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CHARACTERISING PHYSICAL HABITAT AT THE REACH SCALE: RIVER TERN, SHROPSHIRE

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for the degree of Doctor of Philosophy

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ABSTRACT

Characterisation of the complex geomorphological and ecological structure of river channels into workable units of instream habitat is a key step in enabling the assessment of habitat 'quality' for river management purposes. The research presented in this thesis uses a range of methodological approaches at a variety of spatial scales in order to improve the conceptual basis of habitat characterisation at the reach and sub-reach scale. An appraisal of published works is used in conjunction with an extensive analysis of habitat features for sites across the UK, and intensive field studies on the River Tern, Shropshire, to improve the conceptual basis and ecological validity of the 'physical biotope' as the basic unit of instream habitat. Physical biotopes demonstrate correlations with biologically functional habitat units at relatively broad scales, suggesting that *assemblages* of habitat units may provide the most appropriate level of simplification of aquatic habitat structure. A simplified, but more transferable classification using biotope assemblages is suggested, with potential application to a range of instream assessment and river design needs. Reach-scale field surveys reveal complex and dynamic relationships between channel hydraulics and morphology and highlight the influence of sampling design and hydrological context on the outcomes of rapid field surveys. A microscale research component addresses within-biotope variation at small scales by focusing on high frequency flow behaviour and sediment transport mechanisms which have, to date, been largely overlooked in biotope studies. This provides both detailed descriptions of hydraulic behaviour, and an indication of differences in internal spatial and temporal heterogeneity between biotopes, with implications for instream biota.

KEYWORDS: physical biotope; functional habitat; eco-hydraulics, River Habitat Survey, river restoration, habitat quality.

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CHAPTER 1 INTRODUCTION

1.1 RESEARCH AIMS AND OBJECTIVES

This research forms an extension of a NERC (Natural Environment Research Council) LOCAR (Lowland Catchment Research) project carried out at the University of Nottingham. The LOCAR thematic programme was developed to promote interdisciplinary hydro-environmental research into the input-storage-discharge cycle and instream, riparian and wetland habitats within groundwater dominated river systems (LOCAR, 2004). Three instrumented 'flagship' catchments were identified for field study; the Frome/Piddle (Dorset), the Pang/ Lambourn (Berkshire) and the Tern (Shropshire). The former two are chalk streams while the Tern catchment is underlain by Permo-Triassic Sandstone.

Research presented in this thesis is affiliated with the NERC-LOCAR project '*Vegetation influences on fine sediment and propagule dynamics in groundwater-fed rivers: Implications for river management, restoration and riparian biodiversity*' (NER/T/S/2001/00930) focusing on the River Frome and River Tern. The two sites chosen for the field component of the research presented in this thesis are approximately 120 m in length and are located within the upper Tern catchment in North Shropshire, Northeast of Market Drayton and close to the village of Norton-in-Hales. The first study reach, 'Oakley Hall' (NGR SJ 704 377), is part of an instrumented LOCAR site. The second, 'Napely Lodge Farm' which is located approximately 0.5 km upstream (NGR SJ 707 384), has been used previously for geomorphological investigation (Emery, 2003). Further details on field site characteristics are presented in Section 2.5.

The overall aim of the research is:

> *to enhance the scientific basis of ecohydraulics within the wider context of river habitat assessment and rehabilitation through the characterisation of aquatic habitat at the reach scale and the evaluation of mesoscale habitat concepts.*

This aim is addressed through five principal research objectives using a variety of exploratory and analytical techniques incorporating both desk- and field-based study. These principal objectives, the associated methods used, and the chapters in which the findings are reported and discussed are outlined in Table 1.1. A research context is provided in the following sections by considering the changing field of river management over recent decades, more specifically the changing paradigm from engineering to conservation and restoration perspectives which has taken place, in conjunction with the associated legislative drivers and experiences from river restoration and ecohydraulics.

1.2 THE RESEARCH CONTEXT

Four broad research strands and one specific research programme form the context for the research aims and objectives presented in the previous section and these are outlined below.

Research Objective	**Methods**	**Chapter(s)**
1. Examine the correlations between physical biotopes and functional habitats.	Extensive analysis of a national database of surveyed reaches.	Chapter 3
2. Evaluate output data derived from rapid field survey techniques.	Critical evaluation of analysis outcomes and comparison of different survey resolutions.	Chapter 3 Chapter 4
3. Investigate the existence and integrity of physical biotopes at the reach scale.	Intensive approach focused at the mesoscale incorporating visual identification of habitat units and quantitative measurement of hydraulic parameters.	Chapter 4
4. Assess the robustness of physical biotopes with varying flow stage.	Surveys repeated at relative ‘low’ and ‘intermediate’ flow stages	Chapter 4 Chapter 5
5. Explore higher resolution ‘within-biotope’ hydraulic characteristics.	Intensive approach focused at the microscale within selected physical biotopes to identify variations in turbulence and sediment transport.	Chapter 5

Table 1.1 Research objectives and methods.

1.2.1 Directions in river research and management

Historically, stream ecologists and geomorphologists have followed separate research paths, both theoretically and empirically. Theoretical approaches from ecology tend to be extensive, involving the investigation of representative patterns and features of large ‘populations’, while geomorphological research is generally intensive in nature, exploring and attempting to explain the processes operating in individual, or small numbers of cases (Sayer, 1992; Richards, 1996). Empirically, ecologists have often considered the physical structure of the channel inferior to chemical properties in its affect on biota, while geomorphologists have focused much effort into characterising the physical structure of river channels (Rosgen, 1994), but often with little regard to how this translates into habitat for aquatic biota. However, a need for true integration of the two disciplines has become increasingly important in the context of river management and conservation.

Recent decades have witnessed a decisive shift in river management, from an exploitative focus on abstraction, waste disposal and flood defence, to a more ecologically sensitive approach to flood mitigation and energy production (LeClerc, 2002). Within fluvial geomorphology, this has been characterised by a transition from an engineering framework, viewing morphological adjustments as signs of instability which must be controlled, to the realisation that dynamism is a natural feature of fluvial systems (Petts *et al.*, 1995; Newson, 2002). This has been accompanied by a growing appreciation of the influence of organic channel and bank components on instream hydraulics (Gregory, 1992; Brooks and Brierley, 2002; Wallerstein and Thorne, 2004).

