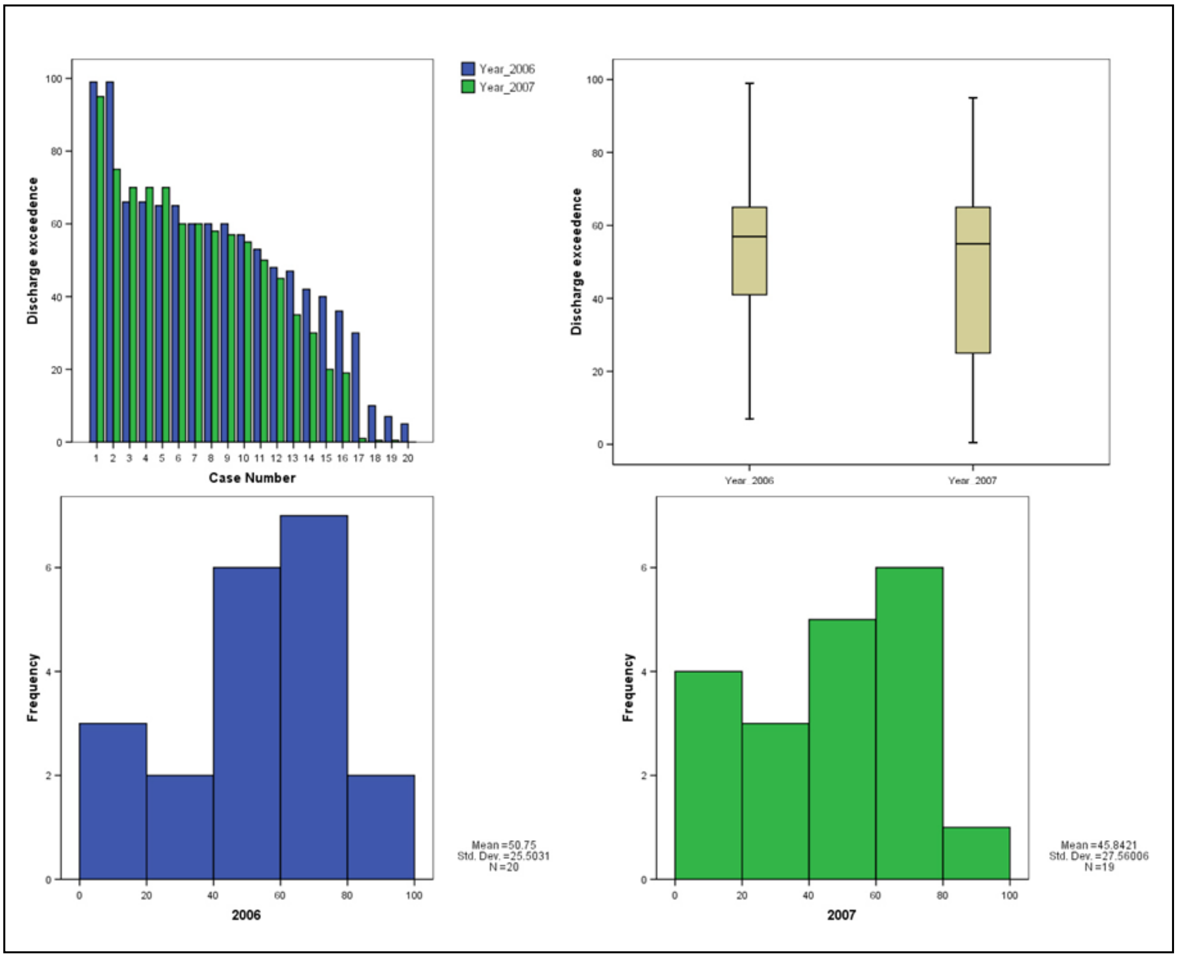


Figure 5:25 Discharge exceedence (2006:2007) across all surveys undertaken in eight British lowland rivers.

5.3.10 Relationship between Surface Flow Type Extent and Discharge

Surface Flow Type area extent varies with discharge and the nature of the relationship between the two is important. Surface Flow Type mesohabitats are influenced by geomorphic and hydraulic conditions, but are they influenced by hydrological conditions? If they are then changes in SFT mesohabitat area at different discharges, as water depth changes, might be expected. From field observations it was apparent at very high (spate) discharges that RP SFT mesohabitat dominated. In some cases (Leigh Brook, 2006) the extent of UW SFT mesohabitat expanded as discharge lowered allowing it to be more influenced by bed roughness. Smooth and RP SFT mesohabitats appear to have an inverse relationship, in that as discharge increases the proportion of SM SFT mesohabitat decreases as the proportion of RP SFT mesohabitat increases.

Figure 5:26 shows the relationship between the area of each SFT mesohabitat type, as a percentage of channel area, at a range of discharges and for each SFT mesohabitat in each of 2006 and 2007, NP SFT mesohabitat accounted for <15% of channel area and varied little with discharge. Leigh Brook (2007) showed an increase of NP SFT mesohabitat from 2 – 14% at Q_{57}, falling to 1% at Q_{70} and Q_{75} caused by two areas of eddy flow which were replaced with RP SFT mesohabitat at Q_1. Smooth SFT mesohabitat is more common than NP SFT mesohabitat, generally decreasing with increased discharge. In 2006 macrophyte growth in Badsey Brook, Bailey Brook and the River Tern was the most likely reason for the reduction in the extent of SM SFT mesohabitat at low discharge. In 2007 the high proportion of SM SFT mesohabitat in the River Tern at Q_1 resulted from floodplain inundation. Rippled SFT mesohabitat is also common, generally increasing with discharge; in 2006 increases at lower discharges are most likely due to increased macrophyte growth in Badsey Brook and the River Tern. Unbroken wave SFT mesohabitat is less common than SM or RP SFT mesohabitats. Behaviour is more variable than other SFT mesohabitats, in Leigh Brook (2006) a clear decrease in area of UW SFT mesohabitat with decreasing discharge is evident, whilst in Badsey Brook the peak is at an intermediate discharge – probably due to the harmonic influence of an undulating clay bed exaggerating ripples. Upwelling SFT mesohabitat is rare; in Bailey Brook (2007) small areas occurred in spate conditions at the channel edge.

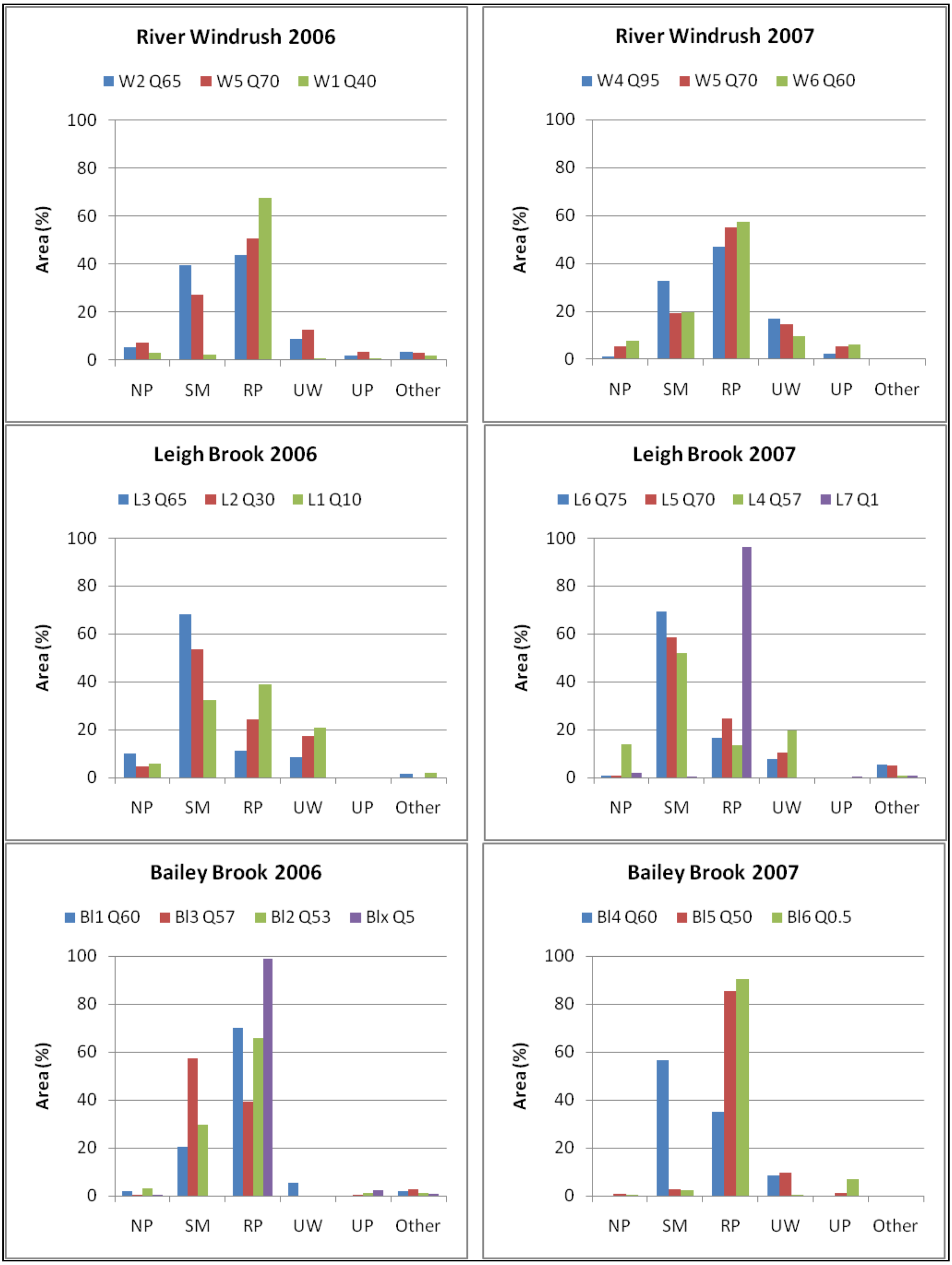


Figure 5:26 Graphs showing the changes in areal proportion (%) of surface flow type area by discharge exceedence (Q_x) in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

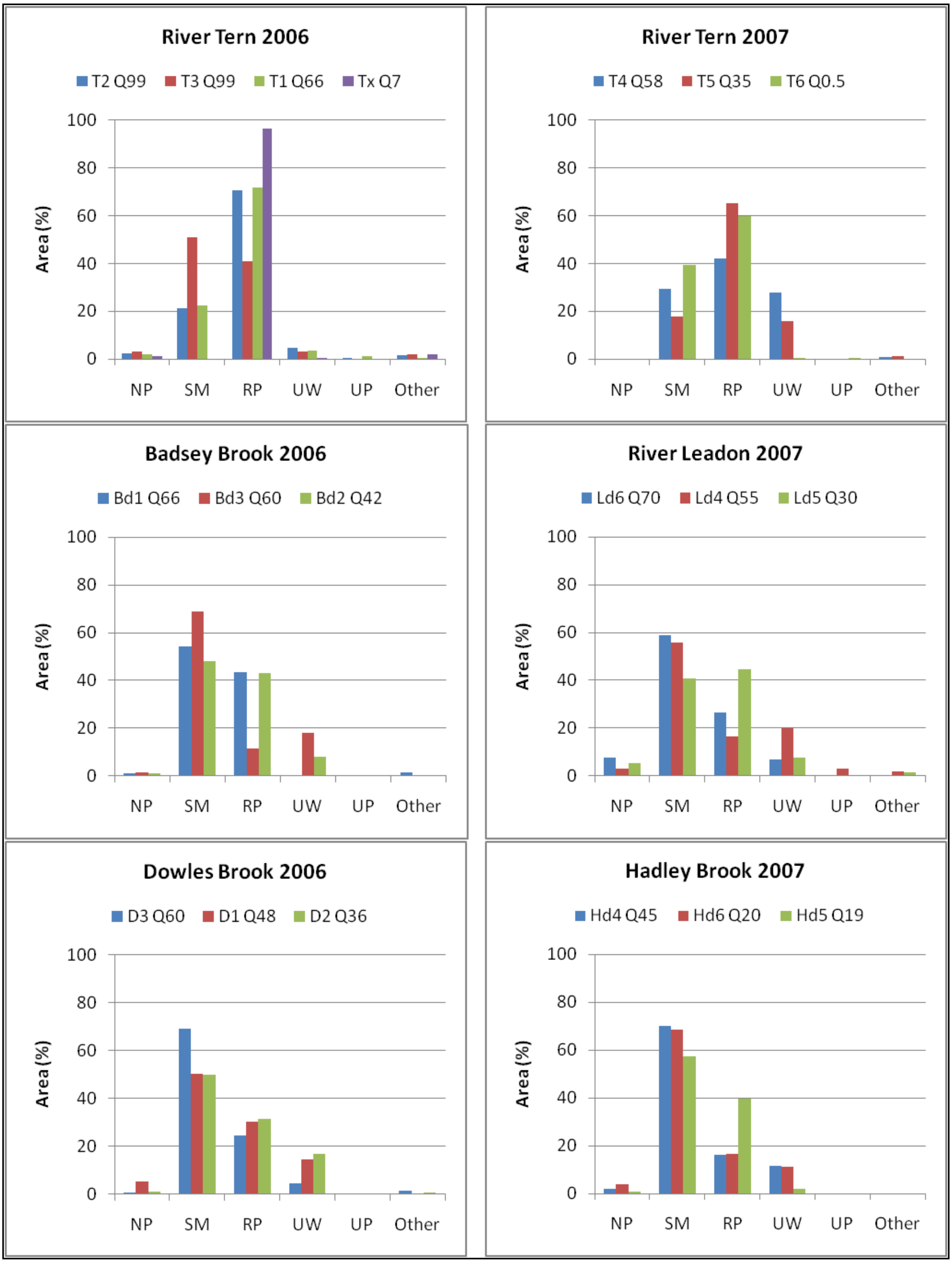


Figure 5:26 (cont) Graphs showing the changes in areal proportion (%) of surface flow type area by discharge exceedence (Q_x) in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Figure 5:27 Shows scatter plots of surface area percentage plotted against discharge exceedence for all surveys in both 2006 and 2007 combined. Note that the scale of the *y*-axis is variable. The scatter of points indicates that there is a complex relationship between discharge and SFT mesohabitat area which is driven by local conditions, for example, bed morphology.

Overall there appears to be no significant pattern to be present in the data for any SFT, with a wide range of scatter across all discharges. However there are some trends in the same data when grouped by flashiness characteristics. Flashy here relates to the five streams with the lowest BFI values (Badsey, Hadley, Dowles and Leigh Brooks and River Leadon) and stable to the three with the highest BFI values (Bailey Brook, Rivers Tern and Windrush). There is little difference between flashy and stable regimes in NP, UW and UP SFTs; however in SM SFT streams with a flashy regime have a greater proportion of surface area than do those in stable regimes, with the reverse being the case for RP SFTs.

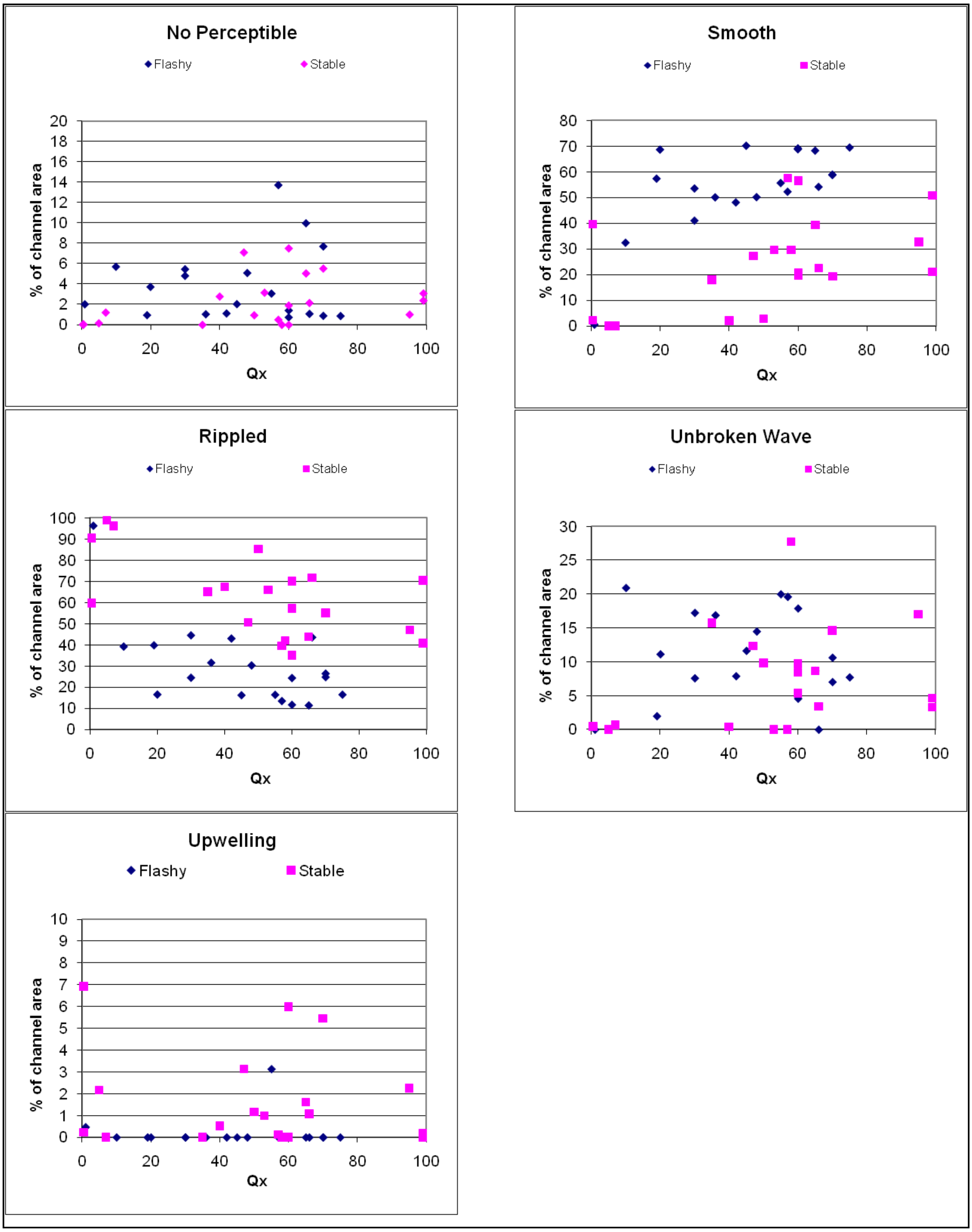


Figure 5:27 Comparisons between SFT extent and discharge exceedence showing the relationship between channel area and discharge exceedence recorded in five Surface Flow Types identified during surveys of eight British lowland rivers in 2006 and 2007, coded to show flashy and stable hydrological regimes. Key: Q_x – discharge exceedence.

In NP SFT mesohabitat, there is little difference between flashy and stable systems, whilst in SM SFT mesohabitat there is greater disparity and better fit in both flashy and stable regimes. Flashy regimes support greater areas of SM SFT mesohabitat than do stable regimes although in both cases there is an increase in area with decreasing discharge. In flashy regimes there is less RP SFT mesohabitat than in stable regimes, and there is a decline with declining discharge. Unbroken wave SFT mesohabitat peaks at intermediate discharges, although flashy regimes peak earlier than do stable regimes. Upwelling SFT mesohabitat is more numerous in stable regimes, with twin peaks, at spate and Q_{80} discharges.

The analyses of the relationship between Surface Flow Type extent and discharge show that:

- The area of the five Surface Flow Type mesohabitats varies with discharge.
- There was no significant difference between stream discharges in 2006 and 2007 although mean discharge in 2007 was marginally higher than in 2006.
- Rippled Flow Type mesohabitats increased in area as discharge increased whilst less energetic Surface Flow Type mesohabitats (NP, SM) decreased in area as discharge increased.
- Unbroken wave Surface Low Type mesohabitat peaks at intermediate discharge.
- Rippled Surface Flow Type mesohabitat occupies almost the entire channel at spate discharge.
- Low energy Surface Flow Type mesohabitats (NP, SM) are present at channel margins during high discharge.
- The reaction of Surface Flow Type mesohabitat extents to changes in discharge in flashy or stable systems is complex.
- Smooth Surface Flow Type mesohabitat occurs on inundated floodplain when the river has burst its banks.

5.3.11 Water Quality

Although there are differences between the rankings of the EA biological water quality grade and the surveyed BMWP and ASPT grades, none of those grades falls below C grade (fairly good), and five of the eight rivers investigated score at least one A grade (very good). BMWP scores (Figure 5:28) were calculated from macroinvertebrate samples collected during surveys. The box shows the extent of the 25th and 75th percentiles, the central line is the median. Whiskers attached to each box show the data range. ‘O’ indicates outliers which are between 1.5 and 3 inter-quartile range (IQR) from the end of the box and '*' indicates extreme values which are >3 IQRs from the end of the box. The IQR is the difference between the 75th and 25th percentiles and corresponds to the length of the box (SPSS, 2005). The figures within (or adjacent to) the box show the value of the mean. This dataset is derived from the three, one-minute kick samples which do not fully comply with the BMWP sampling protocol; nevertheless they provide a comparison between sites.

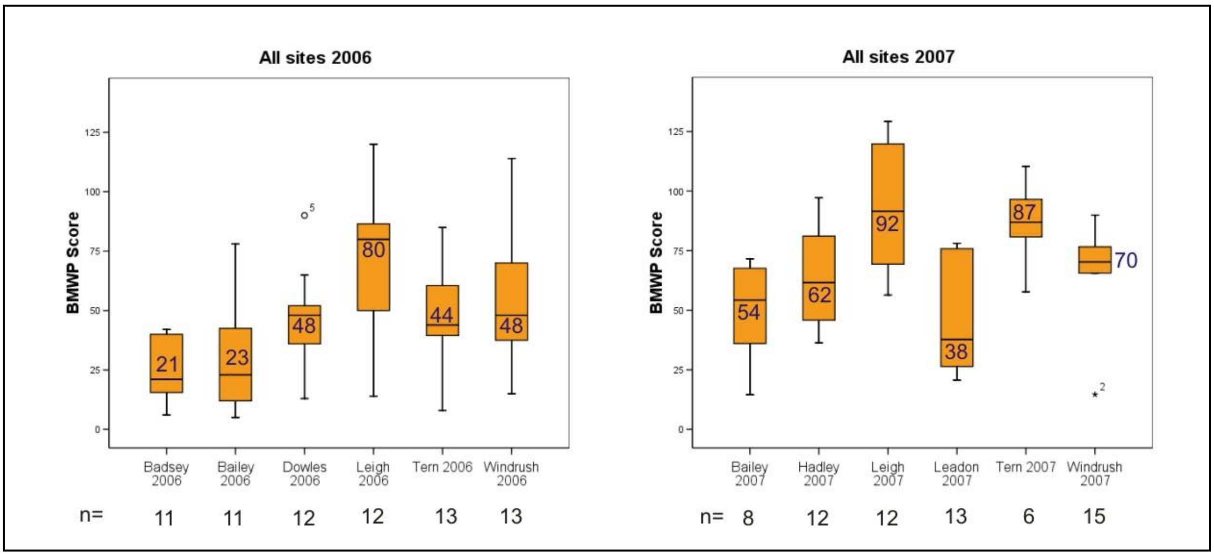


Figure 5:28 Water quality in eight British lowland rivers surveyed during 2006 and 2007 compared using mean Biological Monitoring Working Party scores, (n= the number of SFT mesohabitats from which samples were obtained).

5.4 Depth and Velocity

5.4.1 Range of Depth and Velocity Values in Surface Flow Types

Depth and mean column velocity were recorded at 1 457 data points in 323 SFT mesohabitats during 2006, and from 878 data points in 234 SFT mesohabitats in 2007. The range of values recorded is shown in Table 5.10. Data were recorded from five points in each SFT mesohabitat identified although in a small number of cases small area or excessive depth prevented five sets being collected.

Table 5.10 Depth and mean column velocity data recorded from 1 457 points in six British lowland rivers during 2006. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Depth (m) - 2006	**NP**	**SM**	**RP**	**UW**	**UP**
n =	140	461	584	244	28
Mean	0.51	0.42	0.26	0.19	0.64
Minimum	0.08	0.04	0.04	0.03	0.25
Maximum	1.50	1.20	0.96	0.70	1.10
Range	1.42	1.16	0.92	0.67	0.85
Velocity (m/s) - 2006	**NP**	**SM**	**RP**	**UW**	**UP**
n =	140	461	584	244	28
Mean	-0.03	0.24	0.27	0.53	0.28
Minimum	-0.30	-0.03	-0.09	-0.04	-0.12
Maximum	0.22	0.87	0.94	1.25	0.61
Range	0.52	0.90	1.03	1.29	0.74
Depth (m) - 2007	**NP**	**SM**	**RP**	**UW**	**UP**
n =	77	296	294	187	24
Mean	0.65	0.48	0.43	0.24	0.19
Minimum	0.14	0.08	0.04	0.03	0.00
Maximum	1.60	1.25	1.40	0.90	1.30
Range	1.46	1.17	1.36	0.87	1.30
Velocity (m/s) - 2007	**NP**	**SM**	**RP**	**UW**	**UP**
n =	77	296	294	187	24
Mean	-0.026	0.236	0.337	0.557	0.039
Minimum	-0.363	-0.159	-0.149	-0.045	-0.325
Maximum	0.233	0.777	1.113	1.427	0.574
Range	0.596	0.936	1.262	1.472	0.899

Surface Flow Type mesohabitat water depth is shown as box and whisker plots in Figure 5:29. In both 2006 and 2007 datasets mean depth decreases from UP > NP > SM > RP > UW. Mean depth and 25 – 75%ile range between 2006 and 2007 data shows that broadly 2007 sites were deeper and RP SFT mesohabitats slightly more so. This is likely to be due to higher discharges during the 2007 survey season.

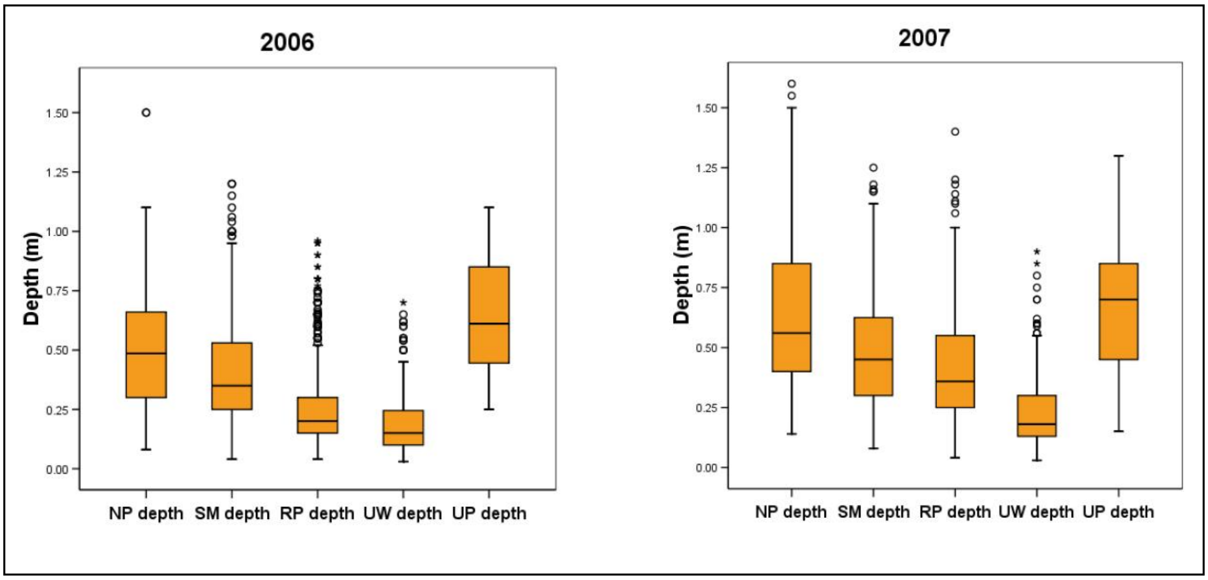


Figure 5:29 Water depth of Surface Flow Type mesohabitats recorded in surveys undertaken in 2006 and 2007 in eight British lowland rivers. Star and circle symbols represent extreme and outlier values respectively. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Histograms of water depth recorded at each of the data collection points in each SFT mesohabitat surveyed in 2006 and 2007 are shown in Figure 5:30. Depth classes are skewed to the right (deeper) in NP, SM, RP and UW SFT mesohabitats whilst UP SFT mesohabitats are normally distributed. Although sites surveyed in 2006 differed from those surveyed in 2007, and the number of samples in 2007 was lower than in 2006, broadly similar frequencies are observed in both years. The observed range of depths differs between SFT mesohabitats.

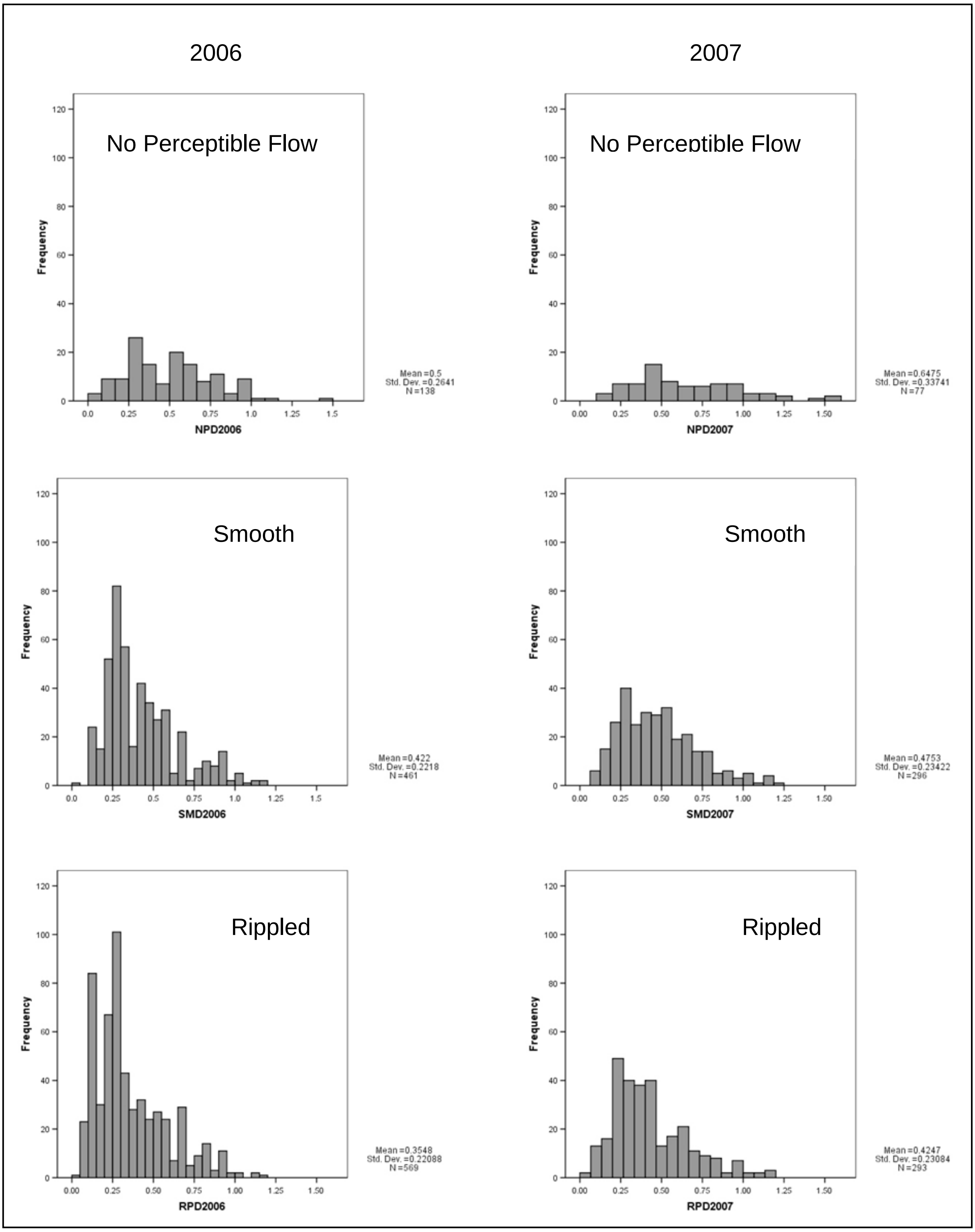


Figure 5:30 Water depth frequencies recorded in Surface Flow Type mesohabitats recorded in surveys undertaken in 2006 and 2007 in eight British lowland rivers.

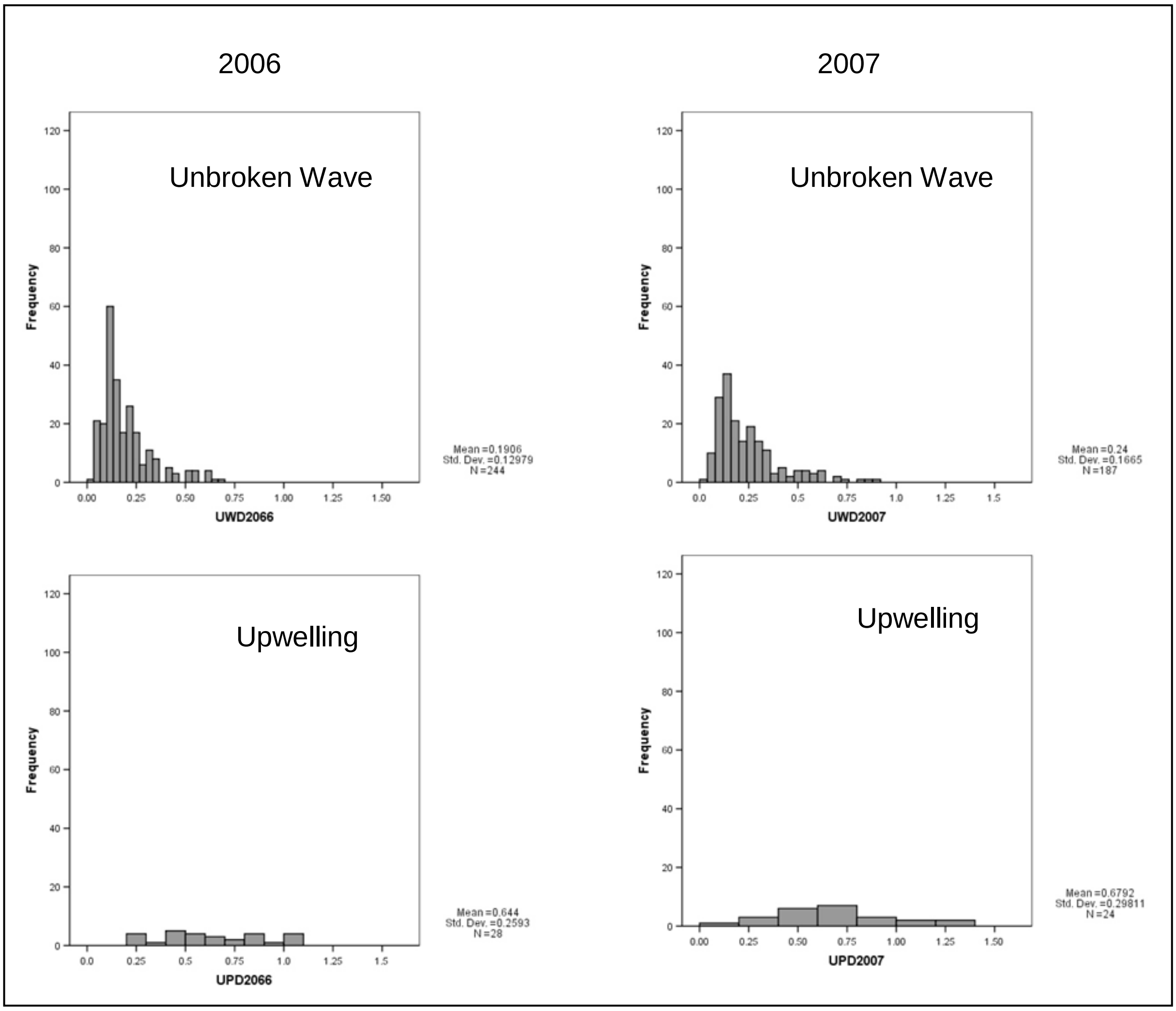


Figure 5:30 (cont) Water depth frequencies recorded in Surface Flow Type mesohabitats recorded in surveys undertaken in 2006 and 2007 in eight British lowland rivers.

Skewness and Kurtosis values from depth data recorded in SFT mesohabitats during surveys undertaken in 2006 and 2007 are shown in Table 5.11. All data are skewed to the left. Values range from 0.256 to 1.634 indicating that these data are not normally distributed. All SFT mesohabitats, except UP, are leptokurtic, with more observations close to the mean and the tails (Dytham, 1999). Upwelling SFT mesohabitat is platykurtic with more observations in the 'shoulders': UP is rare, and therefore there are fewer depth data.

Table 5.11 Skewness and Kurtosis values from depth data recorded in Surface Flow Type mesohabitats during surveys undertaken in 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Surface Flow Type	Depth			
	Skewness 2006	**Skewness 2007**	**Kurtosis 2006**	**Kurtosis 2007**
NP	0.655	0.796	0.394	0.285
SM	1.106	0.765	0.841	0.339
RP	1.040	0.998	0.558	0.751
UW	1.634	1.589	2.660	2.565
UP	0.256	0.411	-0.930	-0.202

Mean column velocity was recorded at 0.6 depth, the range of values is shown in Figure 5:31. Mean column velocity increases from: NP > SM > RP > UP > UW in 2006; and NP > UP > SM > RP > UW in 2007.

In 2006 mean column velocity in UP SFT mesohabitats recorded in surveys undertaken in 2006 and 2007 in eight British Lowland rivers ranked between RP and UW SFT mesohabitats, in 2007 it was ranked between NP and SM SFT mesohabitats. Upwelling SFT mesohabitat has a greater vertical velocity component than other SFT mesohabitat, and whilst the overall column velocity may be similar between the two years, the downstream component was lower in 2007. Velocity in all SFT mesohabitats showed a greater range in 2007 compared to 2006 data. Whilst this may be site specific, it is also likely to reflect the higher discharges during 2007.

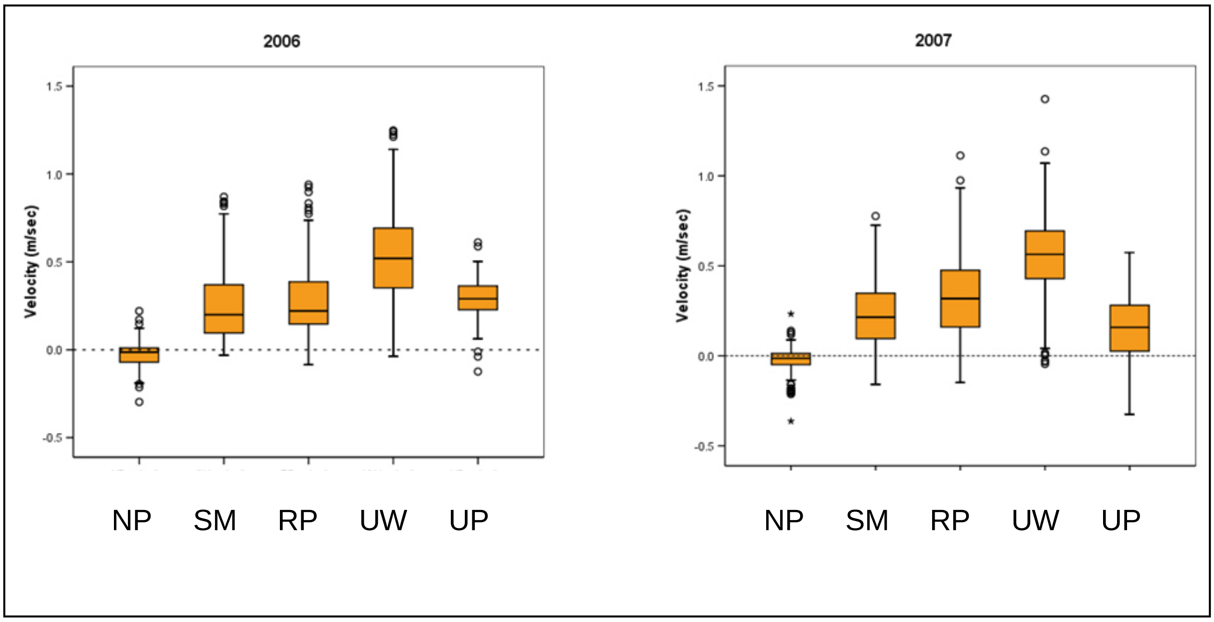


Figure 5:31 Mean column velocity recorded in Surface Flow Type mesohabitats during surveys undertaken in 2006 and 2007 in eight British lowland rivers. Circle symbols represent outlier values. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Histograms of mean column velocities recorded in 2006 and 2007 are shown in Figure 5:32. Data ranges are similar between the two years, although fewer data were obtained during 2007. Velocity data are skewed to both left and right, NP and UP SFT mesohabitat data are both left skewed, SM and RP right skewed whilst UW is right skewed in 2006 and left in 2007, the skewness ranges from -0.772 to 2.416. RP SFT mesohabitat is slightly platykurtic whilst all other SFT mesohabitat data are leptokurtic (Table 5.12).

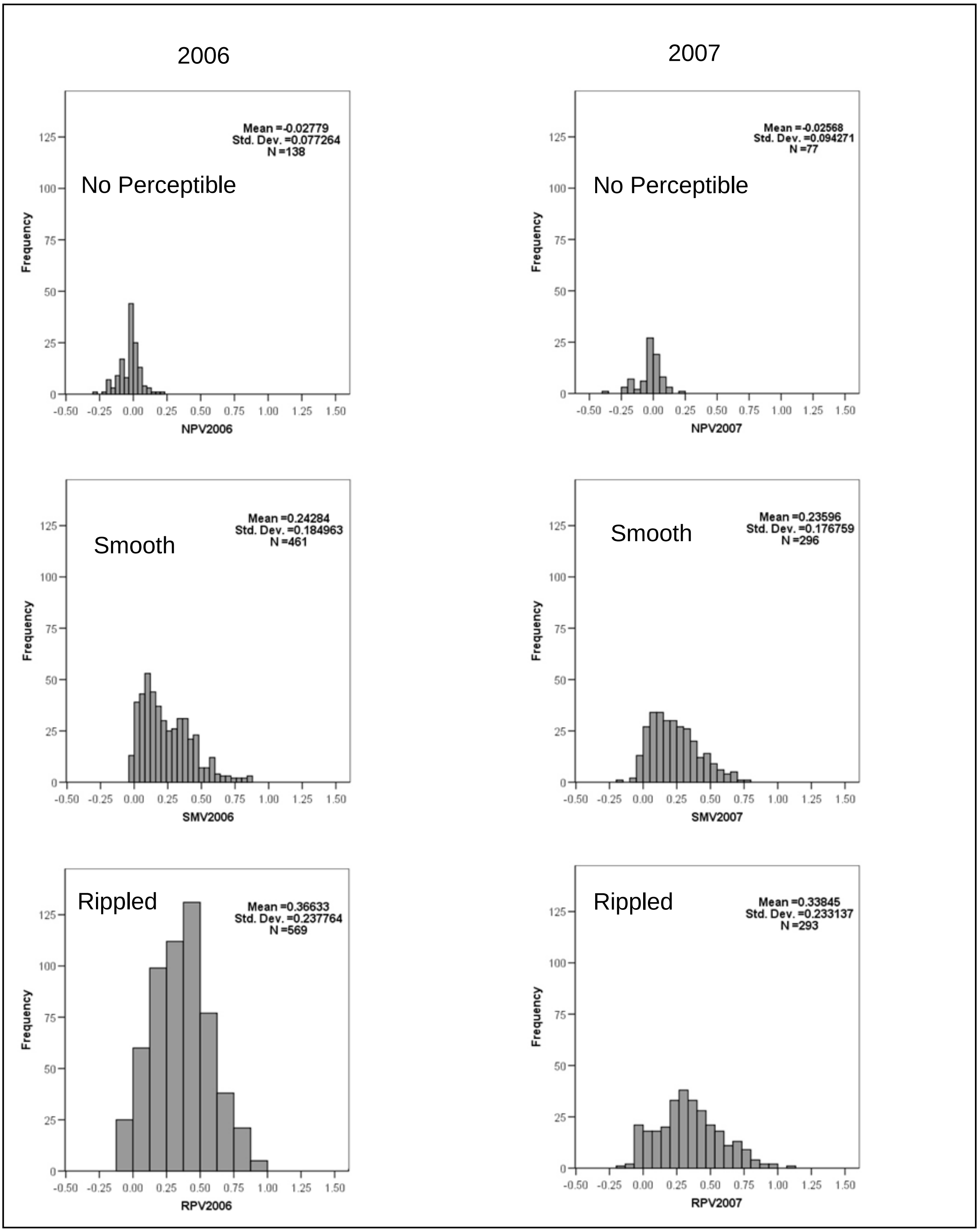


Figure 5:32 Mean column velocity frequencies recorded in Surface Flow Type mesohabitats during surveys undertaken in 2006 and 2007 in eight British lowland rivers.