Concurrently, ecologists have acknowledged the importance of stream hydraulics in habitat provision for invertebrates (Statzner and Higler, 1986) and fish (Aadland, 1993; Rabeni and

Jacobson, 1993). Coupled with the realisation that most of our watercourses have been severely degraded by anthropogenic activity (Brookes, 1995a), the focus of river management has developed further to involve the protection and enhancement of the physical and ecological 'quality' of river systems (Adams *et al.*, 2004), and hence requiring engineering efforts to reconcile management goals such as bank stability and flood defence with the maintenance of aquatic habitats (Gilvear, 1999). This new paradigm necessitates interdisciplinary approaches to research problems, particularly involving close collaboration between fluvial geomorphologists and aquatic ecologists within the emerging field of 'ecohydraulics'. The principal objective of ecohydraulics is the restoration and protection of aquatic ecosystems through the physical enhancement of water courses by focusing on the abiotic factors contributing to habitats (LeClerc, 2002).

Within Europe, these developments are underpinned by two key pieces of international environmental legislation: the EU 'Habitats Directive' (Council Directive 92/43/EEC, 1992) which came into force in May 1992; and the EU Water Framework Directive (WFD) (Directive 2000/60/EC, 2000) which was incorporated into UK law in December 2000. The former focuses on the maintenance or restoration of terrestrial and aquatic habitats of wild flora and fauna, while the latter recognises the need for protection and enhancement of the ecological quality of surface waters:

> *'Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such.'*
> Directive 2000/60/EC (2000: 1).

The focus of the WFD is significant since it represents the first acknowledgement within environmental legislation of the role of biota in determining water quality (Logan and Furse, 2002), and furthermore it recognises that water *quantity* is secondary to *quality* in contrast to the previous focus of management on maintaining ‘minimum acceptable flows’ (Petts *et al.*, 1995). The WFD requires member states to protect ‘good’ ecological status water bodies, and to enhance to ‘good’ status those which have been degraded by anthropogenic activity. These actions demand a sound understanding of the links between habitat and biota (Logan and Furse, 2002) and the development of a robust system for surveying and assessing the quality of inland waters in order to identify practical definitions of ‘good ecological status’ and inventorise resources (Chave, 2002). However, while the WFD applies to entire drainage basins, the scale of practical applicability of measures is necessarily much smaller, requiring a sound understanding not only of the links between ecology and geomorphology, but between different components of the stream system.

1.2.2 Habitat hierarchies and the mesoscale

River catchments are complex ecological, hydrological and geomorphological systems. The ecological organisation of streams is strongly related to physical variables such as temperature and channel hydraulics and a longitudinal gradient in physical conditions; and in sources, forms and processing of organic matter is associated with changes in the structure and function of ecological communities (Vannote *et al.*, 1980). A combination of local spatial heterogeneity in physical variables, and temporal heterogeneity in the form of disturbance regimes is superimposed onto the longitudinal continuum, however, creating a ‘patchy’ habitat structure (Southwood, 1977; Townsend, 1989). Furthermore, different components of the stream system are linked through a hierarchy of scales. Physical and biological processes operating at ‘microscales’ of several metres and over timescales of days or less have the most direct effect on the survival of individual biota. However, the wider 'mesoscale' reach morphology and associated hydraulics, variable over timescales of months and years, determines the community composition and is, in turn, controlled by the broader, 'macroscale' geological and climatic context of the catchment (Frissell *et al.*, 1986; Biggs *et al.*, 2005) (Figure 1.1).

Within this catchment hierarchy, the 'mesoscale', which focuses on variation across the active channel width and along channel lengths that are small multiples of channel width, is advocated as the most appropriate focus for habitat assessment and improvement programmes (Newson and Newson, 2000). The main reason for this is that research at the mesoscale allows both scaling-up to the catchment and scaling-down to the microscale (Kershner and Snider, 1992), providing a 'fulcrum between scientific detail and universality' (Newson and Newson, 2000: 199). 'Habitat' or 'physical habitat' at the mesoscale refers to the physical surroundings of instream biota as determined by the structure of the channel and the hydrological regime (Maddock, 1999), and forms a patchy mosaic whereby different units of habitat perform different 'functions' for instream biota (Harper *et al.*, 1995). For instance, gravely riffles can provide spawning ground for fish (Garcia de Jalon, 1995), emergent macrophytes provide oviposition sites and passage to the water surface for emerging insects (Harper *et al.*, 1995) and low shear stress marginal channel areas can provide important refugia during spates (Lancaster and Hildrew, 1993).

Initial mesoscale approaches to habitat assessment and improvement focused on the (re)creation of favourable hydraulic conditions for specific target species using 'biological response models' (Mosely, 1982). A key example is the 'Physical Habitat Simulation'