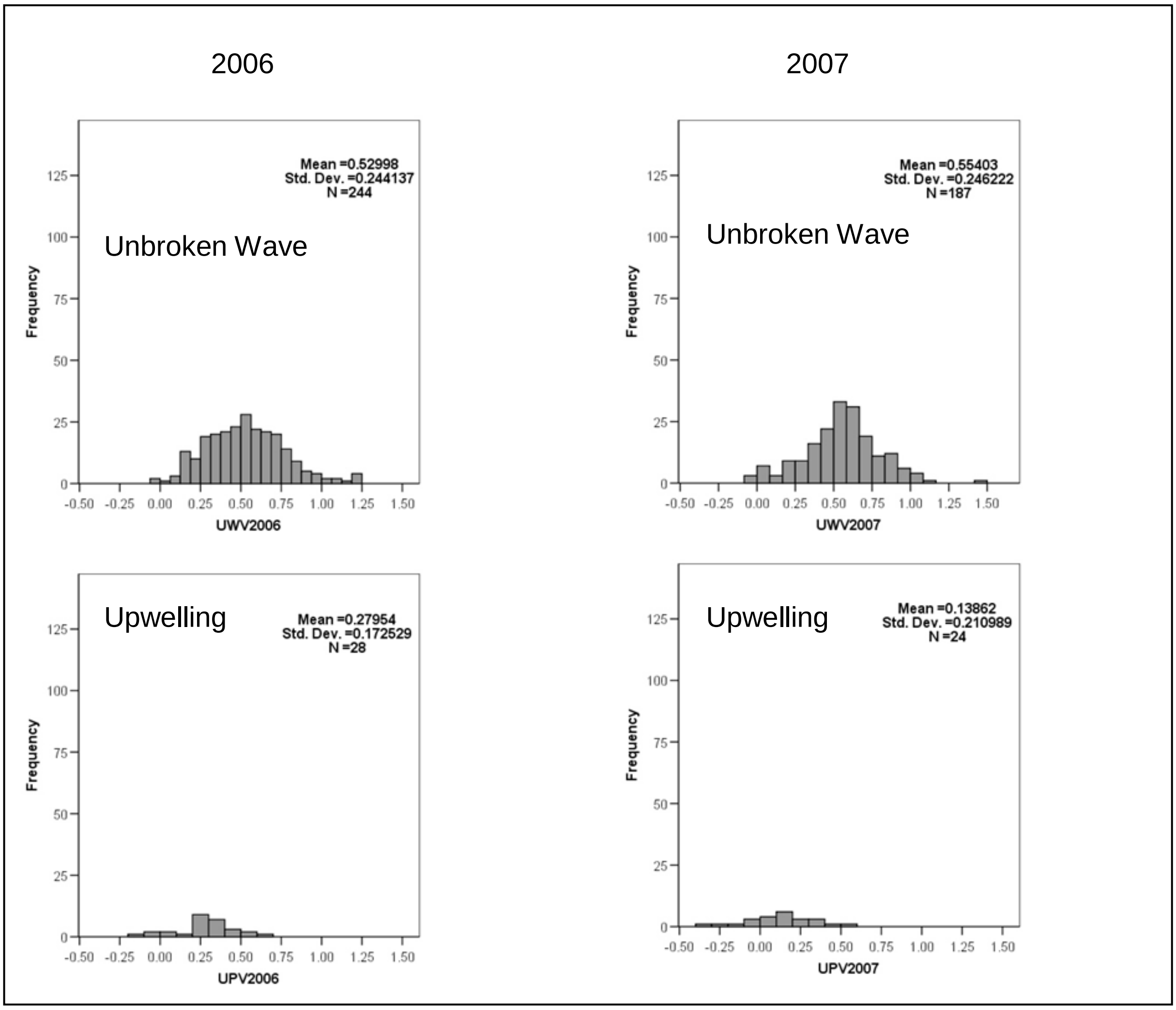


Figure 5:32 (cont) Mean column velocity frequencies recorded in Surface Flow Type mesohabitats during surveys undertaken in 2006 and 2007 in eight British lowland rivers.

Table 5.12 Skewness and Kurtosis values from mean column velocity data recorded in Surface Flow Type mesohabitats during surveys undertaken in 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Surface Flow Type	**Velocity**			
	Skewness 2006	**Skewness 2007**	**Kurtosis 2006**	**Kurtosis 2007**
NP	-0.323	-0.772	1.353	1.910
SM	0.838	0.585	0.346	-0.150
RP	2.416	0.376	23.861	-0.143
UW	0.386	-0.071	0.155	0.635
UP	-0.395	-0.216	0.466	0.918

Depth and mean column velocity distributions in SFT mesohabitats have a negative relationship; this is generally true of sites surveyed in both 2006 and 2007. UP SFT mesohabitat differs from the other SFT mesohabitats in that there is an upward component to water column velocity, which was not measured in this study. The vertical velocity component in UP SFT mesohabitats frequently induces erosion, particularly where it occurs near the bank, this in turn increases water depth making UP SFT mesohabitats rather different from the others recorded. All SFT mesohabitat data sets are skewed, generally to the right, which indicates that the data is not normally distributed.

Kruskal-Wallis non-parametric ANOVA was used to examine the differences between depth and mean column velocity in SFTs investigated using the hypothesis:

H_0: Samples from populations have the same distribution.

H_1: Samples from populations have significantly different distributions.

In all cases there is a significant difference in depth and velocities between SFTs in both 2006 and 2007 (Table 5.13), therefore H_0 is rejected in all cases.

Table 5.13 Kruskal-Wallis test statistics for depth and mean column velocity in surface flow type mesohabitats in 2006 and in 2007.

2006	**Depth**	**Velocity**
Chi-Square	307.905	525.937
df	4	4
Asymp. Sig.	.000	.000
2007	**Depth**	**Velocity**
Chi-Square	203.652	326.293
df	4	4
Asymp. Sig.	.000	.000

Pair-wise analysis of depth and velocity (2006) data shows that all combinations of depth are significantly different in all combinations (Table 5.15) and that there is a significant difference between 80% of mean column velocities combinations (UP/SM and UP/RP are not significantly different).

Table 5.14 Water depth and mean column velocity data from all surveys undertaken in 2006 in eight British lowland rivers using five Surface Flow Type mesohabitats. Mann-Whitney *U* test. Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05.

2006 Depth	No Perceptible	Smooth	Rippled	Unbroken wave	Upwelling
No Perceptible					
Smooth	.001 **				
Rippled	.000 **	.000 **			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.011 *	.000 **	.000 **	.000 **	
2006 Velocity	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.000 **			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.000 **	.133 n.s.	.057 n.s.	.000 **	

Depth and mean column velocity data from 2007 showed similar results to 2006. There was a significant difference between 90% of depth combinations (Table 5.15) (not UP/NP) and mean column velocity combinations (not UP/RP).

Table 5.15 Water depth and mean column velocity data from all surveys undertaken in 2007 in eight British lowland rivers using five Surface Flow Type mesohabitats. Mann-Whitney *U* test. Significance: ** P=<0.01; * P = <0.05; n.s. P = >0.05.

2007 Depth	No Perceptible	Smooth	Rippled	Unbroken wave	Upwelling
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.005 *			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.533 n.s.	.000 **	.000 **	.000 **	
2007 Velocity	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.000 **			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.000 **	.048 n.s	.000 **	.000 **	

5.4.2 Water Velocity at Macroinvertebrate Sample Points

Benthic macroinvertebrates live on or near the river bed and near-bed velocity is important. Downstream water velocity was recorded at each macroinvertebrate sample site, velocities on the bed, above the bed at 0.05m, 0.10m and at 0.10cm intervals to the surface. Mean velocity near the bed, at bed +0.05m and at the surface (2006 data) increase from NP > SM > RP > UW SFT mesohabitats (Figure 5:33). This is also true of data from 2007, except that near-bed velocity increase from NP > RP > SM > UW. Again velocities recorded in 2007 are higher than those recorded in 2006. Velocities in UP SFT mesohabitats are variable in both years.

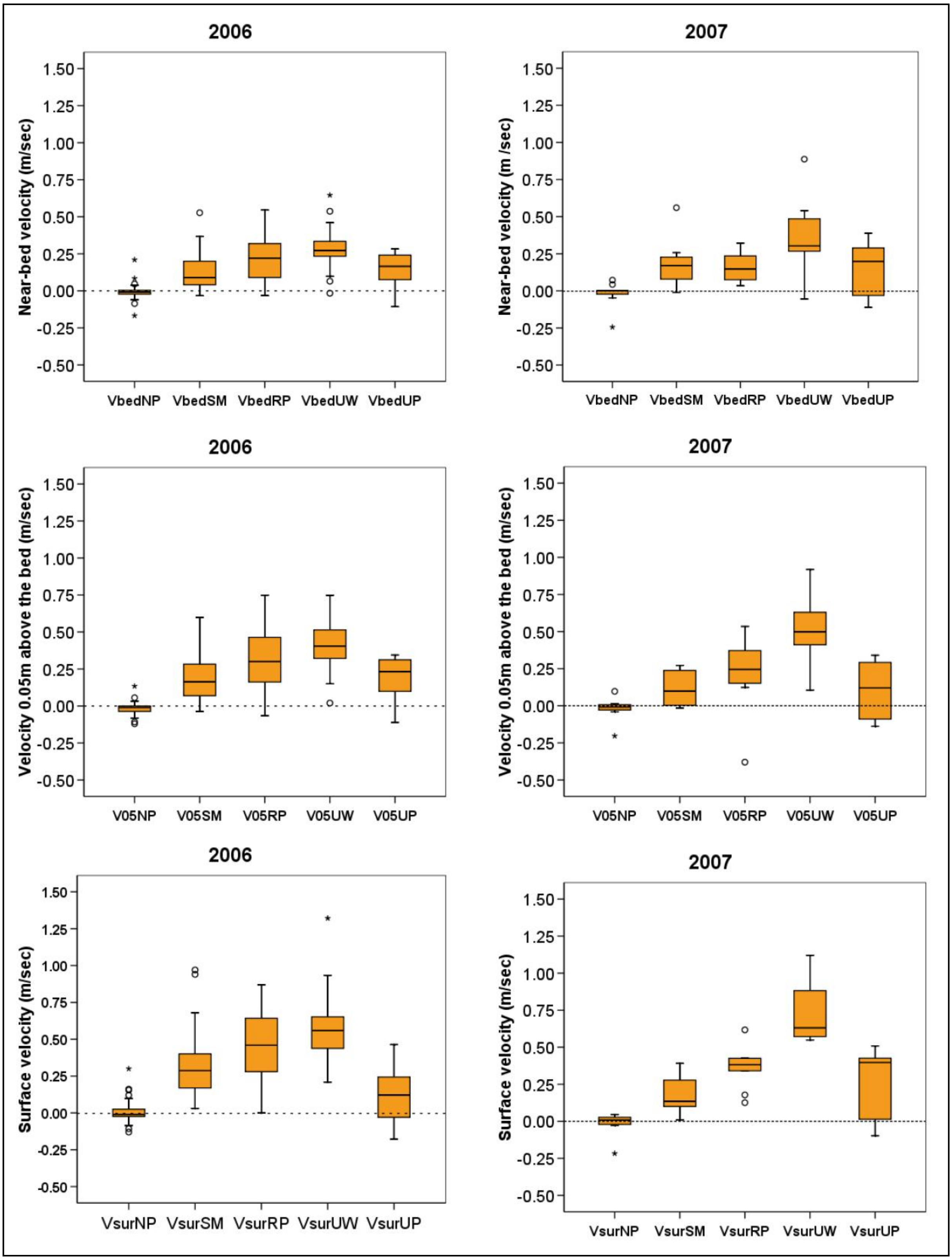


Figure 5:33 Downstream water velocities at three points above macroinvertebrate sample points from eight British lowland rivers in 2006 and 2007. Circle symbols represent outlier values and stars to extreme values.

Kruskal-Wallis Non-parametric ANOVA was used to examine the differences between velocities recorded near-bed, 0.05m above the bed and at the surface using the hypotheses:

H_0: Samples from populations have the same distribution.

H_1: Samples from populations have significantly different distributions.

In all cases there is a significant difference in velocities between SFTs in both 2006 and 2007 (Table 5.16), therefore H_0 is rejected in all cases.

Table 5.16 Kruskal-Wallis test statistics for velocities recorded near-bed, 0.05m above the bed and at the surface in macroinvertebrate sample locations in 2006 and in 2007.

2006	**Bed velocity**	**Velocity at 0.05m**	**Surface Velocity**
Chi-Square	100.255	108.837	121.217
df	4	4	4
Asymp. Sig.	.000	.000	.000
2007	**Bed velocity**	**Velocity at 0.05m**	**Surface Velocity**
Chi-Square	63.174	87.779	104.659
df	4	4	4
Asymp. Sig.	.000	.000	.000

Pair-wise analysis of the 2006 data, velocity at near-bed, bed +0.05m and water surface in SFT mesohabitats using the Mann-Whitney *U* test, showed that there is a significant difference in velocity ($P<0.05$) in 83% of relationships (not UP/SM and UP/RP) (Table 5.17).

Table 5.17 Mann-Whitney *U* test analysis of macroinvertebrate sample point velocity data from five Surface Flow Type mesohabitats (all sites, 2006 data in six British lowland rivers) (Significance: ** P=<0.01; * P = <0.05; n.s. P = >0.05.).

Near-Bed Velocity	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000**				
Rippled	.000**	.001**			
Unbroken wave	.000**	.000**	.018*		
Upwelling	.000**	.302 n.s.	.192 n.s	.002**	
Velocity at bed +0.05m	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken wave**	**Upwelling**
No Perceptible					
Smooth	.000**				
Rippled	.000**	.002**			
Unbroken wave	.000**	.000**	.010*		
Upwelling	.000**	.606 n.s	.115 n.s.	.000**	
Surface Velocity	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken wave**	**Upwelling**
No Perceptible					
Smooth	.015*				
Rippled	.000**	.000**			
Unbroken wave	.000**	.000**	.000**		
Upwelling	.403 n.s.	.004**	.000**	.000**	

The 2007 data were similar. There were significant differences between velocities in 77% of pairs, in each cases, UP SFT was one of the pairs (Table 5.18).

Table 5.18 Mann-Whitney *U* test analysis of macroinvertebrate sample point velocity data from five Surface Flow Type mesohabitats (all sites, 2007 data in six British lowland rivers) (Significance: ** P=<0.01; * P = <0.05; n.s. P = >0.05.).

Near-Bed Velocity	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000**				
Rippled	.000**	.000**			
Unbroken wave	.000**	.000**	.002**		
Upwelling	.249 n.s.	.904 n.s.	.406 n.s	.054 n.s.	
Velocity at bed +0.05m	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken wave**	**Upwelling**
No Perceptible					
Smooth	.000**				
Rippled	.000**	.001**			
Unbroken wave	.000**	.000**	.000**		
Upwelling	.090 n.s.	.387 n.s	.018*	.000**	
Surface Velocity	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken wave**	**Upwelling**
No Perceptible					
Smooth	.000**				
Rippled	.000**	.000**			
Unbroken wave	.000**	.000**	.000**		
Upwelling	.017*	.470 n.s.	.080 n.s.	.000**	

5.4.3 Velocity Profile at Macroinvertebrate Sample Points

Figure 5:34 shows velocity profiles for five SFT mesohabitats using mean data from both 2006 and 2007 macroinvertebrate sample points combined. Mean surface velocity is shown as points along the top of the graph although these points do not relate to depth. Data range is shown in Figure 5:34. In all SFT mesohabitats there are fewer velocity records at greater depths; therefore, the mean velocity from the deepest recorded velocity in each SFT class was ignored as unrepresentative. Near-bed velocities can be expected to be lower than those within the water column due to drag created by bed-roughness (Section 2.2.1).

Downstream velocities from NP SFT were expected to be close to zero or negative, with lower velocity on the river bed, the results from 2006/7 data show this to be the case. Smooth SFT has low positive velocity on the bed increasing to 0.4m depth and then decreasing; the mean surface velocity (0.268m/Sec) is slightly higher than at 0.8m, this is probably the result of lower velocity because of greater depth. Upwelling SFT has velocities very close to those recorded in SM SFT, although the velocity at 0.8m is high (0.383m/sec), this is probably caused by the upward movement of water being forced to move laterally when the water surface is reached. Bed velocities in RP SFT are higher than SM and UP, increasing with distance away from the bed to 0.3m, slightly reducing to 0.5m and then increasing; this is probably due to greater depths and velocities recorded in spate conditions. Unbroken wave SFT shows a classic curve, with increasing velocity away from the bed (Section 2.2.1).

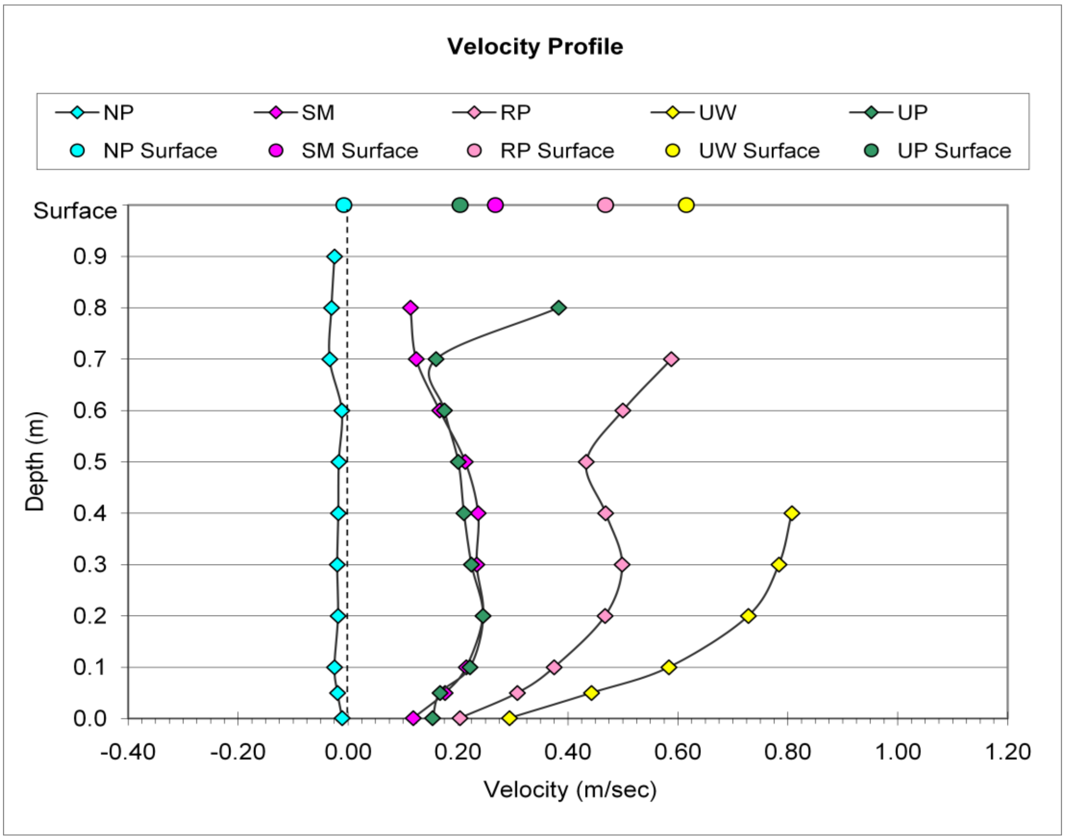


Figure 5:34 Velocity profiles for five Surface Flow Types mesohabitats constructed from mean velocities recorded in both 2006 and 2007 from eight British lowland rivers. Dashed lines show data range. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

There were a range of velocities recorded at each depth interval in each SFT; these are presented in Figure 5:35. Note that the X and Y axes are transposed to better relate to Figure 5:34, that the range of depths on the vertical axis is variable and that the upper classes in each SFT contain few data and have been ignored as unrepresentative in the velocity profile (Figure 5:34). Readings were obtained from a wide range of discharges which explains some spread of the data.

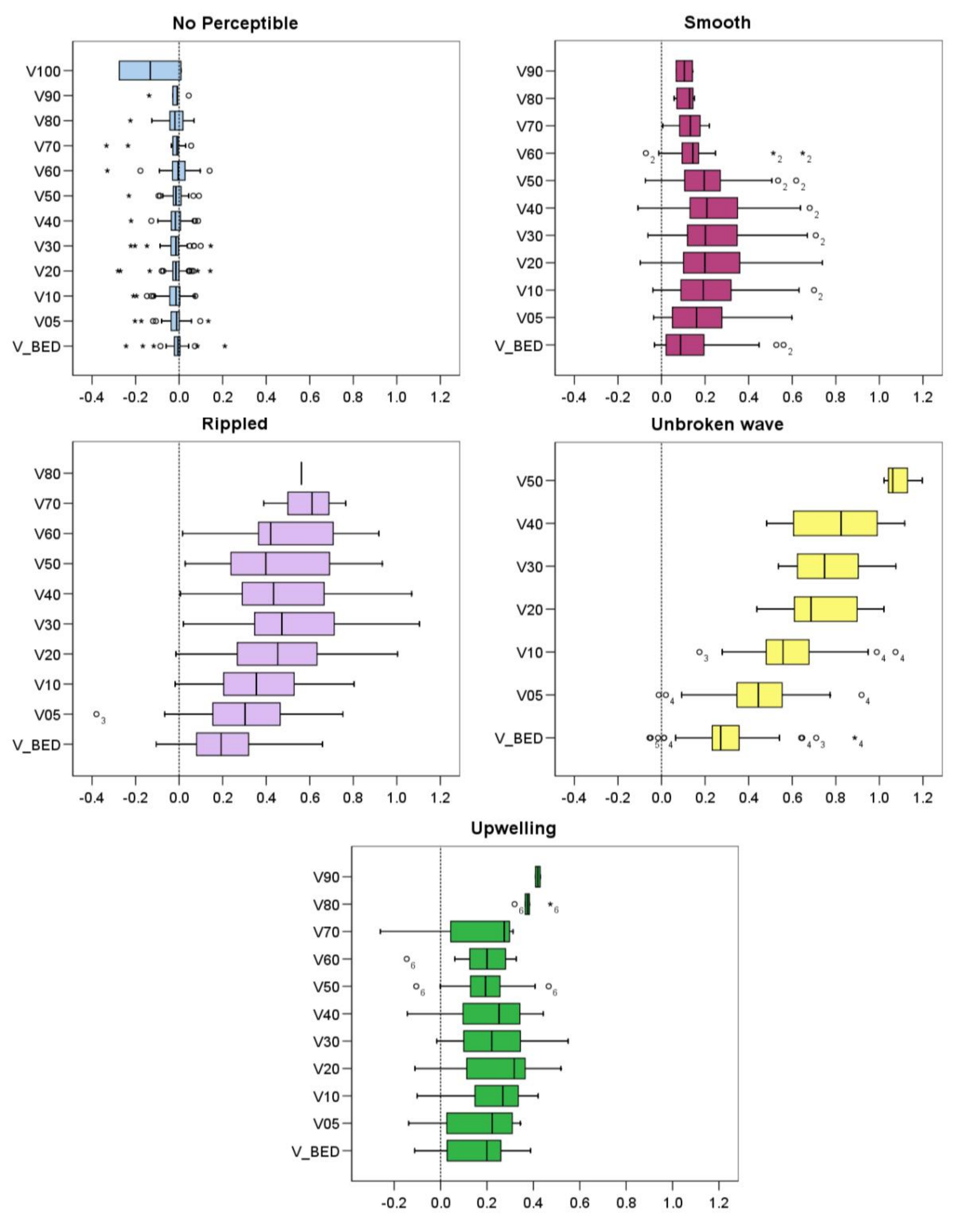


Figure 5:35 Range of velocities recorded at macroinvertebrate sample points in five SFTs during 2006 and 2007 (combined data) used to construct the velocity profile in figure 5:34. Circle symbols represent outlier values and stars to extreme values.

5.4.4 Correlation of Surface and Near Bed Velocities at Macroinvertebrate Sample Sites

SFT mesohabitats can be ranked according to the characteristic downstream velocity (Wadeson and Rowntree. 1998; Reid and Thoms, 2008) (Section 2.5.4). In this research four SFTs were ranked by mean water velocity – NP, SM, RP and UW; the fifth SFT - UP has variable hydraulic properties. Downstream water velocity is an important variable in habitat identification and is used by the four methods discussed in Section 2.4.4 MesoHABSIM, RHM, NMCM and MesoCaSiMiR. Therefore, if velocity is important in determining the identification of mesohabitats by their SFT, it is important to determine the relationship between surface velocity and velocity on and near the bed where macroinvertebrates live. This section investigates the significance of the correlation between surface and both near-bed velocities and those 0.05m above the bed.

Figure 5:36 and Figure 5:37 show scatter-plots of downstream velocity recorded at the water surface plotted against velocities recorded near-bed and at 0.05m above the bed. In all plots there is a highly significant correlation (Spearman Rank Order Correlation) overall in both 2006 and 2007 between velocity at the surface and 0.05m above the bed and between velocity at the surface and velocity at the near-bed (Table 5.19). Taking each SFT within the plots, NP, SM and RP (2006) and SM and RP (2007) have significant correlations in both the near-bed and 0.05m above the bed categories, and UW significant at 0.05m above the bed. Correlations which are not significant include UP in all categories and UW at the bed.

These analyses suggest that there is a strong relationship between surface velocity and at both near-bed and + 0.05m above the bed in SM and RP SFT mesohabitats, and surface velocity in UW SFT mesohabitats. Bed + 0.05m velocity is not significant in NP SFT mesohabitats (P = 0.054) although the range of values is small and P is close to being significant. In UW SFT mesohabitats the correlation between surface and velocity at 0.05m above the bed is significant whilst between the surface and near-bed the correlation is not significant. This is due to greater friction and drag near the bed (Section 2.2.1). There is no significance in the correlation between any classes involving UP SFT mesohabitats.

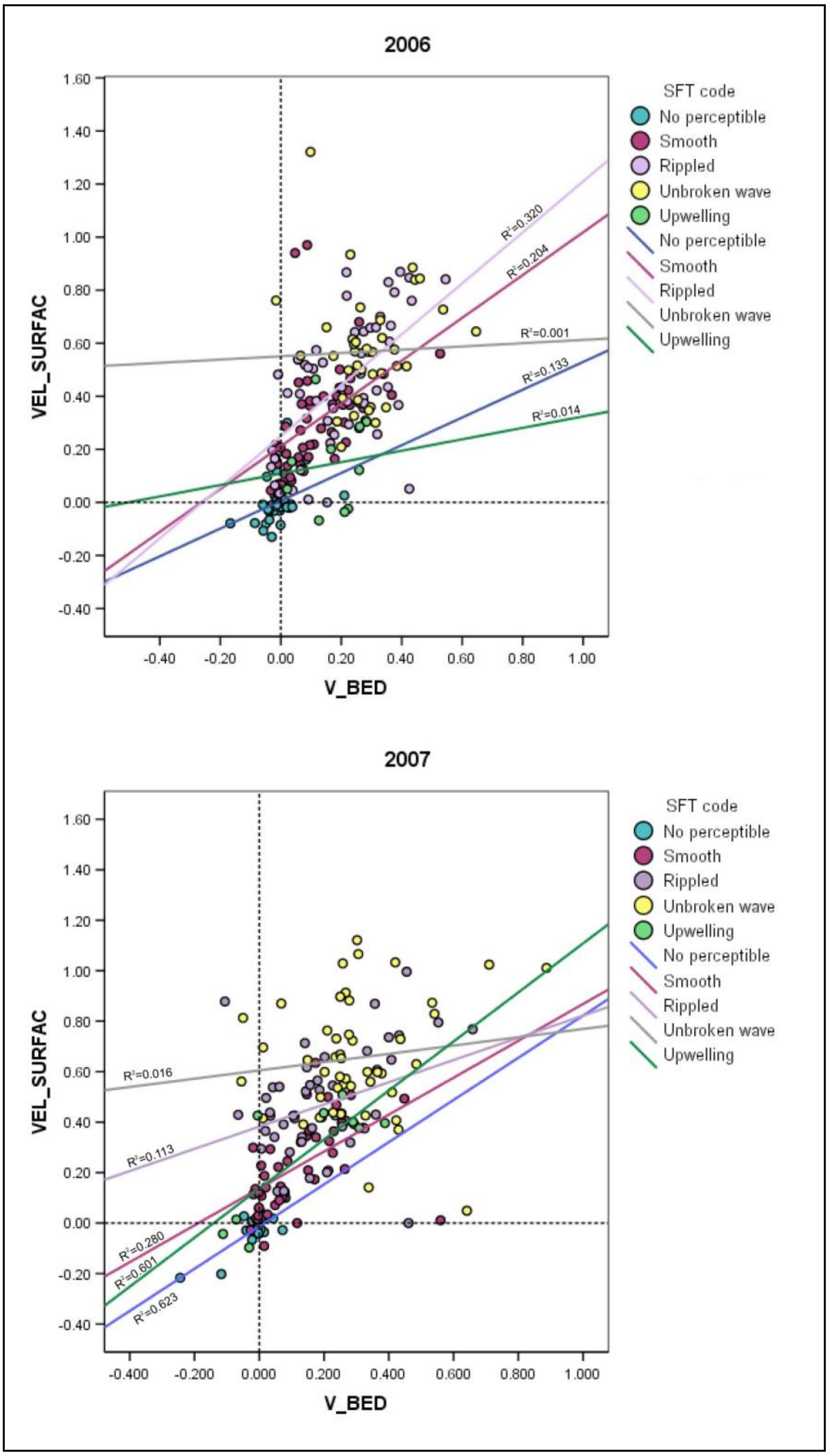


Figure 5:36 Surface velocity plotted against near-bed velocity, using macroinvertebrate sampling points from 2006 and from 2007 separately.

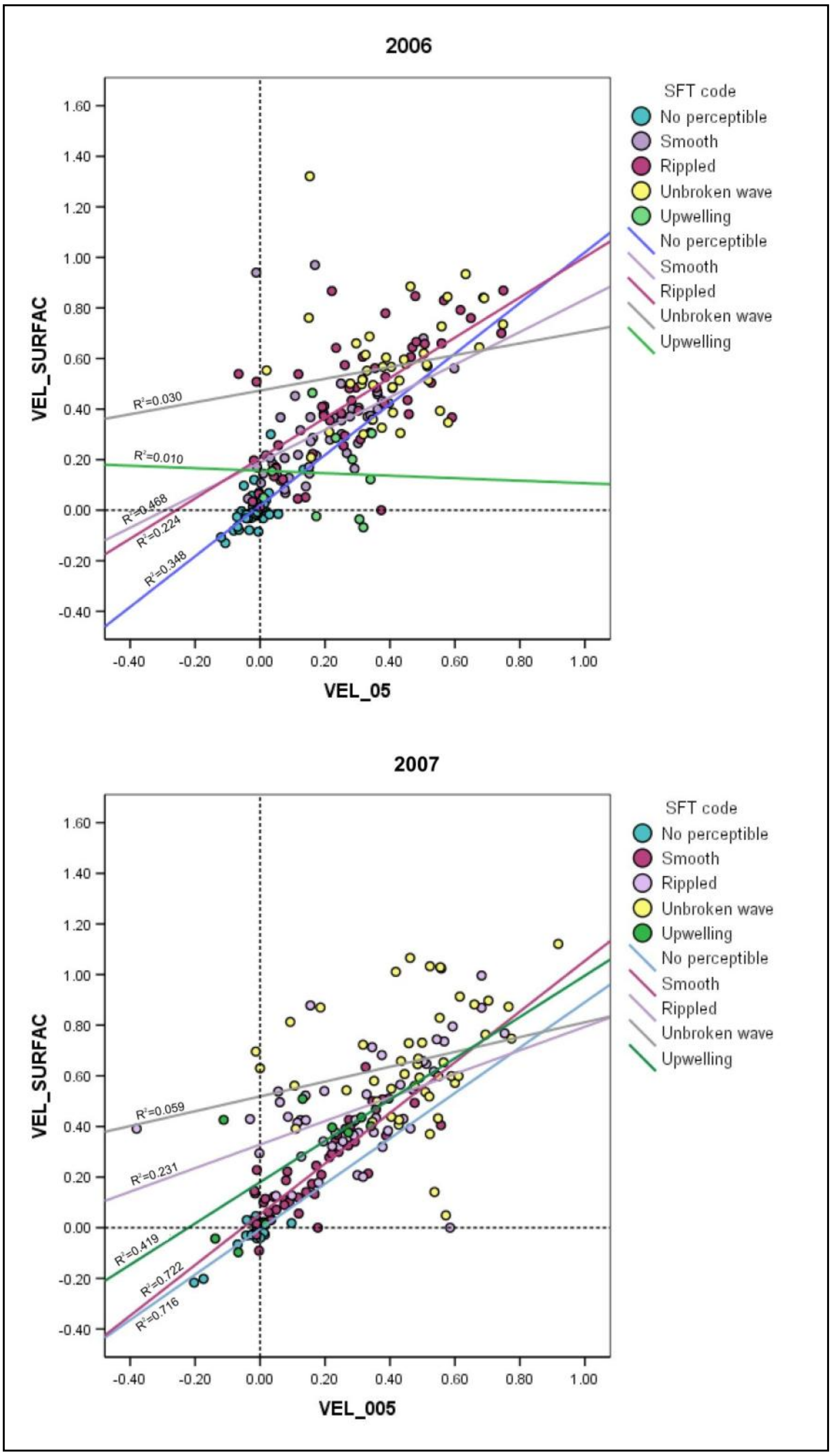


Figure 5:37 Surface velocity plotted against velocity 0.005m above the bed, using macroinvertebrate sampling points from 2006 and from 2007 separately.

Table 5.19 Spearman Rank Order Correlation analysis of downstream velocity recorded in five Surface Flow Type mesohabitat types during surveys undertaken in 2006 and 2007 in eight British lowland rivers (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05.). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Surface Velocity	Near-Bed Velocity 2006	Near-Bed Velocity 2007	Bed +0.05m Velocity 2006	Bed +0.05m Velocity 2007
NP	.402 ** .003	.308 n.s. .082	.505 ** .000	.352 n.s. .054
SM	.643 ** .000	.632 ** .000	.663 ** .000	.833 ** .000
RP	.531 ** .000	.300 * .019	.663 ** .000	.490 ** .000
UW	.110 n.s. .249	.113 n.s .221	.286 * .037	.326 * .012
UP	.212 n.s. .278	.450 n.s .112	-.067 n.s. .427	.450 n.s. .112
Overall	0.784 ** 0.000	0.842 ** 0.000	0.624 ** 0.000	0.736 ** 0.000

These results suggest that in the lower energy SFTs (NP, SM and RP) the near-bed and bed + 0.05m readings were taken in the main water column, whilst in UW the bed readings were taken in the viscous sub-layer where friction reduces velocity although at 0.05m above the bed readings are taken in the main water column. Upwelling SFT appear to be hydraulically different from the other SFTs, reflecting the observed upward velocity component.

This research has shown that within SFT mesohabitats water depth and velocity are distinctive, both at the mesohabitat scale, using mean column velocity, and at the microhabitat scale, using surface velocity and near-bed velocities. This provides strong evidence that in-stream-habitats associated with SFT mesohabitats are hydraulically distinct.

5.4.5 HydroSignature Analysis

HydroSignature analysis is used here to address the issue of the distinctiveness of SFT mesohabitats. HydroSignature quantifies the hydraulic variety, for a given flow, of an area of aquatic habitat by calculating the surface percentages in a depth and current velocity cross-classification. Each cell in the HydroSignature output shows the percentage of surface area containing that depth/velocity class. The graphical output of HydroSignature shows the extent of depth/velocity classes and potentially provides a tool to compare species utilisation of depth and velocity.

Separate HydroSignature calculations were made for each group of SFTs for all surveys from 2006 and for all surveys 2007. HydroSignature analysis of depth and velocity from 323 SFT mesohabitats recorded in 2006 is presented in Table 5.20, deep colours show higher depth/velocity concentrations. In NP SFT mesohabitat ~ 90% of velocity is <0.1 m/s (Table 5.20 columns 1 and 2) and ~82% depth is between 0.5 and 0.9m these values plot to the left of the matrix, SM and RP SFT mesohabitats spread across the depth/velocity matrix. The central group of UW SFT mesohabitat cells plot further right and higher, whilst UP SFT mesohabitat occupies a central area of the matrix. Data from 234 SFT mesohabitat mesohabitats recorded in 2007 was analysed (Table 5.21) shows the HydroSignature output for five SFT mesohabitats.

Table 5.20 HydroSignature matrix showing percentage of surface area ascribed to depth/velocity classes from all sites, 2006 data. Cells shaded red indicate depth/velocity classes containing >10% of the SFT, orange shaded cells contain between >5% and <10%, tan shaded cells contain >1% and < 5% and white cells <1%. Red and orange indicate the focus of depth/velocity within the in-stream habitat and lighter colours show the extent of depth and velocity values.

2006	**Depth (m)**	**Percentage Of Surface Area**							
No Perceptible	0	0.2	1.9						
	0.1	1.0	2.2	1.0					
	0.2	4.4	3.0	0.2					
	0.3	11.2	3.7	1.0					
	0.5	15.1	8.2	0.1					
	0.7	15.3	6.3	0.4	0.2				
	0.9	8.6	13.9						
	1.4	2.0							
Smooth	0		1.3	0.1					
	0.1	0.4	2.0	2.1	0.9	0.8	0.0	0.2	
	0.2	0.4	3.3	7.7	3.2	4.2	0.9	0.5	0.2
	0.3	1.3	10.2	9.8	4.4	6.1	2.8	0.5	
	0.5	0.1	5.0	4.5	3.1	4.3	1.3	0.1	
	0.7	0.7	2.7	2.9	1.8	1.5	0.7		
	0.9		5.1	2.2	0.8				
	1.4								
Rippled	0	0.0	0.1	0.3	0.4	0.8	0.1	0.0	
	0.1	0.9	0.7	1.6	3.3	7.7	2.5	0.3	0.1
	0.2	0.1	1.5	2.3	3.1	7.1	5.9	2.7	0.1
	0.3	0.2	1.0	3.1	3.2	14.1	8.1	2.8	0.0
	0.5	0.9	0.7	1.0	1.8	5.1	4.1	1.1	
	0.7	0.2	0.1	0.8	1.3	2.2	1.6	2.0	
	0.9	0.0	0.0	0.5	0.2	1.3	0.7	0.1	
	1.4	0.1	0.0	0.0	0.0	0.0	0.0		
Unbroken wave	0			0.1	3.5	6.2	4.0	0.8	0.5
	0.1	0.0	0.8	2.3	6.9	10.0	18.9	8.9	3.5
	0.2	0.2	0.0	0.9	1.9	5.3	6.4	6.6	0.2
	0.3		0.0	0.2	1.0	1.8	3.6	1.4	0.2
	0.5		0.1	0.1	0.6	0.6	0.8	0.8	0.2
	0.7					0.2	0.2	0.2	
	0.9					0.1	0.1		
	1.4								
Upwelling	0		0.4						
	0.1		0.0	0.0					
	0.2	0.7	0.0	0.1	0.0		7.3		
	0.3	1.8	2.5	1.5	8.1	17.0	0.4		
	0.5	3.7		1.9	13.0	3.2			
	0.7	3.2			1.9	18.2			
	0.9				3.6	11.4			
	1.4								
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5
		Velocity (m/sec)							

Table 5.21 HydroSignature matrix showing percentage of surface area ascribed to depth/velocity classes from all sites, 2007 data. Cells shaded red indicate depth/velocity classes containing >10% of the SFT, orange shaded cells contain between >5% and <10%, tan shaded cells contain >1% and < 5% and white cells <1%. Red and orange indicate the focus of depth/velocity within the in-stream habitat and lighter colours show the extent of depth and velocity values.

2007	**Depth(m)**	**Percentage Of Surface Area**							
No Perceptible	0								
	0.1	2.7	2.9						
	0.2	14.0	6.1						
	0.3	13.3	11.5	0.7					
	0.5	1.2	3.4	0.5					
	0.7	19.4	5.5	0.2					
	0.9	8.3	5.5	0.6	1.7				
	1.4	2.3	0.3						
Smooth	0		0.0		0.3				
	0.1	0.5	0.2	0.9	1.2	2.0	0.0		
	0.2	0.3	0.2	1.8	2.3	3.8	0.9	0.2	
	0.3	2.2	8.0	11.8	4.5	5.5	2.6	0.9	
	0.5	0.2	7.4	7.3	6.4	7.1	3.5	0.5	
	0.7	0.1	5.1	2.7	1.8	0.9	1.2	0.2	
	0.9	0.1	3.1	0.4	0.8	0.7	0.4		
	1.4								
Rippled	0			0.2	0.1	1.1			0.0
	0.1		0.2	0.2	1.1	4.8	1.8	0.1	0.0
	0.2	0.8	0.6	1.5	3.1	7.0	5.3	1.7	0.0
	0.3	0.9	1.5	2.4	7.4	14.0	7.1	2.9	3.1
	0.5	0.2	0.4	1.8	1.8	5.7	7.1	3.1	0.0
	0.7	0.0	0.2	0.4	0.7	1.3	2.3	1.4	
	0.9	0.1	0.5	1.3	0.4	1.7	0.7		
	1.4								
Unbroken Wave	0		0.2		0.5	1.6	1.0	0.1	0.2
	0.1		0.2	0.2	0.1	10.8	17.5	8.4	1.0
	0.2		8.8	1.7	1.7	12.4	7.7	1.5	1.0
	0.3	0.2	0.1	0.4	0.2	4.8	4.9	2.7	2.7
	0.5	0.1	0.4	0.4	0.4	1.3	0.2	1.1	0.9
	0.7						0.5	2.0	
	0.9						0.0		
	1.4								
Upwelling	0								
	0.1		1.3						
	0.2	0.0	0.6						
	0.3	1.9	2.6	2.7		7.1			
	0.5			2.7	14.0	5.5			
	0.7	2.6	0.6	7.2	8.6	11.6	2.3		
	0.9	8.9		10.8	2.3	6.8			
	1.4								
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5
		Velocity(m/s)							

For each depth/velocity class in the HydroSignature matrix, the SFT with the greatest percentage of surface area was identified. For example the third cell down in the left hand column in each of the five SFTs in Table 5.20 and Table 5.21 represent velocities <0m/sec and depths of between 0.2 to 0.3 m, the SFT with the highest value was identified – here NP. The process was repeated for the whole of the matrix and the result presented in Table

5.22 and Table 5.23. In the case of NP SFT mesohabitat, in 2006, 90% of the SFT (by area) is represented by the cells shaded blue. This suggests that an observer mapping NP SFT mesohabitat can correctly identify the depth and velocity of more than 90% of NP SFT mesohabitat in the survey area. Smooth SFT mesohabitat (44%) and RP SFT mesohabitat (33%) values are lower due to greater class overlap. Unbroken wave SFT mesohabitat (73%) and UP SFT mesohabitat (78%) have a stronger relationship although they also overlap with other SFT mesohabitats.

Similar patterns to those identified in 2006 are evident, with slightly less NP SFT mesohabitat and UP SFT mesohabitat identified in 2006; UW SFT mesohabitat remains almost the same whilst SM SFT mesohabitat and RP SFT mesohabitat are both slightly stronger.

Table 5.22 HydroSignature matrix showing the surface flow type most strongly associated with each depth/velocity class from all sites, 2006 data. Key: cells shaded Blue – No Perceptible; Magenta – Smooth; Pink – Rippled; Yellow – Unbroken wave and Green – Upwelling SFTs.

2006	**Depth (m)**								
No Perceptible 90%	0	0.2	1.9						
	0.1	1.0	2.2						
	0.2	4.4							
	0.3	11.2							
	0.5	15.1	8.2						
	0.7	15.3	6.3						
	0.9	8.6	13.9						
	1.4	2.0							
Smooth 44%	0								
	0.1								
	0.2		3.3	7.7	3.2				
	0.3		10.2	9.8					
	0.5			4.5					
	0.7			2.9					
	0.9			2.2					
	1.4								
Rippled 33%	0			0.3					
	0.1								
	0.2					7.1			
	0.3						8.1	2.8	
	0.5					5.1	4.1	1.1	
	0.7						1.6	2.0	
	0.9						0.7	0.1	
	1.4								
Unbroken wave 80%	0				3.5	6.2	4.0	0.8	0.5
	0.1			2.3	6.9	10.0	18.9	8.9	3.5
	0.2							6.6	0.2
	0.3								0.2
	0.5								0.2
	0.7								
	0.9								
	1.4								
Upwelling 73%	0								
	0.1								
	0.2						7.3		
	0.3				8.1	17.0			
	0.5				13.0				
	0.7				1.9	18.2			
	0.9				3.6	11.4			
	1.4								
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5
		Velocity (m/sec)							

Table 5.23. HydroSignature matrix showing the surface flow type most strongly associated with each depth/velocity class from all sites, 2007 data. Key: cells shaded Blue – No Perceptible; Magenta – Smooth; Pink – Rippled; Yellow – Unbroken wave and Green – Upwelling SFTs.

2007	**Depth(m)**								
No Perceptible 79%	0								
	0.1	2.7	2.9						
	0.2	14.0							
	0.3	13.3	11.5						
	0.5	1.2							
	0.7	19.4	5.5						
	0.9		5.5						
	1.4	2.3	0.3						
Smooth 48%	0								
	0.1			0.9	1.2				
	0.2			1.8	3.1				
	0.3			11.8					
	0.5		7.4	7.3		7.1			
	0.7			7.2					
	0.9								
	1.4								
Rippled 50%	0			0.2					
	0.1								
	0.2							1.7	
	0.3				7.4	14.0	7.1	2.9	3.1
	0.5						7.1	3.1	
	0.7						2.3		
	0.9						0.7		
	1.4								
Unbroken Wave 74%	0		0.2		0.5	1.6	1.0	0.1	0.2
	0.1					10.8	17.5	8.4	1.0
	0.2		8.8			12.4	7.7		1.0
	0.3								
	0.5								0.9
	0.7							2.0	
	0.9								
	1.4								
Upwelling 63%	0								
	0.1								
	0.2								
	0.3								
	0.5				14.0				
	0.7				8.6	11.6			
	0.9	8.9		10.8	2.3	6.8			
	1.4								
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5
		Velocity(m/s)							

HydroSignature analysis shows that for each depth/velocity class it is possible to identify the SFT mesohabitat with the greatest proportion of area within that class. In 2006 90% of NP SFT mesohabitat is contained in the blue cells (Table 5.24), with 79% in 2007 (Table 5.25)

Similarly, UW SFT mesohabitat (2006 - 73%; 2007 – 74%) and UP SFT mesohabitat (2006 - 78%; 2007 - 63) have a strong chance of correct identification. Smooth and RP SFT mesohabitats are less likely to be correctly identified SM SFT mesohabitat (2006 - 44%; 2007 – 48%) and RP SFT mesohabitat (2006 - 33%; 2007 – 50%) correctly. The proportion of SFT mesohabitat area of these two flow types move in opposite directions with discharge changes, suggesting that these two SFT mesohabitat types are particularly sensitive to discharge variation.

Table 5.24 Distribution of depth and velocity classes by surface flow type from all sites, 2006 data based on HydroSignature analysis. This table consolidates data in Table 5.21.

	Depth (m)											%
	0	0.2	1.9	0.3	3.5	6.2	4.0	0.8	0.5			
	0.1	1.0	2.2	2.3	6.9	10.0	18.9	8.9	3.5	NP		90
	0.2	4.4	3.3	7.7	3.2	7.1	7.3	6.6	0.2	SM		44
2006	0.3	11.2	10.2	9.8	8.1	17.0	8.1	2.8	0.2	RP		33
	0.5	15.1	8.2	4.5	13.0	5.1	4.1	1.1	0.2	UW		78
	0.7	15.3	6.3	2.9	1.9	18.2	1.6	2.0		UP		80
	0.9	8.6	13.9	2.2	3.6	11.4	0.7	0.1				
	1.4	2.0										
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5			
		Velocity (m/sec)										

Table 5.25 Distribution of depth and velocity classes by surface flow type from all sites, 2007 data based on HydroSignature analysis. This table consolidates data in Table 5.22.

	Depth (m)											%
2007	0		0.2	0.5	1.6	1.0	0.1	0.2	0.0			
	0.1	2.9	0.9	1.2	10.8	17.5	8.4	1.0	0.0	NP		79
	0.2	8.8	1.8	3.1	12.4	7.7	1.7	1.0	0.0	SM		48
	0.3	11.5	11.8	7.4	14.0	7.1	2.9	3.1	0.0	RP		50
	0.5	7.4	7.3	14.0	7.1	7.1	3.1	0.9	0.0	UW		74
	0.7	5.5	7.2	8.6	11.6	2.3	2.0	0.0		UP		63
	0.9	5.5	10.8	2.3	6.8	0.7	0.0					
	1.4	0.3	0.0									
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5			
		Velocity(m/s)										

The analyses above were based on surveys at all discharges during 2006 and 2007 independently. In practice river habitats surveys are often undertaken at low flows, e.g. RHS (Environment Agency, 2003). Table 5.26 shows the depth/velocity classes from 12 surveys each at the lowest discharge at each site in 2006 and 2007. There is broad agreement (Table 5.24 and Table 5.25) with the proportion of depth/velocity cells ascribed to SFT mesohabitats >62% for NP, UW and UP but less so for SM and RP flow types.

Table 5.26 Distributions of depth and velocity classes by surface flow type from HydroSignature analysis using data from 12 surveys of eight British lowland rivers during low discharges.

	Depth(m)											%
Low Flow	0	0.3	1.0	0.6	2.5	6.5	5.9	0.5	0.5			
	0.1	2.0	3.1	1.9	4.0	6.2	21.0	9.6	0.5	NP		88
	0.2	4.1	3.8	5.6	2.8	5.4	7.5	3.0	0.4	SM		49
	0.3	10.9	13.4	9.0	8.2	15.7	5.9	6.0	3.0	RP		36
	0.5	13.7	13.4	2.8	13.3	4.4	5.6	2.4	0.0	UW		62
	0.7	14.4	2.8	1.8	4.8	3.0	4.5	5.6		UP		68
	0.9	13.1	23.1	1.7	0.2	5.2	0.2					
	1.4											
		0	0.1	0.2	0.3	0.5	0.7	0.9	1.5			
		Velocity(m/s)										

5.4.6 Summary – Depth and velocity

The analyses of the relationship between water depth and velocity in Surface Flow Type mesohabitats shows that in SF mesohabitats:

- Water depth decreases from NP > SM > RP > UW in both 2006 and 2007.
- Water depth is significantly different between 90-100% of Surface Flow Type mesohabitats over 2006 and 2007 data.
- Mean column water velocity increases from NP > SM > RP > UW in 2006 and 2007.
- Mean column velocity is significantly different in 80-90% of Surface Flow Type mesohabitats over 2006 and 2007 data.
- Mean downstream water velocity at macroinvertebrate sample points increases from NP > SM > UP > RP > UW using all 2006 and 2007 data.
- There is a significant positive correlation between water surface velocity and velocity at bed +0.05m in NP, SM, RP and UW SFTs in 2006 data.
- There is a significant positive correlation between water surface velocity and velocity at near-bed in NP, SM and RP SFTs in 2006 data.
- There is a significant positive correlation between water surface velocity and velocity at bed +0.05m in SM, RP and UW SFTs in 2007 data.
- There is a significant positive correlation between water surface velocity and velocity at near-bed in SM and RP SFTs in 2007 data.
- SM and RP SFTs are positively correlated with both velocity at near-bed and bed +0.05m in both years.
- Upwelling SFT mesohabitat occurs rarely.
- Upwelling SFT is not significantly correlated with velocity at near-bed or bed +0.05m.
- Upwelling SFT is always present where there was no significant difference in water depth and mean column velocity between two SFTs.
- HydroSignature analyses show similar groupings of Surface Flow Type mesohabitats in both 2006 and 2007.

Based on this research Figure 5:38 shows the extent of depth and velocity in the five SFTs investigated. The shaded areas show the spread of data in the inter-quartile range and the outer lines the overall spread of data. The interquartile range of NP mesohabitats is largely separated from other SFTs, as are UW mesohabitats. SM and RP mesohabitats overlap as does UP although that is deeper than SM or RP. This figure resembles the HydroSignature clusters (Table 5.24and Table 5.25).

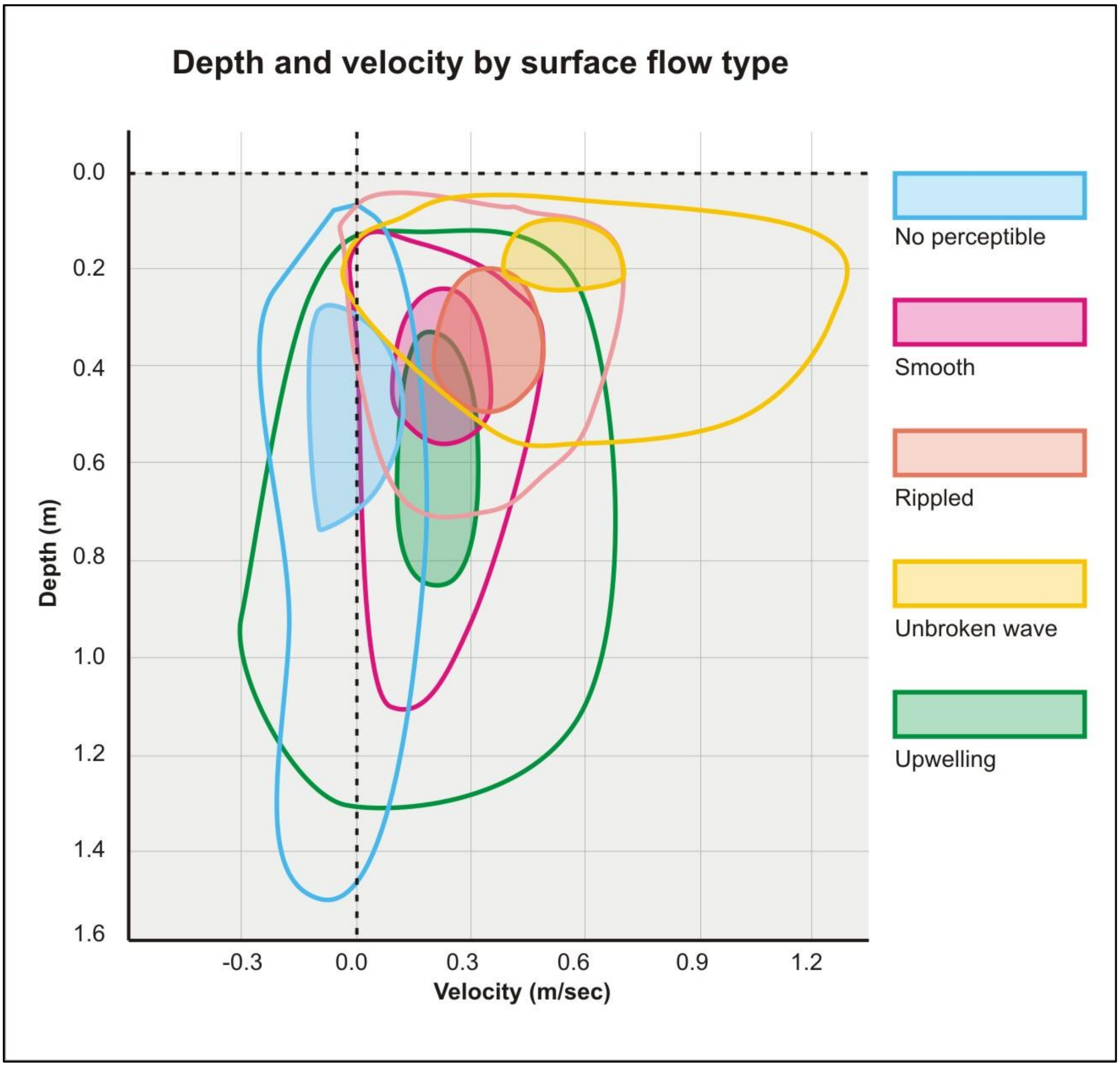


Figure 5:38 The range of depth and velocity values from all surveys, by Surface Flow Type, in eight British lowland rivers in 2006 and 2007. The shaded areas show the range of inter-quartile values, the lines the range of values recorded.

5.5 Substrate and Embeddedness

5.5.1 Substrate

Histograms of the dominant substrate for each SFT mesohabitat for 2006 and 2007 are shown in Figure 5:39. The distributions of substrate frequency differ between SFT mesohabitats. During 2006 surveys the greatest frequency in NP SFT mesohabitat was silt (4), in SM SFT mesohabitat gravel (6) dominates, as it does in RP SFT mesohabitat at a greater frequency and in UP SFT mesohabitat at a lower frequency. Cobble (9) dominates in UW SFT mesohabitat. In 2007 NP SFT mesohabitat is dominated by clay (3), SM, RP and UP SFT mesohabitats remains as in 2006 and UW SFT mesohabitat is dominated by gravel (6).

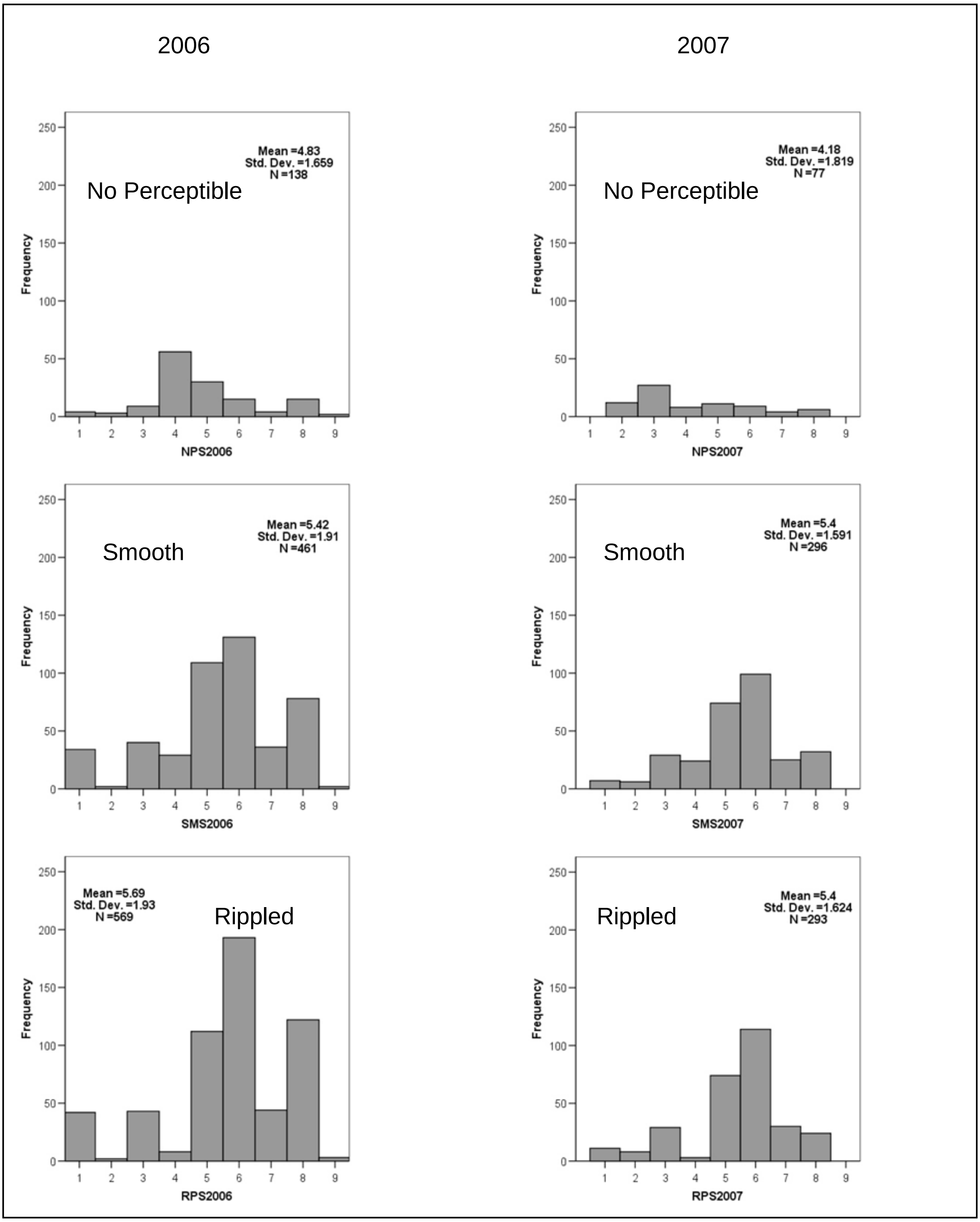


Figure 5:39 Histograms of substrate frequencies recorded at macroinvertebrate sample points in eight British lowland rivers during surveys in 2006 and 2007. Key: 1 – bedrock; 2 – detritus; 3 – clay; 4 – silt; 5 – sand; 6 – gravel; 7 – pebble; 8 – cobble and 9 - boulder.

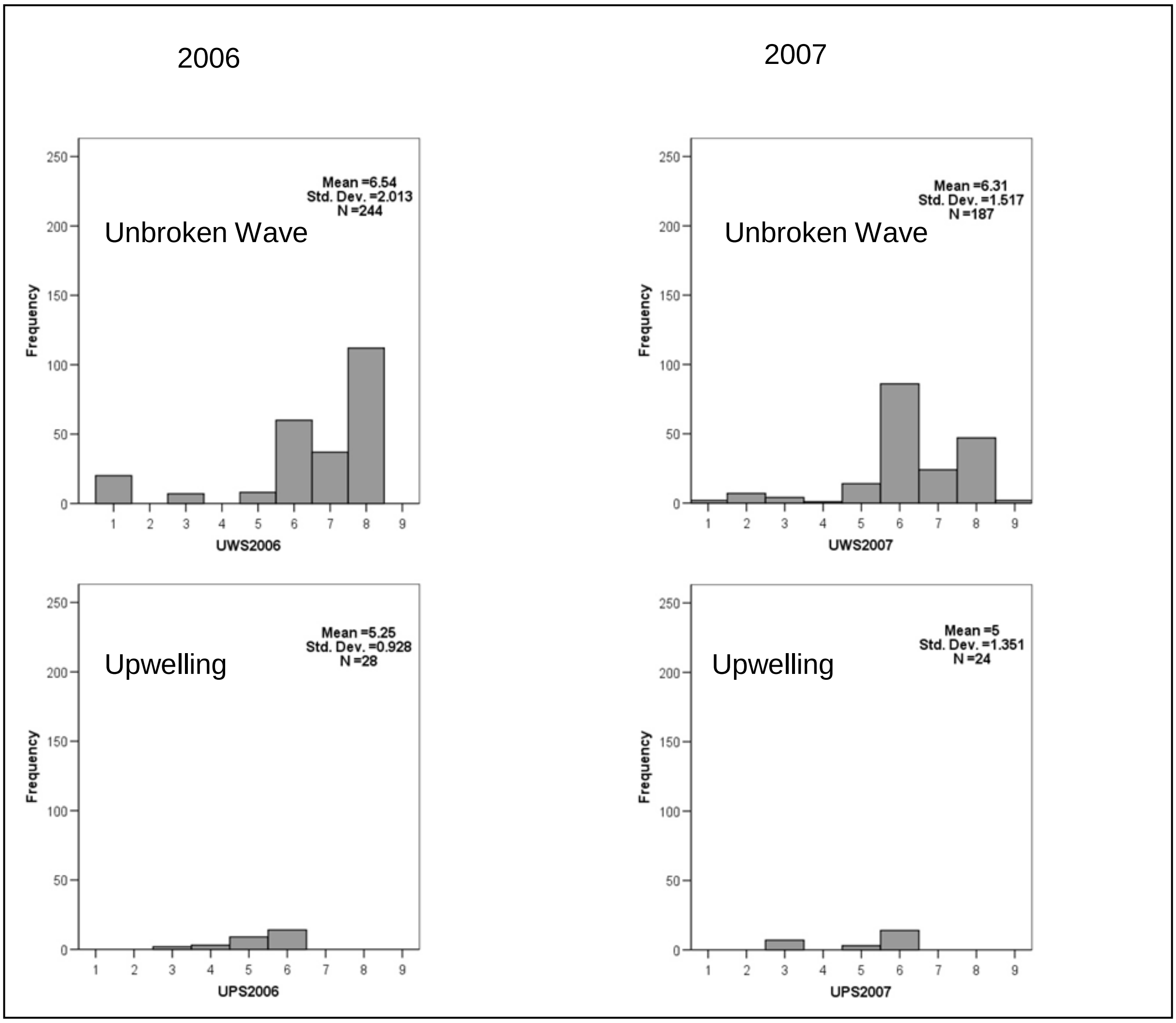


Figure 5.39 (cont) Histograms of substrate frequencies recorded at macroinvertebrate sample points in eight British lowland rivers during surveys in 2006 and 2007. Key: 1 – bedrock; 2 – detritus; 3 – clay; 4 – silt; 5 – sand; 6 – gravel; 7 – pebble; 8 – cobble and 9 - boulder.

There is a relationship between substrate size and SFT mesohabitats, the SFT mesohabitats with lower downstream velocities have finer substrates. Figure 5:40 compares the dominant substrate type across SFT mesohabitats for 2006 and 2007. The relationship between SFT mesohabitat and substrate is complex, partly because substrate availability at a site will naturally constrain the dominant substrate. For example, in areas where sands and gravel dominate, it is unlikely that boulders would be a dominant substrate. Substrate size is an important factor determining bed roughness and drag acting on the water column in contact with the bed (Section 2.5.3). Therefore, it is possible that the relationship between grain size and SFT is not always linked to stage alone. Nevertheless the overall trend here is for less energetic SFT mesohabitat to be dominated by finer substrates.

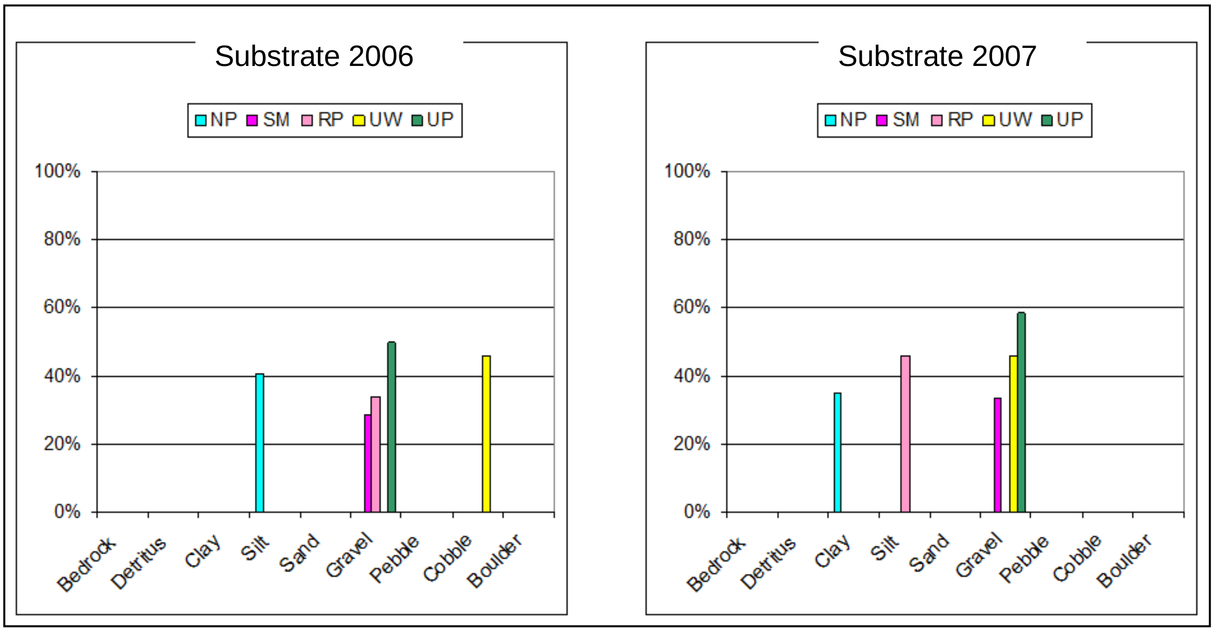


Figure 5:40 Dominant substrate by surface flow type recorded at macroinvertebrate sample points in eight British lowland rivers during surveys in 2006 and 2007.

5.5.2 Embeddedness

Figure 5:41 shows the percentage membership of embeddedness classes (Section 2.5.3) by SFT mesohabitats. Fine material is deposited at low velocity/turbulence; hence fine materials are associated with less energetic SFT mesohabitats *e.g.* NP. In the 2006 data, >80% of NP SFT mesohabitat data points were associated with class 4 embeddedness, with only16% in UW SFT mesohabitat suggesting that fine materials are associated with low velocity/turbulence environments. Upwelling SFT mesohabitat is similar to NP SFT mesohabitat.

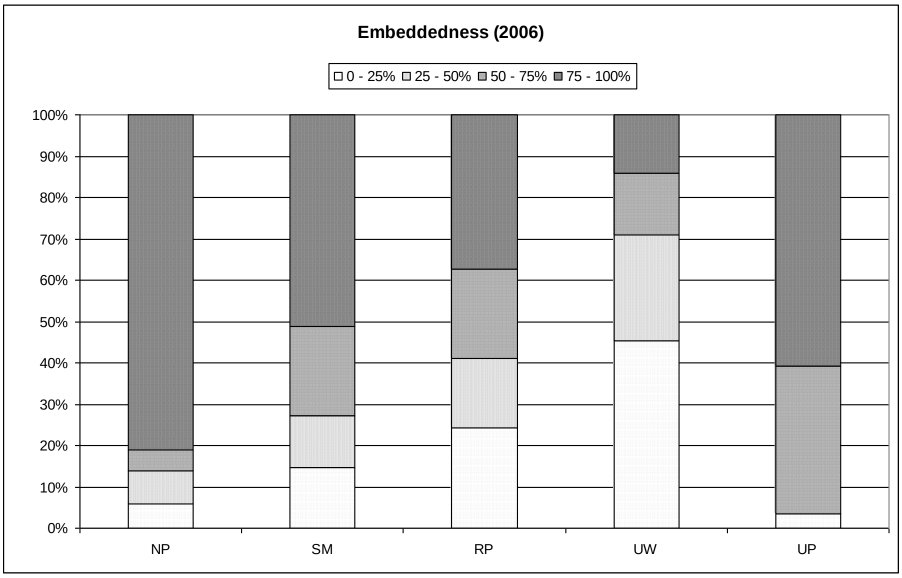


Figure 5:41 Percentage membership of embeddedness classes by Surface Flow Type mesohabitat. Data recorded in five Surface Flow Types identified during surveys of six British lowland rivers in 2006. Excludes data points where dominant substrate was bedrock, clay or not recorded. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

In the 2007 dataset (Figure 5:42) similar trends are evident, although the overall picture is less clear. The greatest degree of embeddedness is associated with NP SFT mesohabitat, UW SFT mesohabitat is associated with low embeddedness, and RP SFT mesohabitat has more class 4 embeddedness than has SM SFT mesohabitat.

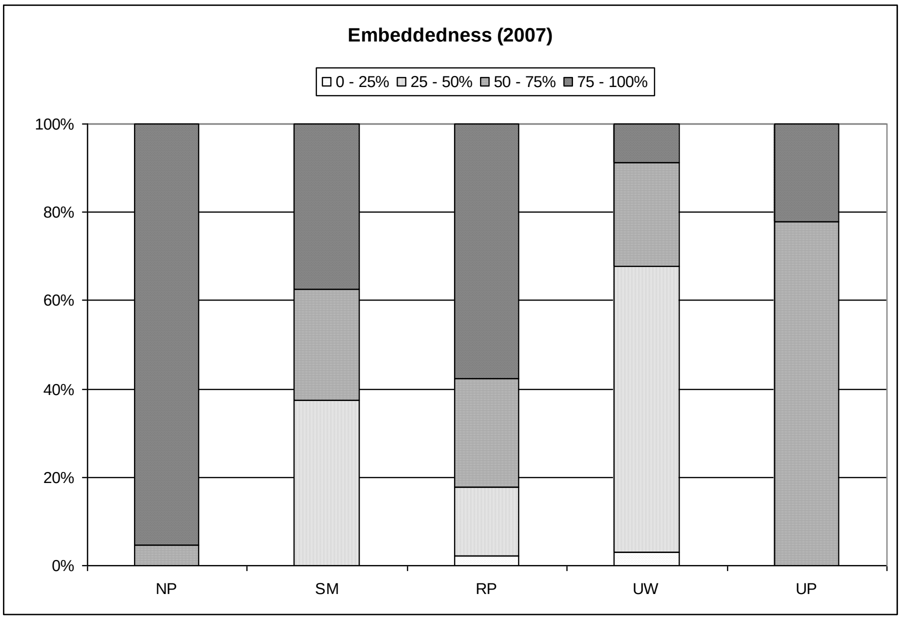


Figure 5:42 Percentage membership of embeddedness classes by Surface Flow Type mesohabitat. Data recorded in five Surface Flow Types identified during surveys of six British lowland rivers in 2007. Excludes data points where dominant substrate was bedrock, clay or not recorded. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Histograms of embeddedness class recorded at macroinvertebrate sample points (Figure 5:43) show that in NP SFT mesohabitat embeddedness is high, with 75-100% most frequently observed. In SM SFT mesohabitat high embeddedness is frequently observed although sites with less embeddedness are more frequent, in RP SFT mesohabitat lower embeddedness is more frequent as high embeddedness decreases. In UW SFT mesohabitat lower embeddedness categories are more frequent that highly embedded categories, UP SFT mesohabitat highly embedded is more frequent.

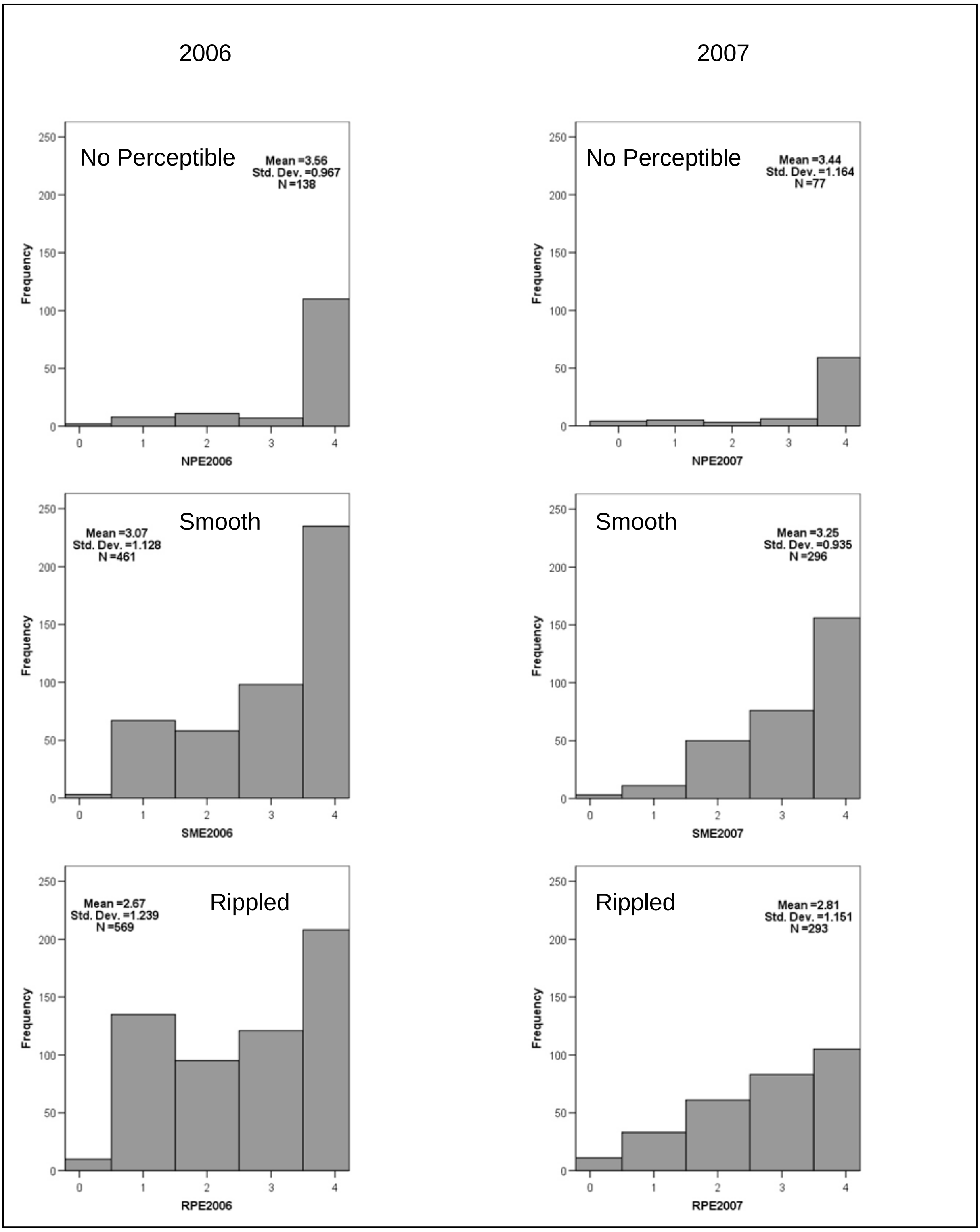


Figure 5:43 Embeddedness frequencies recorded at macroinvertebrate sample points in five Surface Flow Types identified during surveys of eight British lowland rivers in 2006 and 2007.

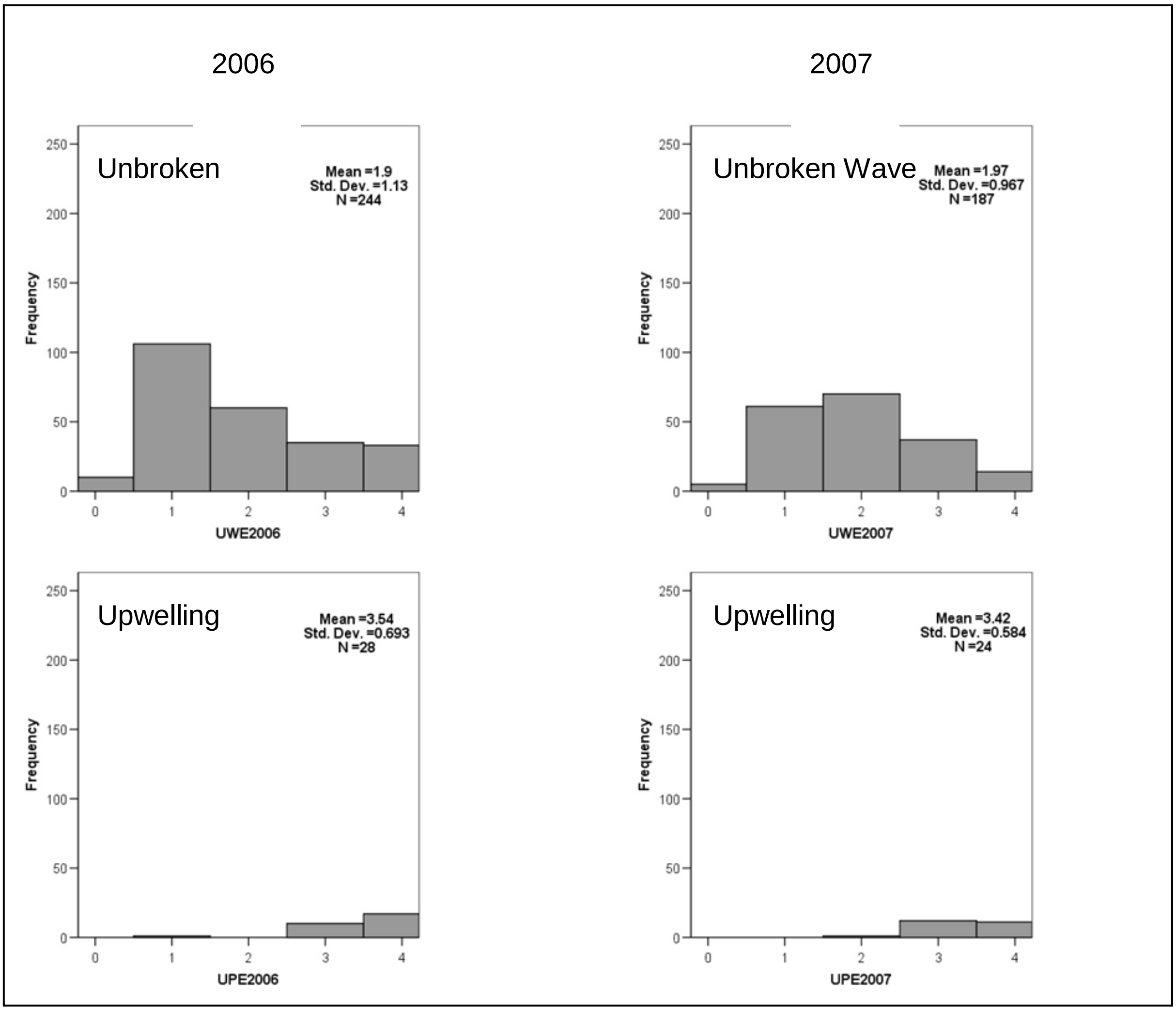


Figure 5:43 (cont) Embeddedness frequencies recorded at macroinvertebrate sample points in five Surface Flow Types identified during surveys of eight British lowland rivers in 2006 and 2007.

Kruskal-Wallis Non-parametric ANOVA was used to examine the differences between substrate size and embeddedness in SFT mesohabitats using the hypotheses:

H_0: Samples from populations have the same distribution.

H_1: Samples from populations have significantly different distributions.

The analysis showed that, in 2006 and in 2007, there were significant differences ($P<0.05$) in all categories of Dominant Substrate, Sub-dominant Substrate and Embeddedness, whilst Substrate Present was not significantly different in 2006 but was in 2007 (Table 5.27).

Table 5.27 Kruskal-Wallis test statistics for substrate and embeddedness at macroinvertebrate sample locations in 2006 and in 2007. (df = degrees of freedom).

2006	**Dominant substrate**	**Sub-dominant substrate**	**Substrate Present**	**Embeddedness**
Chi-Square	140.854	102.186	6.540	219.570
df	4	4	4	4
Significance	.000	.000	.162	.000
2007	**Dominant substrate**	**Sub-dominant substrate**	**Substrate Present**	**Embeddedness**
Chi-Square	102.351	45.270	27.656	186.047
df	4	4	4	4
Significance	.000	.000	.000	.000

Therefore H_0 is rejected in all cases - Dominant Substrate, Sub-dominant Substrate and Embeddedness and Substrate Present (2007) but not for Substrate Present (2006).

Pair-wise analysis, using the Mann-Witney *U* Test (Table 5.28) shows that in 2006 80% of pairs differ in dominant substrate and in embeddedness, 70% in sub-dominant substrate and 40% in substrate present.

Table 5.28 Mann-Whitney *U* test analyses of substrate class size and embeddedness from five Surface Flow Types using data collected in six British lowland rivers in 2006 (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05.).

2006 Dominant substrate	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.003 **			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.018 *	.332 n.s	.023 *	.000 **	
Sub-dominant substrate	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.115 n.s.			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.722 n.s.	.001 *	.000 **	.000 **	
Substrate present	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.169 n.s.				
Rippled	.018 *	.124 n.s			
Unbroken wave	.004 **	.002 **	.021 *		
Upwelling	.603 n.s.	.789 n.s.	.927 n.s.	.739 n.s.	
Embeddedness	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.001 **				
Rippled	.000 **	.000 **			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.111 n.s	.077 n.s *	.000 **	.000 **	

Similar analysis of 2007 data (Table 5.29) shows 80% of pair differ in embeddedness, 60% in dominant substrate, 40% in subdominant substrate, 30% in substrate present.

Table 5.29 Mann-Whitney *U* test analyses of substrate class size and embeddedness from five Surface Flow Types using data collected in six British lowland rivers in 2007 (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05).

2007 Dominant substrate	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.001 **	.019 *			
Unbroken wave	.000 **	.245 n.s.	.001 **		
Upwelling	.001 **	.410 n.s	.381 n.s	.082 n.s	
Sub-dominant substrate	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.019 *	.210 n.s.			
Unbroken wave	.000 **	.109 n.s.	.006 **		
Upwelling	.053 n.s.	.216 n.s.	.783 n.s	.012 *	
Substrate present	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.050 n.s.				
Rippled	.027 *	.783 n.s			
Unbroken wave	.377 n.s.	.135 n.s.	.074 *		
Upwelling	.716 n.s.	.056 n.s.	.038 *	.192 n.s.	
2007 Embeddedness	**No Perceptible**	**Smooth**	**Rippled**	**Unbroken Wave**	**Upwelling**
No Perceptible					
Smooth	.000 **				
Rippled	.001 **	.011 *			
Unbroken wave	.000 **	.002 **	.000 **		
Upwelling	.000 **	.162 n.s	.469 n.s.	.000 **	

5.5.3 Summary – Substrate and Embeddedness

Although there are significant differences in substrate size and embeddedness between SFT mesohabitats, there was a wide range of both substrate and embeddedness recorded in each SFT. Figure 5:44 shows the range of type and embeddedness for all surveys combined. All classes of substrate and embeddedness were recorded in NP, SM, RP and UW SFTs. However, the inter-quartile ranges show high degrees of embeddedness and small substrate size in NP SFTs, whilst in SM SFTs lower degrees of embeddedness and larger substrate size are shown. In RP SFTs the range of embeddedness is the same as in SM although substrate size is increased. In UW SFTs embeddedness is low and substrate largest. UP SFTs is highly embedded with moderate substrate size, the overall range of substrate size and embeddedness was lower because UP SFT is rare and there were few measurements.

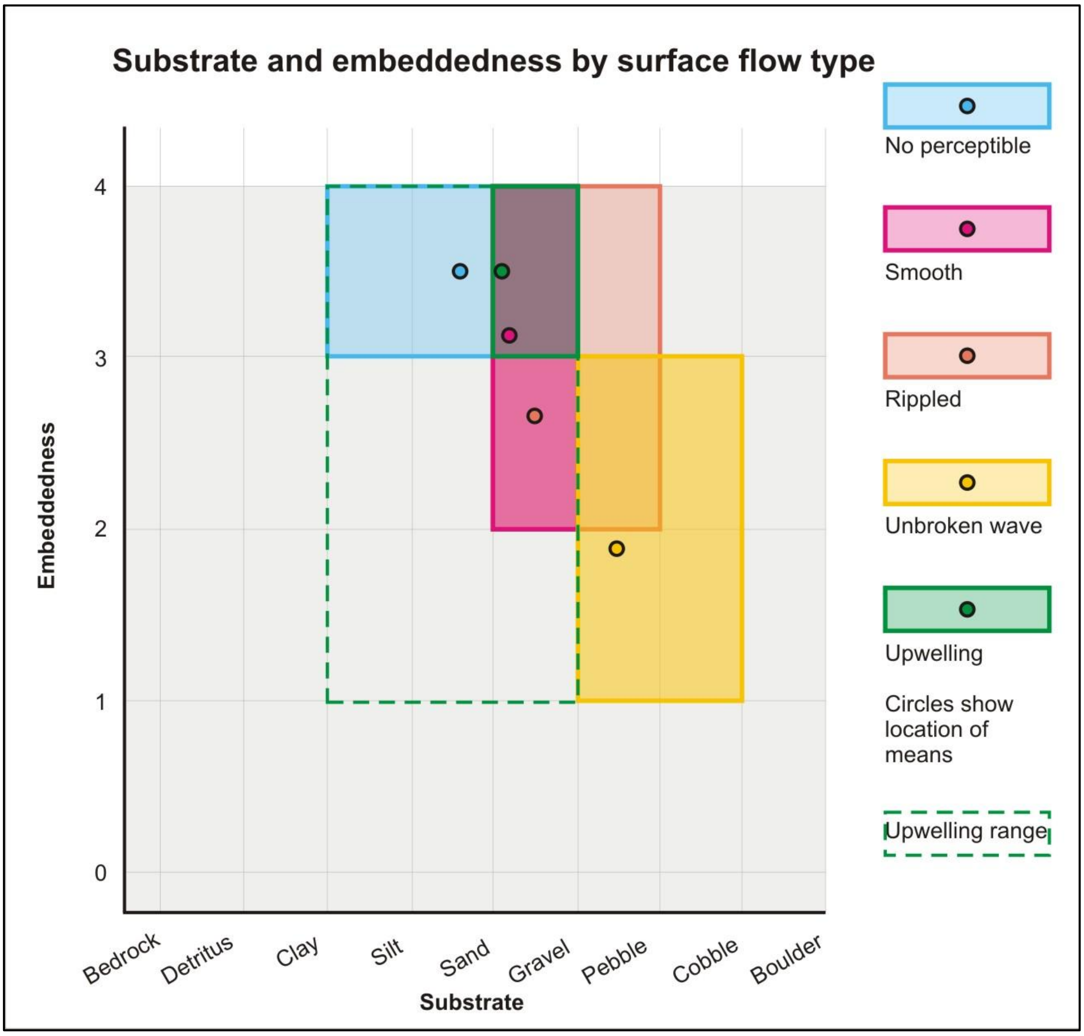


Figure 5:44 Range of substrate and embeddedness values from all surveys of eight British lowland rivers in 2006 and 2007. The circle show mean values, the shaded boxes the interquartile range and the green dashed line the spread of data from Upwelling surface flow type.

5.6 Principal Component Analysis

The results of Principal Component Analysis of hydraulic and substrate variables for 2006 and 2007 mesohabitat data is presented here. The percentage of variance derived from analyses of the 2006 and 2007 data is shown in Table 5.30. The amount of variance explained by each axis varies slightly between 2006 and 2007 and decreases with each axis. Shaw (2003, p111) suggests the axes with less than a certain percentage of variance should be disregarded because the variance cannot be separated from ‘random noise’. This suggests that Axis 1 in 2006 and 2007 is very slightly above the threshold. In both years axes 2 and 3 fall below Shaw's threshold whilst axes 4 and 5 are both above. Therefore, whilst Axis 1 in both 2006 and 2007 explains >45% of the variance in the data, this is only slightly above the minimum value.

Table 5.30 Eigenvector loadings from Principal Component Analysis of hydraulic and substrate variables.

Eigenvector loadings (% Variance)	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5
Minimum variance (Shaw, 2003, p111)	45.6	25.6	15.6	8.9	3.9
2006	45.7	20.4	15.4	12.0	6.4
2007	46.0	18.9	13.6	11.7	9.9

The PCA shows that the depth and velocity have the longest vectors in both 2006 (Table 5.31) and 2007 (Table 5.32) data, and therefore the strongest influence. The other four vectors have variable influence in 2006 and 2007. Figure 5:45 shows vectors plotted with reference to Axis 1 and Axis 2 for 2006 and Figure 5:46**Error! Reference source not found.** shows vectors for 2007. In both cases substrate (dominant and sub-dominant) opposes embeddedness and velocity opposes depth.

Table 5.31 Vector lengths from Principal Component Analysis of 2006 Data.

PCA 2006	Vector length	
Depth	0.99	
Velocity	0.99	
Dominant Substrate	0.63	
Embeddedness	0.60	
Sub-Dominant Substrate	0.52	

Table 5.32 Vector lengths from Principal Component Analysis of 2007 Data.