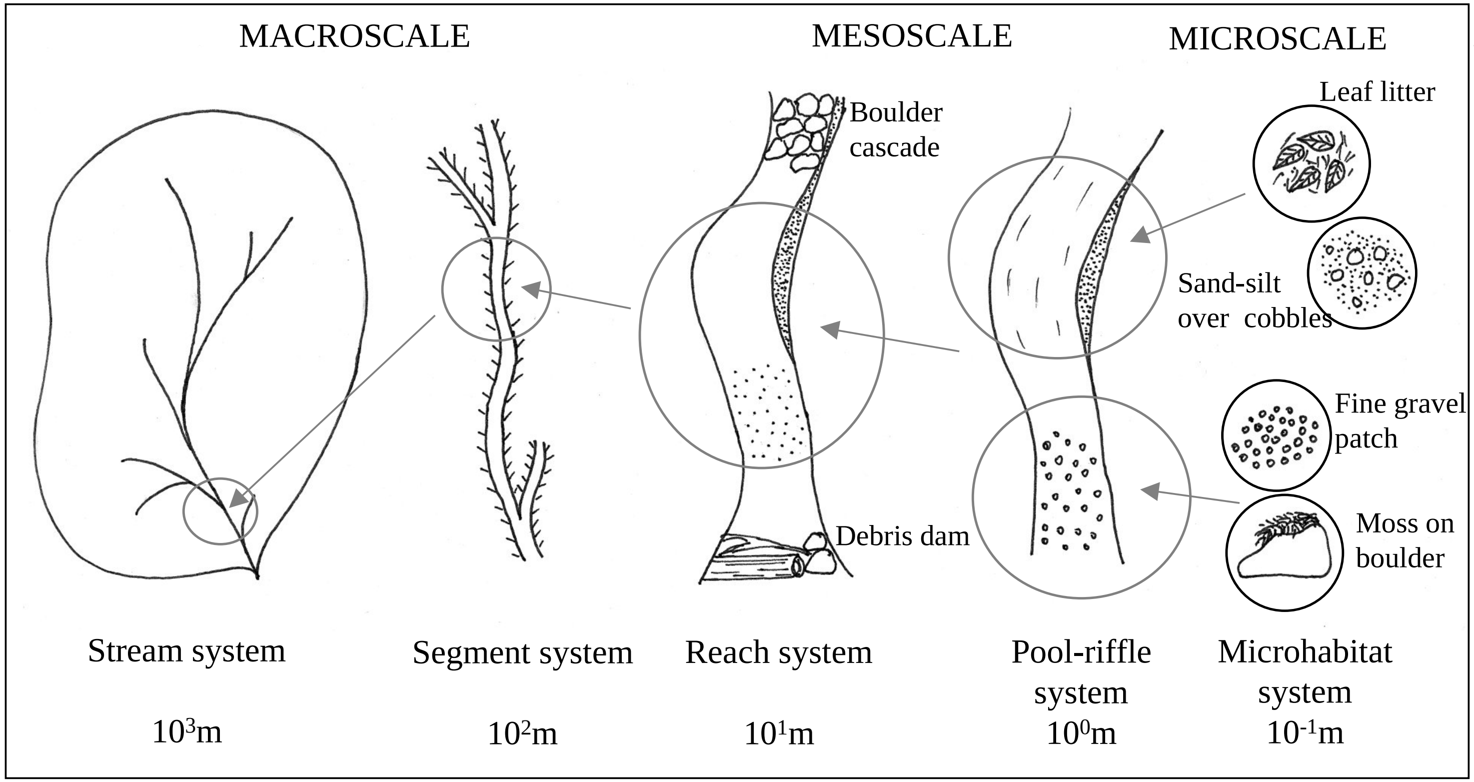


Figure 1.1 Hierarchical organisation of a stream and its habitat subsystems, adapted from Frissell *et al.* (1986: 202).

model (PHABSIM), developed by the US Fish and Wildlife Service as part of the Instream Flow Incremental Methodology (IFIM) decision-making framework for addressing instream flow issues (Bovee *et al.*, 1998). PHABSIM has been applied within the UK to support water resources decision-making (Spence and Hickley, 2000), but the technique identifies only the weighted usable area (WUA) of habitat for specific life stages of target species, and may therefore be undermined by community-level interactions such as competition and predation.

More recently, researchers have favoured a more holistic habitat-level approach focused at the community rather than individual target species. However, geomorphologists and ecologists have attempted to make sense of the spatial organisation of habitat within the channel in different ways (Figure 1.2). Geomorphological approaches are classed as 'top-down', identifying units of channel morphology associated with different flow velocities, water depths and bed material sizes (Jowett, 1993; Wadeson, 1994; Padmore, 1997a). These features are commonly termed 'physical biotopes' and refer variations on the riffle-pool structure associated with intermediate sized streams (Church, 1992), e.g. riffle, pool, run, glide, rapid, cascade. In contrast, ecologists have worked from the 'bottom-up', identifying 'functional' or 'meso-' habitats which incorporate substrate and vegetation types associated with distinct assemblages of invertebrates (Harper *et al.*, 1992; Tickner *et al.*, 2000). Both approaches require further empirical field-testing, but offer a potentially efficient means of assessing habitat quality and thus a practical solution to requirements for large-scale resource cataloguing and appraisal arising from legislative change. The reconciliation of these two approaches, as well as the study of finer-scale interactions between channel hydraulics and aquatic biota, represent two significant research challenges for the field of ecohydraulics.

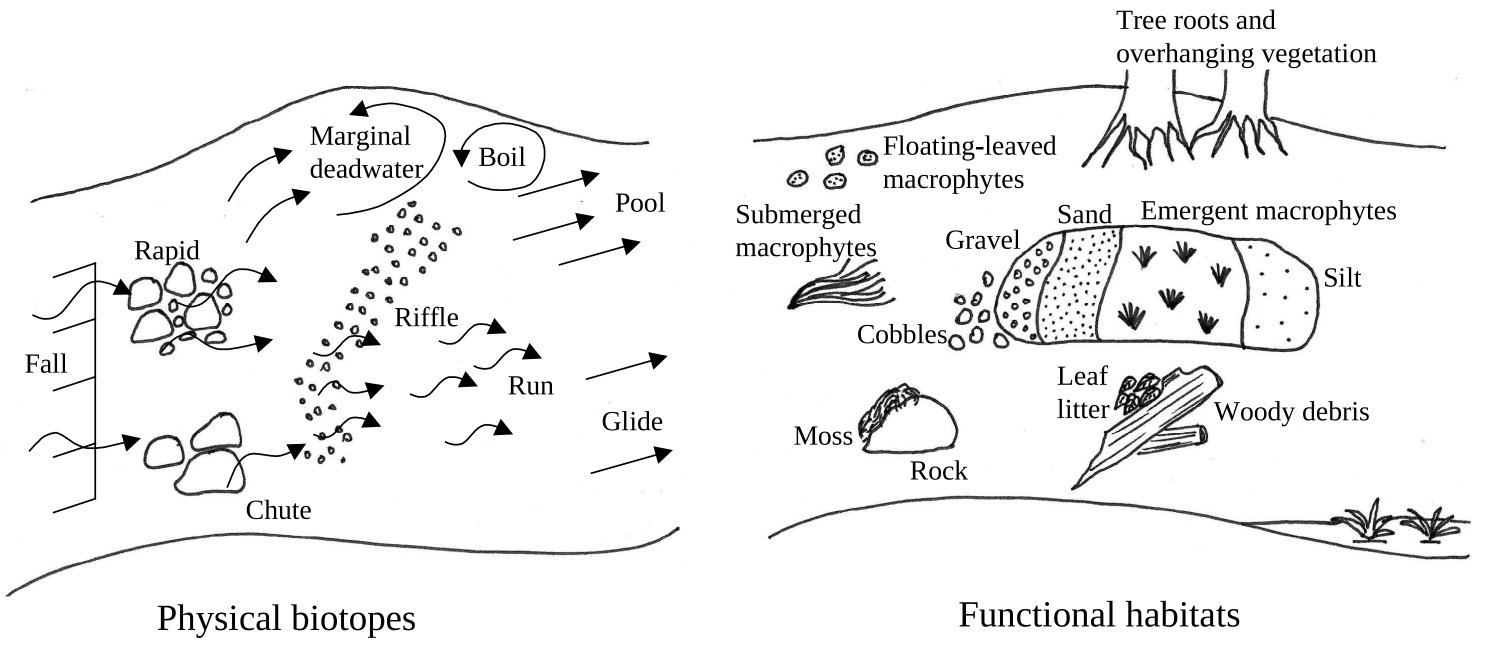


Figure 1.2 Physical biotopes and functional habitats, adapted from adapted from Newson *et al.* (2000: 200).

1.2.3 Habitat inventory and assessment

As a result of the recognition of the importance of mesoscale habitat quality within the context of international legislation and the increased environmental sensitivity of river management, a demand has arisen for cost-effective methods of assessing river ‘health’ and identifying benchmark conditions at a national scale (Maddock, 1999). Within England and Wales, the authority responsible for the implementation of environmental legislation is the Environment Agency (EA), which has developed a system for cataloguing and subsequently appraising, the physical and ecological condition of lotic ecosystems in the form of the River Habitat Survey (RHS). RHS represents an expansion and development of the River Corridor Survey methodology (National Rivers Authority, 1992), and was designed to provide: (i) a rapid, robust, and reproducible field method requiring little ‘expert’ training; (ii) a network of reference sites across the UK; and (iii) a working classification, or ‘typology’ of UK rivers based on information derived from the database of reference sites (Raven *et al.*, 1997; Fox *et al.*, 1998). RHS provides a standardised methodology for recording the physical structure of a 500m long river reach, incorporating mesoscale habitat concepts such as physical biotopes and functional habitats.

An extensive reference database of surveyed reaches across the UK has been developed using a stratified random sampling procedure. This information can be applied to a range of research problems ranging from the assessment of habitat provision for individual target species (Hastie *et al.*, 2003) to environmental assessments at the reach and catchment scale (Raven *et al.*, 2000; Walker *et al.*, 2002). Furthermore, at the national level, the reference network of RHS sites reveals that only 28.2% of lowland sites in England and Wales may be classified as having a ‘semi-natural' physical structure (Raven *et al.*, 1998a). The remaining 71.8% are associated with some form of modification to the channel or surrounding corridor, highlighting a serious requirement for the improvement of degraded reaches.

1.2.4 Enhancement, rehabilitation and restoration

The types of anthropogenic impacts responsible for the degradation of river habitats are varied, ranging from direct 'planned' modifications such as dam construction and channelisation, to 'unplanned' effects such as land use change and diffuse-source pollution (Hynes, 1970; Clifford, 2001a). The physical effects of most modifications generally involve an overall loss of physical diversity which in turn leads to a reduction in biological diversity (Smith *et al.*, 1995). Irrespective of the cause of degradation, the management response can take several forms depending on the severity of the modifications and the physical and ecological objectives (Boon, 1992) (Figure 1.3). While lower levels of habitat modification require either limitation of catchment development or mitigation of the effects of modifications on habitats, more heavily degraded sites will require some kind of assisted recovery (Boon, 1992). A distinction can be made between the *enhancement* of a degraded system, and the *rehabilitation* or *restoration* of a system, which imply some return to the pre-disturbance state (Brookes, 1995a). Since the complete restoration of a 'natural' state is generally considered impossible due to the difficulties of establishing the pre-disturbance condition and the continued human occupation of river basins (Downs and Thorne, 2000), a partial structural and functional return (rehabilitation) is generally adopted as the management goal.

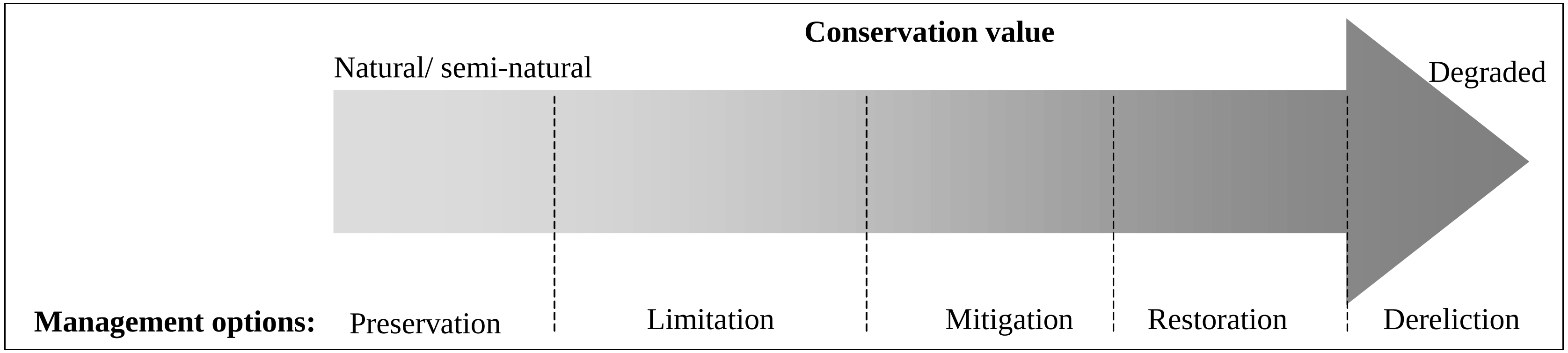


Figure 1.3 The range of river management options along a spectrum of decreasing conservation value, adapted from Boon (1992: 19).

Mesoscale habitat concepts provide an appropriate scale of rehabilitation for smaller streams, and the installation or rehabilitation of riffle and pool features frequently forms one of the principal management techniques (Clifford and French, 1998; Harper *et al.*, 1998b; Downs and Thorne, 2000; Sear and Newson, 2004). Unfortunately, to date many rehabilitation projects have been associated with only limited success, owing partly to excessive emphasis on the 'elimination of threats' such as flooding and erosion, rather than on ecological improvements (Zalewski, 1999) and the failure of projects to consider processes within the wider catchment hierarchy (Sear, 1994).

Post-project monitoring and appraisal is vital to improving the success of rehabilitation projects through the development of scientific understanding and to aid the planning stages of future projects (Habersack and Nachtnebel, 1995; Downs and Kondolf, 2002), but despite this it is rarely budgeted for in rehabilitation projects (Brookes, 1995a). Rapid surveys utilising mesoscale habitat concepts may offer a solution by providing a robust, efficient and low-cost interdisciplinary approach to the assessment of habitat quality throughout the long timescales associated with project monitoring (Harper *et al.*, 1998b).

1.2.5 The LOCAR research programme

The aims and objectives of the thesis are nested within the broader aims of the NERC LOCAR programme introduced in Section 1.1. The research focuses specifically on the first scientific aim of the programme:

> *'To develop an improved understanding of hydrological, hydrogeological, geomorphological and ecological interactions within permeable catchment systems, and their associated aquatic habitats, at different spatial and temporal scales and for different land uses'.*
> LOCAR (2004)

In particular, the research addresses the objectives of the programme to study:

- *Physical, chemical and biological processes within the valley floor corridor.*
- *In-stream, riparian and wetland habitats and their dependence on flow regimes.*

1.3 THESIS STRUCTURE

The following five Chapters address the research aims introduced in Table 1.1. The research objectives are met through a combination of proof of concept studies involving theoretical evaluation and ecological validation of the biotope concept, more specific methodological evaluations of field methods and data outputs, and by objective field applications focusing on the River Tern, Shropshire (Figure 1.4).