PCA 2007	Vector length	
Depth	0.89	
Velocity	0.80	
Embeddedness	0.81	
Sub-Dominant Substrate	0.72	
Dominant Substrate	0.63	

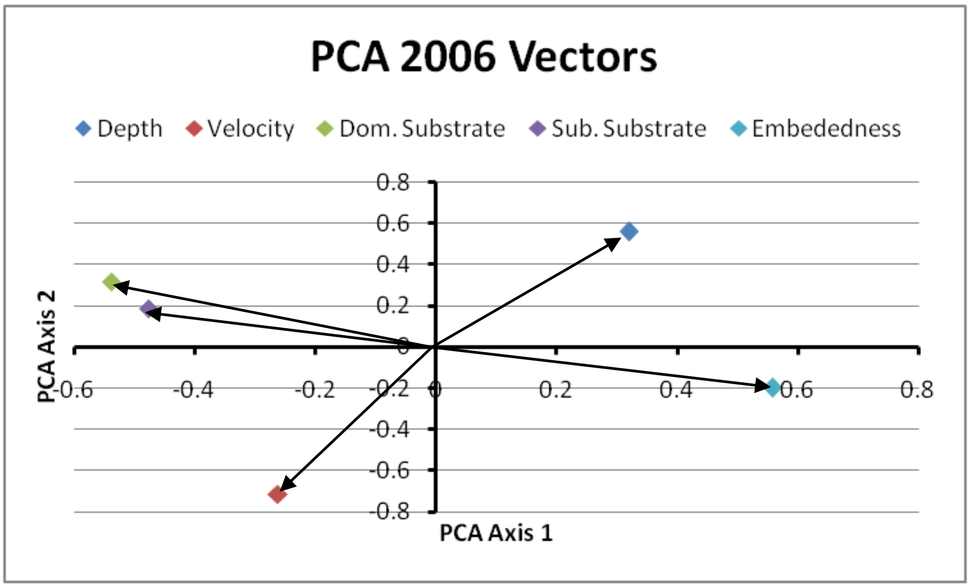


Figure 5:45 PCA vectors from 2006 Data

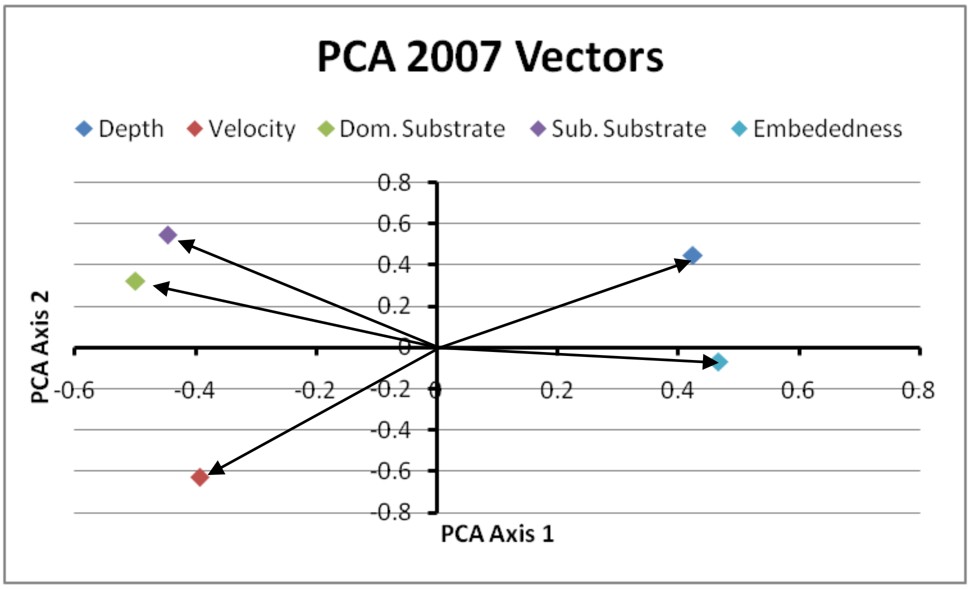


Figure 5:46 PCA vectors from 2007 Data.

Ordination plots from PCA as presented in Figure 5:47 and Figure 5:48 for 2006 and 2007 data respectively. Both figures show that data from NP mesohabitats plot towards the upper right, indicating low velocity, high embeddedness and smaller substrate size whilst UW plots towards high velocity, low embeddedness and coarser substrate. Data from SM and RP mesohabitats group towards the middle, with SM trending towards NP and RP towards UW. These plots suggest that there is no separation between the SFTs although NP and SM trend towards low velocity whilst RP and UW trend towards high velocity. UP SFT is placed in the central part.

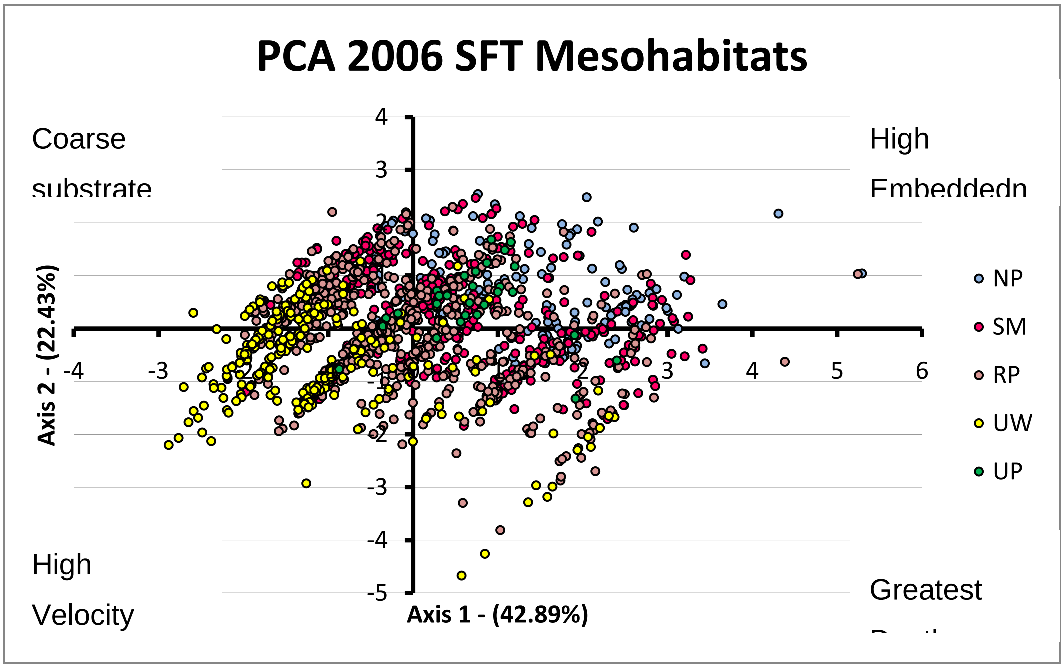


Figure 5:47 Ordination plot from PCA of 2006 data

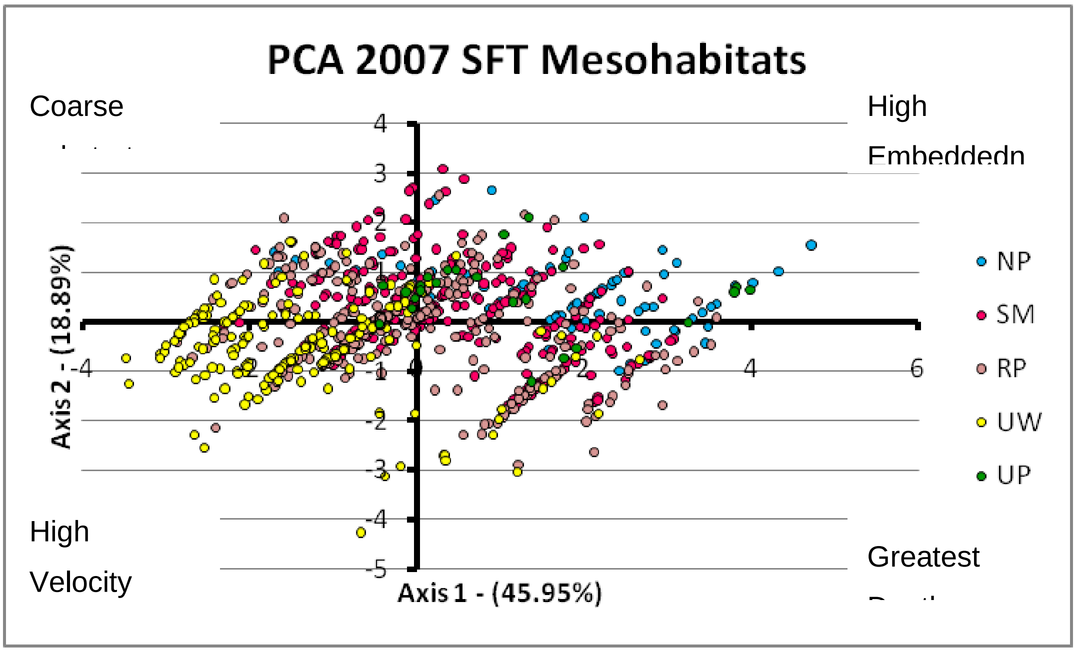


Figure 5:48 Ordination plot from PCA of 2007 data

Principal Component Analysis shows a negative relationship between depth and velocity, and between substrate size and embeddedness and a positive relationship between depth and embeddedness and between substrate size and velocity. All of these variables have been shown to be significantly different between SFTs in ANOVA and in pair-wise analyses.

5.7 Surface Flow Type Mesohabitat Diversity

The results of this research show that at high flows SFT diversity is low. Surface Flow Type mesohabitat maps of the River Windrush, Leigh Brook, Bailey Brook and the River Tern at the highest discharge surveyed show that ripple SFT mesohabitat dominates, although small areas of other SFT mesohabitat exist, often at the margins of the channel. SFT habitat maps of surveys at lower flows show greater SFT diversity. Figure 5:49 shows the range of Shannon-Weiner Diversity values based on SFT mesohabitats surveyed. Two surveys (Txa and Blxa) were the only SFT surveys conducted in 2006 when MiTG samples were not taken. Surveys are grouped by river and ranked by increasing discharge exceedence. Surveys conducted at high discharge are clearly less diverse than surveys at lower discharges. Survey T6 (River Tern, June 2007) was conducted at overbank discharge i.e. the river had burst its banks. Although the channel was dominated by RP SFT mesohabitat, the SM SFT mesohabitat on the floodplain adds diversity to the site and this is reflected in the Shannon-Weiner diversity index score.

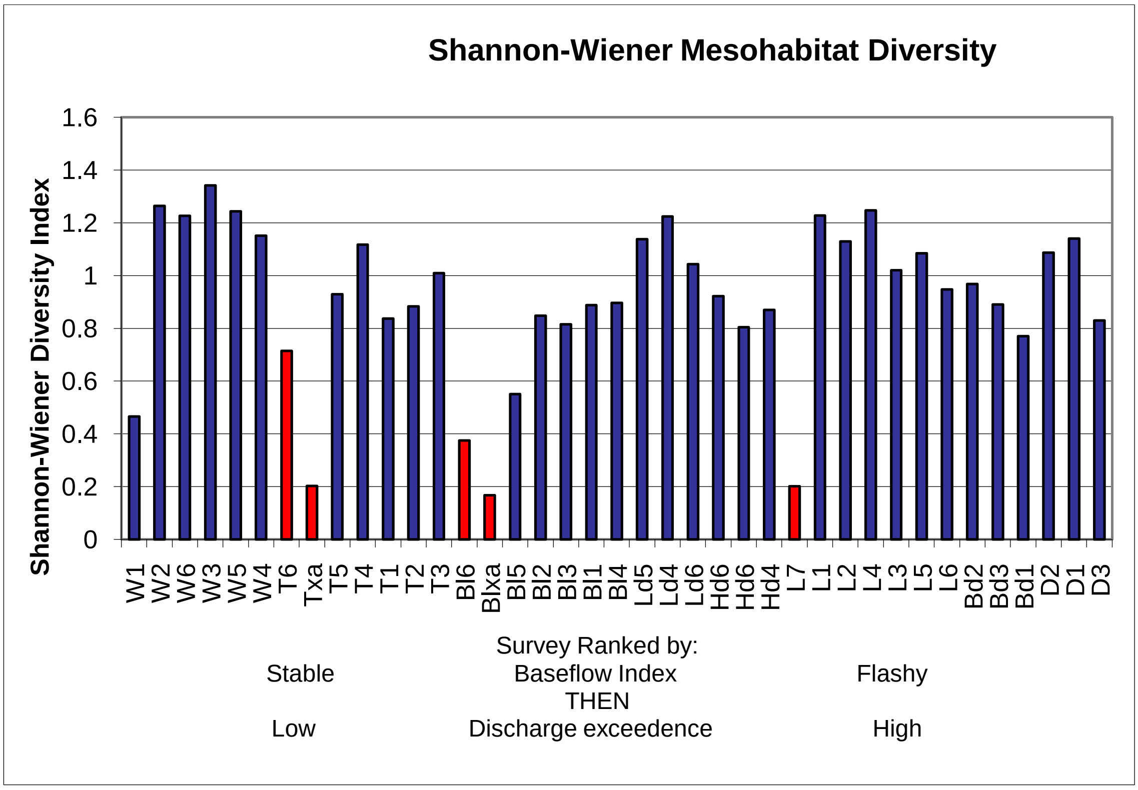


Figure 5:49 Habitat heterogeneity using Shannon Wiener Diversity Index for 36 Surface Flow Type mesohabitat surveys in 2006 and 2007 in eight British lowland rivers. Key: W = River Windrush; T = River Tern; Bl = Bailey Brook; Hd = Hadley Brook; L = Leigh Brook; Bd = Badsey Brook and D = Dowles Brook. Surveys conducted at high discharge are shown in red.

Spearman Rank Correlation showed that there is correlation between Shannon-Wiener Diversity and Discharge Exceedence, (R^2 = 0.343, P = 0.032 (sig. at 0.05 level)). The significant relationship between Shannon-Wiener Diversity and Discharge exceedence provides evidence that there is greater SFT mesohabitat diversity at lower discharges.

5.8 Discussion - Physical Distinctiveness of Surface Flow Types

Primary research question 1 considered whether SFT mesohabitats in British lowland rivers can be accurately recorded. This research has shown that estimating the extent of SFT mesohabitats by eye from the bank is practical, allowing a reach of several hundred metres to be assessed within one day of fieldwork, and is comparable to other methods (RHM, MesoHABSIM, NMCM and MesoCaSiMiR). Allowing SFT mesohabitats to be recorded as seen in the channel by recording the mosaic of habitat patches, offers advantages over methods that treat the whole channel width as one mesohabitat type (RHM and MesoHABSIM) and those where lateral variability is limited (NMCM). MesoCaSiMiR uses this type of recording and, although not explicit in the method, surveyors record areas that 'are visually distinct' which are likely to be driven at least to some degree by SFTs. In this research, survey 1 on the River Windrush using SFT mapping identified 11 mesohabitats in six categories (Section 5.3.1) where a method using a single habitat across the channel (RHM) would have identified five mesohabitats in four categories.

Recording mesohabitats 'as seen' provides a more complete picture of habitat structure (Shoffner and Royall, 2008) and reflects the spatial results of remotely sensed surveys (e.g. Gilvear *et al*., 1995; Large and Heritage, 2007; Milan *et al.,* 2010). Positional accuracy in this research was biased towards collecting large amounts of data within a short time and would have been improved if more accurate methods had been employed. For example, triangulation using a Total Station would have been more accurate although more time consuming. Differential GPS is useful (Dauwalter *et al.,* 2006) although poor signal quality, as experienced at sites used in this research, can prevent its use or degrade positional accuracy to that obtained here. Therefore, whilst positional accuracy in this research could have been improved in theory, in reality this might have not always have been possible and the new approach used was nevertheless appropriate to the mesohabitat scale at which this research project was focused and it is comparable with other, rapid, survey methods.

Accurate identification of mesohabitat classes is a pre-requisite of effective recording. Hydraulic classifications are widely used in Europe (Padmore, 1998; EA, 2003; Harby *et al*., 2004; Eisner *et al*., 2005). However, they are subjective in nature and prone to identification errors (Poole *et al*., 1997; Marcus 2002; Maddock and Hill, 2005). SFTs have been successfully used to define mesohabitat extent in other studies (Dyer and Thoms, 2006; Reid and Thoms, 2008) although concerns have been expressed in relation to the subjective nature of descriptions (Clifford *et al.,* 2006) and misclassification by operators (Poole, 1997; Marcus, 2002).

The results from this research suggest that SFT identification is sufficiently robust for use at scales used in this research and that recording and sampling in the core area of SFT mesohabitats reduced the likelihood of errors. Errors may result from either the misclassification of SFT mesohabitat type and/or extent (boundaries). Poole *et al*. (1997) criticised the repeatability of rapid habitat assessment methods because habitat identification is subjective and relies heavily on the skills and training of the surveyors. They advocate that surveyors are rigorously trained and assessed in the survey method and that the training/assessment is repeated at regular intervals to provide a degree of consistency between surveys and surveyors. This approach is taken by the UK EA in approving it's RHS surveyors, who undergo a four day training and assessment course, with two day re-fresher courses after three years (EA, 2003). To improve on the reliability of SFT identification the RHS uses photographs and descriptions and has produced a training aid using video footage of surface flow types used in surveyor training sessions. A similar approach to SFT mapping could provide consistency between surveys and surveyors at the scale of interest.

Primary research question 2 examined the distinctiveness of SFT mesohabitats by examining the physical characteristics of five SFTs encountered in lowland British rivers. The physical distinctiveness of SFTs has been addressed in several studies (Wadeson and Rowntree, 1998; Padmore, 1998; Reid and Thoms, 2008; Principie *et al.,* 2007) although their research sites were in upland rivers.

Water depth, mean column velocity, water velocity near the bed, at 0.05m above the bed and at the surface were significantly different between the five SFTs examined in this research. The results, however, suggest that adjacent SFT mesohabitats are more similar than those separated by at least one other type. Hence, NP & SM are similar as are SM & RP, RP and UW whilst NP & RP, SM & UW and NP & UW are more distinct. This corresponds with Reid and Thoms (2008) who concluded that hydraulic character differs significantly between SFTs, except NP/SM and SM/RP.

This research has shown that, using Kruskal-Wallace ANOVA and Pair-wise analysis with Mann-Witney *U* test, between flow types dominant and sub-dominant substrate size was significantly different between SFTs. Smaller substrate, often clay or silt, was associated with NP whilst gravel and pebble were associated with both SM and RP. The largest substrate size was associated with UW, commonly cobble, gravel and pebble. The increase in substrate size follows the downstream velocity gradient recorded in SFTs. This, again, is supported by Reid and Thoms (2008) who noted that fine substrate sizes were strongly related to NP, moderate sizes to RP and large sizes to UW. Principie (2007) concluded that macroinvertebrate communities were determined by a combination of surface flow type and substrate size, although their study sites were upland streams. The degree of embeddedness was examined in this research, and a significant difference found between SFTs. Embeddedness appears to be strongly associated with downstream velocity, as the fine material settling out in deeper, slow flowing areas. These results echo those of Lisle and Hilton (1992) who describe fine material winnowing from riffles into pools.

There is a long held view that flow (water velocity) is an important driver of both the physical (Petts, 1994; Wadeson, 1994; Gordon *et al.,* 2004) and the biological (Hynes, 1970; Lancaster and Belyea, 2006; Lancaster and Downes, 2010) environments. Velocity is spatially variable (Thorne and Hey, 1979; Wadeson and Rowntree, 1998; Clifford *et al.,* 2006) and linked to local morphology (Gordon *et al.,* 2004, Robert, 2003). Stream-wise velocity has been shown in this research to be significantly different between SFTs, although the rare SFT – UP – is less distinct; sharing characteristics of depth with NP and velocity with SM SFTs. Principal Component Analysis showed that depth and velocity are negatively related and that substrate size and embeddedness were opposed, the ordination plots from both 2006 and 2007 show the overlapping of SFT groups although it also suggests a NP > SM > RP > UW gradient which is supported by the means of the five variables considered and the output from HydroSignature Analysis.

Velocity is considered to be the primary variable in SFT mesohabitats (Hynes, 1970; Charlton, 1997). The energy derived from water velocity is largely (although not entirely) responsible for channel shape (including depth), substrate transport (substrate size and embeddedness) and turbulence (SFTs). Downstream velocity is recognisable on the surface and has been shown here to have a significant correspondence with near-bed velocities in most of the SFTs investigated here (Section 5.4.4).

HydroSignature analysis demonstrated that depth and velocity is related to SFT mesohabitat, although SM and RP less so. Apart from UP SFT, depth decreases and velocity increases along the gradient NP > SM > RP > UW. Depth, velocity and bed roughness combine with channel shape to create turbulence which is manifested as distinct patterns on the water surface. Wadeson and Rowntree (1998) concluded that hydraulic biotopes, apart from rapid and cascade, where hydraulically distinct, although there is overlap in their data between groups. The SFTs investigated in this research have shown that those with greatest surface disturbance (RP and UW) are located in areas of channel with shallow water and greatest water velocity, suggesting that these factors are driving the SFT. Clearly this is a simplification of complex hydraulics (Lancaster and Belyea, 2006; Harvey and Clifford, 2009) although describing mesohabitat scale hydraulics necessarily requires simplification or generalisation to be effective. Time-averaged downstream velocity was measured in this study, which is commonly used in these types of study, although it measures only one component of water movement. Reid and Thoms (2008) used three dimensional time-averaged velocities from which turbulence (in three dimensions) was determined providing more detail of the complexities of flow. Harvey and Clifford (2009) measured velocity as a time series, identifying the fluctuations in flow at the microhabitat level, further work at this scale of investigation is probably required to address the issues raised by Lancaster and Belyea (2010).

SFT extent varies with stage, a quality described by Dyer and Thoms (2006) and proposed by them as a means of identifying appropriate discharge in regulated rivers. At high stage RP, analogous to runs, dominate the channel (Leopold *et al*., 1964). In this research it is clear that bed controls on SFT are evident, e.g. in the location and extent of UW SFT in Leigh Brook (Section 5.3.2) and UP flow on the outside of bends on the River Windrush (Section 5.3.1) similar to those discussed by Thorne and Hey (1979) although a deep hollow in the bed was responsible for UP flow at the downstream end of 2007 reach. Diversity of SFT mesohabitats was low at high discharges, generally increasing with lower discharge. However the relationship between SFT extent and stage is not straightforward as, at low discharge, bed shape has greater influence on hydraulics (Wadeson and Rowntree, 1998).

Reid and Thoms (2008, p1054) suggest that SFT mapping could be an effective, efficient tool for assessing physical habitat heterogeneity and, potentially, biological diversity. They suggest that the biological relevance of SFTs needs testing in other types of stream, e.g. lowland and unregulated. The results of this research shows a similar range of physical conditions in SFTs (overlapping ranges of depth, velocity and substrate size with significant differences between SFTs in ANOVA and pair-wise analysis) to those found in an upland regulated stream by Reid and Thoms (2008). This suggests that there is merit in examining the relationship between SFTs and macroinvertebrate communities in British lowland rivers and will add to current understanding of the biological relevance of mesohabitats, an area of study which is currently of importance to river management.

HydroSignature (Le Coarer, 2005) was used to examine the depth/velocity composition of SFT mesohabitats. The results suggest that HydroSignature distinguished NP, UW and UP SFTs better than SM and RP, which occupy similar cells in the matrix at different discharges. Section 5.3.10 shows that as discharge increases, SM SFT decreases as RP SF increases. The HydroSignature results were derived from data collected using a sub-optimal method – NOXY3 (Section 4.4.5). Collecting data where the spatial (X, Y) co-ordinates are known using a Triangular Irregular Network (TIN) should improve the accuracy of the analysis (Le Coarer, 2005), it is assumed therefore, that data collected using an optimal method would be more robust, although that has not been tested here. This research suggests that HydroSignature could be useful in determining the nature of depth/velocity characteristics of SFT mesohabitats, two factors that are important variables determining macroinvertebrate habitat, by allowing comparison of results either at a site over different discharges or before and after restoration work, or between different sites.

In-stream macrophytes were uncommon in this research and probably responsible for an increase in the extent of rippled flow in Badsey Brook (Section 5.3.5), because of increased turbulence caused by the vegetation in the water column. In this study, macrophyte growth in the channel was limited, apart from Badsey Brook only the River Tern (2006 site) had any noticeable growth. The use of SFTs as mesohabitat descriptors in rivers with significant macrophyte growth (e.g. chalk streams) would have to take into account the increased turbulence generated, alongside the change in macroinvertebrate community associated with macrophytes, *e.g*. Leptophlebiidae (Elliott *et al*., 1988). In addition, the seasonal nature of macrophyte growth and presence is likely to lead to a more complex relationship between discharge and SFT. For example, for a given discharge in late winter when macrophyte presence may be low, the depth is likely to be lower and velocity higher than for the same discharge in late summer when macrophytes are present, channel roughness increases and hence depth is higher and velocity lower. This will lead to different SFTs being present in summer and winter for the same discharge due to changes in macrophytes and their corresponding effect on the hydraulic environment. The exact nature of this effect is worthy of further research.

5.8.1 The Physical Nature of Surface Flow Type Mesohabitats

Despite the complexities of physical variables recorded in the five SFTs, and the overlap between SFTs within those ranges, some generalisations about the physical properties of each SFT mesohabitat investigated in this research can be made. The figures in the brackets show the IQR from all surveys, velocity is mean column velocity. Graphic interpretations of those conditions are presented in (Figure 5:38 and Figure 5:44).

No Perceptible

No perceptible SFT mesohabitats have a flat water surface with very little downstream flow or with upstream (eddy) flow, (-0.06 to 0.013m/sec). These SFT mesohabitats are relatively deep (0.32 – 0.75m), with clay, silt, sand or gravel substrate completely embedded with fine material.

Smooth

Smooth SFT mesohabitats have a flat water surface with some downstream flow (0.10 – 0.36m/sec). The water is moderately deep (0.27 – 0.57m) with sand or gravel substrate which is embedded 50% - 100% with fine material.

Rippled

Ripple SFT mesohabitats have small (<1cm) surface ripples, which move downstream or laterally, and moderate downstream velocity (0.20 – 0.49m/sec). The water is slightly shallower than smooth mesohabitats (0.20 – 0.50m) with sand, gravel or pebble substrate which is embedded 50% - 100% with fine material.

Unbroken Wave

Unbroken wave SFT mesohabitats have small waves that are stationary in relation to the river bed, and do not have white tumbling crests, downstream water velocity is fast (0.39 – 0.70m/sec). Unbroken wave mesohabitats are relatively shallow (0.11 – 0.26m) with a coarse substrate of gravel, pebble or cobble which is embedded with 25%-75% with fine material.

Upwelling

Of the five SFT mesohabitats investigated UP was the rarest. The water surface is flat to slightly convex and often roughly circular in shape, driven by upwardly moving water spreading out as it reaches the surface before descending on the margins of the SFT, therefore it has the appearance of boiling water. This SFT mesohabitat is associated with flow on the outside of meander bends or with obstructions, tree roots or bed morphology all of which deflect flow causing some to move vertically. Although mean column velocity is low (0.09 – 0.33m/sec) vertical velocity is important (not measured in this research). Upwelling SFT mesohabitats are deep (0.45 – 0.85m), with substrates of sand or gravel and embeddedness more than 75%.

5.9 Summary

CHAPTER 5 analysed the distinctiveness of SFT mesohabitats using spatial extents, depth and velocity, substrate and embeddedness. The results show that at a mesohabitat scale:

- Surface Flow Type mesohabitats in British lowland rivers can be identified and recorded, with improvements over other similar methods.
- The physical characteristics of NP, SM, RP, UW SFT mesohabitats in British lowland rivers are distinctive in terms of both water depth and mean column velocity.
- There is correlation between water velocity at the surface and water velocities near the bed in NP, SM, RP, UW SFT mesohabitats in British lowland rivers.
- Substrate and embeddedness is distinctiveness between NP, SM, RP and UW SFT mesohabitats in British lowland rivers.
- UP SFT mesohabitat is rare and less distinguishable from the four other types investigated.

Five SFTs were investigated at the mesohabitat scale and their extents were found to be recordable. Spatial accuracy was diminished by the scale of investigation and the nature of the recording protocol; however the results are comparable with other mesohabitat survey methods (MesoHABSIM, RHS, NMCM and MesoCaSiMiR).

The distinctiveness of physical characteristics of each of the SFT mesohabitat were found to be variable. However, both analysis of variance and pair-wise analysis showed significant differences between the SFTs. These contrary findings suggest some differences between SFTs although the ability to discriminate between them is impaired. Water depth and velocity ranges within each SFT were considerable; resulting in similar depths and velocities being found in several SFTs. This range of values relate to the range of discharges surveyed. These finding are weaker than found by Reid and Thoms (2008) and a likely to be a result of this research investigating discharges of between Q_{99} and Q_1. Mesohabitat type diversity varied with discharge, and whilst the results are not conclusive, generally at higher flows diversity was less than at low flows. Whilst there are statistically significant differences between the physical variables in the five SFTs investigated there are also other examples where the distinctiveness of SFT mesohabitats is less clear, particularly between SM and RP mesohabitats (Section 5.4.5). The rare flow type, UP, was consistently the one that was least distinctive. The question of the biological relevance of NP, SM, RP, UW and UP SFT mesohabitats in investigated in CHAPTER 6.

6 RESULTS: MACROINVERTEBRATE COMMUNITIES AND SURFACE FLOW TYPE MESOHABITATS

6.1 Introduction

CHAPTER 6 will consider the relationship between macroinvertebrate communities and NP, SM, RP, UW and UP SFT mesohabitats. Statistical analyses examine differences between macroinvertebrate samples collected from a range of SFT mesohabitats. Simple measures *e.g.* abundance and richness are presented first, TWINSPAN will be used to group macroinvertebrate samples. Detrended Correspondence Analysis will be used to identify axis length to determine the suitability for Canonical Correspondence Analysis which will be used to identify relationships between macroinvertebrate communities and the physical variables. The Chi-square test will be use to identify MiTGs significantly associated with SFT mesohabitats. This analysis will answer Primary Research Question three (Section 1.4.)

6.2 Macroinvertebrate Samples

A total of 375 macroinvertebrate samples were collected from 139 SFT mesohabitats. In 2006, 200 macroinvertebrate samples from 73 SFT mesohabitats were collected, and in 2007 175 macroinvertebrate samples from 66 SFT mesohabitats (Table 6.1).

Forty-three Macroinvertebrate Taxonomic Groups (MiTGs) were identified in the samples, seven MiTGs containing <5 individuals were removed from further analysis. Fewer samples were obtained during 2007 because high discharges during June prevented samples being obtained from Bailey Brook and the River Tern.

Table 6.1 Macroinvertebrate sample points by Surface Flow Type mesohabitat recorded in eight British lowland rivers between 1st April and 30th June 2006 and 2007.

	Macroinvertebrate Samples	Surface Flow Type Mesohabitats Sampled
2006		
No perceptible	46	19
Smooth	49	17
Ripple	54	18
Unbroken wave	41	14
Upwelling	10	5
Total	200	73
2007		
No perceptible	22	12
Smooth	48	16
Ripple	48	17
Unbroken wave	48	16
Upwelling	9	5
Total	175	66
Overall total	375	139

In samples collected during 2006, macroinvertebrates from 43 MiTGs were identified, ranging from a minimum of 5 to a maximum of 6712 individuals. In 2007, 37 MiTGs were identified, (1 to 7440 individuals). The MiTGs are shown in Figure 6:1 and Figure 6:2 with numbers of individuals from each group (note log^{10} scale on the x-axis). The relative abundance of individuals in 2006 in each SFT mesohabitat varied and Figure 6:3 shows the percentage MiTGs in each SFT mesohabitat in 2006. This suggests that some MiTGs favour lower energy SFT mesohabitats, *e.g.* 52% of Oligochaeta (n= 1 081) were found in NP SFT mesohabitats, whilst 88% of Glossosomatidae (n = 114) were found in UW SFT mesohabitats. These data suggest a relationship between SFT mesohabitats and the benthic macroinvertebrate community. In 2007 the proportions differ from that of 2006 (Figure 6:4), with macroinvertebrates less well associated with SFT mesohabitats. Seven MiTGs collected in 2006 were not found in 2007, in all cases these MiTG individuals were found in a few samples. Although the reason is not clear it is likely that the use of new sites in 2007 was a factor. Heavy rain resulted in higher flows in June 2007 and may have removed some individuals, although this does not account for the lack of individuals in the earlier part of the survey season. Two surveys at the end of June 2007 were restricted to SFT mapping due to water depth and velocity, they were not repeated later because of bed mobility induced drift disturbing community composition.

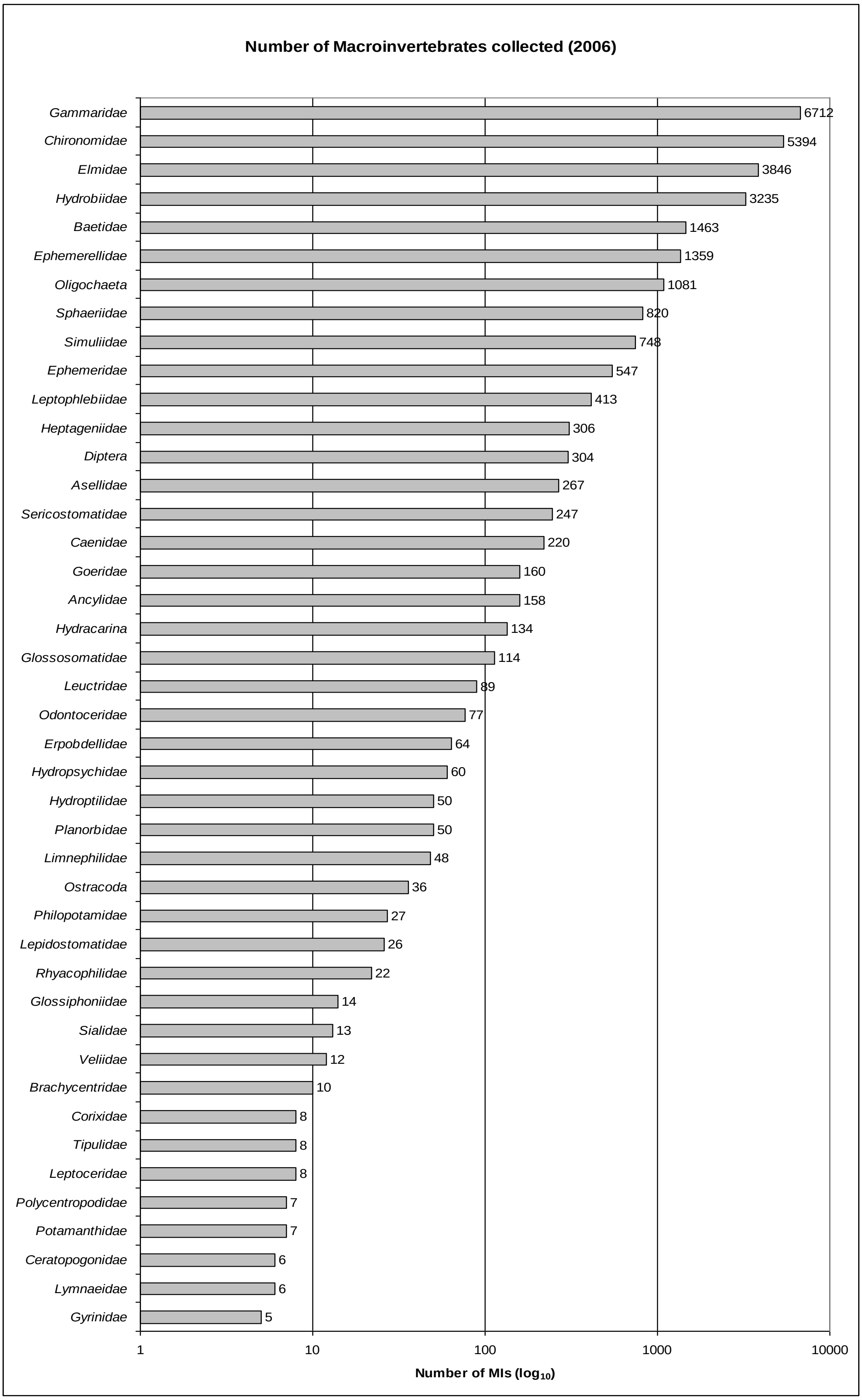


Figure 6:1 Number of macroinvertebrate individuals in all samples from six British lowland rivers in 2006. (Note logarithmic scale on x-axis).

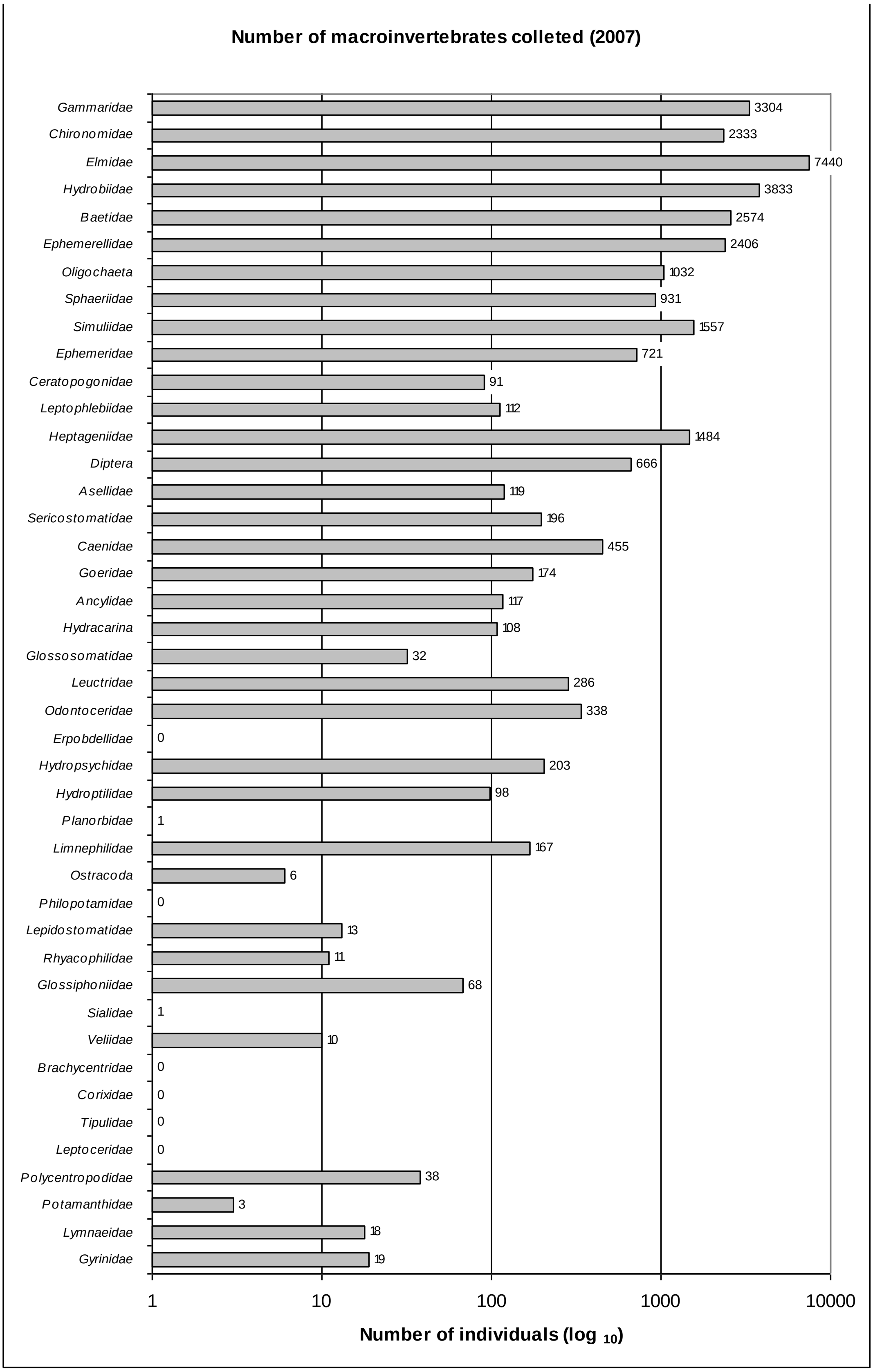


Figure 6:2 Number of macroinvertebrate individuals in all samples from six British lowland rivers in 2007. (Note logarithmic scale on x-axis).

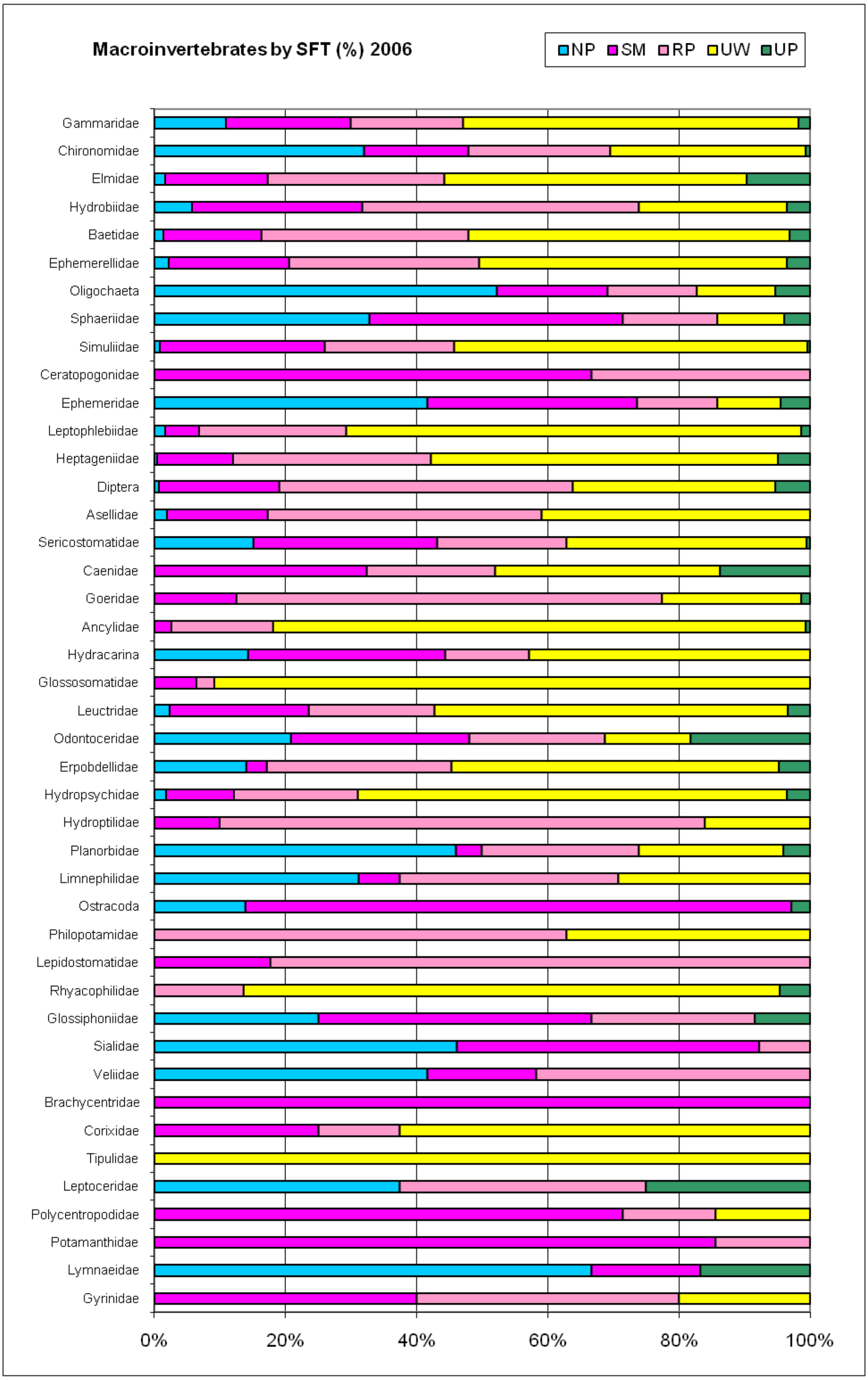


Figure 6:3 Percentages of macroinvertebrates in No perceptible, Smooth, Ripple, Unbroken wave and Upwelling Surface Flow Type mesohabitats, in all samples from six British lowland rivers, in 2006. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

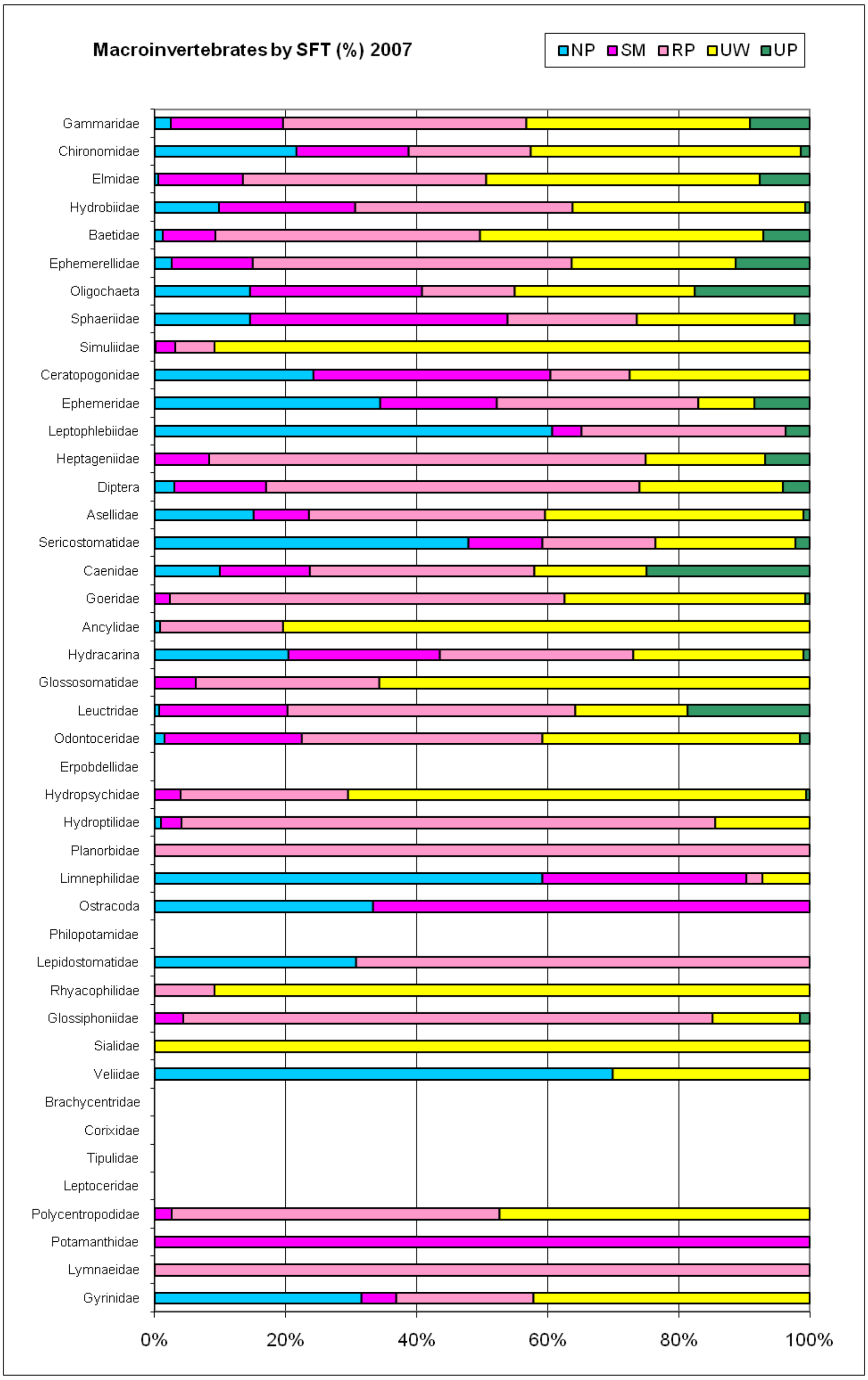


Figure 6:4 Percentages of macroinvertebrates in No perceptible, Smooth, Ripple, Unbroken wave and Upwelling Surface Flow Type mesohabitats in all samples from six British lowland rivers, in 2007. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Figure 6:3 and Figure 6:4 show the range of MiTGs present in samples collected from 2006 and from 2007, whilst Figures 6:3 and 6:4 show the percentages of MiTGs found in samples from the five SFTs investigated. Although these data show the relative percentage of MiTGs by SFT it does not take into account sample size, nor does it indicate a statistical relationship – that was investigated later in this research.

6.3 Macroinvertebrate metrics

6.3.1 Introduction

Simple measures of macroinvertebrate community in SFT mesohabitats were investigated first. Measures of MiTG abundance or richness in SFT mesohabitats could provide useful information about the relative abundance/richness of SFTs. The ASPT can be used to infer the dissolved oxygen rank between SFTs. Diversity and equitability measures could provide information on the relative size of MiTGs within a SFT mesohabitat. LIFE scores have been derived for many MiTGs, it incorporates a velocity category against which to test the nature of SFT mesohabitat conditions and Any of these measures would be useful in determining the biological relevance of SFT mesohabitats even if the individual MiTGs comprising the community were not statistically related.

6.3.2 Surface Flow Type Mesohabitat and Macroinvertebrate Taxonomic Group Relative Abundance

Data from both 2006 and 2007 shows a wide range of individual macroinvertebrates present in samples. Based on 2006 results (n=200) (Figure 6:5), UW SFT mesohabitat supported the largest mean number of individuals per sample, followed by RP, SM and UP SFT mesohabitats with NP SFT mesohabitat supporting the fewest. In the 2007 samples (n=175) UW SFT mesohabitat again supported the greatest number of individuals, followed by UP, RP, SM and NP SFT mesohabitats (Table 6.2). Broadly, more macroinvertebrate individuals were found in samples from more turbulent SFT mesohabitats although UP SFT mesohabitat differs in 2006 and 2007 data. However, even within the 25 – 75thpercentiles there is a great deal of overlap, particularly between NP, SM, RP and UP SFTs.

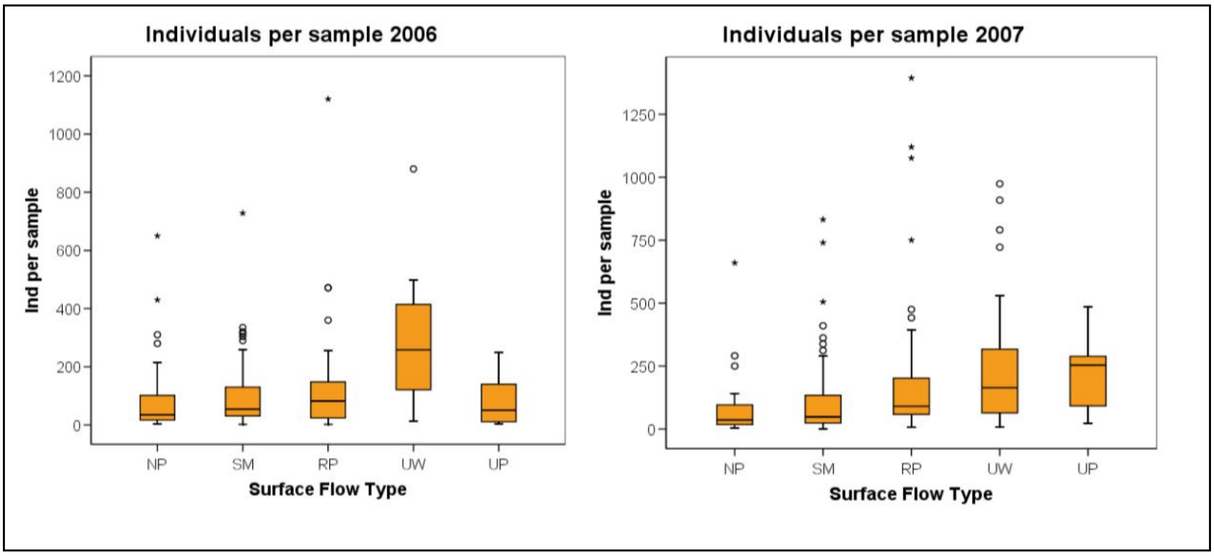


Figure 6:5 The range of macroinvertebrate abundance, grouped by Surface Flow Type mesohabitats, from samples collected during 2006 and 2007 in eight British lowland rivers. Key: NP -No perceptible, SM - Smooth, RP - Ripple, UW - Unbroken wave, UP – Upwelling.

Table 6.2 Mean macroinvertebrate abundance, grouped by Surface Flow Type mesohabitats, from samples collected during 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Year	NP	SM	RP	UW	UP
2006	80.67	112.39	128.02	269.65	91.80
2007	93.05	121.73	206.67	241.07	215.78

The results from analysis with Kruskal-Wallis ANOVA show that there is a significant difference (p = <0.05) between MiTG abundance (2006: X^2 = 41.606; df = 4; Sig = 0.000. 2007: X^2 = 26.498; df = 4; Sig = 0.000) in SFTs in both 2006 and 2007, whilst the Mann-Whitney *U* Test (Table 6.3) showed that in 2006 there were six combinations of surface flow type (60%) with significant differences between macroinvertebrate abundance; in these cases H_0 was rejected, indicating that in these cases the data range, and specifically the mean, were different. In 2007, there were significant differences between six combinations (60%), although the pairs differ from those found to be significant in 2006.

Table 6.3 Mann-Whitney *U* test of macroinvertebrate abundance between Surface Flow Type mesohabitats, 2006 and 2007 data collected from eight British lowland rivers. (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

	Relative Macroinvertebrate Abundance				
	NP	**SM**	**RP**	**UW**	**UP**
2006					
No Perceptible					
Smooth	.036 *				
Rippled	.024 *	.590 n.s.			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.834 n.s.	.505 n.s	.454 n.s.	.002 **	
2007					
No Perceptible					
Smooth	.364 n.s.				
Rippled	.005 **	.004 **			
Unbroken wave	.000 **	.000 **	.107 n.s.		
Upwelling	.017 *	.046 *	.352 n.s.	.917 n.s.	

Although there are significant differences between SFTs in Kruskal-Wallis ANOVA and some pairs using the Mann-Witney *U* Test, the results suggest that NP and SM are similar and differ from RP and UW. This is similar to the findings of Reid and Thoms (2008).

6.3.3 Surface Flow Type Mesohabitat and Macroinvertebrate Taxonomic Group Richness

Data from both 2006 and 2007 shows a wide range of MiTGs present in samples. Based on 2006 results (n=200) (Figure 6:6), UW SFT mesohabitat supported the largest mean number of MiTGs per sample, followed by UP, RP, SM SFT mesohabitats with NP SFT mesohabitat supporting the fewest. In the 2007 samples (n=175) UW SFT mesohabitat again supports the greatest number of MiTGs, followed by RP, UP, SM and NP SFT mesohabitats (Table 6.4). Broadly, more MiTGs were found in samples from more energetic SFT mesohabitats. There is slightly more separation of MiTG richness between SFTs than was evident with abundance. The inter-quartile range in 2006 data shows SM and RP are very similar, as are UW and UP, whilst the 2007 data shows NP and SM are similar and separate from RP, UW, and UP.

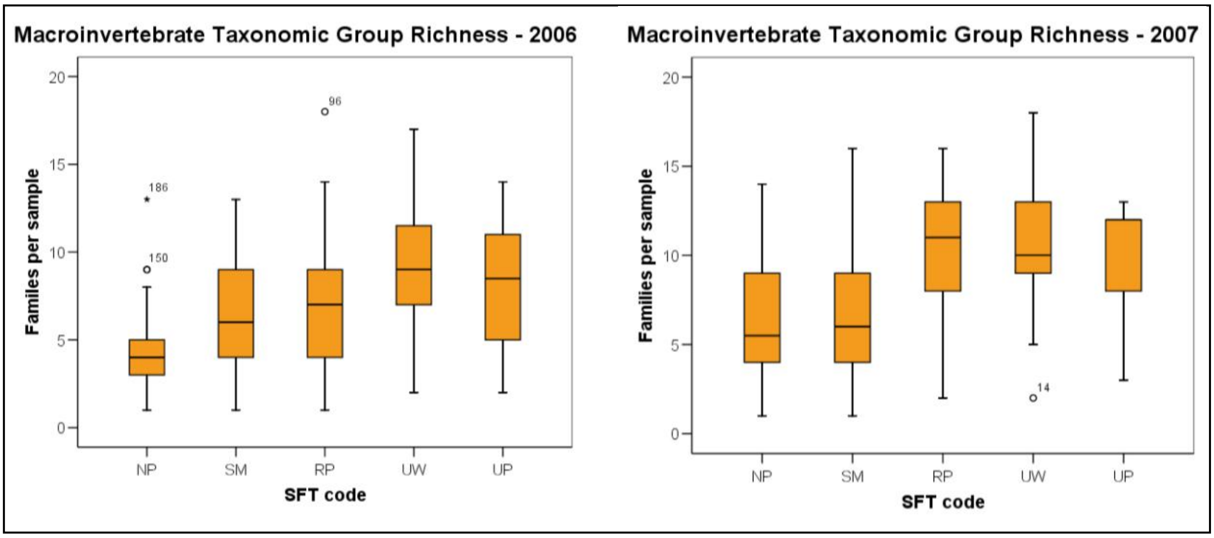


Figure 6:6 The range of Macroinvertebrate Taxonomic Group richness (defined by the number of families per sample) by Surface Flow Type mesohabitats from samples collected during 2006 and 2007 in eight British lowland rivers. Key: NP -No perceptible, SM - Smooth, RP - Ripple, UW - Unbroken wave, UP – Upwelling.

Table 6.4 Mean Macroinvertebrate Taxonomic Group richness, grouped by Surface Flow Type mesohabitats, from samples collected during 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Year	NP	SM	RP	UW	UP
2006	4.16	6.70	6.89	9.10	8.20
2007	6.45	6.88	10.23	10.40	9.56

The results from analysis with Kruskal-Wallis ANOVA show that there is a significant difference (p = <0.05) between MiTG richness (2006: X^2 = 41.688; df = 4; Sig = 0.000. 2007: X^2 = 37.523; df = 4; Sig = 0.000) in SFTs in both 2006 and 2007, whilst the results of the Mann-Whitney *U* Test (Table 6.5) showed that in 2006 there were six combinations (60%) where there were significant differences between MiTG richness, in these cases H_0 was rejected with NP SFT and UW SFT mesohabitats being the most significantly different. In 2007, there were significant differences between five combinations (50%), although the pairs differ from those in 2006.

Table 6.5 Mann-Whitney *U* test of macroinvertebrate taxonomic richness between Surface Flow Type mesohabitats, from samples collected during 2006 and 2007 in eight British lowland rivers (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

	Macroinvertebrate Taxonomic Richness				
	NP	**SM**	**RP**	**UW**	**UP**
2006					
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.902 n.s.			
Unbroken wave	.000 **	.004 **	.005 **		
Upwelling	.004 **	.273 n.s	.294 n.s	.641 n.s.	
2007					
No Perceptible					
Smooth	.599 n.s.				
Rippled	.000 **	.000 **			
Unbroken wave	.000 **	.000 **	.877 n.s.		
Upwelling	.057 n.s.	.048 *	.716 n.s	.683 n.s	

These results suggest that there are groups of SFT with similar MiTG richness. In 2006 NP was significantly different from all others, SM and RP were similar as were UW and UP. In the 2007data NP and SM are similar, as are RP and UW.

6.3.4 Surface Flow Type Mesohabitat and Average Score per Taxon

Data from both 2006 and 2007 shows a wide range of ASPT calculated from samples grouped by individual SFT mesohabitat. Based on 2006 results (n=200) (Figure 6:7), UP SFT mesohabitat had the highest ASPT, followed by RP, UW and SM SFT mesohabitats and NP SFT mesohabitat. In the 2007 samples (n=175) again UP SFT mesohabitat had the highest score, followed by RP, UW, SM and NP SFT mesohabitats (Table 6.6).

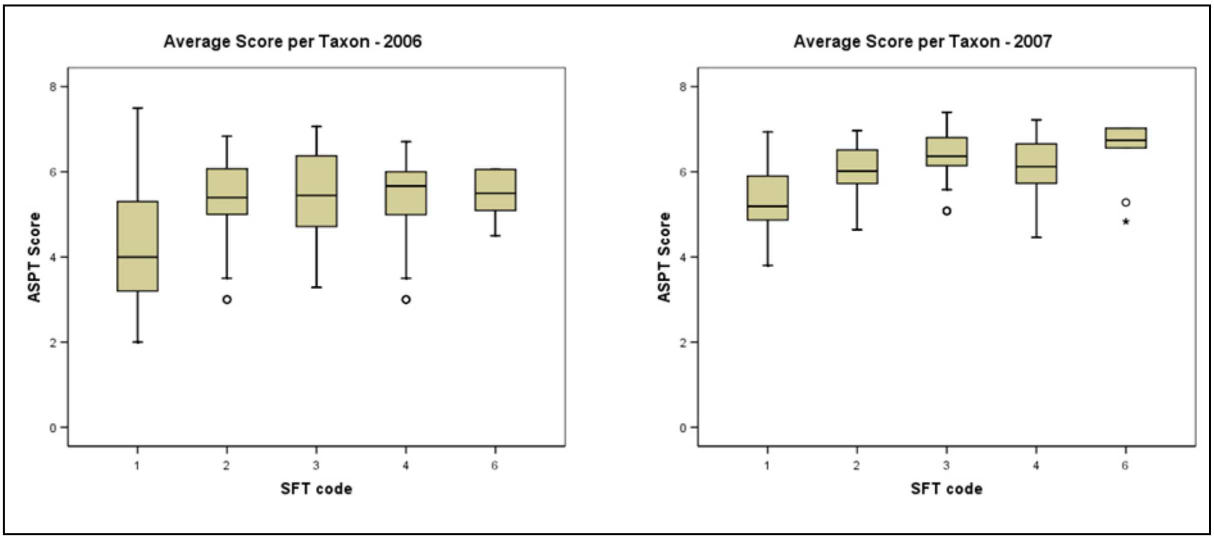


Figure 6:7 The range of Average Score Per Taxon by Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers. Key: 1 -No perceptible, 2 - Smooth, 3 - Ripple, 4 - Unbroken wave, 5 – Upwelling.

Table 6.6 Mean Average Score Per Taxon from 2006 and 2007, grouped by Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Year	NP	SM	RP	UW	UP
2006	4.14	5.34	5.36	5.34	5.51
2007	5.33	6.01	6.35	6.06	6.44

The results from analysis with Kruskal-Wallis ANOVA show that there is a significant difference (p = <0.05) between ASPT (2006: X^2 = 30.014; df = 4; Sig = 0.000. 2007: X^2 = 27.294; df = 4; Sig = 0.000) in SFTs in both 2006 and 2007, whilst the results of the Mann-Whitney *U* Test (Table 6.7) showed that in 2006 there were four combinations (40%) with significant differences between ASPT; in these cases H_0 was rejected; NP being the most significantly different. In 2007, there were significant differences between seven combinations (70%), although the pairs differ from those in 2006. NP SFT mesohabitat is significantly different from other SFT mesohabitats.

Table 6.7 Mann-Whitney *U* test of Average Score Per Taxon between Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling; ASPT – Average Score per Taxon.

	Average Score Per Taxon				
	NP	**SM**	**RP**	**UW**	**UP**
2006					
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	1.000 n.s.			
Unbroken wave	.000 **	.898 n.s.	.973 n.s.		
Upwelling	.002 **	.936 n.s.	.868 n.s	.852 n.s.	
2007					
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.025 *			
Unbroken wave	.000 **	.716 n.s.	.045 *		
Upwelling	.002 **	.032 *	.237 n.s.	.088 n.s.	

6.3.5 Surface Flow Type Mesohabitat and Shannon-Wiener Diversity

Data from both 2006 and 2007 shows the range of Shannon-Wiener Diversity scores per sample, calculated from samples grouped by individual SFT mesohabitat. Based on 2006 results (n=200) (Figure 6:8) UP SFT mesohabitat had the highest score, followed by UW, RP, SM and NP SFT mesohabitats. In the 2007 samples (n=175) RP SFT mesohabitat had the highest score, followed by UW, UP, SM and NP SFT mesohabitats (Table 6.8). Broadly, higher values were recorded in samples from more turbulent SFT mesohabitats.

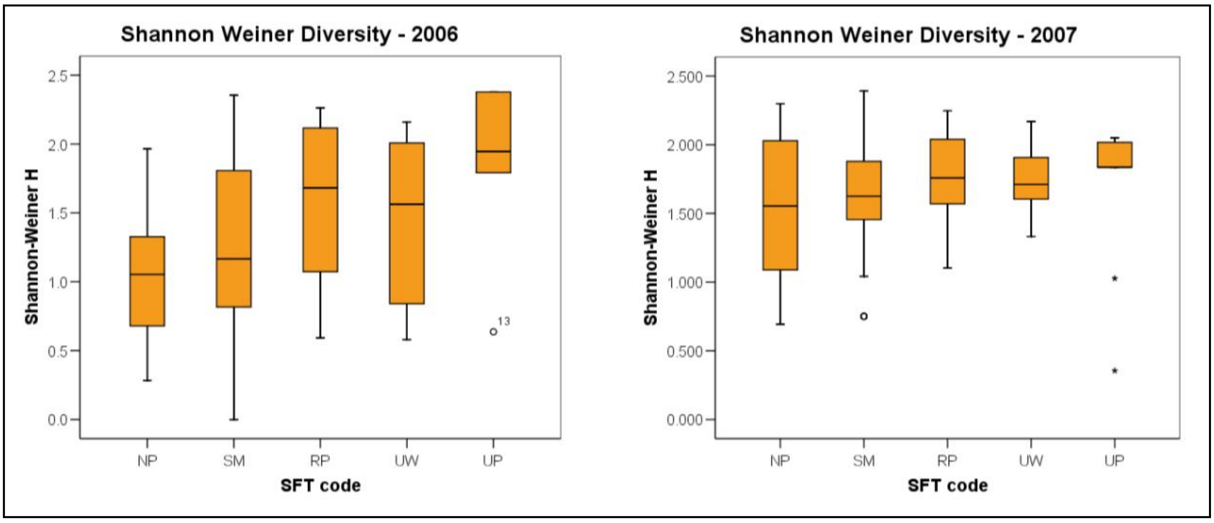


Figure 6:8 Range of Shannon-Wiener Diversity values by Surface Flow Type from samples collected during 2006 and 2007 in eight British lowland Rivers. Key: NP -No perceptible, SM - Smooth, RP - Ripple, UW - Unbroken wave, UP – Upwelling.

Table 6.8 Mean Shannon-Wiener Diversity values per sample, grouped by Surface Flow Type mesohabitat, collected during 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Year	NP	SM	RP	UW	UP
2006	1.04	1.30	1.57	1.42	1.91
2007	1.53	1.63	1.77	1.76	1.87

The results from analysis with Kruskal-Wallis ANOVA show that there is a significant difference (p = <0.05) between MiTG diversity in 2006: X^2 = 30.572; df = 4; Sig = 0.000. but not in 2007 (X^2 = 7.759; df = 4; Sig = 0.101.) whilst the results of the Mann-Whitney *U* Test (Table 6.9) showed that in 2006 there were seven combinations (70%) with significant differences between Shannon-Wiener diversity score; in these cases H_0 was rejected; SM and RP SFT mesohabitats being similar. In 2007, there were significant differences between two combinations (20%). Both significant differences involved NP with RP and UW habitats.

Table 6.9 Mann-Whitney U test of Shannon-Wiener Diversity values between Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

	Shannon-Wiener Diversity				
	NP	**SM**	**RP**	**UW**	**UP**
2006					
No Perceptible					
Smooth	.036 *				
Rippled	.000 **	.013 *			
Unbroken wave	.001 **	.291 n.s.	.113 n.s.		
Upwelling	.000 **	.002 *	.076 n.s.	.032 *	
2007					
No Perceptible					
Smooth	.427 n.s.				
Rippled	.048 *	.051 n.s.			
Unbroken wave	.041 *	.092 n.s.	.446 n.s.		
Upwelling	.663 n.s.	.277 n.s.	.844 n.s.	.423 n.s.	

Although there are significant differences between many SFTs in both years the range of data in each SFT is considerable resulting in overlap between SFTs, making them less distinct than might appear from the Mann-Whitney *U* Test results alone.

6.3.6 Surface Flow Type Mesohabitat and Shannon-Weiner Equitability

Data from both 2006 and 2007 shows the range of equitability scores per sample, calculated from samples grouped by individual SFT mesohabitat. Based on 2006 results (n=200) (Figure 6:9), UP SFT mesohabitat had the highest score, followed by RP, NP, UW and SM SFT mesohabitats. In the 2007 samples (n=175) NP and UW SFT mesohabitat tied with the highest score, followed by SM, RP and UP SFT mesohabitats (Table 6.10). Ranges recorded in NP, SM, RP and UW SFTs in 2006 are similar although the medians differ. In 2007 the ranges are slightly less although there is still considerable overlap between SFTs.

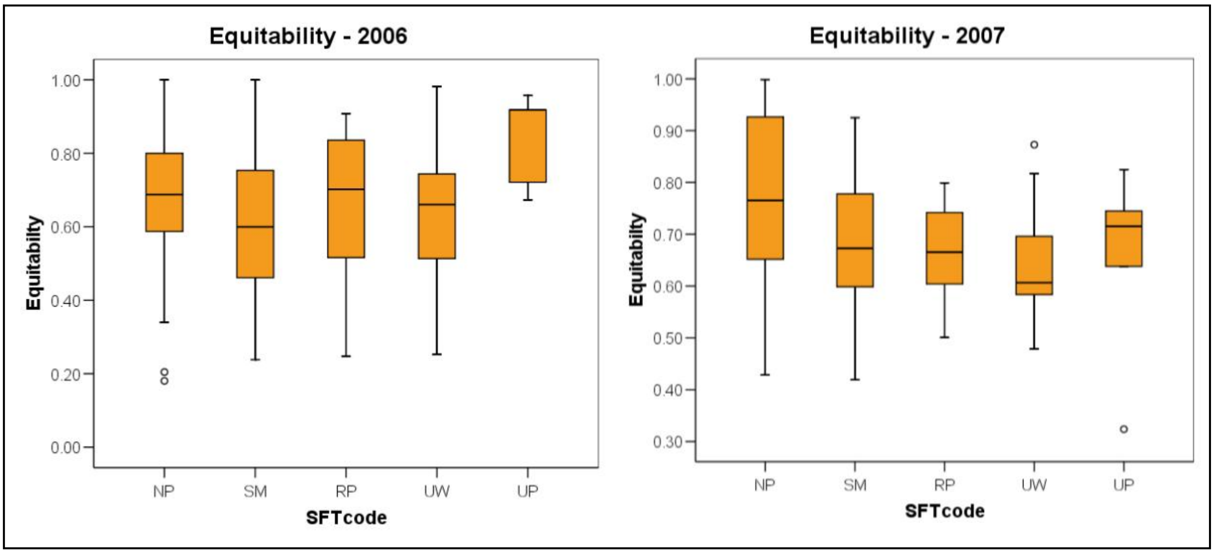


Figure 6:9 The range of Shannon-Weiner Equitability values by Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers. Key: NP -No perceptible, SM - Smooth, RP - Ripple, UW - Unbroken wave, UP – Upwelling.

Table 6.10 Mean Shannon-Weiner Equitability per Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Year	NP	SM	RP	UW	UP
2006	0.65	0.59	0.66	0.62	0.84
2007	0.77	0.69	0.66	0.77	0.65

The results from analysis with Kruskal-Wallis ANOVA show that there is a significant difference (p = <0.05) between MiTG equitability in 2006 (X^2 = 41.688; df = 4; Sig = 0.000) although not in 2007 (X^2 = 8.223; df = 4; Sig = 0.084), whilst he results of the Mann-Whitney *U* Test (Table 6.11) showed that in 2006 there were two combinations (20%) with significant differences between Shannon-Weiner Equitability score; in these cases H_0 was rejected. In 2007, there was a significant difference between one of the combinations (10%). Equitability is a measure of the evenness of distribution of species in a sample, for a given species richness the index increases with greater equitability. Combinations with no significant difference are likely to have similar proportions of MiTGs relative to the number MiTGs present. The combinations where equitability is significantly different involve two UP combinations in 2006 and UW/NP in 2007.

Table 6.11 Mann-Whitney *U* test of Shannon-Weiner Equitability values between Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

	Shannon-Weiner Equitability				
	NP	**SM**	**RP**	**UW**	**UP**
2006					
No Perceptible					
Smooth	.428				
Rippled	.825	.291			
Unbroken wave	.649	.662	.470		
Upwelling	.080	.031*	.044*	.052	
2007					
No Perceptible					
Smooth	.164				
Rippled	.070	.651			
Unbroken wave	.014*	.309	.429		
Upwelling	.246	1.00	.680	.409	

Equitability, a measure of the evenness of taxa abundance in a sample, differs little between SFTs in both years. This suggests that the difference between relative proportions of the mixture of MiTGs in SFTs is not significant.

6.3.7 Relationship between Surface Flow Type Mesohabitat and Lotic Invertebrate Index for Flow Evaluation Score

Data from both 2006 and 2007 shows the range of average LIFE (Family) scores calculated from samples grouped by individual SFT mesohabitat. Based on 2006 results (n=200) (Figure 6:10), UW SFT mesohabitat had the highest score, followed by RP, UP and SM SFT mesohabitats (tie) and NP SFT mesohabitat. In the 2007 samples (n=175) again UP SFT mesohabitat had the highest score, followed by UW, RP, SM and NP SFT mesohabitats (Table 6.12). Broadly, higher values were recorded in samples from more turbulent SFT mesohabitats. The range of LIFE scores from NP SFT mesohabitat in 2006 encompasses the range of other SFT mesohabitat types, whilst the range is less in 2007 and consequently more distinct.

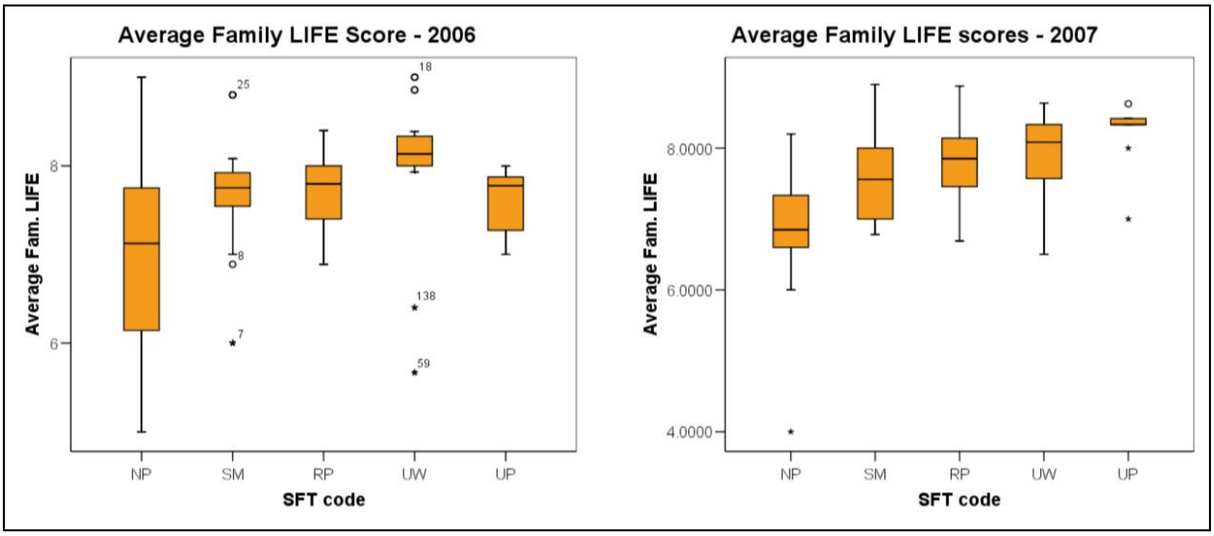


Figure 6:10 The range of Average Lotic Invertebrate Index for Flow Evaluation (Family) scores by Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers. Key: NP -No perceptible, SM - Smooth, RP - Ripple, UW - Unbroken wave, UP – Upwelling.

Table 6.12 Mean Lotic Invertebrate Index for Flow Evaluation scores, grouped by Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

Year	NP	SM	RP	UW	UP
2006	6.95	7.60	7.69	7.94	7.60
2007	6.88	7.58	7.81	7.85	8.20

The results from analysis with Kruskal-Wallis ANOVA show that there is a significant difference (p = <0.05) between LIFE scores (2006: X^2 = 41.461; df = 4; Sig = 0.000. 2007: X^2 = 37.583; df = 4; Sig = 0.000) in SFTs in both 2006 and 2007, whilst the Mann-Whitney *U* Test (Table 6.13) showed that in 2006 there were seven combinations of SFT (70%) with significant differences between Average LIFE score, UP SFT mesohabitat being similar to SM and RP SFT mesohabitats. In 2007, there were significant differences between nine combinations (90%) only RP and UW are not significantly different.

Table 6.13 Mann-Whitney U test of the Average Lotic Invertebrate Index For Flow Evaluation Score between Surface Flow Type mesohabitats, collected during 2006 and 2007 in eight British lowland rivers (Significance: ** P=<0.01; * P = <0.05 ; n.s. P = >0.05). Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling.

	Average Lotic Invertebrate Index For Flow Evaluation Score				
	NP	**SM**	**RP**	**UW**	**UP**
2006					
No Perceptible					
Smooth	.001 **				
Rippled	.000 **	.812 n.s.			
Unbroken wave	.000 **	.000 **	.000 **		
Upwelling	.049 *	.671 n.s.	.597 n.s	.001 **	
2007					
No Perceptible					
Smooth	.000 **				
Rippled	.000 **	.023 *			
Unbroken wave	.000 **	.006 **	.283 n.s.		
Upwelling	.000 **	.004 **	.007 **	.023 *	

Although there was considerable overlap between ranges of LIFE scores there are also significant differences between more SFT pairs than with abundance, richness, diversity and equitability. This suggests that LIFE score is better at differentiating between SFTs than other measures.

6.3.8 Summary

Although there was a wide range of values recorded, mean macroinvertebrate abundance and richness increased from NP>SM>RP>UW, reflecting the increase in mean velocity. ASPT peaked at RP in both years scores were lower in NP, SM and UW. Although there were significant differences between some pairs of SFT, in abundance, richness and ASPT, these suggest that adjacent pairs are more similar than pairs separated by one SFT, a situation identified by Reid and Thoms (2008). UP SFT does not fit easily into this pattern, suggesting that not only is it rare, but variable.

Similarly, greater diversity is linked to SFTs with high velocity (RP and UW), particularly in 2006. There are significant differences which set NP apart in 2006 and to a lesser extent in 2007, suggesting that SFTs with lower velocity are incapable of supporting the range of

MiTGs supported by more energetic SFTs. There is less difference between the SFTs in terms of equitability, meaning that none are dominated by a few MiTGs.

LIFE scores show the most significant difference between SFTs, with the inter quartile ranges being generally much less than with the other measures investigated here. There are significant differences between NP, SM, RP and UW SFTs, suggesting that the MiTGs identified are linked to the LIFE velocity classes. SM and RP are similar in 2006 whilst RP and UW are similar in 2007.

The results show that these metrics increase, generally, along the energy gradient. This potentially supplies increases in dissolved oxygen and suspended food particles to mesohabitats with higher velocity, providing niches for a wider range of MiTG and individuals than in the lower energy environments.

UP SFT is generally one of the pairs where there is no significant difference between SFT pairs, this reflects the unusual physical characteristics and, perhaps, it’s rare occurrence.

6.4 Two Way Indicator Species Analysis of Macroinvertebrate Samples

6.4.1 Two Way Indicator Species Analysis of all 2006 and 2007 Sites

2006

TWINSPAN analyses were performed on frequency data of all macroinvertebrate samples collected from all sites in 2006. The number of times that the data were divided (cut levels) was set at two, producing a maximum of four TWINSPAN end-groups. The dendrogram showing the TWINSPAN division illustrates the hierarchical relationship within the samples (Figure 6:11). There was no clear separation of SFT mesohabitats in the TWINSPAN end-groups, however there was a clearer separation by river. Samples from Dowles Brook and the River Tern were concentrated into End-group 3, and Bailey Brook into End-group 2. The River Windrush samples were concentrated in Groups 3 and 4, whilst samples from Badsey Brook were in End-groups 1 and 2, and Leigh Brook End-groups 1 and 3. This suggests that between site variables are stronger than between SFT mesohabitat variables and that there is greater difference between rivers than between SFT mesohabitats within rivers in the 2006 data.

2007

A similar situation exists in the 2007 data, with no clear separation between End-groups based on SFTs. Samples from Hadley and Bailey Brooks are concentrated into End-group 1, whilst samples from the Rivers Windrush and Tern and Leigh Brook are concentrated into End-group 2. End-groups 3 and 4 are dominated by samples from the River Leadon.

These analyses suggest that inter-river variables have a strong influence on macroinvertebrate communities. To eliminate those variables, as far as possible, TWINSPAN was also run on a river by river basis to see if SFT mesohabitats were better defined than using all sites.

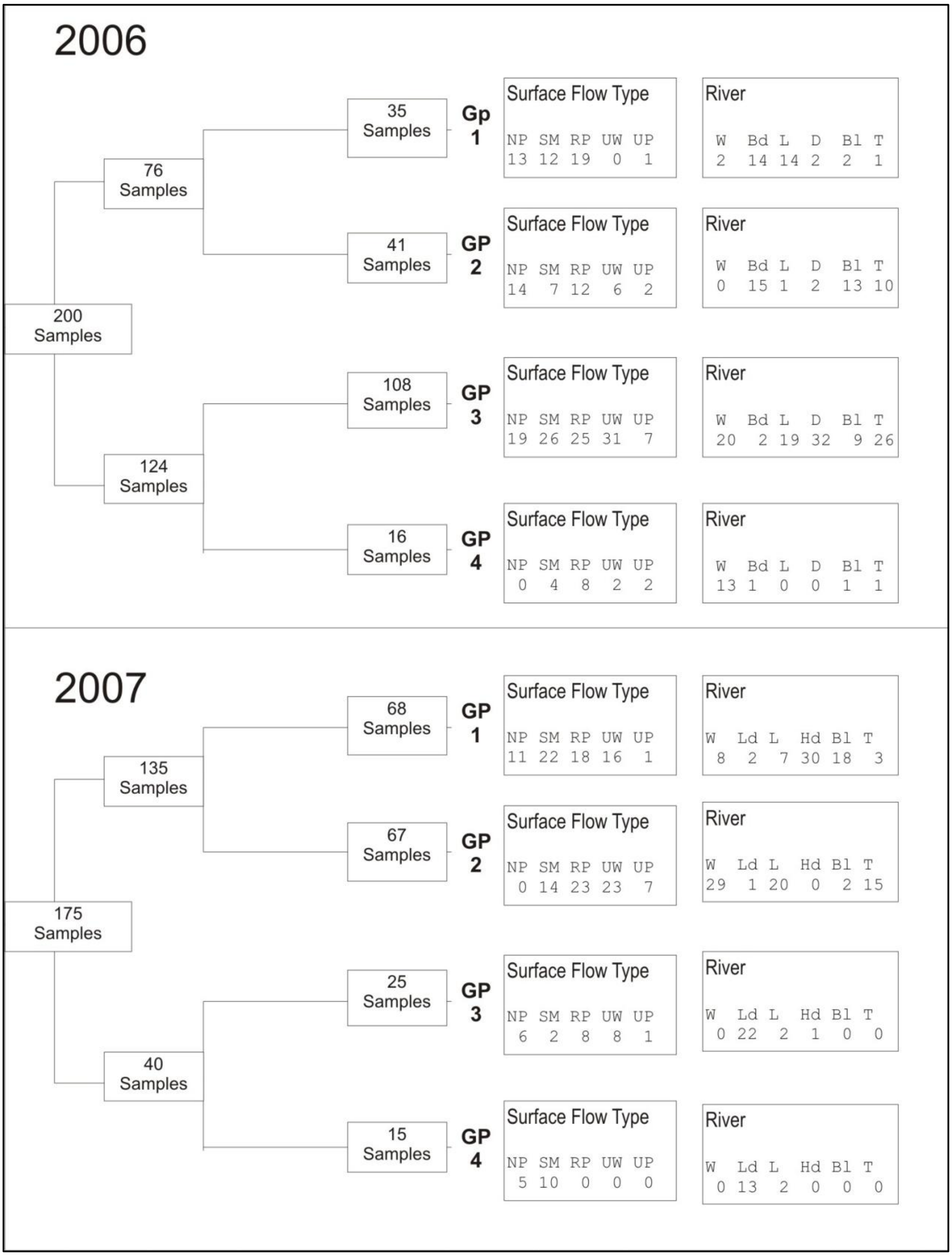


Figure 6:11 Dendogram showing results of Two Way Indicator Species Analysis – 2006 and 2007 data. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling and W - River Windrush; Bd – Badsey Brook; L – Leigh Brook; D – Dowles Brook; Bl – Bailey Brook; T – River Tern.

6.4.2 Two Way Indicator Species Analysis by River

To eliminate between-site variation, TWINSPAN analyses of macroinvertebrate samples from individual river sites for each year independently were undertaken, frequency data was used and the number of cut levels set at two. In the tables below, the greyed columns separate data at the first cut level. For each end-group, the number of occasions that a sample was drawn from each of five flow types and for each of the surveys is shown. The lower part of the table shows, in bold, the indicator species at the first cut level and below those the indicator species at the second cut level.

River Windrush - 2006

TWINSPAN analyses of macroinvertebrate data sorted into four groups from three surveys of the River Windrush in 2006 showed that Gammaridae, Ephemeridae and Ephemerellidae were indicators species at the first level and that Hydroptilidae, Gammaridae and Ephemerellidae TWINSPAN end groups one and two, whilst Goeridae, Sphaeriidae and Lymnaeidae separated TWINSPAN end-groups three and four. TWINSPAN end-group 1 contains an even range of SFTs but is dominated by samples from Survey 3. TWINSPAN end-group 2 has two samples each from SM and RP, mostly from survey 2. TWINSPAN end-group 3 is dominated by samples from SFTs with moderate velocities (RP, UW and UP SFT mesohabitats) and TWINSPAN end-group 4 with NP and UP SFTs (Table 6.14). Survey 1 is associated with TWINSPAN end-groups 3 and 4; survey 2 is associated with TWINSPAN end-groups 1, 2, and 3 but most strongly with TWINSPAN end-group 3; survey 3 is associated strongly associated with TWINSPAN end-group 2.

Table 6.14 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from the River Windrush, using data collected in 2006. The grey sections show the TWINSPAN end-groups separated at the first division. Key: NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Windrush 2006	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	4			1
SM	3	2	1	
RP	2	2	5	
UW	3		3	
UP	3		1	2
Survey 1			4	3
Survey 2	3	3	6	
Survey 3	14	1		
	Baetidae	Baetidae		
	Ephemeridae	Ephemeridae		
	Ephemerellidae	Ephemerellidae		
	Hydroptilidae	Gammaridae	Goeridae	Sphaeriidae
		Ephemerellidae		Lymnaeidae

Windrush - 2007

In 2007, four TWINSPAN end-groups were identified (Table 6.15). Heptageniidae, Goeridae, Hydrobiidae, Ephemeridae and Chironomidae were the indicator species at the first division whilst Heptageniidae and Elmidae separated TWINSPAN end-groups 1 and 2; TWINSPAN end-groups 3 and 4 were separated by Gammaridae. TWINSPAN end-group 1 is generally associated with higher velocities, whilst end-groups 2 and 3 have no clear association; end-group 4 is associated with low velocity (NP and SM). Surveys 1 and 2 have no clear association, although survey 3 dominated end-group 3.

Table 6.15 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from the River Windrush, using data collected in 2007. The grey sections show the TWINSPAN end-groups separated at the first division. Key: NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Windrush 2007	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP			2	1
SM	2	4	4	3
RP	1		4	
UW	4	3	2	
UP	1	1	5	
Survey 4	5	3	2	1
Survey 5	3	4	4	2
Survey 6		1	11	1
	Heptageniidae	Heptageniidae	Hydrobiidae	Hydrobiidae
	Goeridae	Goeridae	Ephemeridae	Ephemeridae
			Chironomidae	Chironomidae
		Heptageniidae	Gammaridae	
		Elmidae		

Leigh Brook – 2006

TWINSPAN analyses of macroinvertebrate data from three surveys of Leigh Brook in 2006 (Table 6.16) sorted into four groups and showed that Elmidae, Ephemerellidae, Baetidae and Sialidae are the indicator species at the first division. Baetidae, Caenidae, Heptageniidae, Asellidae and Polycentropodidae separate end-groups 1 and 2, whilst Sialidae separates end-groups 3 and 4. End-group 1 is associated with higher velocities (RP and UW), end-group 2 with moderate velocities and end-groups 3 and 4 with lower velocities. Survey 1 dominates TWINSPAN end-group 1 survey 2 has associations with end-groups 1, 3 and 4, whilst survey 3 is solely associated with end-group 2.

Table 6.16 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Leigh Brook, using data collected in 2006. The grey sections show the TWINSPAN end-groups separated at the first division. Key: NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Leigh 2006	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	3		4	2
SM	4	3	1	1
RP	5	2	1	1
UW	8	1		
UP				
Survey 1	12			
Survey 2	6		3	2
Survey 3	2	6	3	1
	Elmidae	Elmidae	Sialidae	Sialidae
	Ephemerellidae	Ephemerellidae		
	Baetidae	Baetidae		
	Baetidae	Asellidae		
	Caenidae	Polycentropodidae		Sialidae
	Heptageniidae			

Leigh Brook - 2007

TWINSPAN analyses of macroinvertebrate data from three surveys of Leigh Brook in 2007 produced three groups (Table 6.17). Limnephiliidae was the indicator at the first division. Gyrinidae, Ancylidae, Heptageniidae, Simuliidae and Leptophlebiidae separated TWINSPAN end-groups 1 and 2. There is, again, and apparent gradient from higher water velocity in TWINSPAN end-group 1 to lower velocity in TWINSPAN end-group 4. There was no association between end-groups and surveys.

Table 6.17 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Leigh Brook, using data collected in 2007. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling

Leigh 2007	**Two Way Indicator Species Analysis End-group**		
	1	**2**	**3**
NP			4
SM	1	8	
RP	2	7	
UW	9		
UP			
Survey 4	5	4	2
Survey 5	4	5	1
Survey 6	3	6	1
			Limnephiliidae
	Gyrinidae	Leptophlebiidae	
	Ancylidae		
	Heptageniidae		
	Simuliidae		

Bailey Brook – 2006

TWINSPAN analyses of macroinvertebrate data from three surveys of Bailey Brook in 2006 sorted into three groups (Table 6.18) showed that Sphaeriidae, Simuliidae and Hydracarina were indicator species at the first level. Sericostomatidae and Gammaridae separated TWINSPAN end-groups 1 and 2. TWINSPAN end-groups 3 and 4 were separated by Veliidae. TWINSPAN end-group 1 is the low velocity group (NP and SM) and TWINSPAN end-group 2 is associated with moderate velocities (SM and RP). End-group 3 is associated with higher velocities and end-group 4 showing no association. Surveys are not particularly associated with TWINSPAN end-groups.