Chapter 2 introduces the research design, methods and data sets for both desk-based and field study components of the research and provides quantitative descriptions of the field sites used. Methodologies and analytical techniques are then discussed in further detail as appropriate in the subsequent results chapters.

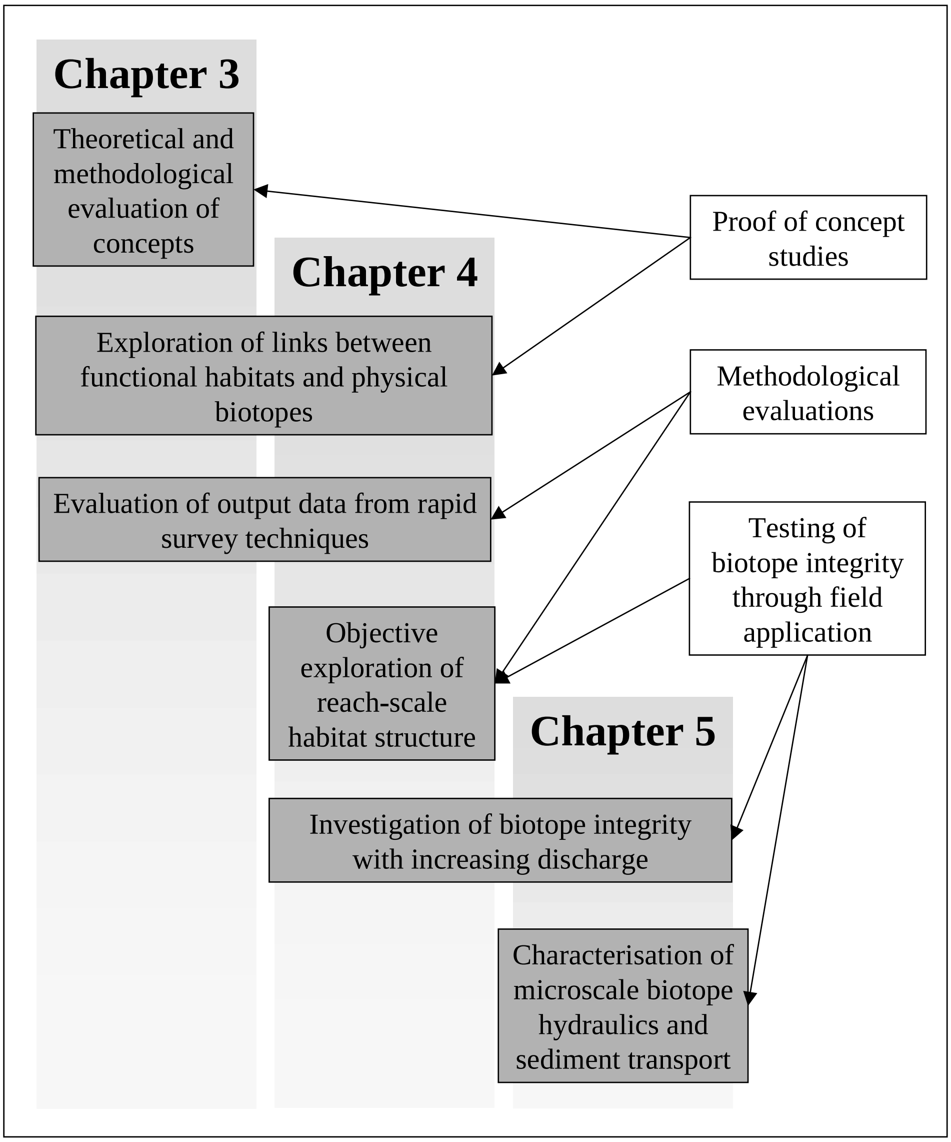


Figure 1.4 Overview of the principal research topics, their purpose and chapters in which they are addresses.

Chapter 3 details an attempt to improve the conceptual basis of mesoscale physical habitat characterisation. This is approached initially by evaluating the theoretical and methodological issues associated with the definition and identification of physical biotopes and appraising previous approaches to their study. The review acknowledges a fundamental requirement for the ecological 'validation' of physical biotopes, which is then attempted in the subsequent sections using a national data set derived from the RHS database. Relationships between habitat features and broad-scale environmental variables are explored, and a preliminary ecological 'classification' of flow biotopes derived from frequency distributions is validated by two multivariate statistical techniques.

Chapter 4 provides an intensive exploration of mesoscale habitat concepts assessed at two physically contrasting field sites on the River Tern, Shropshire. Various methods for classifying instream habitat are explored through spatial analysis and geostatistics, and the implications of survey resolution for analytical outcomes are evaluated. The reach-scale organisation of hydraulic habitat is quantitatively explored both subjectively, by identifying hydraulic ranges of visually identified phenomena, and objectively, by classifying channel hydraulics through multivariate analysis.

Chapter 5 is focused at a smaller spatial scale in order to examine the higher-frequency flow properties and sediment transport mechanisms associated with different physical biotopes. A range of statistical techniques are applied to high frequency velocity records in order to examine the detailed flow characteristics of biotopes spatially, with relative depth, and with discharge. An experimental investigation of the transfer of fine sediment through different biotopes provides some insight into the distributional pathways taken by suspended sediments, organic matter, nutrients and pollutants.

Chapter 6 summarises the principal conclusions of the research in the context of the research objectives outlined in Table 1.1, together with recommendations for further research.

CHAPTER 2 RESEARCH DESIGN AND FIELD SITES

2.1 CHAPTER SYNOPSIS

This chapter presents the research design and an overview of methodologies for the desk-based and field study components of the research. Field methods, data sets and analytical techniques are dealt with in detail as appropriate in the subsequent chapters. The methodological framework of the research is described with respect to both scientific approach and the scale of investigation within the wider hierarchical structure of stream habitat. The morphological, sedimentological, hydrological and vegetative characteristics of the two field study reaches are also quantitatively described and set within the context of national reference sites and the Tern catchment.