Table 6.18 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Bailey Brook, using data collected in 2006. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Bailey 2006	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	6			1
SM	3	6	1	
RP		2	3	1
UW			1	
UP		1		
Survey 1	2	4	1	
Survey 2	4	2	2	1
Survey 3	3	3	2	1
	Sphaeriidae	Sphaeriidae	Simuliidae	Simuliidae
			Hydracarina	Hydracarina
		Sericostomatidae		Veliidae
		Gammaridae		

Bailey Brook - 2007

In 2007 TWINSPAN analyses produced four TWINSPAN end-groups (Table 6.19). Gammaridae, Ephemeridae, Baetidae, Chironomidae and Sphaeriidae were indicators at the first division. Oligochaeta, Hydrobiidae, Simuliidae and Odontoceridae separated TWINSPAN end-groups 1 and 2 whilst Sphaeriidae separated TWINSPAN end-groups 3 and 4. TWINSPAN end-groups 1 and 2 contained the higher velocity SFT mesohabitats and TWINSPAN end-groups 3 and 4 the lower velocity SFT mesohabitats. Survey 4 dominates end-group 2.

Table 6.19 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Bailey Brook, using data collected in 2007. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Bailey 2007	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP		1		
SM	1	2	2	1
RP	1	5		
UW	3	2		
UP			1	1
Survey 4	1	6	1	1
Survey 5	4	4	2	1
	Gammaridae	Gammaridae	Sphaeriidae	Sphaeriidae
	Ephemeridae	Ephemeridae		
	Baetidae	Baetidae		
	Chironomidae	Chironomidae		
	Oligochaeta		Sphaeriidae	
	Hydrobiidae			
	Simuliidae			
	Odontoceridae			

River Tern - 2006

TWINSPAN analyses of macroinvertebrate data from three surveys of the River Tern in 2006 sorted into four groups (Table 6.20) showed that Baetidae, Ephemerellidae, Hydrobiidae and Oligochaeta were indicator species at the first level of division. Baetidae separated TWINSPAN end-groups 1 and 2, Oligochaeta separated TWINSPAN end-groups 3 and 3. End-groups 1, 3 and 4 are associated with low velocities with end-group 2 associated with higher velocities. Survey one is associated with TWINSPAN end-groups 1 and 2, whilst surveys two and three are associated with TWINSPAN end-groups 2 and 3.

Table 6.20 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from the River Tern, using data collected in 2006. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Tern 2006	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	2		2	5
SM	2	6	1	
RP	1	7		1
UW		6		
UP		1		
Survey 1	5	6		1
Survey 2		9		4
Survey 3		8	3	1
	Baetidae	Baetidae	Oligochaeta	Oligochaeta
	Ephemerellidae	Ephemerellidae		
	Hydrobiidae	Hydrobiidae		
		Baetidae	Oligochaeta	

River Tern - 2007

In 2007 TWINSPAN analysis produced three groups, with TWINSPAN end-group three having only one SM sample (Table 6.21). TWINSPAN end-group 1 is associated with higher velocities, although there are only 4 groups, whilst end-group 2 is associated with moderate velocities. There were no samples from NP mesohabitats in the analysis. Odontoceridae, Ephemerellidae and Oligochaeta were the indicator species at the first division. Gammaridae separated TWINSPAN end-groups 2 and 3. Surveys are not particularly associated with TWINSPAN end-groups.

Table 6.21 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from the River Tern, using data collected in 2007. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Tern 2007	**Two Way Indicator Species Analysis End-group**		
	1	**2**	**3**
NP			
SM		5	1
RP	1	5	
UW	3	3	
UP			
Survey 4		9	
Survey 5	4	4	1
	Odontoceridae	Oligochaeta	Oligochaeta
	Ephemerellidae		
		Gammaridae	

River Leadon – 2007

TWINSPAN analysis of macroinvertebrate data from three surveys of the River Leadon in 2007 produced four groups (Table 6.22). Hydrobiidae, Ancylidae, Asellidae, Gammaridae and Ostracoda are indicator species at the first division, whilst Glossiphoniidae Glossosomatidae, Ceratopogonidae and Asellidae separate TWINSPAN end-groups 1 and 2. Ostracoda separated TWINSPAN end-groups 3 and 4. There is an apparent gradient from higher water velocity in TWINSPAN end-group 1 through TWINSPAN end-group 2 to lower velocities in TWINSPAN end-groups 3 and 4. There is little association between season and TWINSPAN end-groups.

Table 6.22 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from the River Leadon, using data collected in 2007. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Leadon 2007	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	2	2	3	2
SM	1		5	3
RP	6	3		
UW	5	4		
UP	1			
Survey 4	9		4	
Survey 5	6	3	2	1
Survey 6		6	2	4
	Hydrobiidae	Hydrobiidae	Ostracoda	Ostracoda
	Ancylidae	Ancylidae		
	Asellidae	Asellidae		
	Gammaridae	Gammaridae		
	Glossiphoniidae	Ceratopogonidae		Ostracoda
	Glossosomatidae	Asellidae		

Badsey Brook – 2006

TWINSPAN analysis of macroinvertebrate data from three surveys of Badsey Brook in 2006 sorted into four groups (Table 6.23) showed that Oligochaeta, Elmidae, Erpobdellidae, Hydroptilidae and Glossiphoniidae were indicators at the first level. Hydroptilidae, Glossiphoniidae, Oligochaeta Philopotamidae and Simuliidae separated TWINSPAN end-groups 1 and 2 and Erpobdellidae and Asellidae separated TWINSPAN end-groups 3 and 3. There is no clear separation of TWINSPAN end-groups by flow type. TWINSPAN end-group 4 is associated with survey three.

Table 6.23 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Badsey Brook, using data collected in 2006. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Badsey 2006	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	3	1	1	3
SM	4	2	1	2
RP		4	1	3
UW	1		2	3
UP				
Survey 1	4	4		
Survey 2	5	2	4	2
Survey 3		1	1	10
	Oligochaeta	Oligochaeta	Hydroptilidae	Hydroptilidae
	Elmidae	Elmidae	Glossiphoniidae	Glossiphoniidae
	Erpobdellidae	Erpobdellidae		
	Hydroptilidae	Philopotamidae	Erpobdellidae	Asellidae
	Glossiphoniidae	Simuliidae		
	Oligochaeta			

Dowles Brook - 2006

TWINSPAN analysis of macroinvertebrate data from three surveys of Dowles Brook in 2006 sorted into four groups (Table 6.24) showed that Rhyacophilidae, Heptageniidae, Gammaridae, Baetidae and Elmidae were indicator species at the first level. Glossosomatidae separated TWINSPAN end-groups 1 and 2, whilst Elmidae, Chironomidae, Ephemerellidae and Leptophlebiidae separated TWINSPAN end-groups 3 and 4. There appears to be a gradient associated with decreasing water velocity from TWINSPAN end-group 1 to 4. End-group 4 is associated with survey 2, although there are only four samples placed in this end-group.

Table 6.24 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Dowles Brook, using data collected in 2006. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Dowles 2006	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP			8	1
SM	1	2	3	3
RP		4	4	
UW	2	6	1	
UP				
Survey 1	2	5	5	
Survey 2	1	1	5	4
Survey 3		5	7	
	Rhyacophilidae	Rhyacophilidae		
	Heptageniidae	Heptageniidae		
	Gammaridae	Gammaridae		
	Baetidae	Baetidae		
	Elmidae	Elmidae		
	Glossosomatidae		Elmidae	Ephemerellidae
			Chironomidae	Leptophlebiidae

Hadley Brook - 2007

TWINSPAN analysis of macroinvertebrate data from three surveys of Hadley Brook in 2007 produced four groups (Table 6.25) Sericostomatidae, Baetidae, Glossosomatidae and Ancylidae were indicators at the first division and placed into end-groups 3 and 4; whilst Gammaridae and Ephemeridae separated TWINSPAN end-groups 1 and 2 and Ephemerellidae separated TWINSPAN end-groups 3 and 4. There is an apparent gradient from lower water velocity in TWINSPAN end-group 1 through TWINSPAN end-groups 2 and 3 to TWINSPAN end-group 4. There is little association between end-groups and surveys.

Table 6.25 Summary of Two Way Indicator Species Analysis of macroinvertebrate samples from Hadley Brook, using data collected in 2007. The grey sections show the TWINSPAN end-groups separated at the first division. NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling.

Hadley 2007	**Two Way Indicator Species Analysis End-group**			
	1	**2**	**3**	**4**
NP	2	3		
SM		9		
RP		8	1	
UW		5	3	1
UP				
Survey 4		8	4	
Survey 5	1	9		
Survey 6	1	8		1
			Sericostomatidae	Sericostomatidae
			Baetidae	Baetidae
			Glossosomatidae	Glossosomatidae
			Ancylidae	Ancylidae
		Gammaridae		Ephemerellidae
		Ephemeridae		

Summary of TWINSPAN results

During TWINSPAN analysis of 12 data sets from river sites, 32 MiTGs were identified as indicator species at either the first or second cut level (Table 6.26). Because many MiTGs occur as indicator species on a few occasions none are associated with TWINSPAN end-groups. Few patterns emerge from TWINSPAN analysis, although Leigh Brook in both years shows apparent velocity gradients between end-groups 1 and 4, although survey 1 also dominates end-group 1 in 2006. Dowles Brook exhibits a similar gradient.

The Leigh Brook data suggests that Baetidae, Caenidae, Heptageniidae, Ancylidae, and Simuliidae may be associated with higher velocities; Asellidae, Polycentropodidae and Leptophlebiidae with moderate velocities and Limnephilidae and Sialidae with lower velocities.

Table 6.26 Occurrence of Macroinvertebrate Taxonomic Group as indicator species in Two Way Indicator Species Analysis of river sites.

MiTG	Occurrences
Baetidae	8
Ephemerellidae	8
Gammaridae	8
Heptageniidae	7
Elmidae	5
Asellidae	4
Oligochaeta	4
Sphaeriidae	4
Ancylidae	3
Chironomidae	3
Ephemeridae	3
Glossosomatidae	3
Hydrobiidae	3
Erpobdeliidae	2
Glossiphoniidae	2
Goeridae	2
Hydroptilidae	2
Leptophlebiidae	2
Ostracoda	2
Sericostomatidae	2
Sialidae	2
Caenidae	1
Ceratopogonidae	1
Gyrinidae	1
Hydracarina	1
Limnephilidae	1

MiTG	Occurrences
Lymnaeidae	1
Odontoceridae	1
Polycentropodidae	1
Rhyacophilidae	1
Simuliidae	1
Veliidae	1
Hydropsychidae	0
Lepidostomatidae	0
Leuctridae	0
Planorbidae	0

The analyses of the relationship between macroinvertebrate communities and SFT mesohabitats USING TWINSPAN shows that:

- Using all data, macroinvertebrate communities grouped better by river than by SFT mesohabitat.
- River by river data grouped macroinvertebrate communities slightly better by SFT mesohabitat.
- Between-river variables, particularly water quality, are probably responsible for the poor separation of macroinvertebrate communities grouped by SFT mesohabitats.

6.5 Ordination

6.5.1 Introduction

Ordination techniques are used to present a spatial representation of differences between samples and the environmental variables that drive those differences. Shaw (2003, p73) describes ordination as *'the more abstract concept of finding a concise and useful summary of patterns within multivariate data'*. Here Detrended Correspondence Analysis and Canonical Correspondence Analysis are used.

6.5.2 Detrended Correspondence Analysis

Exploratory analysis of MiTG data using Detrended Correspondence Analysis showed that the length of all axes from both 2006 and 2007 exceeded 3 (Table 6.27) therefore Canonical Correspondence Analysis was favoured.

Table 6.27 DECORANA axis ranges derived from MiTG data from 2006 and 2007.

Axis	Minimum	Maximum	Length
2006			
1	0	429	429
2	-28	342	370
3	-73	415	488
4	-46	407	453
2007			
1	-88	448	531
2	-32	412	444
3	-183	341	524
4	-11	355	366

6.5.3 Canonical Correspondence Analysis

Canonical Correspondence Analysis was performed using ECOM2 (Seaby and Henderson, 2007) (Section 4.4.12). MiTGs occurring in <5 of the samples were removed from the analysis on a year by year basis. CCA was run, initially, with all environmental variables used. After each analysis the vector lengths were examined. In each case the variable with the shortest vector was removed until 10 remained: SFT – using dummy coding for NP, SM, RP, UW and UP; Velocity on the bed, at 0.05 above the bed and at the surface and dominant substrate. Water chemistry data had been collected once during each survey, and was not used in this analysis to prevent pseudoreplication (Hurlbert, 1984). BMWP scores were deemed an inappropriate measure of water quality because they were derived from MiTG data. The analyses was run using data from 2006 and 2007 separately and, to circumvent correlations errors in coding the SFTs, each analysis was run omitting UP and then NP SFTs. SFT centroids and vector lengths were extracted and combined into a single plot, this appeared to have no adverse effect on the analysis.

Vector lengths for 2006 data (Table 6.28) were determined from Bi-plot scores using axes 1, 2 and 3. Vector lengths indicate the relative strength of the environmental variables (Lepš and Šmilauer, 2003), in 2006, four of the five SFT have the longest vectors.

Table 6.28 Vector lengths (largest to smallest) based on Canonical Correspondence Analysis of 2006 data collected from six British lowland rivers. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling SFTs.

2006 Variable	Vector Length
UW	0.80164
UP	0.699907
RP	0.679302
NP	0.559931
Bed velocity	0.527484
SM	0.516324
Surface velocity	0.50766
Dominant substrate	0.475604
Depth	0.460255
Velocity 0.05m above the bed	0.326769

Variance explained by CCA axis 1 was 6.07%, axis 2: 2.53% and axis 3: 1.85%, totalling 10.45%. Analyses of 2006 biological and environmental data showed that amongst the environmental variables, UW SFT had the strongest relationship (0.80) with the biological data; the other SFTs were ranked 2, 3, 4 and 6 (Table 6.28). Velocity on the bed was ranked 5 (0.53) followed by surface velocity (0.51) and velocity 0.05m above the bed. Dominant substrate (0.48) and depth were less strongly linked (0.46). Figure 6:12 and Figure 6:13 show the environmental vectors plotted against axes 1, 2 and 3.

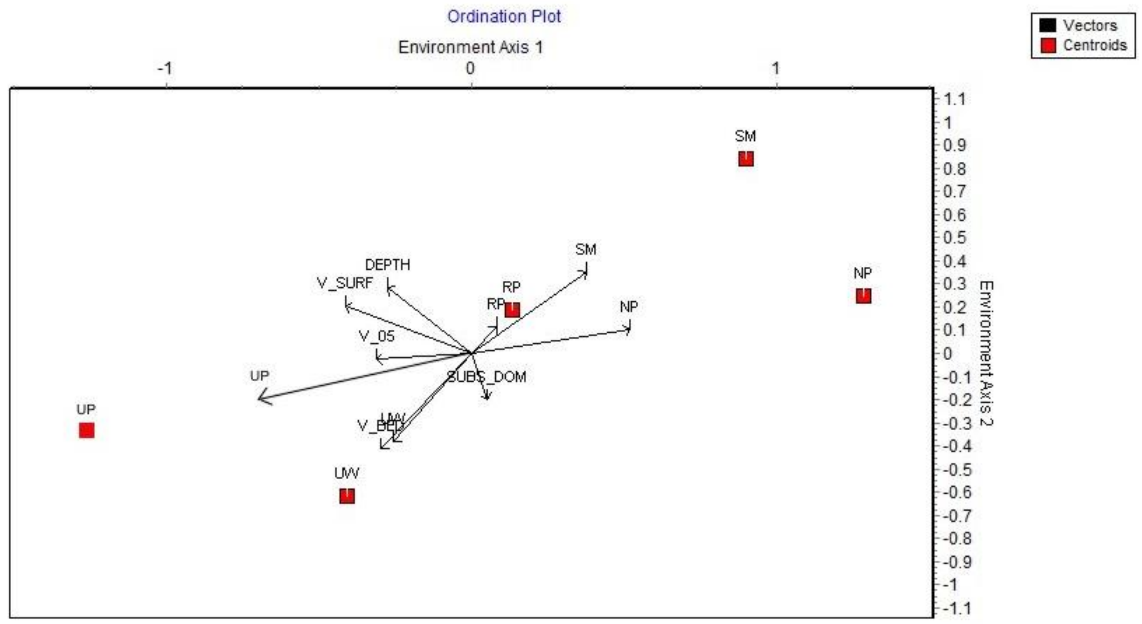


Figure 6:12 Environmental vectors and centroids from Canonical Correspondence Analysis axes 1v2, using data collected during 2006 in eight British lowland rivers. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling SFTs.

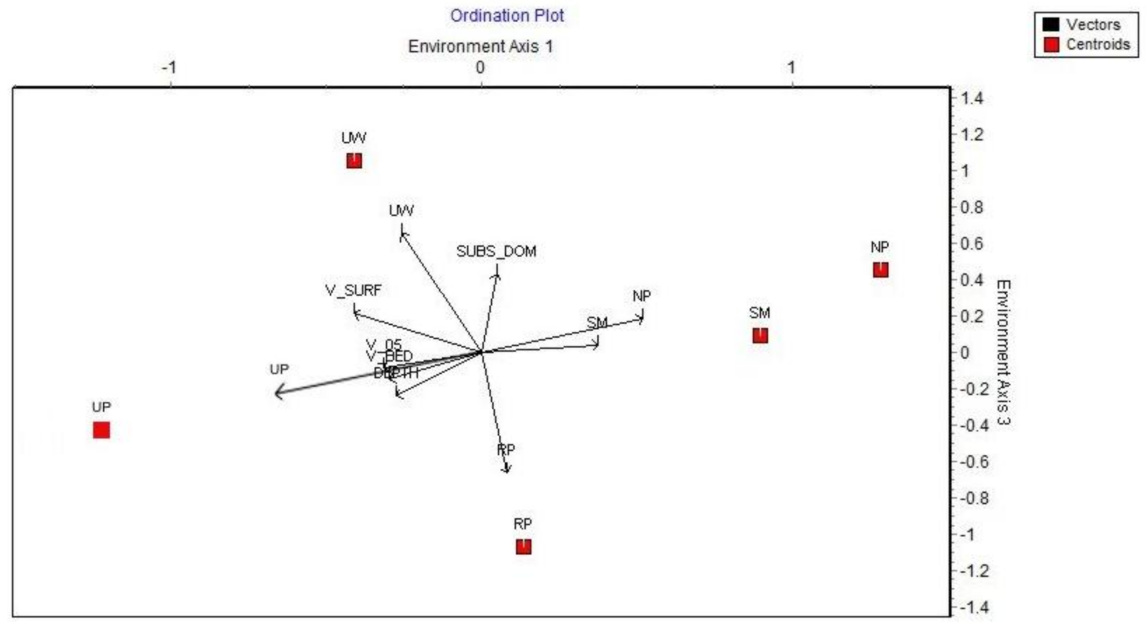


Figure 6:13 Environmental vectors and centroids from Canonical Correspondence Analysis axes 1v3, using data collected during 2006 in eight British lowland rivers. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling Surface Flow Types.

Grouping samples by SFT shows a considerable amount of overlap between the groups, (Figure 6:14 and Figure 6:15), although NP samples group in the negative side of Axis 2. RP and SM samples overlap, although SM is biased towards the negative end of Axis 2 and RP has low positive scores on axis 2. UW samples are placed in the positive side of axis 2. UP samples occupy the central part of Axis 2.

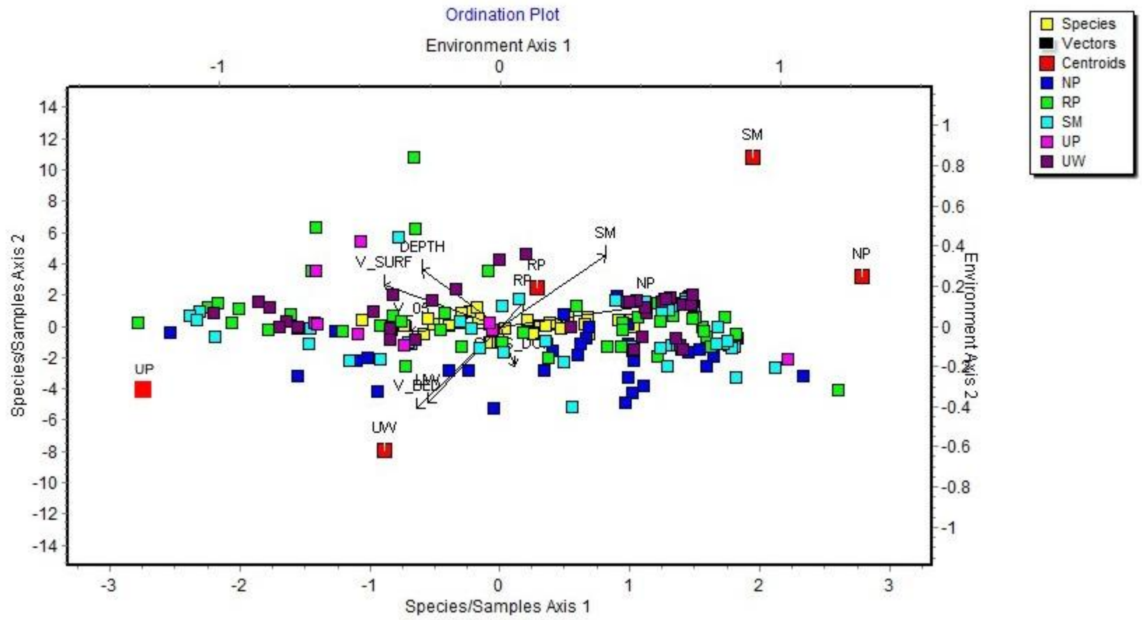


Figure 6:14 Ordination plot from Canonical Correspondence Analysis showing Axes 1 and 2 from 2006 data. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling Surface Flow Types; V_Bed: Velocity on the bed, V_0.05: Velocity 0.05m above the bed, V_SURF: Velocity at the surface, DEPTH: water depth, SUBS_DOM: Dominant substrate.

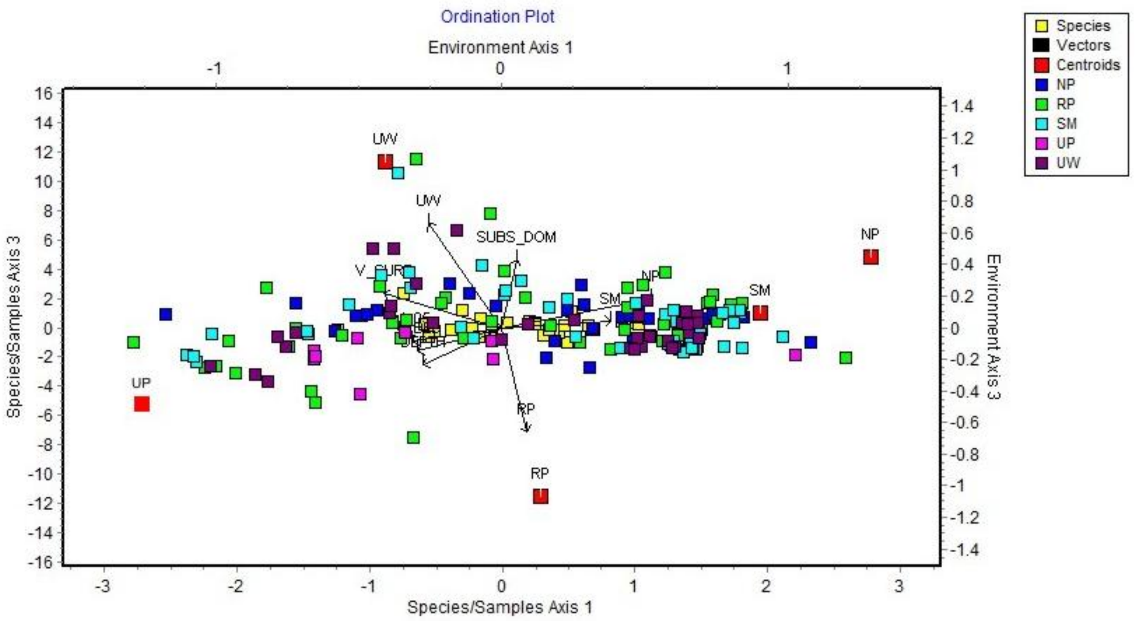


Figure 6:15 Ordination plot from Canonical Correspondence Analysis showing Axes 1 and 3 from 2006 data. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling Surface Flow Types; V_Bed: Velocity on the bed, V_0.05: Velocity 0.05m above the bed, V_SURF: Velocity at the surface, DEPTH: water depth, SUBS_DOM: Dominant substrate.

The same environmental variables were used for both data sets, tests for multi-collinearity showed that these variables were appropriate. Vector lengths for 2007 data (Table 6.29) were determined from Bi-plot scores using axes 1, 2 and 3. Vector lengths indicate the relative strength of the environmental variables (Lepš and Šmilauer, 2003) in 2007; four SFT vectors had the stronger influence.

Table 6.29 Vector lengths (largest to smallest).based on Canonical Correspondence Analysis of 2007 data using data collected from six British lowland rivers. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling SFTs.

2007 Variable	Vector Length
NP	0.98881
RP	0.982318
SM	0.967345
UW	0.730676
Surface velocity	0.638064
Velocity at 0.05m	0.582015
Bed velocity	0.42561
UP	0.410842
Dominant substrate	0.318936
Depth	0.181088

Analysis of 2007 biological and environmental data showed that amongst the environmental variables, NP, RP, SM and UW SFTs again had strong relationships. The lengths of the velocity vectors showed that velocity at the surface had the strongest relationship (0.64) followed by velocity at 0.05m (0.58) and near-bed velocity (0.43). Depth was not strongly linked (0.18), whilst dominant substrate (0.32) had a stronger association. Figure 6:16 and Figure 6:17 show the environmental variables plotted against axes 1, 2 and 3.

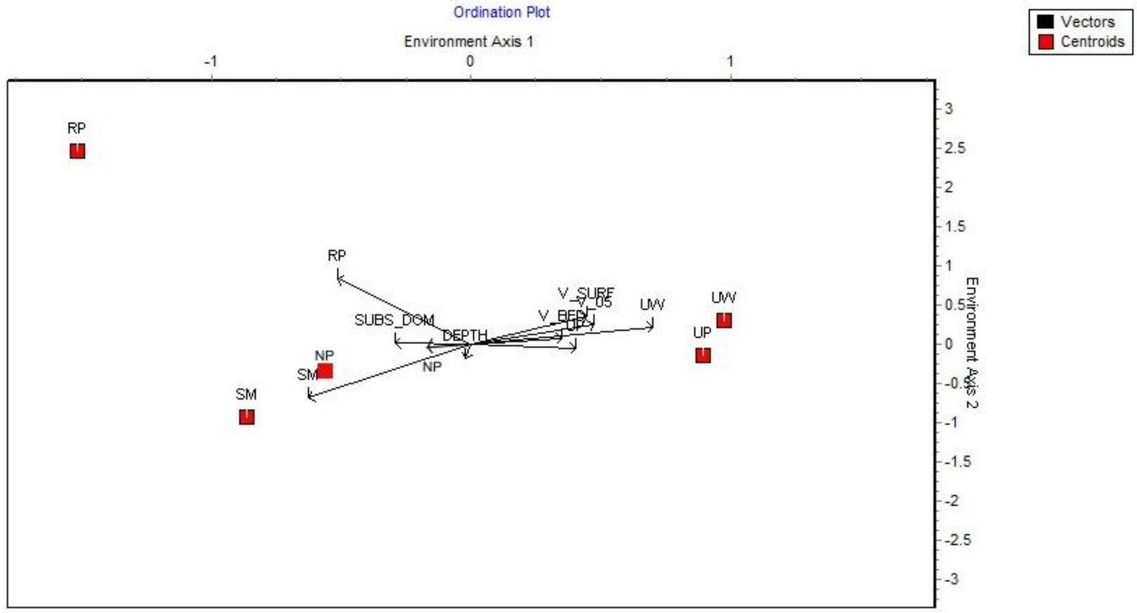


Figure 6:16 Environmental vectors and centroids from 2007 data axes 1v2. Note variable scales on the vertical axis. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling Surface Flow Types.

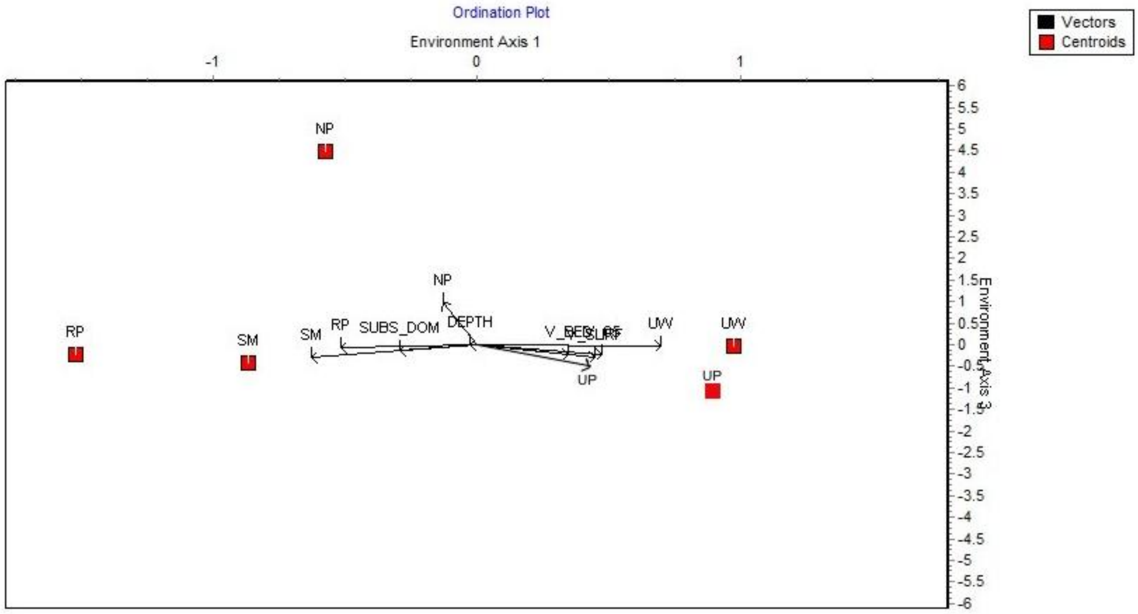


Figure 6:17 Environmental vectors and centroids from 2007 data axes 1v3. Note variable scales on the vertical axis. Key: NP: No perceptible, SM: Smooth, RP: Rippled, UW: Unbroken wave, UP: Upwelling Surface Flow Types.

Grouping samples by SFT shows a considerable amount of overlap between the groups (Figure 6:18 and Figure 6:19), although NP samples group in the top left of axes 1 and 2. Note variable scale on vertical axis.

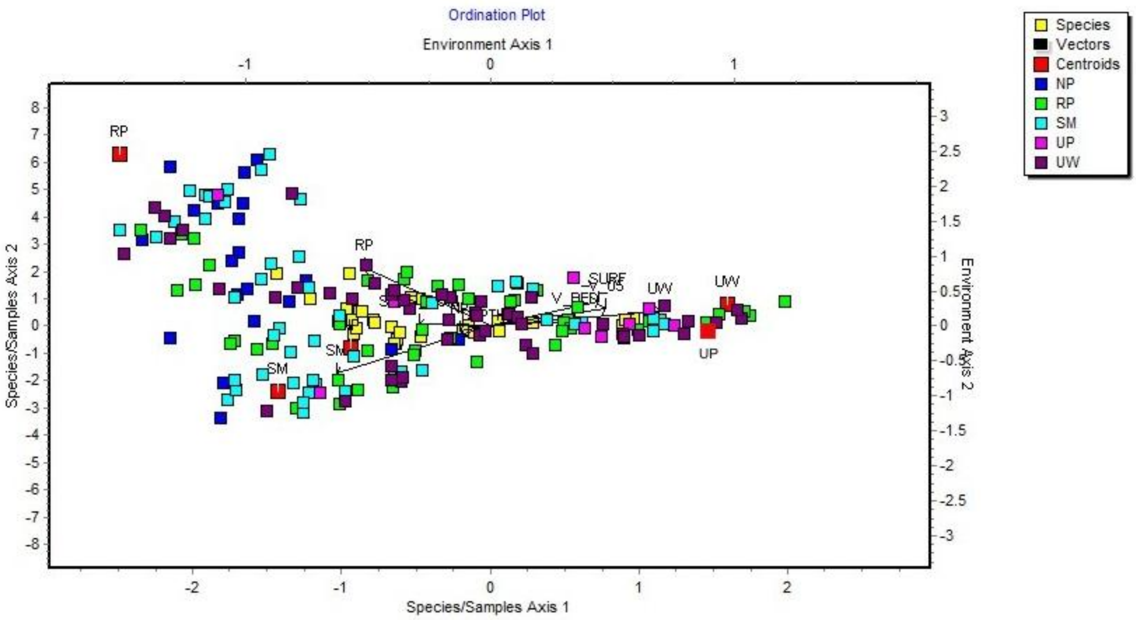


Figure 6:18 Ordination plot from Canonical Correspondence Analysis showing Axes 1 and 2 from 2007 data. Note variable scales on the vertical axis. Key: Biological Monitoring Working Party score; Surface Flow Type; V_BED - Velocity on the bed; V_05 - velocity at 0.05 above the bed; and V_10 - velocity at 0.10m above the bed and V_SURFACE – velocity at the surface; SURFACE_DE – depth, SUB_DOM - dominant substrate, and; EMBED - embeddedness.

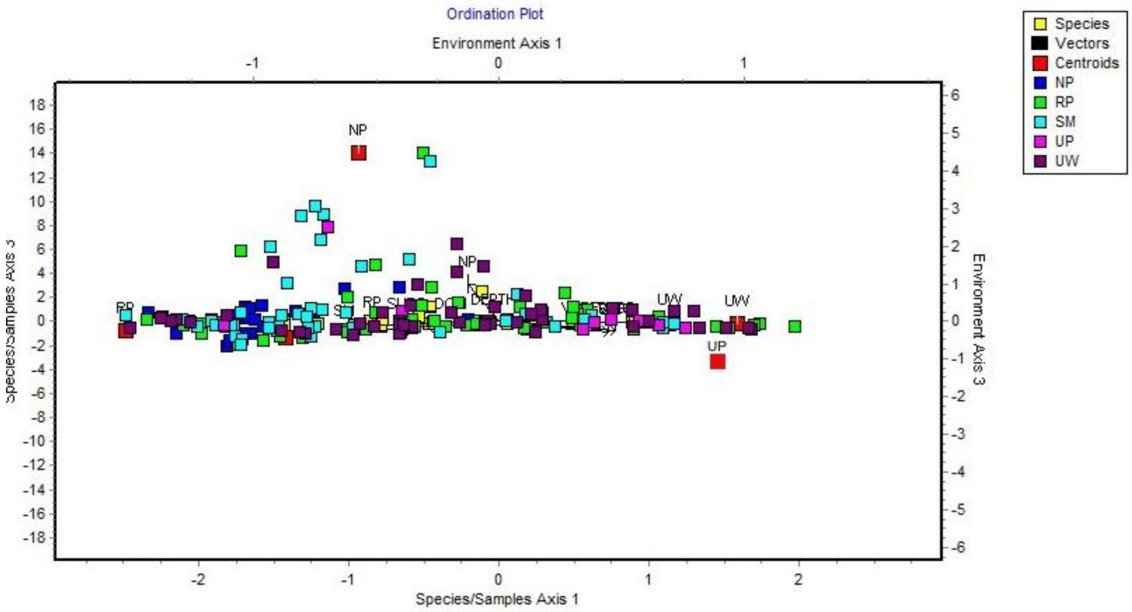


Figure 6:19 Ordination plot from Canonical Correspondence Analysis showing Axes 1 and 3 from 2007 data. Note variable scales on the vertical axis. Key: Biological Monitoring Working Party score; Surface Flow Type; V_BED - Velocity on the bed; V_05 - velocity at 0.05 above the bed; and V_10 - velocity at 0.10m above the bed and V_SURFACE – velocity at the surface; SURFACE_DE – depth, SUB_DOM - dominant substrate, and; EMBED - embeddedness.

Canonical Correspondence Analysis showed that, in both years, Surface Flow Types were the environmental variables with the longest vectors. Velocity, substrate and depth were also strongly associated with the biological data.

6.5.4 Limitations

Water quality data (temperature, pH, DO and conductivity) were recorded once during each survey and were unsuitable for use in CCA. Hurlbert (1984) warns against using data collected at the wider level (here the reach level) with other data collected at the MiTG sample site (microhabitat). Differences between water-quality at sites have been identified by BMWP scores derived from macroinvertebrate samples collected during these surveys. Although some CCA programmes use environmental variables to remove the influence of between-site variables (‘partialling out’), using BMWP scores derived from the same biological data as that being analysed is inappropriate. Therefore it was not possible to eliminate the effects of variable water quality in this research.

6.6 Taxa associated with Surface Flow Types

The previous sections have investigated the difference between the macroinvertebrate communities within five SFTs, this section, and the ones following, look at which particular MiTGs use specific SFTs.

6.6.1 Chi-Square Test of Individual Taxa

The Chi-Square test is used here to identify those MiTGs which have significantly different populations than are predicted. The test was run for each MiTG using data from all five STFs for both 2006 or 2007separately. The results of the test indicate if there is a significant difference between expected and actual abundance and is followed by an investigation to identify the differences between expected and actual abundance to identify the nature of those differences.

6.6.2 2006 Data

Ten MiTGs had significantly different frequencies in expected and observed categories, and H_0 was rejected (Table 6:30). P values for Simuliidae (0.050), Odontoceridae (0.067), Asellidae (0.085) and Oligochaeta (0.088) are close to being significant, and are therefore close to being associated with SFT mesohabitats. The numbers in each box (SFT columns) represent the difference between expected and observed frequencies. Negative values indicate that fewer samples than expected contained that MiTG, positive values indicate that more samples than expected contained that MiTG. Table 6.30 is ranked by MiTGs LIFE velocity category (Table 6.31) (Extence *et al.,* 1999), where available.

Table 6.30 Chi-square analysis of macroinvertebrate data, using data collected in 2006 from six British lowland rivers. Entries in red indicate Macroinvertebrate Taxonomic Groups statistically associated with Surface Flow Type (P=<0.05). D.F. – Degrees of Freedom; NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling; LIFE, Lotic Invertebrate Index for Flow Evaluation. (Significant - P=<0.01; not significant - P = >0.05).

2006	x^2	**D.F.**	**P**	**NP**	**SM**	**RP**	**UW**	**UP**	**LIFE Velocity**
Hydrobiidae	11.44	4	0.022	-7.04	-3.85	3.13	5.8	1.95	4
Sphaeriidae	1.82	4	0.770	1.78	-1.74	-1.04	-0.4	1.4	4
Erpobdellidae	2.44	4	0.655	-0.53	-1.68	-0.05	2	0.25	4
Asellidae	8.18	4	0.085	-4.46	2.18	0.28	3.8	-1.8	4
Caenidae	17.95	4	0.001	-5.88	0.88	-1.75	4	2.75	4
Chironomidae	16.93	4	0.002	7.64	-1.96	-4.93	2.2	-2.95	
Ancylidae	20.83	4	0.000	-6.11	-3.37	2.98	6.8	-0.3	2
Gammaridae	14.99	4	0.005	-10.15	3.79	-0.89	4.6	2.65	2
Baetidae	33.33	4	0.000	-16.62	1.46	3.16	11.6	0.4	2
Leptophlebiidae	5.22	4	0.266	-4.52	1.16	1.36	2.6	-0.6	2
Ephemeridae	3.87	4	0.424	2.37	1.96	-4.07	-1.2	0.95	2
Ephemerellidae	12.54	4	0.014	-9.45	3.85	0.1	5	0.5	2
Elmidae	31.13	4	0.000	-13.15	-5.22	7.11	9.6	1.65	2
Hydropsychidae	17.59	4	0.001	-4.41	-3.64	0.79	6.4	0.85	2
Sericostomatidae	7.36	4	0.118	-3.05	0.65	-2.1	5	-0.5	2
Simuliidae	9.5	4	0.050	-6.34	-0.78	2.12	5.2	-0.2	2
Heptageniidae	25.54	4	0.000	-8.64	-2.05	-0.07	9.8	0.95	1
Odontoceridae	8.76	4	0.067	-2.88	0.88	-0.75	0	2.75	1
Oligochaeta	8.11	4	0.088	7.62	-1.3	-1.57	-5.2	0.45	
Hydracarina	6	4	0.199	-1.52	3.16	-2.64	2.6	-1.6	

Table 6.31 Comparison of Lotic Invertebrate Index for Flow Evaluation velocity groups and Surface Flow Type mesohabitats.

LIFE scores	**LIFE flow category**	**Possible SFT association**
1	Rapid	Unbroken wave
2	Moderate/Fast	Unbroken wave / rippled
3	Slow/Sluggish	Smooth
4	Flowing/Standing	No perceptible

6.6.3 2007 Data

Ten MiTGs had significantly different frequencies in expected and observed categories, and H_0 was rejected (Table 6.32). P values for Ephemeridae (0.076) are close to being significant, and are therefore close to being associated with SFT mesohabitat groups.

Table 6.32 Chi-square analysis of macroinvertebrate data, using data collected in 2007 from six British lowland rivers. Entries in red indicate Macroinvertebrate Taxonomic Groups statistically associated with Surface Flow Type (P=<0.05). D.F. – Degrees of Freedom; NP, No Perceptible Flow, SM, Smooth; RP Ripple; UW, Unbroken Wave; Up, Upwelling; LIFE, Lotic Invertebrate Index for Flow Evaluation. (Significant - P=<0.01; not significant - P = >0.05).

									LIFE
2007	X^2	**D.F.**	**P**	**NP**	**SM**	**RP**	**UW**	**UP**	**Velocity**
Hydrobiidae	3.52	4	0.475	-0.56	-4.04	-0.04	4.96	-0.32	4
Sphaeriidae	4.98	4	0.289	-0.93	0.33	1.33	2.33	-3.06	4
Caenidae	4.85	4	0.303	0.21	-1.01	0.99	-3.01	2.81	4
Chironomidae	12.15	4	0.016	3.15	1.25	-0.75	0.25	-3.89	
Gammaridae	26.44	4	0.000	-5.09	-9.91	7.09	5.09	2.83	2
Baetidae	33.04	4	0.000	-8.57	-9.23	8.77	6.77	2.27	2
Leptophlebiidae	16.75	4	0.002	3.11	-2.31	4.69	-6.31	0.82	2
Ephemeridae	8.46	4	0.076	0.95	-2.75	5.25	-5.75	2.3	2
Ephemerellidae	17.43	4	0.002	-7.31	-4.49	3.51	6.51	1.78	2
Elmidae	24.46	4	0.000	-6.33	-9.07	7.93	5.93	1.55	2
Hydropsychidae	18.26	4	0.001	-3.9	-5.5	2.5	7.5	-0.59	2
Simuliidae	18.18	4	0.001	-5.29	-5.91	3.09	9.09	-0.98	2
Odontoceridae	14.77	4	0.005	-5.16	-4.44	2.56	7.56	-0.52	1
Oligochaeta	3.91	4	0.419	0.29	-0.09	1.91	-4.09	1.98	

In the 2007 data, 10 MiTGs were significantly associated with SFT mesohabitats, of these; the preferences of nine were consistent with LIFE scores, whilst Leptophlebiidae showed a complex preference for both fast and slow conditions. In both 2006 and 2007 data, two MiTGs, Diptera and Chironomidae do not have LIFE scores, Diptera preferred UW and avoided NP suggesting a LIFE score of 1 or 2, whilst Chironomidae avoided RP and preferred NP, suggesting a LIFE score of 4.

A Chi-square analysis of the strength of the association between SFT mesohabitats and macroinvertebrate samples showed that in 2006 12 MiTGs were significantly associated with one or more SFT mesohabitat. This analysis showed that a suite of MiTGs were positively associated with high energy SFT mesohabitats, notably UW SFT mesohabitat and negatively associated with low energy SFT mesohabitats, particularly NP SFT mesohabitat. The 2007 data are more varied. Although SFT mesohabitat energy still drives the preference for avoidance of SFT mesohabitat types, the pattern is less strong and less extreme. Table 6.33 shows the MiTGs for which Chi-squared tests indicated a significant result, In 2007 better overall water quality provided an opportunity for the distribution of Odontoceridae and Leptophlebiidae to influence the results.

Table 6.33 Chi-square analysis and associated species ranked by descending Lotic Invertebrate Index for Flow Evaluation score. Key: NP - No perceptible; SM – Smooth; RP – Rippled; UW – Unbroken wave; UP – Upwelling; sig – significant; n.s. – not significant. Where observed frequencies differ by more than 1 from that expected (Chi-square test) preference or avoidance is highlighted in SFT columns 2006 and 2007: Red Bold indicates the strongest avoidance, Red indicates avoidance, Black Bold indicates the strongest preference, Black indicates preference, Double strikethrough indicates no preference.

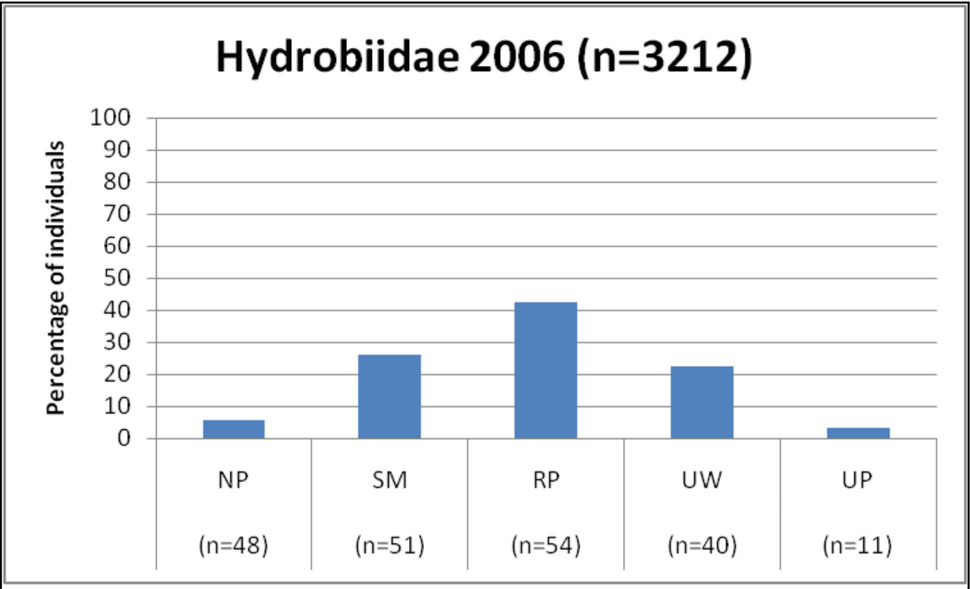
	Chi-square		Associated Surface Flow Types	
	2006	2007	2006	2007
Hydrobiidae	sig.	n.s.	**NP**/SM/RP/**UW**/UP	n/a
Caenidae	sig.	n.s.	**NP**/ ~~SM~~/RP/UW/UP	n/a
Chironomidae	sig.	sig.	**NP**/SM/**RP**/UW/UP	**NP**/SM/~~RP/UW~~/**UP**
Ancylidae	sig.	n.s.	**NP**/SM/RP/**UW**/ ~~UP~~	n/a
Gammaridae	sig.	sig.	**NP**/SM/ ~~RP~~/**UW**/UP	NP/**SM**/**RP**/UW/UP
Baetidae	sig.	sig.	**NP**/SM/RP/**UW**/~~UP~~	NP/**SM**/**RP**/UW/UP
Leptophlebiidae	n.s.	sig.	n/a	NP/SM/**RP**/**UW**/~~UP~~
Ephemerellidae	sig.	sig.	**NP**/SM/~~RP~~/**UW**/~~UP~~	**NP**/SM/RP/**UW**/UP
Elmidae	sig.	sig.	**NP**/SM/RP/**UW**/UP	NP/**SM**/**RP**/UW/UP
Hydropsychidae	sig.	sig.	**NP**/SM/~~RP~~/**UW**/~~UP~~	NP/**SM**/RP/**UW**/~~UP~~
Simuliidae	n.s.	sig.	n/a	NP/**SM**/RP/**UW**/UP
Heptageniidae	sig.	n.s.	**NP**/SM/~~RP~~/**UW**/~~UP~~	n/a
Odontoceridae	n.s.	sig.	n/a	**NP**/SM/RP/**UW**/~~UP~~

6.7 The Nature of Macroinvertebrate Communities in Surface Flow Type Mesohabitats

Previous sections have shown that there is some difference between SFTs in terms of both physical and biological parameters, although these differences are less clear when looking at MiTG communities. This section considers the relationship of 13 MiTGs, significantly associated to SFTs by the X^2 Test. The discussion here related to use of SFT mesohabitats by these MiTGs and not to their preference for them (Section 2.5.6).

The abundance of macroinvertebrates recorded in SFT mesohabitats are presented in Figure 6:20 to Figure 6:32. Each graph shows the abundance of one MiTG using data from either 2006 or 2007 (graphs are only shown for those MiTGs with significant associations). For example, in 2006 Hydrobiidae(n=3212) 6% were found in NP SFT mesohabitats, 26% in SM SFT mesohabitats, 42% in RP SFT mesohabitats, 23% in UW SFT mesohabitats and 3% in UP SFT mesohabitats; in 2007 Hydrobiidae was not significantly associated with any SFT mesohabitat. There is some agreement between the proportion of SFT mesohabitats containing Hydrobiidae and the X^2 results, which suggest that it less likely to be found in NP and SM SFT mesohabitats and more likely in UW, RP and UP SFT mesohabitats. In the following descriptions of MiTG abundance charts, the numbers in brackets show the difference between the expected and actual number of occurrences based on the Chi-square analysis; negative numbers show that the MiTG occurred less frequently than might be expected, positive numbers that there were more than expected.

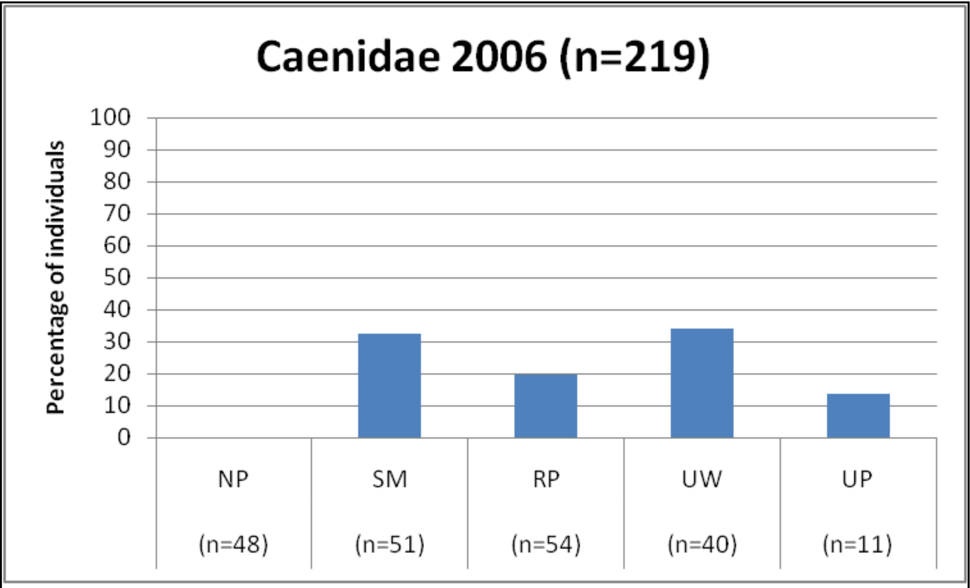
Hydrobiidae were only significantly associated with SFT mesohabitats (X^2 test) in 2006. Chi-square analysis shows that Hydrobiidae is rarely found in NP SFT mesohabitats (-7.04), and is found in SM SFT mesohabitats (-3.85). Hydrobiidae frequently found in UW SFT mesohabitats (+5.80) and often found in RP SFT mesohabitats (+3.13) and UP SFT mesohabitats (+1.95). These results are close to the family LIFE category (1), rapid flow.



2007 - Not significant

Figure 6:20 Abundance of Hydrobiidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Caenidae were only significantly associated with SFT habitats (X^2 test) in 2006. Chi-square analysis shows that Caenidae is rarely found in NP habitats (-5.88), occasionally found in RP habitats (-1.75), they occasionally found in SM (+0.88) and UP (+2.75). Caenidae are frequently found in UW habitats (+4.00).



2007 - Not significant

Figure 6:21 Abundance of Caenidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Chironomidae was significantly associated with SFT mesohabitats (X^2 test) in both 2006 and 2007. Chi-square analysis shows that Chironomidae are frequently found in NP SFT mesohabitats in both years (+7.64 in 2006 and +3.15 in 2007) and often found in UW SFT mesohabitats (+2.20 in 2006 and +0.25 in 2007). It is occasionally found in RP SFT mesohabitats in both years, (-4.93 in 2006 and -0.75 in 2007) as it does UP SFT mesohabitats (-2.95 in 2006 and -3.89 in 2007). Chironomidae is occasionally found in SM SFT mesohabitats avoiding in 2006 (-1.96) and preferring in 2007 (+1.25). The taxonomic group Chironomidae contains many species, which have differing habitat preferences. Chironomidae is not categorised in the LIFE scheme.

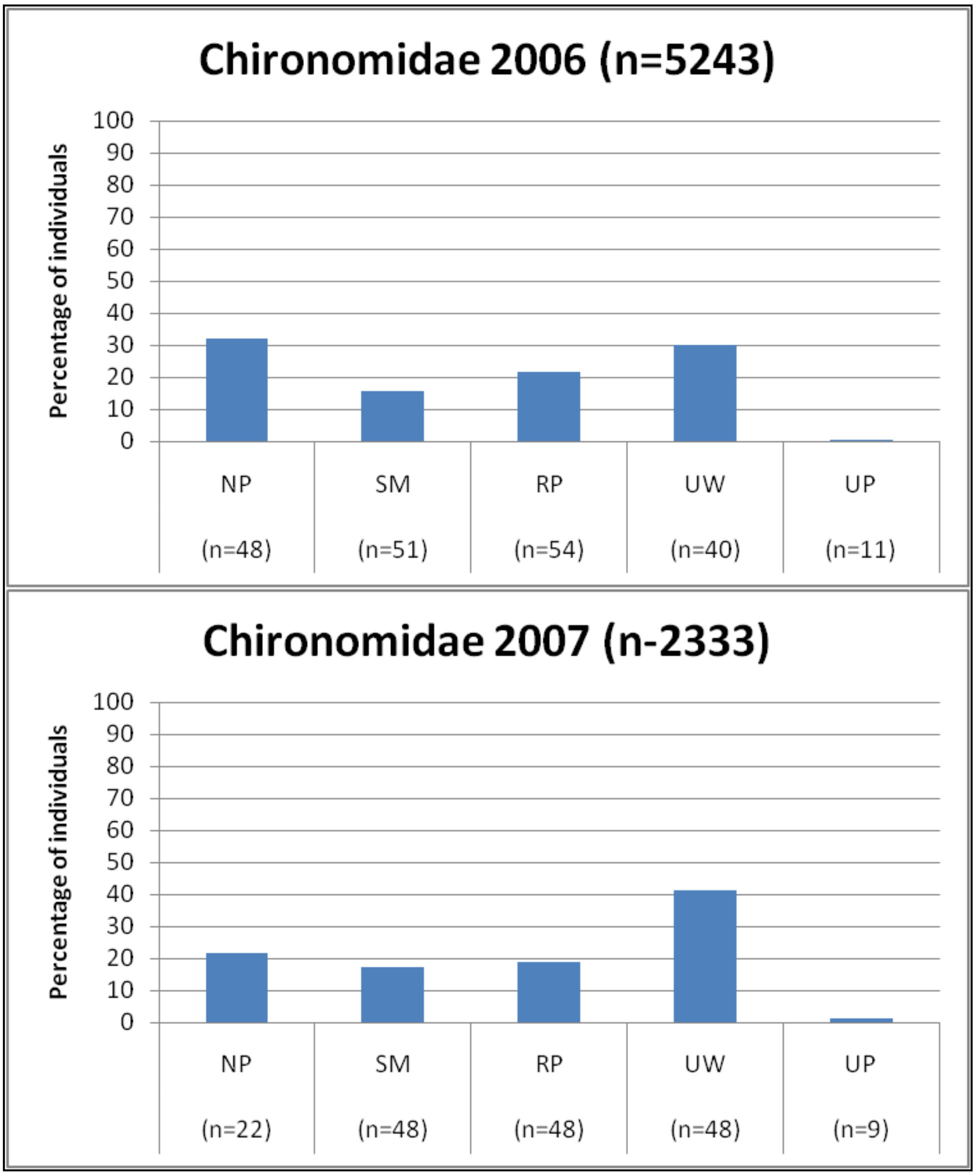


Figure 6:22 Abundance of Chironomidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Ancylidae were only significantly associated with SFT mesohabitats (X^2 test) in 2006. Chi-square analysis shows that Ancylidae is rarely found in NP SFT mesohabitats (-6.11), is occasionally found in SM SFT mesohabitats (-3.37) and UP SFT mesohabitats (-0.30). It is frequently found in UW SFT mesohabitats (+6.80) and is often found in RP SFT mesohabitats (+2.98). This broadly agrees with the assigned LIFE flow category (2).

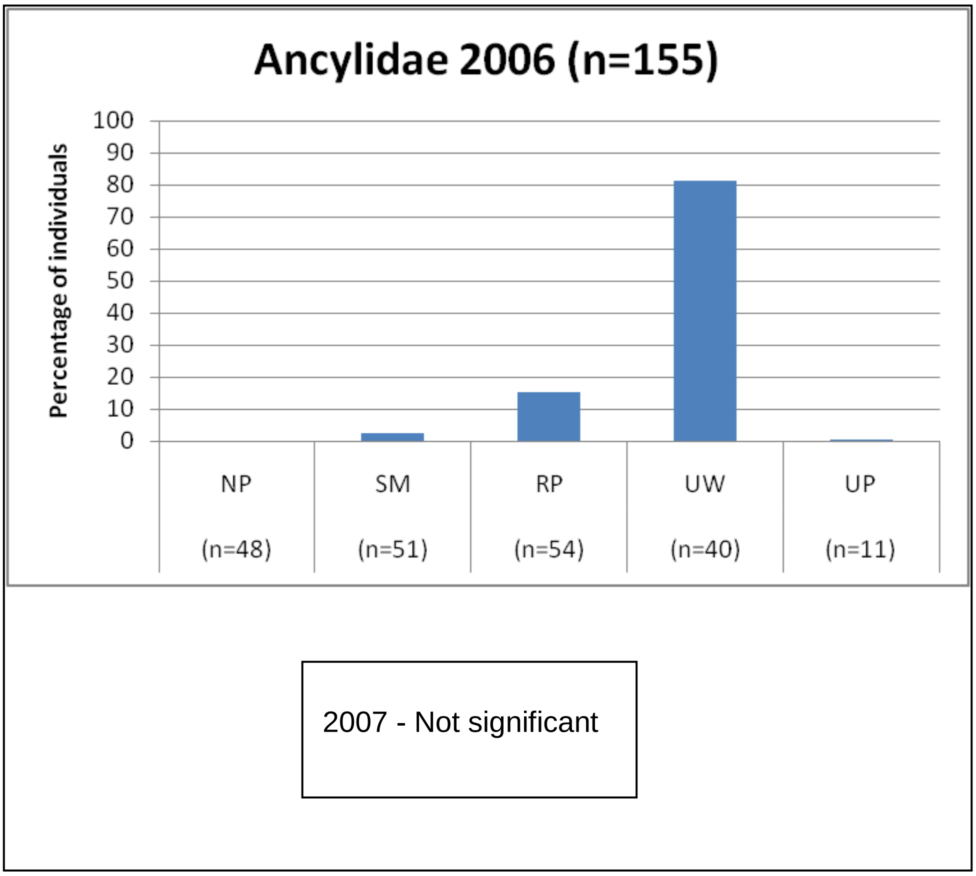


Figure 6:23 Abundance of Ancylidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Gammaridae was significantly associated with SFT mesohabitats (X^2 test) in both 2006 and 2007. Chi-square analysis shows that Gammaridae is frequently found in UW SFT mesohabitats in both years (+4.60 in 2006 and +5.09 in 2007) is often found in UP SFT mesohabitats (+2.65 in 2006 and +2.83 in 2007). Gammaridae is rarely found in NP SFT mesohabitats in 2006 (-10.15) in 2007 (-5.09). SM and RP SFT mesohabitats are variable, SM SFT mesohabitats often in 2006 (+3.79) and rarely in 2007 (-9.91), RP SFT mesohabitats occasionally in 2006 (-0.89) but often found in 2007 (+7.09). These results broadly agree with the LIFE category (2).

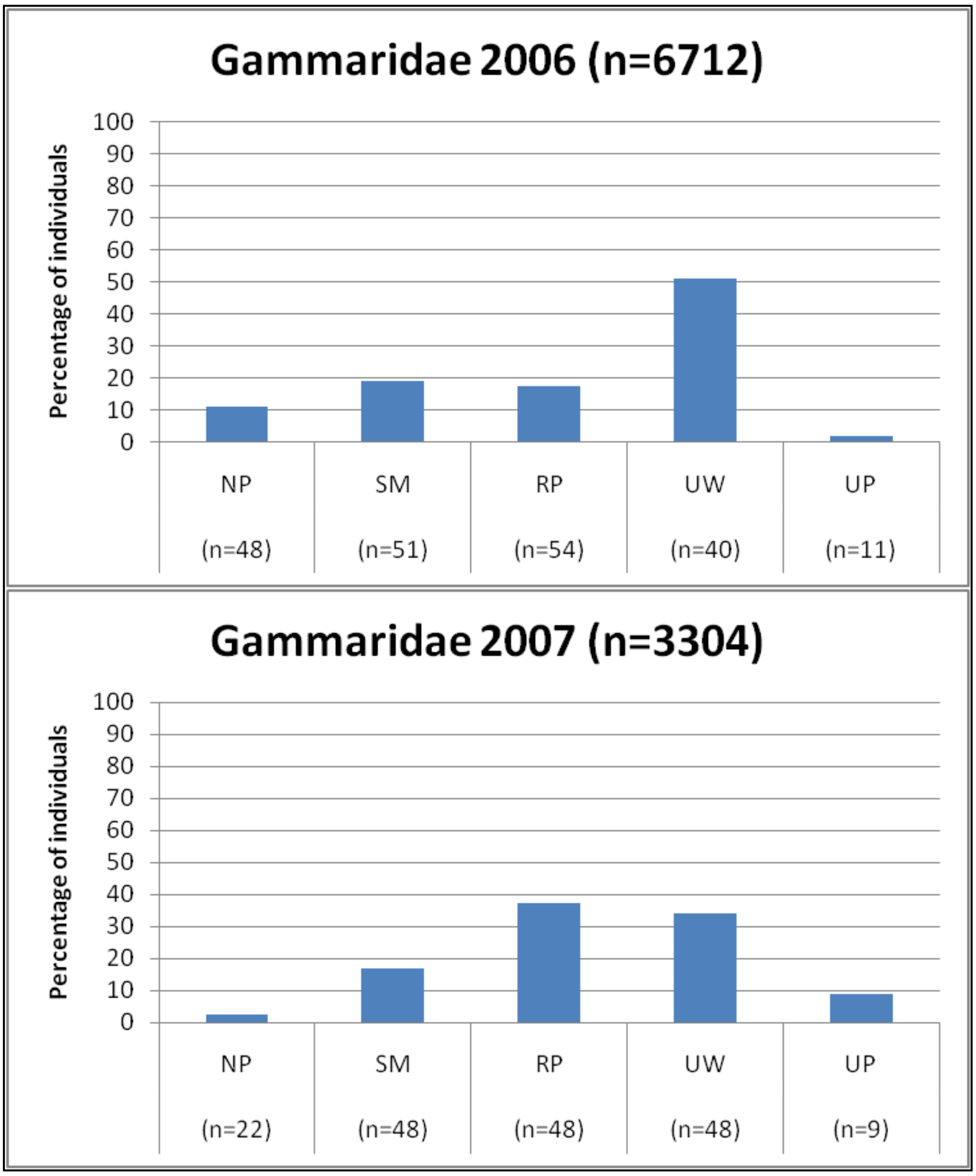


Figure 6:24 Abundance of Gammaridae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Baetidae were significantly associated with SFT mesohabitats (X^2 test) in both 2006 and 2007. Chi-square analysis showed that Baetidae is frequently found in UW SFT mesohabitats in 2006 (+11.60) although less so in 2007 (+6.77), and frequently found in RP SFT mesohabitats in 2007 (+8.77), less so in 2006 (+3.16) and is frequently found in UP SFT mesohabitats in 2007 (+2.27) less so in 2006 (+0.40). They were rarely found in NP SFT mesohabitats in 2006 (-16.62) and in 2007 (-8.57), SM SFT mesohabitats are variable, often found in 2006 (+1.46) and rarely in 2007 (-9.23). These results generally agree with the LIFE flow category (2).

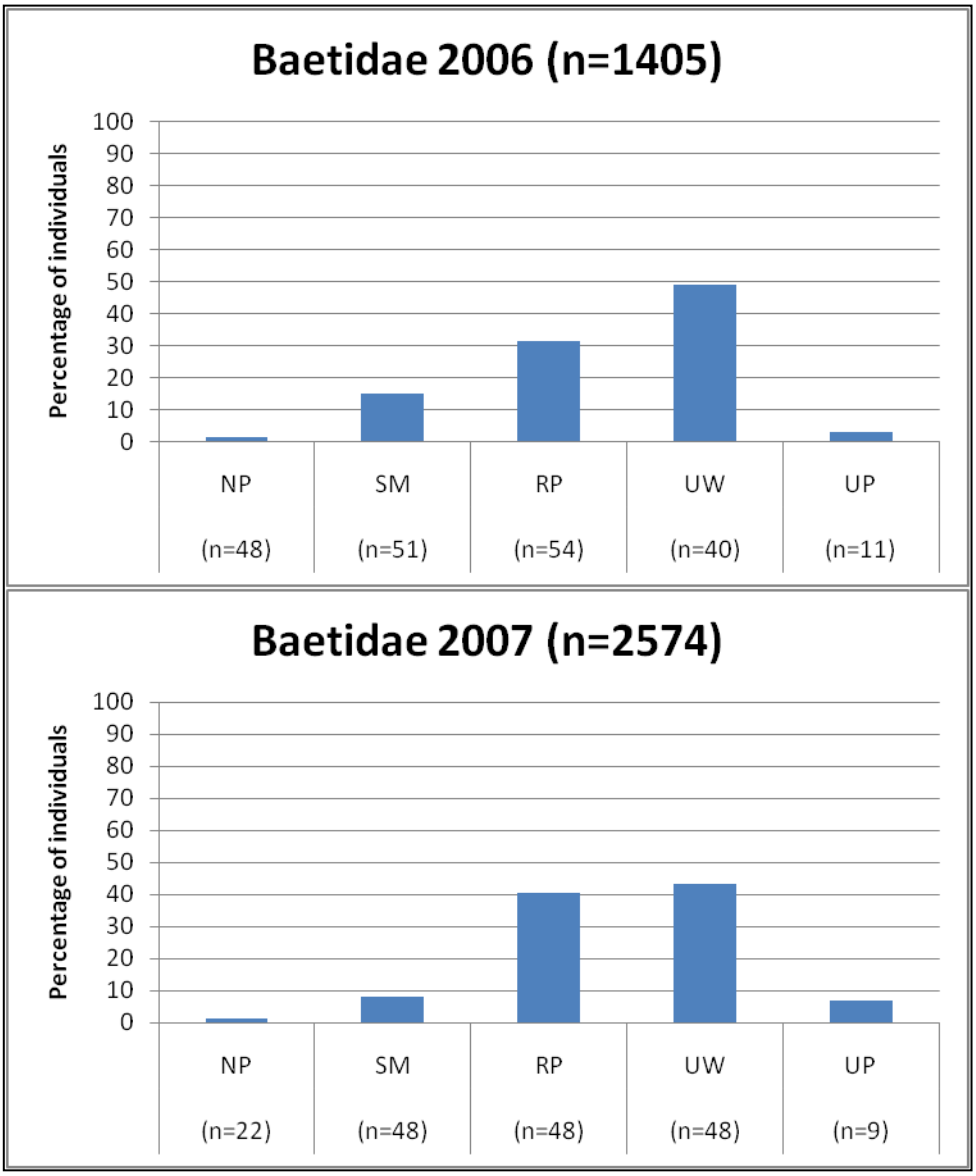


Figure 6:25 Abundance of Baetidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Leptophlebiidae were only significantly associated with SFT mesohabitats (X^2 test) in 2007. Chi-square analysis shows that Leptophlebiidae is frequently found in RP SFT mesohabitats (+4.69), less so with NP (+3.11) and occasionally in UP SFT mesohabitats (+0.82), they are rarely found in UW SFT mesohabitats (-6.31), and occasionally in SM SFT mesohabitats (-2.31). Leptophlebiidae are associated with in-stream vegetation. These results broadly agree with the LIFE category (2).

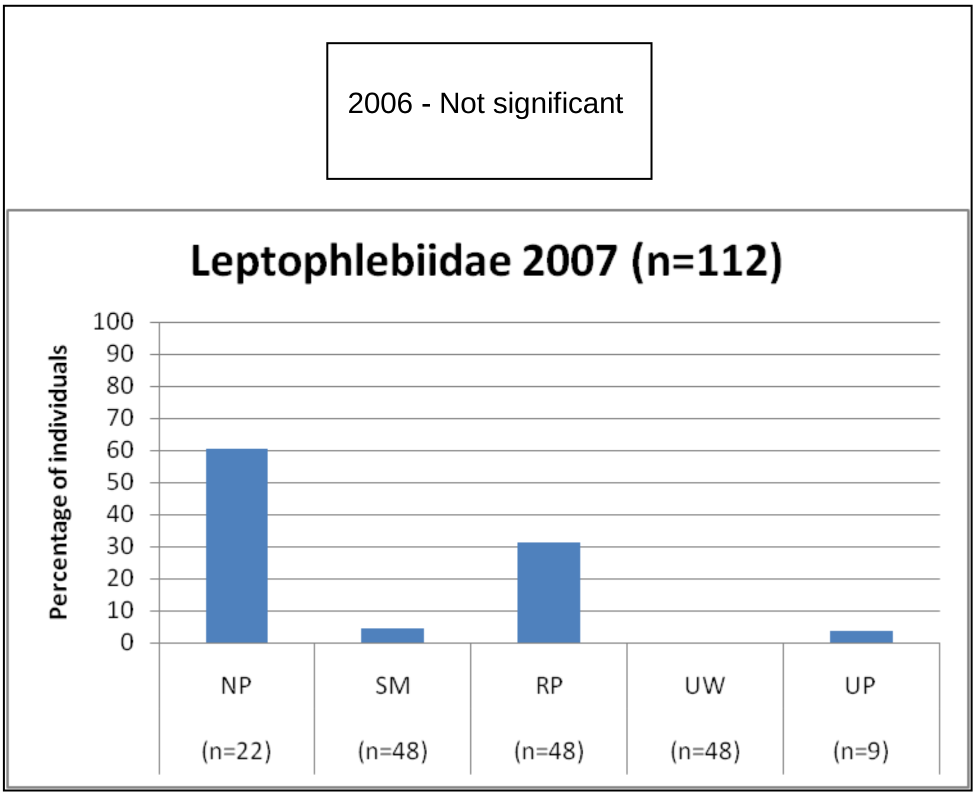


Figure 6:26 Abundance of Leptophlebiidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Ephemerellidae were significantly associated with SFT mesohabitats (X^2 test) in both 2006 and 2007. Chi-square analysis shows that Ephemerellidae is frequently found in UW SFT mesohabitats in 2006 and 2007 (+5.00 and +6.51 respectively) although the abundance by SFT is less clear. It is often found in RP SFT mesohabitat (+0.10 in 2006 and 3.51 in 2007) and UP SFT mesohabitats (+0.50 in 2006 and 1.78 in 2007) in both years. Ephemerellidae is rarely found in NP SFT mesohabitats in both years (-9.45 in 2006 and -7.31 in 2007). Occurrence in SM SFT mesohabitat is variable, positively associated in 2006 (+3.85) and negatively in 2007 (-4.49), again suggesting that factors other than SFT mesohabitats are also involved in the distribution of Ephemerellidae. These results broadly agree with its LIFE category of 2 (Moderate/Fast).

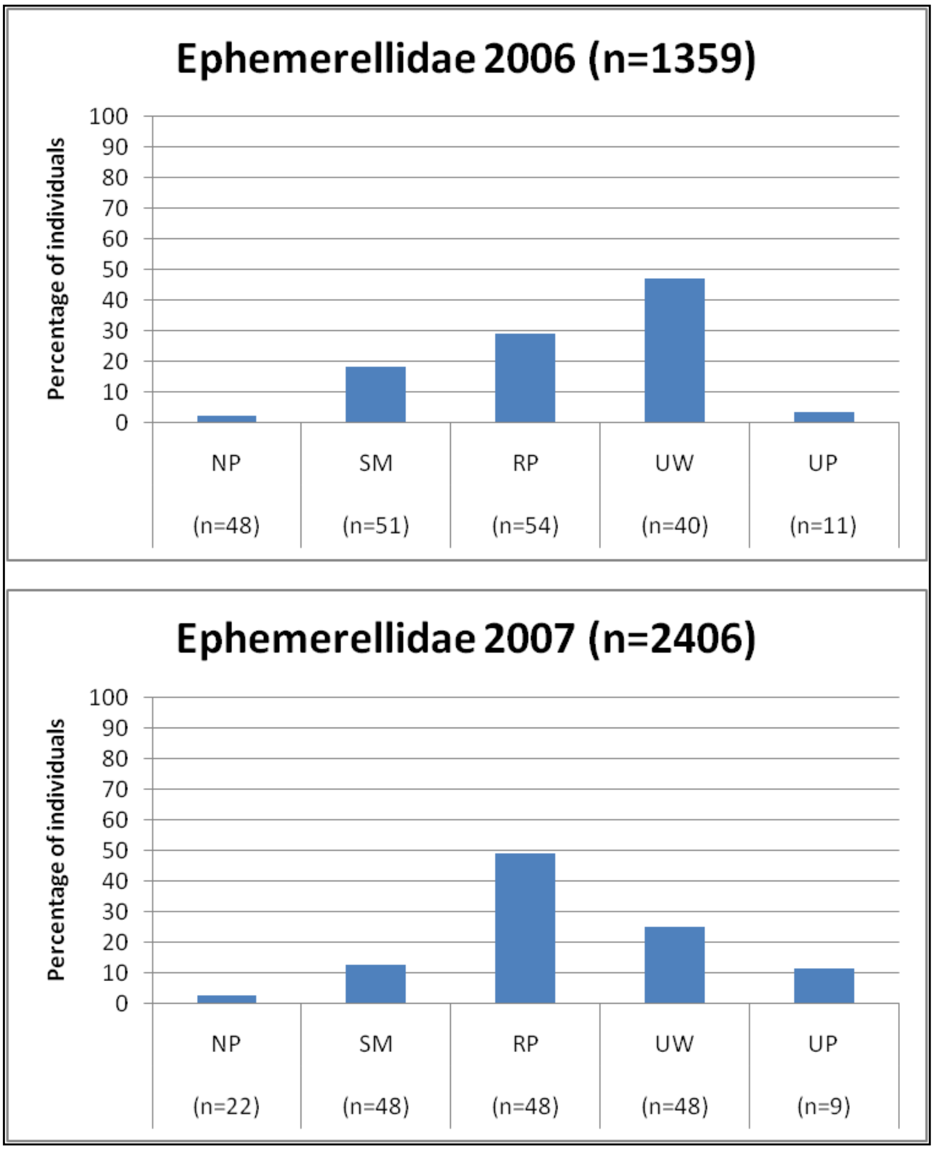


Figure 6:27 Abundance of Ephemerellidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Elmidae were significantly associated with SFT mesohabitats (X^2 test) in both 2006 and 2007. Chi-square analysis shows that Elmidae is frequently found in RP SFT mesohabitat in 2006 and 2007 (+7.11 and +7.93 respectively), and often in UW SFT mesohabitat in 2006 and 2007 (+9.60 and +5.93 respectively) and UP (+1.65 and 1.55). Elmidae is found in NP SFT mesohabitats in both years, rarely in 2006 (-13.15) and occasionally in 2007 (-6.33). It also is occasionally found in SM SFT mesohabitat (-5.22) in 2006 (-9.07) in 2007. These results broadly agree with its LIFE category of 2 (Moderate/Fast).

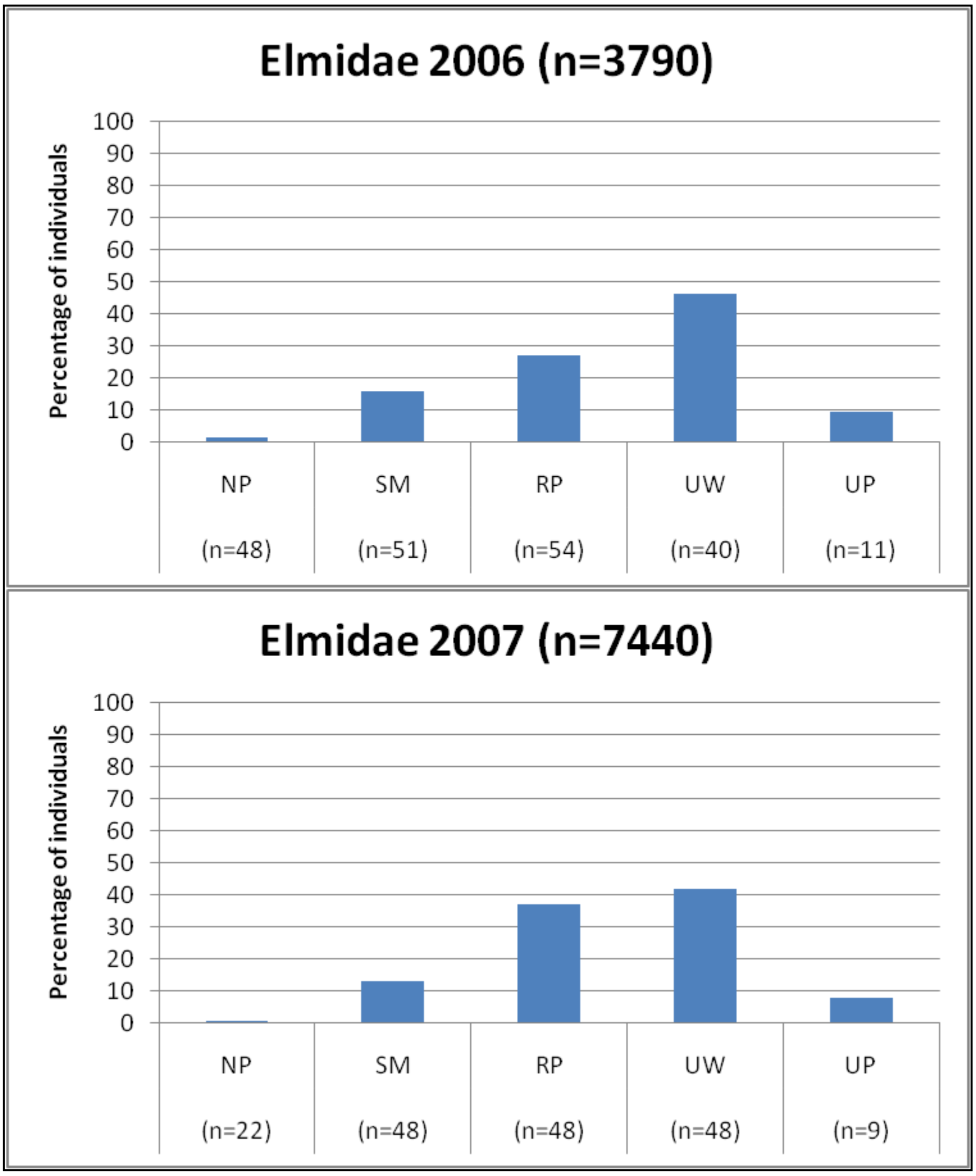


Figure 6:28 Abundance of Elmidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Hydropsychidae were significantly associated with SFT mesohabitats (X^2 test) in both 2006 and 2007. Chi-square analysis shows that Hydropsychidae is frequently found in UW SFT mesohabitats in 2006 and 2007 (+6.40 and +7.50 respectively) and often in RP SFT mesohabitats in 2006 and 2007 (+0.79 and +2.50 respectively). Hydropsychidae is rarely found in NP SFT mesohabitats in both years, 2006 (-4.41), 2007 (-3.90), it is also occasionally found in SM SFT mesohabitat (-3.64) in 2006 (-5.50) in 2007. UP SFT mesohabitats are variable, being often found (+0.85) in 2006 and occasionally found (-0.59) in 2007. These results agree with Hydropsychidae LIFE category of 2 (Moderate/Fast).

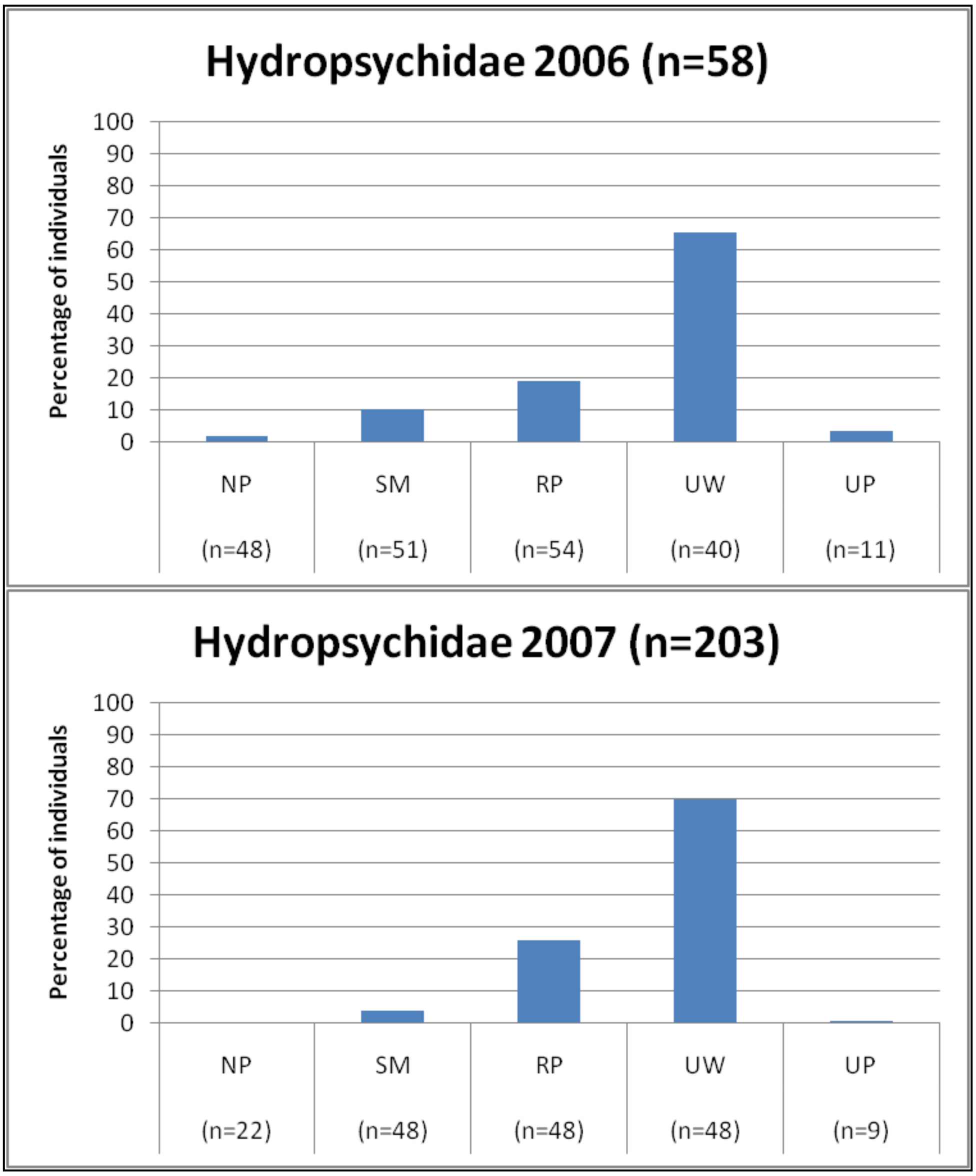


Figure 6:29 Abundance of Hydropsychidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Simuliidae were only significantly associated with SFT mesohabitats (X^2 test) in 2007. Chi-square analysis shows that Simuliidae is frequently found in UW SFT mesohabitat (+9.09), and often in RP (+3.09), it is occasionally found in SM SFT mesohabitats (-5.91) and NP SFT mesohabitat (-5.29), rarely in UP SFT mesohabitats (-0.98). These results show clear agreement with Simuliidae LIFE category 2 (Moderate/Fast).

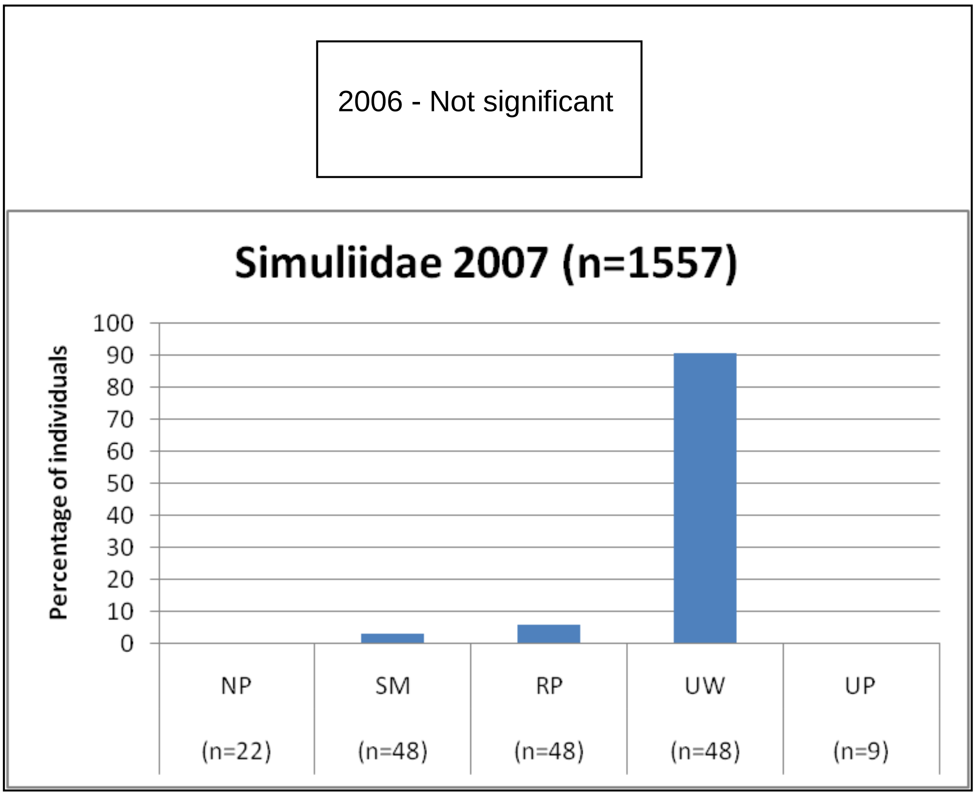


Figure 6:30 Abundance of Simuliidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Heptageniidae were only significantly associated with SFT mesohabitats (X^2 test) in 2006. Chi-square analysis shows that Heptageniidae is frequently found in UW SFT mesohabitats (+9.80) and often in UP SFT mesohabitats (+0.95), Heptageniidae is rarely found in NP SFT mesohabitats (-8.64), and occasionally in SM SFT mesohabitat (-2.05) and RP SFT mesohabitats (-0.07). Heptageniidae has a LIFE category of 1 (Rapid).

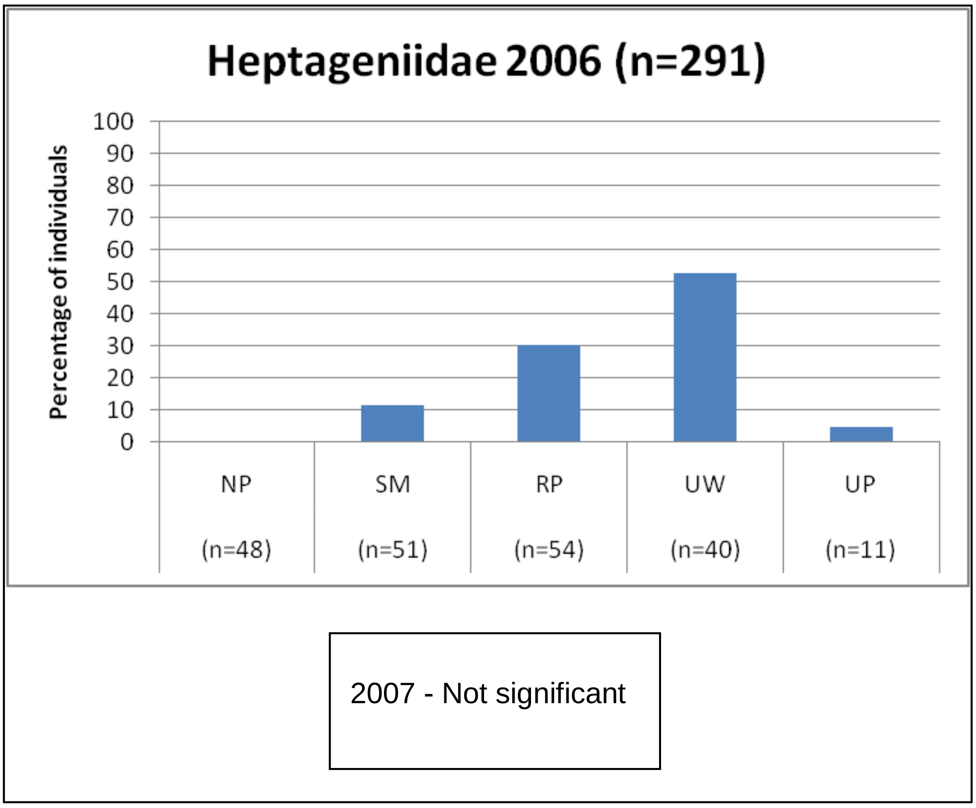


Figure 6:31 Abundance of Heptageniidae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

Odontoceridae were only significantly associated with SFT mesohabitats (X^2 test) in 2007. Chi-square analysis shows that Odontoceridae is frequently found in UW SFT mesohabitats (+7.56), and less so, RP SFT mesohabitats (+2.56) whilst it is occasionally found in NP SFT mesohabitats (-5.16), and SM SFT mesohabitat (-4.44) and occasionally in UP SFT mesohabitats (-0.52).