2.2 METHODOLOGICAL FRAMEWORK

2.2.1 Scientific approach

The research design comprises both ‘positivist’ and ‘realist’ methodological approaches (Table 2.1). The desk-based RHS research component takes a positivist, ‘extensive’ or ‘large-N’ approach by searching for patterns within a large sample population in order to identify representative characteristics and make generalisations (Sayer, 1992). Positivist approaches are common within biological and ecological investigations and, in the case of this study, the approach permits an analysis of the broad trends within a large comprehensive data set. However, positivist methodologies are often associated with limited explanation and exploration of causal relationships. Richards (1996) observes that large-N research is often undertaken at the beginning of investigations, and is then followed by intensive (‘small-N’) research when it becomes necessary to consider the mechanisms responsible for the observed relationships.

Intensive, ‘realist’ approaches are common in geomorphology, where form-process interactions are considered within a particular case, or a small number of cases. Realist approaches search for connections and relationships and attempt to produce a causal explanation which is not necessarily representative (Sayer, 1992). In this thesis, the intensive component takes the form of a field study focused at two spatial scales. The first field element uses an objective, systematic sampling regime to measure parameters along equally-spaced transects in order to capture mesoscale variation in physical habitat structure along the entire river reach. The second element uses a purposive sampling design whereby more detailed measurements are made within subjectively selected sampling units.

The empirical research presented in this chapter was designed and conducted within the framework of a nested hierarchy of stream habitat. Such a system acknowledges the physical and ecological linkages between different spatial and temporal scales nested within a ‘catchment hierarchy’ (Townsend, 1996). Three theoretical scales are often employed both in geomorphological studies (Hey, 1987; Lane *et al.*, 1998) and ecological research (Bayley and Li, 1996) which may be associated with broad spatial and temporal dimensions (Figure 2.1). At the ‘microscale’, organisms are influenced by flow hydraulics and sediment transport processes over timescales of seconds or minutes and over spatial scales of millimetres to centimetres (Carling, 1995), relating

	Positivism	**Realism**
Epistemology	Empirical Concrete Extensive research Large-N	Theoretical Abstract Intensive research Small-N
Subject	Form and product	Process and mechanism
Relations	Formal relations of similarity	Substantial relations of connection
Type of account produced	Descriptive representative generalisations	Causal explanation of the production of certain objects or events.
Limitations	Limited explanatory power. May not be generalisable to other populations at different times and places.	Patterns and relations are unlikely to be representative.

Table 2.1 Scientific methodological approaches employed in the research. Source: Sayer (1992) and Richards (1996)

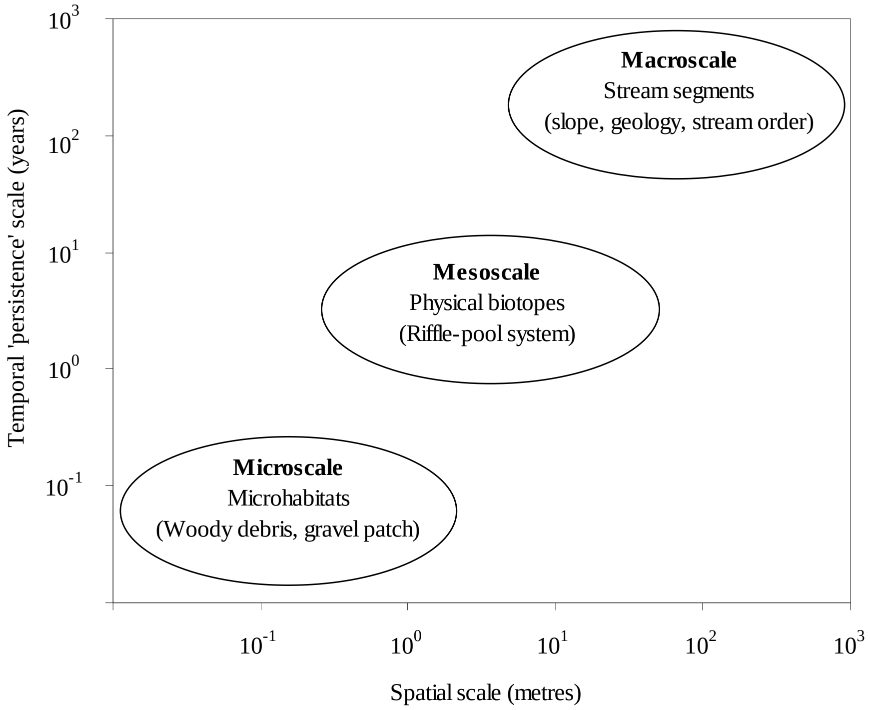


Figure 2.1 Hierarchical structure of stream habitat, modified from Bayley and Li (1996: Figure 6.1a p. 94).

to habitat units such as individual boulders or accumulations of organic matter. The ‘mesoscale’ refers to the larger-scale and more temporally stable morphological structures such as glides, pools and riffles (Bisson *et al.*, 1981) where variables such as velocity, depth, position in channel and turbulence are of greatest significance in habitat provision (Kershner and Snider, 1992). Both meso- and microscale habitats are nested within the morphological context of a reach or stream segment (‘macroscale’), which is determined by broader-scale factors such as channel gradient and sinuosity. The environmental context of stream segments is in turn determined by the drainage basin or ‘ecoregion’ characteristics at ‘mega-scales’ of thousands of metres and over timescales of centuries and longer (Hey, 1987; Bayley and Li, 1996).

This research is focused at the meso- and microscales of investigation within a single river segment, although the desk-based component incorporates a macroscale aspect by considering relationships between macroscale landscape variables and mesoscale habitat features within a national data set.

2.2.2 Methods and data sets

Table 2.2 briefly outlines the methods, data sets and analytical approaches taken. Further detail is provided in the respective analytical chapters. The desk-based study incorporates a review and re-evaluation of published works together with an analysis of a comprehensive national data set derived from the RHS database V. 3.34 (the most up-to-date version of the database available at the time of study). The database comprises 15, 948 UK river reaches (surveyed up until the end of 2002), cataloguing both map-derived ‘macroscale’ data and ‘mesoscale’ surveyed field data (Raven *et al.*, 1997). Relationships between mesoscale habitat features are assessed in the context of

Scientific approach	**Scale**	**Methods**	**Data sets**	**Analytical techniques**
Positivist (extensive)	Macro- mesoscale	• Analysis of River Habitat Survey data • Review and re-appraisal of published literature	• Flow type and functional habitat data for UK reference sites derived from RHS V 3.34 • Froude ranges for flow types and functional habitats from published field data.	• Exploration of frequency distributions • Multivariate statistical analysis
Realist (Intensive)	Mesoscale	• Topographic surveys of each study reach • Reach-scale hydraulic surveys incorporating visual assessment of biotopes and quantification of stream hydraulics (velocity, depth, substrate), fine sediment accumulations and vegetation cover within a rectangular grid.	• Reach-scale topographic surfaces • Hydrological (stage and discharge) data • Habitat features and channel hydraulics for ‘low’ (summer) and ‘intermediate’ (spring) discharges.	• GIS visualisations • Data exploration • Geostatistics • Multivariate analysis
Realist (Intensive)	Microscale	• Collection of high frequency velocity time series at a finer spatial resolution within selected physical biotopes • Turbidity monitoring of simulated suspended sediment pulses within selected physical biotopes	• Velocity time series at varying relative depths for ‘low’ and ‘intermediate’ discharges for each physical biotope. • Turbidity time series for different depths through each physical biotope for each simulated sediment pulse.	• Exploratory statistics • ‘Event’ analysis • Time series analysis • Hydrograph-style pulse characterisation

Table 2.2 Methods, data sets and techniques.

the broader environmental characteristics of sites using exploratory data analysis and multivariate statistical techniques. Detailed descriptions of the data sets and analytical techniques used are provided in Chapter 3 (Sections 3.4 and 3.6 respectively)

The field component of the research is subdivided into detailed mesoscale and microscale investigations of habitat organisation at the sub-reach scale within two physically contrasting reaches of the River Tern, Shropshire. Details of the field sites are provided in Section 2.3. Mesoscale habitat surveys were conducted under relative 'low flow' (July 2005) and 'intermediate flow' (March 2005) conditions (see Section 2.3.5 for discharges and exceedances). Detailed topographic surveys conducted during January 2005 provide a morphological context for each field site.

Hydraulic parameters were measured within a structured rectangular grid throughout a 120 m study reach at each field site and compared with visual assessments of substrate types, vegetation cover, surface flow characteristics and physical biotopes. Geodata for each velocity/ depth sample point were available in the form of Easting and Northing values which were calculated post-survey using co-ordinates of cross section markers and measurements taken during each survey. This allowed a combination of geostatistical and multivariate analytical techniques to be applied to the data sets in order to explore the organisation of mesoscale physical habitat. Full details on sampling design, field survey methods and equipment, data sets and analytical techniques are provided in Chapter 4.

For the microscale field component, high frequency streamwise and vertical velocity components were sampled within selected physical biotopes under low and intermediate flow conditions in order to explore the detailed flow characteristics of biotopes, which are often overlooked in favour of simpler mean parameters. A combination of turbulent event analysis and time series analyses were employed in order to quantitatively examine the turbulent properties of different physical biotopes. Full descriptions of velocity data collection are provided in Chapter 5, Section 5.3 and analytical techniques are discussed as appropriate within Section 5.4. An experimental microscale component involved the monitoring of turbidity levels within different physical biotopes for the duration of artificial sediment 'pulses' created upstream. The characteristics of detected pulses were explored in an attempt to gain greater insight into the localised transport pathways of sediments, nutrients and pollutants within different physical biotopes. Full details of this novel field methodology and the analytical techniques employed to interpret the observed patterns are provided in Chapter 5, Section 5.5.

2.3 FIELD SITE CHARACTERISTICS

2.3.1 Geological context

The two study reaches used for the field component of the research are each 120 m in length and are located approximately 0.5 km apart within the upper Tern catchment, north Shropshire. The Tern, a tributary of the River Severn, flows south across the north Shropshire Plain to its confluence with the Severn at Shrewsbury. The upper Tern catchment is underlain by geologically 'young' (less than 300 million years old) Permian and Triassic continental sandstone systems, often collectively known as 'The New Red Sandstones' (Toghill, 1990). These sandstones were laid down during the Permo-Triassic period under desert conditions whilst Great Britain was part of the Pangea continent (Owen, 1976) and the resultant soft, permeable characteristics of the sandstone geology have shaped both catchment topography and reach-scale channel structure.

Of the 15, 948 sites within the RHS database V 3.34, 12% are characterised by New Red Sandstone geology, and these are generally restricted to the Midlands and northern England, and to a lesser extent south west England and Wales (Figure 2.2a). Of these, 25% are classed as either pristine or semi-natural according to the EA's Human Modification Score (see Chapter 3, Section 3.4.1) and a further 20% are predominantly unmodified. This leaves 55% of New Red Sandstone Rivers showing obvious signs of human modification to the river channel and surrounding corridor (Figure 2.2b). Of the modified sites, a relatively small percentage are classed as 'severely modified' but 30% of the total New Red Sandstone reaches are classified as 'significantly modified', suggesting a strong need for rehabilitation.

These relatively high levels of modification reflect the location of sites: the majority of New Red Sandstone reaches are associated with 'lowland' locations according to EA's statistical classification of landscape characteristics (Figure 2.2c, see Chapter 3, Section 3.4.1 for further details). The landscape characteristics of the ten reaches of the River Tern included in the database appear relatively representative of the wider New Red Sandstone data set, falling within the central portion of the New Red Sandstone cluster (Figure 2.2c). All surveyed reaches on the Tern are classified as 'lowland' by the EA's statistical classification, but most of these are associated with relatively high energy conditions reflecting the close proximity of sites to the river source.