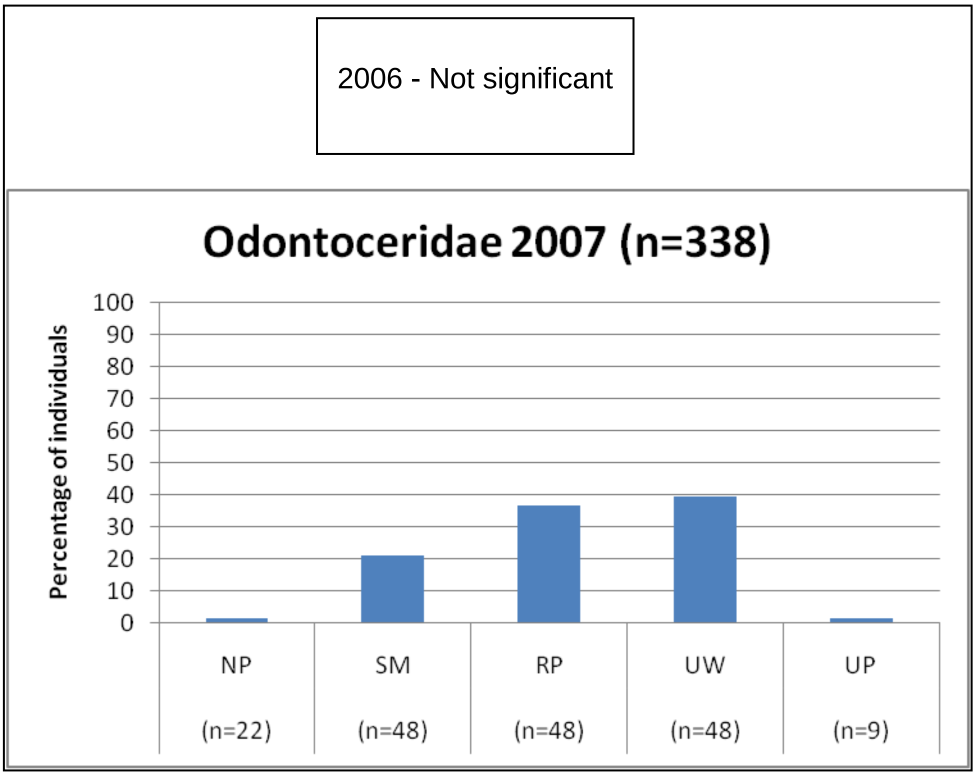


Figure 6:32 Abundance of Odontoceridae by Surface Flow Type mesohabitat during 2006 and 2007 in eight British lowland rivers.

The results of the X^2 analysis generally agree with the assigned LIFE category, for those MiTGs that have been categorised. However, this is on an individual MiTG basis. Fourteen MiTGs are statistically associated, positively or negatively, with SFT mesohabitats. The nature of that association has been explored by considering the frequency with which they are found in samples from SFT mesohabitats.

Based on data collected in 2006 and 2007, Figure 6:33 shows the MiTGs likely to be identified in samples taken from the same populations as these data, the figures in brackets show the probability of being found in that SFT mesohabitat. Some MiTGs are likely to be found in more than one SFT mesohabitat, e.g. Chironomidae is associated with NP, SM and UW although not with RP and UW mesohabitats. The reasons for this may be chance, although this particular taxonomic group contains a large number of species, each of which are frequently found in NP, SM or UW.

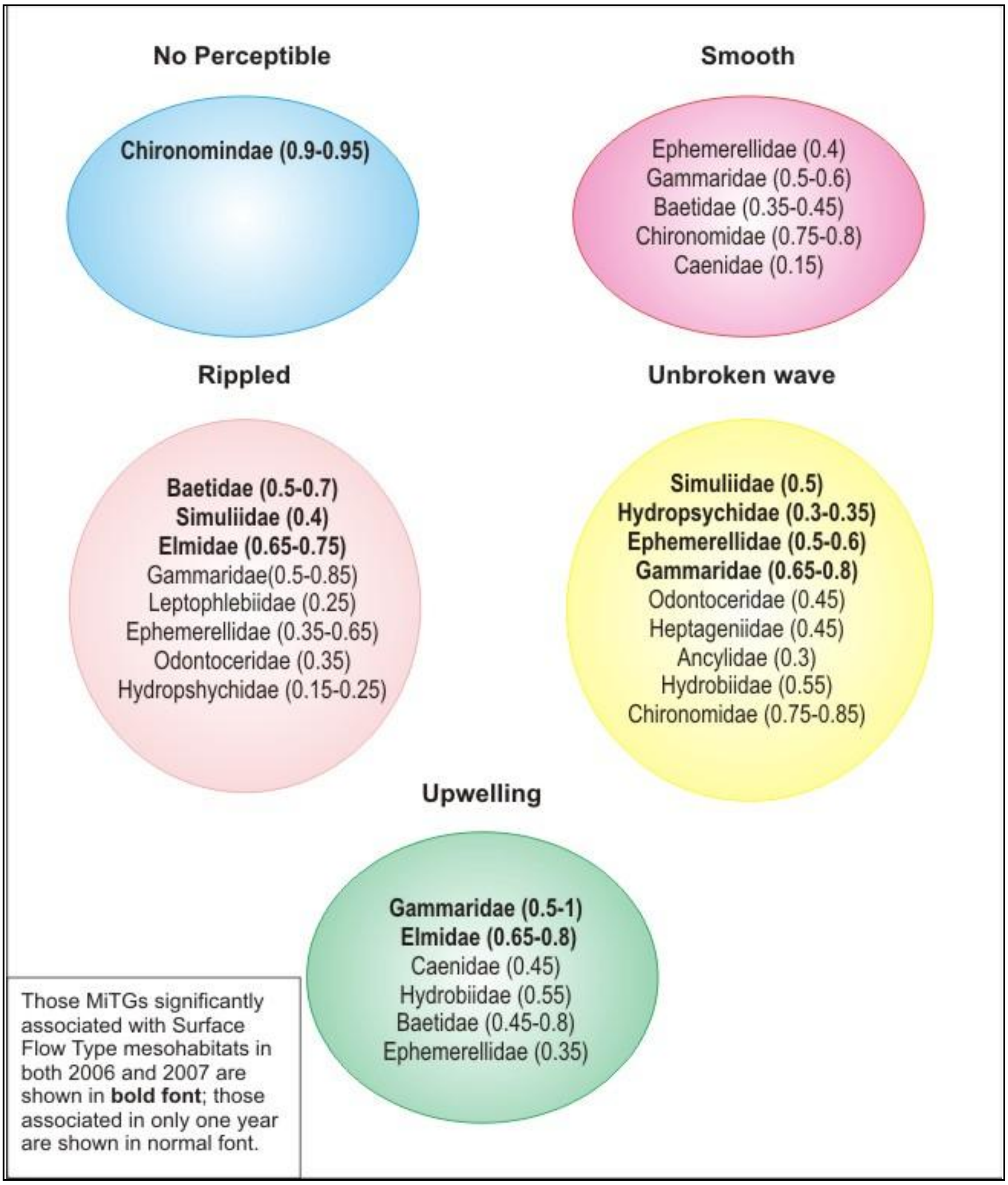


Figure 6:33 Diagram showing the Macroinvertebrate Taxonomic Groups statistically associated with Surface Flow Type mesohabitats, the figures in brackets show the probability of being found in that SFT mesohabitat

6.8 Macroinvertebrate Depth and Velocity Matrices

Table 6.34 shows the relationship between near-bed velocity and water depth for 14 MiTGs that were shown to be significantly associated with SFTs using the X^2 test. The velocities associated with LIFE velocity group and each MiTG is shown (where determined) in yellow on the x-axis. The matrices are laid out using the output template from HydroSignature (Section 4.4.5) and show, in red the depth/velocity cell where the median values occur, the interquartile range of values is in brown and the spread of data in tan. Visualisation of the depth/velocity data determined where the MiTGs were collected provides data comparable with a Category III preference curve data (Conallin *et al*, 2010) and could provide a method, compatible with HydroSignature, from which biotic interest of in-stream habitats could be indicated.

Table 6.34 Matrix showing depth/velocity associated with 13 MiTGs, combining data collected in 2006 and 2007 from six British lowland rivers. The median values are shown in red, the extents of the 25th and 75th quartiles are shown in brown and the extents of maxima and minima are shown in tan. The velocity ranges of flow groups from LIFE (Extence, *et al.,* 1999) are shown below the x-axis in yellow.

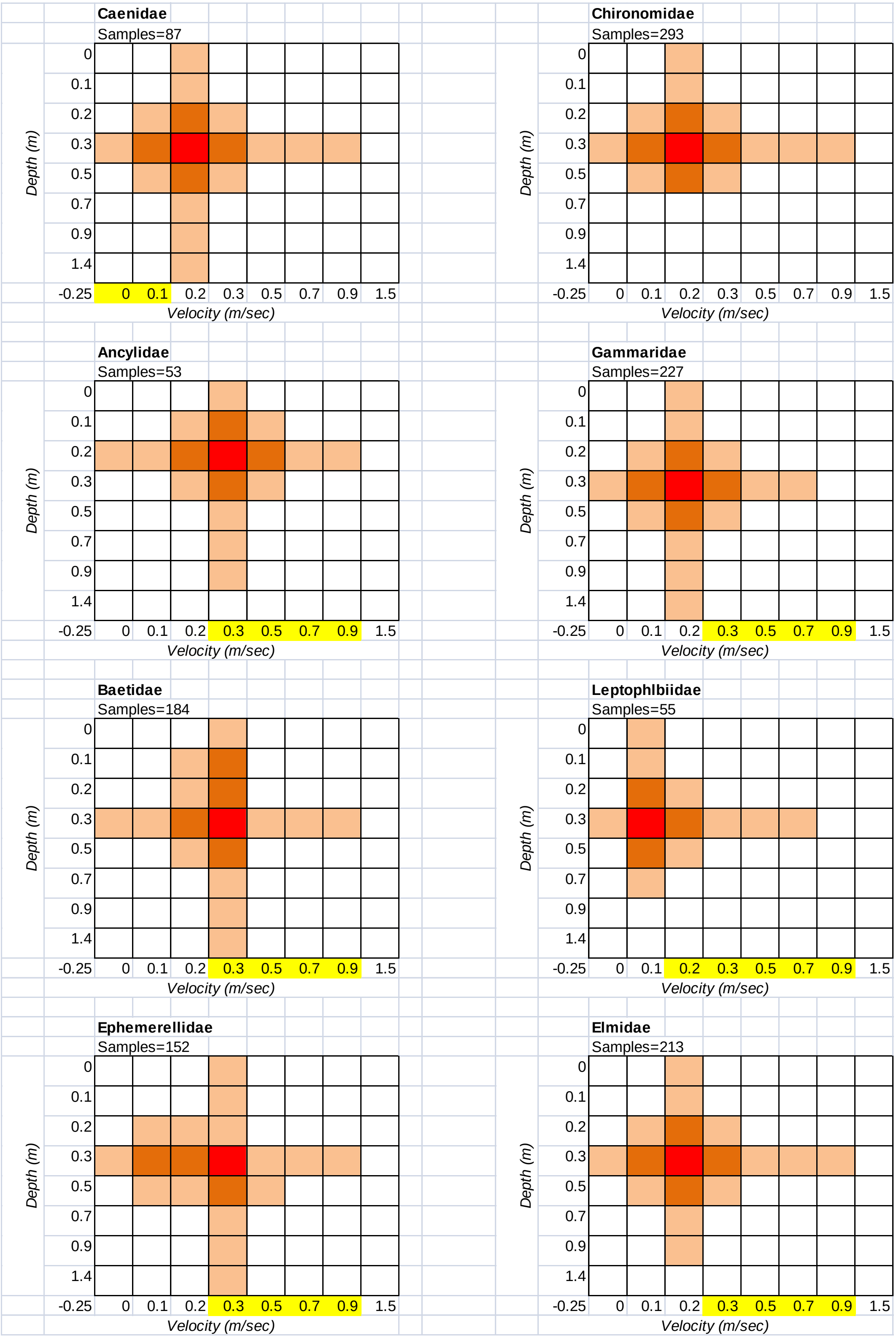


Table 6.34 (cont) Matrix showing depth/velocity associated with 14 MiTGs, combining data collected in 2006 and 2007 from six British lowland rivers. The median values are shown in red, the extents of the 25th and 75th quartiles are shown in brown and the extents of maxima and minima are shown in tan. The velocity ranges of flow groups from LIFE (Extence, *et al.,* 1999) are shown below the x-axis in yellow.

Lancaster and Downes (2010) (Section 2.5.6) suggest that environmental factors limiting the presence of MiTGs are more helpful than seeking their central tendency. The matrices presented here could be populated with appropriate habitat suitability data, providing more biological information, to address this point. It is considered that, if a simple method of comparison between HydroSignature outputs and the occurrence / preference matrix could be developed this might provide a method for predicting macroinvertebrate communities in SFT mesohabitats, although this is beyond the scope of this research.

6.9 Discussion

This research has shown that relationships between benthic macroinvertebrate communities and NP, SM, RP, UW and UP SFT mesohabitats in British lowland rivers are mixed. In this research 43 MiTGs were identified, slightly more in 2006 than in 2007, this closely corresponds with Beisel *et al.* (2000) and Reid and Thoms (2008) who identified organisms to similar taxonomic levels. Reid and Thoms (2008) found that macroinvertebrate abundance and MiTG richness was highest in UW and RP, lowest in NP which is mirrored here in this research. UW mesohabitats benefit from higher water velocity and coarser substrate which increase water column turbulence and provide higher levels of dissolved oxygen – ASPT scores are generally higher in UW mesohabitats (Section 6.3.4). Coarse substrate provides a wide range of microhabitats, *e.g.* low velocities in the substrate, and places to hide (*refugia*) whilst the higher water velocity is capable of delivering a supply of food to filter feeders (*e.g.* Hydropsychidae). Coarse substrate and shallow water provide stable surface on which algae grow, providing food for grazers (e.g. Ancylidae). NP mesohabitats are more likely to have lower oxygen concentrations and a soft substrate providing suitable conditions for a smaller range of MiTGs, whilst SM and RP mesohabitats grade between NP and UW.

Analysis of variance in MiTG abundance, richness and LIFE scores within five SFTs (Kruskal-Wallis ANOVA) showed that they are significantly different in both 2006 and 2007. This is supported by pair-wise analysis (Mann-Witney *U* test) which shows 50 – 90% of SFT pairs are significantly different. However, there is a wide range of values recorded in each SFT and the strength of the relationships needs to be used with caution. Diversity is a measure of the relative abundance of taxa, whilst equitability identifies dominant taxa. There was little difference between SFT pairs in terms of diversity (also found by Principie *et al.,* 2007) suggesting that all SFTs are contain a similar range and abundance of taxa, whilst equitability suggests that no individual taxa dominates (Figure 6:1; Figure 6:2).

BMWP scores, and ASPT (the average BMWP score per taxon) are measures of sensitivity to organic pollution, which has a strong impact on dissolved oxygen. The BMWP score of a taxon can be regarded as a measure of sensitivity to low dissolved oxygen.Taxa with low BMWP score are tolerant to low oxygen saturation whilst those with a higher tolerance are scored higher (max 10), this suggests that highly turbulent SFTs are likely to be able to support less tolerant taxa, and so have a higher BMWP score, whilst slowly moving SFTs

(NP) are likely to support taxa with low BMWP scores. There are only small differences between mean values of ASPT between SFTs, and the range exceeds the differences between the means. This suggests that, for example, NP SFTs support communities requiring less O_2 than does RP, UW and UP SFTs. It is also likely that O_2 saturation is partly determined by upstream SFT composition. If the turbulent nature of UW SFTs increases O_2 saturation then as water flows downstream into other SFT mesohabitats it will carry dissolved O_2 with it. Therefore a NP mesohabitat immediately downstream of an UW SFT is likely to contain higher dissolved O_2 that a NP mesohabitat below a long glide.

LIFE (Extance *et al*., 1999) categorised MiTGs by velocity class which suggests that Category 1 might be associated with BW or CH SFTs, Category 2 with UW or RP, Category 3 with SM or RP and Category 4 with NP or SM. In this research LIFE scores showed the strongest relationship to SFTs (Section 6.3.7) suggesting that velocity is an important driver of MiTG community in SFT mesohabitats. Velocity was also shown to be a key variable in the physical characterisation of SFTs (Section 5.4.6).

TWINSPAN was used by Extance *et al.* (2000) in research leading to the LIFE technique, however here the results were inconclusive. Using all data from 2006 and from 2007, macroinvertebrate samples were grouped better by site than by SFT. Such differences between sites may be due to water quality (Hynes, 1970; Hawkes 1997) and in this research water pollution (as ASPT) varied between rivers (Section 5.3.11). On a site-by-site basis, SFT appeared to be more important in the end-groups, although still weak. Principie *et al.* (2007) also found it necessary to analyse their four sites independently in order to detect temporal differences between macroinvertebrate samples.

Other research (Heino *et al.,* 2004; Lancaster and Beylea, 2006; Principie, 2007; Reid and Thoms 2008) used a limited number of rivers for their research, potentially reducing or eliminating the impact of water quality. However near-bed hydraulic and sedimentary conditions are also important (Section 2.2.1). A total of 39 indicator species were identified by TWINSPAN (in the site by site analysis) as summarising the divisions of the data. Baetidae, Ephemerellidae, Gammaridae, Heptageniidae and Elmidae were the only ones to appear in five or more divisions. Chi-Square Analysis showed that these five MiTGs are significantly associated with UW SFT, avoiding NP SFTs, these result correspond with velocity categories from LIFE (Extence *et al.,* 1999) and with the findings of Reid and Thoms (2008). Chironomidae was associated with NP SFT, avoiding more energetic SFTs (RP) also found by Reid and Thoms (2008).

CCA showed that, in both years, there was little separation between macroinvertebrate samples grouped by SFT, although SFTs were the variable with the greatest influence on the biological data. Further, the variance explained by each axis was only slightly above that of randomness, suggesting that within the data collected in each of the two years, there is little relationship between SFT mesohabitats and macroinvertebrate communities. Nevertheless, velocities at the surface and at 0.05m above the bed have similar effects in both years, whilst velocities nearer the bed were less strongly related, which is probably a function of a wide range of values (Section 2.2.1) particularly in UW SFTs.

Reid and Thoms (2008, p1048) found clear separations between macroinvertebrate communities in five replicate patches from each SFT investigated, with 25 samples being obtained from 25 SFT patches, fewer than the 375 from eight rivers in this study. Here, macroinvertebrate community composition is far less clear, and is probably a function of the range of sites investigated. Nevertheless, some MiTGs do have statistical associations with SFTs across all samples collected.

Hydraulic and sedimentary conditions vary considerably at the micro-habitat scale, which is the scale of interest to MiTGs. Heino *et al.* (2004) suggested that many replicate samples were needed to establish macroinvertebrate community whilst Lancaster and Belyea (2006) found considerable variability in 99 macroinvertebrate samples obtained from one mesohabitat. Macroinvertebrate data obtained during this research was obtained from five SFT mesohabitat types in eight different rivers.

Greater taxa richness has been linked to increasing habitat heterogeneity (Beisel *at al*., 2000, Tickner *et al*., 2000) and attributed to the range of niches available to macroinvertebrates and to the (relatively) short distances between suitable niches which allow organisms to move from one to another. These findings are likely to be responsible for differences in MiTG abundance and diversity between rivers examined here. Sites with high levels of MiTG richness (Leigh Brook, River Leadon and River Windrush) had a wide range of substrates in the study reach whilst Bailey Brook and Badsey Brook had a much more limited range. Substrate heterogeneity within SFTs will have similar effects – low energy SFTs (NP and SM) are dominated by small substrate size whilst higher energy SFTs (RP and UW) have larger substrate sizes and provide a wider range of niches for animals to colonise, explaining the high number (10) of MiTGs positively associated with UW SFT. It is also likely that these factors are responsible for range of data obtained by Lancaster and Belyea (2006), in one riffle.

Reid and Thoms (2008) concluded that macroinvertebrate communities related to SFTs were not significantly different from adjacent SFTs along the energy gradient (NP>SM>RP>UW), although there is a clear break between SM and RP SFTs. This research has shown similar trends with nine MiTGs being associated with more energetic SFTs (UW) and one for low energy SFT (NP).

In this research, 14 MiTGs were associated with SFTs (X^2 test, Section 6.6), here this refers to habitat use and not to preference (Section 2.5.6). Of these 14 only one was associated with low energy SFTs: Chironomidae is positively associated with NP and negatively with RP and UW. Chironomidae comprise over 450 species occupying a wide range of habitats with a wide range of feeding traits, in rivers they are often found in muddy sediments which are related to low energy SFTs. Their ability to withstand low oxygen concentrations allows them to colonise slow moving water where oxygen is less abundant.

Four MiTGs with grazing feeding habits were positively associated with high energy mesohabitats (UW and RP). Hydrobiidae and Ancylidae are both grazers (Conchological Society of Britain, 2010a; 2010b) grazing algae from hard surfaces on bedrock or large substrate. Ancylidae favours areas where water turbulence is sufficient to keep the substrate clean and has developed a streamlined morphology suited to higher velocities. Elmidae are assumed to be grazers of algae and bryophyte and rarely found in deep water where the food source doesn't grow well, larvae live between stones where velocity is lower (Elliott, 2008), whilst the adults cling to stones or vegetation. It is thought that Elmidae 'breath' through pores as they have no gills, they benefit from high oxygen levels in turbulent SFTs. Suitable conditions for these MiTGs are generally found within the UW SFT.

Six MiTGs are gatherers or collector gatherers – Baetidae, Gammaridae, Heptageniidae, Leptophlebiidae, Ephemerellidae and Caenidae – all are associated with more energetic SFTs, UW or RP where a steady food supply is delivered by the higher velocity water. The niches occupied by these six groups are separated by the physical conditions they are associated with. The common Baetidae species are swimmers, although they cling to coarse substrate or vegetation, Gammaridae are frequently found in or under the substrate and Heptageniidae cling to coarse substrate or occupy gaps between the particles. Leptophlebiidae is common in slower flowing waters, which is reflected in its association with RP and UW SFTs, whilst Ephemerellidae are clinger / sprawers from faster water. Caenidae is also a sprawler, and associated with UW and UP in this study, it is better able to cope with silty conditions because of its gill covers. Caenidae were common in Leigh Brook which, according to a local resident, has suffered from increasing silt deposition in the past several decades.

Odontoceridae is a shredder and found in fast running waters under stones – it is associated with UW SFTs, whilst Hydropsychidae and Simuliidae are both filterers (although Hydropsychidae also predates) and rely on the faster waters to deliver an adequate food supply although both need large stable substrates on which to anchor their shelters, appropriate conditions are often found in UW SFTs.

The 14 MiTGs referred to above are generally the more commonly found species, with seven drawn from the top ten most abundant groups discovered in this research. It is probable that the X^2 Test was better able to discriminate between large numbers of individuals.

Causal links between organisms and their environment are complex and not fully understood by ecologists and is well demonstrated by Lancaster and Beylea (2006) who sampled one mesohabitat and found considerable biological variety. This research has shown that relationships between SFT mesohabitats and MiTG community exist; they are complex and not particularly robust. This is probably because mesohabitats contain a number of niches (microhabitats) with a range of physical variables (Beisel *et al,* 2000; Principie *et al.,* 2007). Therefore, scaling up macroinvertebrate community relationships with SFTs from micro- to mesohabitats requires an amalgamation of microhabitat conditions, and will inevitably need generalisation of the microhabitat conditions within the mesohabitats to be effective.

At each macroinvertebrate sample site water depth, velocity and substrate size, together with degree of embeddedness; algal, bryophyte, overhead and macrophyte cover was recorded. This allowed the construction of Category II (Connalin *et al*., 2010) HSIs. Category II has been shown to be ecologically appropriate (Connalin *et al*., 2010). Category III ‘preference’ curves (Moir *et al*., 2005) (Section 2.5.6) have the potential to recognise some of the limitations of habitat use identified by Lancaster and Beylea (2003) and Deudal (2007). The indices, here, have been constructed using the same depth/velocity matrix template as HydroSignature output, which has been shown to be able to identify, reasonably well, proportions of depth and velocity SFT habitats, despite data collection methods being less than optimum (Le Coarer, 2005). The HSI matrices presented here (Table 6.34) are only coloured to represent the range of data collected, and are therefore ‘dummies’. Assuming that the appropriate data can be used to populate the matrix, HydroSignature could, perhaps, be used to provide an estimate of habitat availability for target species.

6.10 The Biological Character of Surface Flow Type Mesohabitats

Despite the complexities of SFT mesohabitats, some generalisations can be made about the mature of macroinvertebrate communities they support.

No Perceptible

No perceptible SFT mesohabitats are likely to have the lowest relative abundance, richness, diversity and LIFE scores. One MiTG is strongly associated - Chironomidae.

Smooth

Macroinvertebrates in SM SFT mesohabitats are likely to be relatively more abundant than in NP, richer, and more diverse, have higher LIFE scores. Four MiTGs are associated – Chironomidae, Gammaridae, Baetidae and Ephemerellidae.

Rippled

Macroinvertebrates in RP SFT mesohabitats are likely to be more abundant than in NP and SM, richer, and more diverse, have higher LIFE scores. Two MiTGs are strongly associated (Gammaridae and Baetidae) with a further seven less so.

Unbroken Wave

Macroinvertebrates in UW SFT mesohabitats are likely to be relatively the most abundant, richer, more diverse, have higher LIFE scores. Ten MiTGs are strongly associated (Hydrobiidae, Ancylidae, Gammaridae, Baetidae, Ephemerellidae, Elmidae, Hydropsychidae, Simuliidae, Heptageniidae and Odontoceridae) with a further two being weakly associated.

Upwelling

Upwelling SFT mesohabitats are rare. Biologically they are variable with only LIFE scores significantly different to the other SFT mesohabitats. In terms of richness they are similar to UW and RP; Diversity similar to RP and UW and in the other measures too variable between survey years to present a clear picture. No MiTGs are strongly associated with eight being weakly associated. The small number of samples from this SFT mesohabitat degrades the strength of any statistical tests.

6.11 Summary

CHAPTER 6 has shown that there is a complex relationship between macroinvertebrate communities and NP, SM, RP, UW and UP SFT mesohabitats. There are stronger relationships between macroinvertebrate communities locally (on a site by site basis) than across all sites, although 14 MiTGs were significantly associated with one or more of the five SFT mesohabitats investigated. Macroinvertebrate abundance, family richness and LIFE velocity score increase along the same gradient as velocity: NP>SM>RP>UW, suggesting that velocity is a key variable. Upwelling SFT mesohabitats were shown to be physically variable in CHAPTER 5, this is also true of their macroinvertebrate communities. CHAPTER 7 concludes this research and considers its place within current understanding and proposes a practical application of Surface Flow Type Mapping linking the physical and biological aspects of this research.

7 CONCLUSION

7.1 Introduction

This research aimed to answer three Primary Research Questions (Section 1.4), to add to the understanding of the relationship between benthic macroinvertebrates and surface flow types in British lowland rivers. British lowland rivers have been investigated less than upland rivers (Wheater and Peach, 2004) which led to the instigation of the Lowland Catchment Research programme, from which this research was developed. Although the ecology of many organisms is well known the causal inks between benthic macroinvertebrate communities and their physical environment is less well understood, and is complex (Lancaster and Belyea, 2006; Lancaster and Downes, 2010). Surface flow types offer a method of identifying the complex near-bed hydraulic and sedimentary conditions and have been shown to be physically relevant (Wadeson and Rowntree, 1998; Newson and Newson, 2000) and potentially useful to river management (EA, 2003; Dyer and Thoms, 2006). However, this research has also shown that, using a wide range of discharges, there is a considerable overlap between physical variable ranges in the five SFTs investigated. This reduces the viability of using SFTs to describe meso-habitats.

Research Question 1. Can Surface Flow Type mesohabitats in British lowland rivers be identified and recorded effectively?

The results of this research show that, at a mesohabitat scale, five SFT mesohabitats in British lowland rivers can be identified and recorded. Although spatial accuracy here was diminished, in favour of rapid recording, the results are likely to be comparable with other rapid mesohabitat survey methods (MesoHABSIM, RHM, NMCM and MesoCaSiMiR) in terms of estimating location, and an improvement on MesoHABSIM, RHM and NMCM by allowing mesohabitats to be recorded as they occur in the channel. Identification of SFT is subjective, which can lead to misidentification and inter-operator error, this is also true of the other rapid habitat assessment methods. Field identification training is known to reduce operator variability (Poole *at al*., 1997, EA, 2003; Szoszkiewicz *et al*., 2006).

Reid and Thoms (2008) suggest that SFTs could provide an effective, biologically sound method of identifying in-stream habitats at the meso-scale in upland streams. This research supports their findings and suggests that this may also be the case for lowland rivers too.

HydroSignature analysis showed that depth/velocities classes in five SFTs can be quantified although SM and RP SFTs overlap and if data is collected using the Triangular Irregular

Networks, where spatial locations of data are determined, then comparisons between sites and/or over time can be made.

Effective rapid meso-scale habitat mapping will inevitable require a degree of generalisation about the microhabitat conditions within them. However, adopting these generalisations could provide a rapid assessment of in-stream habitats. Remotely sensing British lowland rivers is challenging. LiDAR has some potential, although its ability to survey the river bed is limited (Bailly *et al*., 2010). Nevertheless Milan *et al*. (2010) demonstrated water surface roughness can be identified and linked to amalgamated NP/SM and RP/UW SFTs.

Research Question 2. Which hydraulic variables best characterise Surface Flow Type mesohabitats found in British lowland rivers?

This research has shown that the physical characteristics of NP, SM, RP, UW and UP SFT mesohabitats in British lowland rivers are distinctive in terms of water depth, mean column velocity, substrate size and embeddedness.

There is significant correlation between water velocity at the surface and water velocities 0.05m above the bed except in UP SFT mesohabitats, although there is less correlation between surface and near-bed velocities, with UW having the weakest relationship.

The physical characteristics of each of the SFT mesohabitat were found to be variable although both analysis of variance and pair-wise analysis showed significant differences between the characteristics of SFTs. The rare flow type, UP, was consistently the one SFT that was least distinctive. Mesohabitat type diversity varied with discharge, similarly to that found by Dyer and Thoms (2006) and whilst the results are complex, generally at higher flows diversity was less than at low flows. Differences in mesohabitat diversity between stable and flashy rivers were inconclusive.

Research Question 3. What is the relationship between benthic macroinvertebrate communities and Surface Flow Type mesohabitats in British lowland rivers?

There is a complex relationship between macroinvertebrate communities and NP, SM, RP, UW and UP SFT mesohabitats in British lowland rivers. A somewhat stronger relationship between macroinvertebrate communities exists on a site by site basis (TWINSPAN) than across all sites, although overall the relationship remains weak.

CCA showed that the macroinvertebrate samples were not well separated, unlike the results found by Reid and Thoms (2008). However, this research investigated sites on eight rivers, at a wide range of discharges whereas Reid and Thoms (2008) investigated one regulated river with discharge varying between 0.21 and 0.51 m^3sec. Water quality differed between the eight rivers in this study, and may be partly responsible for the better separation of macroinvertebrate data locally, although substrate characteristics also differed between sites. Study design, here, precluded the use of water quality data as co-variants in the CCA, which prevented the question of water quality being investigated further.

Fourteen MiTGs were significantly associated with one or more of the five SFT mesohabitats investigated. Macroinvertebrate abundance, richness and LIFE score increase along the same gradient as velocity: NP>SM>RP>UW, suggesting that velocity is a key variable. Upwelling SFT mesohabitats were shown to be physically variable, this is also true of their macroinvertebrate communities.

Water depth and velocity data collected at the site of each macroinvertebrate sample allowed a form of HSI, based on the HydroSignature depth/velocity matrix, to be developed. Using the mean, IQR and range of data Category II HSI have been designed, whilst they are coloured appropriately, they have not been populated with values. If the matrix can be populated with appropriate values, and a method be devised to compare HydroSignature data from surveys with HSI matrices for species, then a potential new method of predicting species presence could be available.

7.2 Surface Flow Type Mesohabitats Described

Surface Flow Type mesohabitats have been shown to have some degree of physical distinction, although the range of physical data recorded has a considerable degree of overlap between SFTs. Nevertheless, there is some degree of biological relevance: more so if used at the river reach or sector scale although this is weaker than the physical distinctiveness. Based upon this research, the general characteristics of SFTs in British lowland rivers can be summarised as:

- No Perceptible SFT mesohabitats are deep and slow, with a fine substrate of silt or clay, or larger substrate totally embedded with fine material. Macroinvertebrate abundance and richness would be low with Chironomidae likely to be present.
- Smooth SFT mesohabitats are less deep than NP, with low velocity, substrate would be sand and gravel 50% embedded in fine material. Macroinvertebrate abundance

and richness would be a little higher than in NP SFT with Ephemerellidae, Gammaridae, Baetidae, Chironomidae and Caenidae likely to be present.

- Rippled mesohabitats are moderately shallow with moderate downstream velocity; substrate would be gravelly with 50% embeddedness. Macroinvertebrate abundance and richness would be greater than in SM or NP SFT mesohabitats and are likely to include Baetidae, Simuliidae, Elmidae, Gammaridae, Leptophlebiidae, Ephemerellidae, Odontoceridae and Hydropsychidae.

- Unbroken wave mesohabitats are shallow with high water velocity, pebble or cobble substrate with 25% embeddedness. Macroinvertebrate abundance and richness would be greatest and would probably include Simuliidae, Hydropsychidae, Ephemerellidae, Gammaridae, Odontoceridae, Heptageniidae, Ancylidae, Hydrobiidae and Chironomidae.

- Upwelling mesohabitats are deep with moderate downstream water velocity, substrates of sand or gravel with 75% embeddedness. Macroinvertebrate abundance and richness is moderate, and is likely to include Gammaridae, Elmidae, Caenidae, Hydrobiidae, Baetidae and Ephemerellidae. Upwelling mesohabitats are special cases because they are rare, and consequently the analyses are less robust than for the other mesohabitat types.

Based upon data collected in this research project, the physical and macroinvertebrate nature of five SFTs is summarised in Figure 7:1.

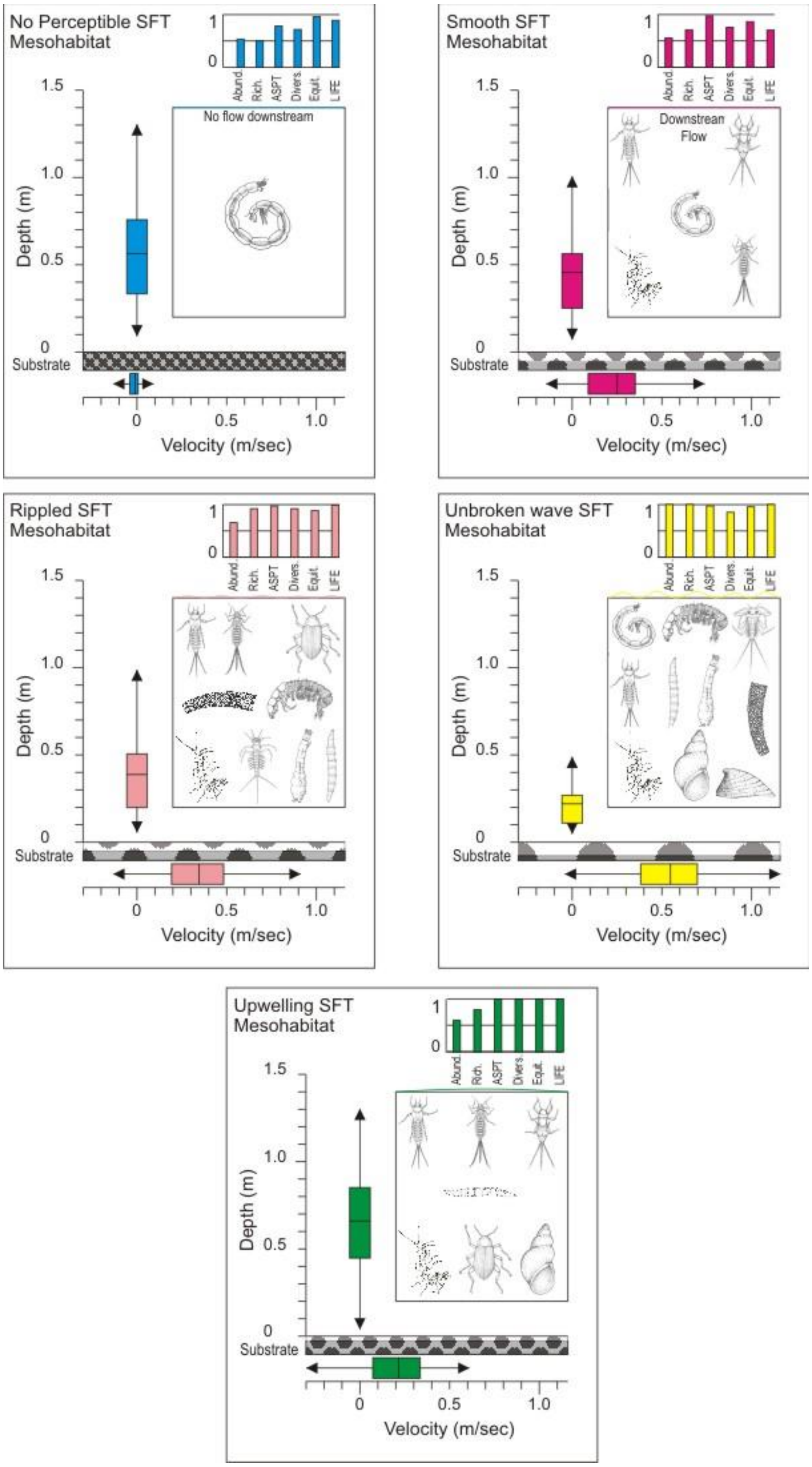


Figure 7:1 Summary diagram showing physical and biological features of Surface Flow Type mesohabitats from data gather in this research.

7.3 Application of Surface Flow Type Mapping

This research has demonstrated that Surface Flow Type Mapping (SFTM) is practical although the biologically relevance of SFTs is weak. Mapping habitats ‘as seen’ represents an improvement over some other mesohabitat mapping methods. SFTM provides a cost-effective survey method which can be used in both research and applied sectors and has been used to provide a baseline assessment of a 1.5km reach of the River Avon, where two days were sufficient to complete the fieldwork and identify macroinvertebrate samples to family level. In the field of river restoration, SFTM could be used to provide baseline information in the planning stages, but it could provide a cost-effective method of monitoring the post-restoration mesohabitat structure. Working at the meso-habitat scale, the generalisations required to scale up from micro-habitat surveys are provided. Several factors would need to be taken into account before a SFTM survey was undertaken:

Site

Water quality is a driver of macroinvertebrate community, particularly in lowland streams where quality is frequently degraded by human interference. Therefore the reach under investigation should have consistent water quality, which may mean separating the reach of interest into more than one site, for example at a Water Treatment Works outflow, or a major tributary. In-stream macrophyte growth was seen to override hydro-morphological variables and disturb the water surface, this variable ought to be considered when selecting reach boundaries to ensure appropriate comparability between surveys.

Surface Flow Type descriptors

The surveyor should be experienced in the identification of SFTs. In the UK, the EA provide training for River Habitat Surveyors, they also produce a manual for RHS operators which contains descriptions and photographs of SFTs.

Survey conditions

SFTs are related to the underlying geomorphology and become drowned out at high discharges. For a baseline survey, SFTM should be undertaken in summer low flow conditions, $>Q_{90}$, although surveying at a range of discharges could identify at-a-site links between flow and geomorphology. Surveys should not be undertaken in windy conditions where the water surface may be influenced by atmospheric disturbance.

Mapping

At its simplest, SFT Mapping requires a large scale plan of the river channel and the ability of the surveyor to estimate the position and extents of the SFT mesohabitats. The channel plan could be based on proprietary maps, aerial photography or could be surveyed from scratch. GPS has been shown to be useful in identifying changes in channel position and in updating maps, also in locating SFT mesohabitats and bankside features to assist with the survey. GPS requires good satellite signals, which can be a problem under trees or in deep valleys.

Other mapping methods might also be used. A portable laptop computer running appropriate GIS software and linked to a GPS unit to provide positional information would allow the operator to draw in the SFT mesohabitat extents directly into the GIS in the field. Photography, either aerial or terrestrial could provide data for SFT mesohabitat survey, although still photographs may be insufficient to differentiate between NP and SM flow types. Remote sensing, using LiDAR or other methods is a possibility, if the surface patterns can be distinguished.

Discrimination between SFT mesohabitats is subjective with boundaries that are not clearly defined. Experience and training is necessary to provide a degree of consistency between operators.

Physical characteristics

Although this research collected data from five points in each SFT mesohabitat identified, this level of detail is, perhaps, unnecessary. The amount of data collected will depend upon the objectives of the survey.

To characterise each SFT mesohabitat unit a minimum of one measurement of representative water depth, velocity and substrate is required. This will assist in determining the representative SFT mesohabitats from which biological sampling will be undertaken. Photographs of each SFT mesohabitat unit identified and mapped should be taken.

Biological characteristics

Biological samples should be taken from at least one representative example of each class of SFT mesohabitat identified. Larger SFT mesohabitat units where depth, velocity and substrate were representative of the whole site and preferably separated from other representative SFT mesohabitats by at least one other SFT mesohabitat should be selected. Macroinvertebrate samples should be taken within the core of the selected units and a minimum of three replicate samples for each unit. Macroinvertebrate sampling should start at the downstream end of the reach and work upstream to prevent contamination by drift. Physical conditions in the field will dictate the precise method used. Deep water may require grab samples, whilst shallow water could allow the use of Surber type samplers. It would be possible to adopt the UK EA standard method for sampling macroinvertebrates (three minutes of kick-netting divided proportionally between micro habitats, plus one minute of hand searching) making the SFT mesohabitat the focus of the sample. This protocol would potentially allow use of the River InVertebrate Prediction and Classification System (RIVPACS) (Wright, 2000). Macroinvertebrates should be identified to a minimum of BMWP groups, species level identification would be useful although more expensive.

7.4 Limitations

Whilst this research has addressed important questions in Hydroecology, it has done so at a small scale, *i.e.* over a limited range of lowland river types. Rivers across the whole of Britain exhibit a wide range of hydrological and geomorphological characteristics, although when compared to others globally even this range is limited. Consequently it would unwise to extrapolate this research beyond its current scope without careful consideration. This research might be considered a ‘proof of concept’; if the concept was tested on a larger scale it is possible that this could provide the foundation for rapid biologically relevant in-stream mesohabitat assessment.

Conclusions reached in this research are limited to the study area, 12 sites on eight small British lowland rivers surveyed over two summers. It is possible that selection of a similar number of sites on one river system and over a smaller geographic area would have produced more robust results. Identifying macroinvertebrates to species level, rather than family, would eliminate variable habitat requirements within families; however identification to species level is time consuming and was impractical here when countered with the need to sample numerous sites over two years within the limitations of a PhD research project. Data in relation to water quality were not collected at the macroinvertebrate sample sites and limited the ability of CCA to examine the effects of water quality between sites.

The biological gradients and macroinvertebrate communities identified are likely to be most consistent at the reach or sector scale. Many variables have been shown to influence the nature of these communities. However, by focusing on reaches/sectors the influence of many variables are minimised and part of other rapid habitat assessments.

7.5 Further work

This research has shown that there is some association between SFT mesohabitat and a range of macroinvertebrate taxonomic groups. There are variables, other than SFT, velocity, substrate and embeddedness that are responsible for MiTG community composition; it is likely these are related to water quality and species recruitment.

Small British lowland rivers have been shown by this research to be suitable for SFTM. However, this does not address the issues around small headwater streams and large rivers. Surface Flow Types are distinguishable in headwater streams although their extent is generally much smaller and spatial variability much greater than those investigated here. Large rivers have SFT mesohabitats of much greater spatial extent. Whilst it is simplistic to say that this is only a matter of scale; investigations into the biological relevance of both smaller and larger rivers would be useful. The influence of mesohabitat and SFT patch size would be particularly pertinent and could provide a method to address some of the issues of scale currently under investigation.

A wider study, perhaps nationally or even internationally, could be used to assess the biological relevance of SFTM and the several mesohabitat assessment methods currently in use. The study could aim to select the best elements of each method with the intention of identifying a survey method that was effective. Coupled with macroinvertebrate data, this would be useful, although it would have to take into account the issues raised by some (Lancaster and Downes, 2009; Lamouroux *et al*., 2010). Training for surveyors using whatever method was developed from this work would be crucial to ensure consistency (Poole et al., 1997).

This research has also shown that HydroSignature (Le Coarer, 2005) can describe the depth and velocity relationships in the five SFTs investigated here, although SM and RP SFTs share many depth/velocity cells. Physical data collected at the site of the macroinvertebrate samples have been used to generate depth and velocity matrices for several MiTGs in a similar manner to the output from HydroSignature. Using such data with HydroSignature could provide a novel model from which the Hydroecology of rivers could be established.

Whilst this research used macroinvertebrates as a biological reference, further work using fish, macrophytes, bryophytes and algae would also be worthwhile.

7.6 Conclusion

The completed study has added to the growing knowledge of SFT mesohabitats and their biological relevance by investigating British lowland rivers. Although the physical distinctiveness of SFTs is weak, there are significant trends, similarly the strength of the relationship between SFTs and their macroinvertebrate communities is also limited. Nevertheless, some conclusions may be drawn from (relative) abundance and community richness being higher in the more energetic SFTs. This suggests that water velocity is a key variable driving both physical and biological domains.

Reid and Thoms (2008) suggest that, energetically, SFTs are similar to their immediate neighbour, and that differences occur one step beyond the immediate neighbour. In this study NP differs biologically most strongly from UW and less strongly from RP whilst UP (not encountered by Reid and Thoms (2008) remains a special case.

Surface Flow Type Mapping is a rapid and therefore cost-effective application with the potential to support remotely sensed riverine habitats. It is likely to be at least as robust as other methods in current use, especially allowing meso-habitats to be drawn ‘as seen’ rather than generalised to channel width. The study will help inform conservation strategies that seek to improve riverine habitats in a local, British and European context.

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