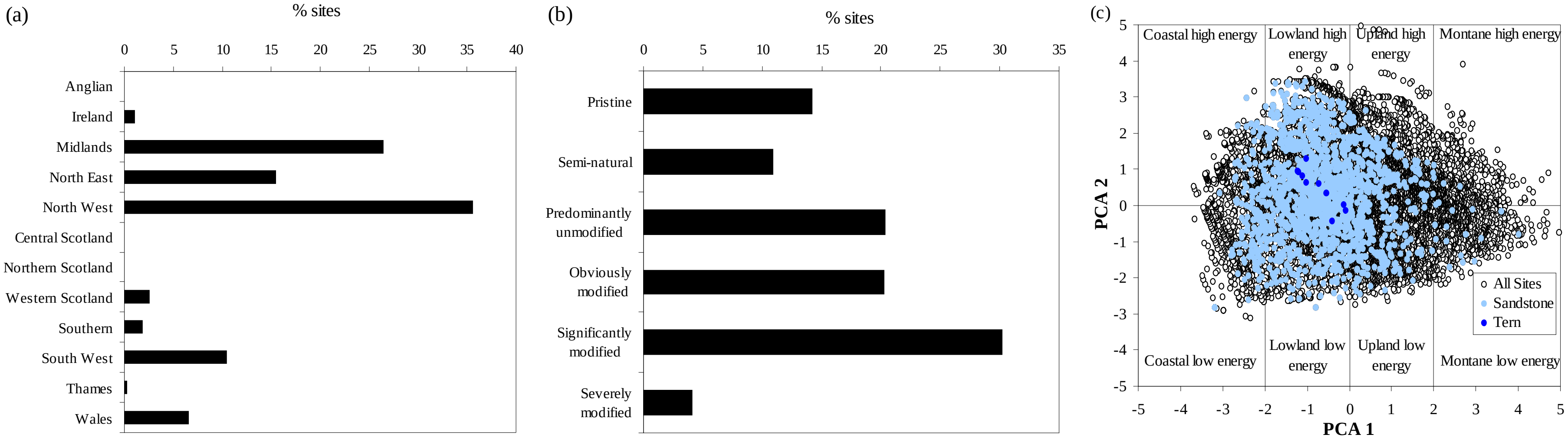
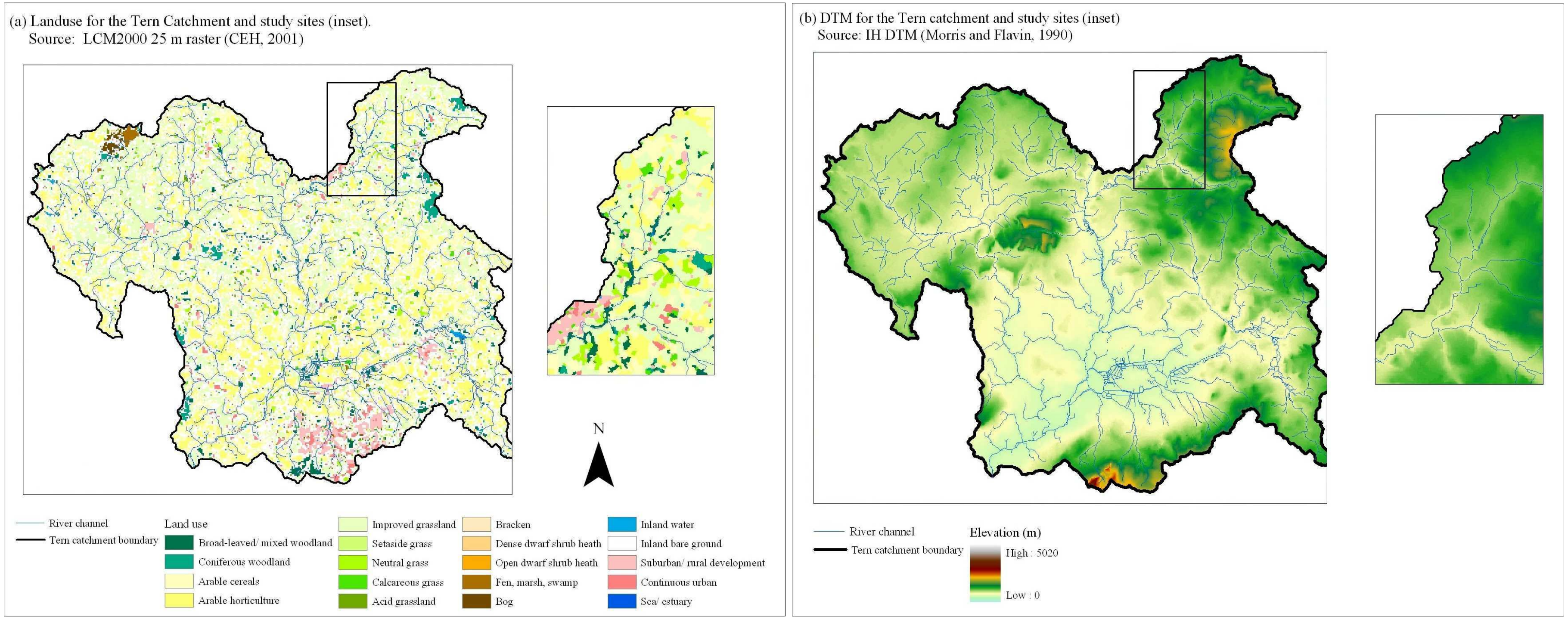


Figure 2.2 (a) Geographical distribution of New Red Sandstone RHS sites, (b) Proportions of New Red Sandstone sites associated with varying levels of human modification and (c) landscape context of all sites within the RHS database compared to New Red Sandstone sites and sites on the River Tern. Source: RHS database V. 3.34 (see Chapter 3, Section 3.4.1 for further details of the EA's PCA-based river typology).

2.3.2 Catchment topography and land use

Land use data were available from the Centre for Ecology and Hydrology (CEH) in the form of the Land Cover Map (LCM) 2000, a thematic classification of spectral data recorded by satellite images. This provides a classification of 25 m land parcels into one of 25 subclasses following the ITE (now CEH) Landsat-derived cover type descriptions. The final subclasses represent an aggregation of many subclasses which have been short-listed according to a selection of 'target' classes considered ecologically meaningful. A digital terrain model (DTM) with a 50 m grid interval and 0.1 m vertical resolution developed for hydrological purposes (Morris and Flavin, 1990) was also obtained from CEH for the Tern catchment, providing a wider topographic context for the study reaches.

The land-use of the catchment is predominantly agricultural and mixed grassland, and urban areas are sparse (Figure 2.3a). Despite the lack of urban development, the catchment has suffered degradation and reduced biodiversity of river corridors as a result of agricultural 'improvements' (LOCAR/ JIF, 2000). The study reaches are characterised by a combination of improved grassland, arable cereals and horticulture but a thin strip of broad-leaved woodland is observed to follow the main channel intermittently downstream, suggesting some buffering of the channel to surrounding agricultural impacts. A DTM for the Tern catchment (Figure 2.3b) illustrates the subdued nature of the topography resulting from the soft underlying geology. The two study sites within the upper Tern catchment are located within the headwater reaches and are surrounded by some of the highest elevations of the catchment, but these are still relatively low (500 to 1500 m), producing a 'rolling hills' topography.



(a) Landuse for the Tern Catchment and study sites (inset).
Source: LCM2000 25 m raster (CEH, 2001)

(b) DTM for the Tern catchment and study sites (inset)
Source: IH DTM (Morris and Flavin, 1990)

Figure 2.3 (a) Land use characteristics for the Tern catchment derived from the Land Cover Map (LCM) 2000 obtained from the Centre for Ecology and Hydrology (CEH) and (b) Digital Terrain Model (DTM) for the Tern catchment (created by the Institute of Hydrology)
Insets (black rectangles) highlight the location of the study sites.

2.3.3 Reach morphology

Topographic surveys were undertaken at each field site during January 2005 using a Leica Geosystems TCR 307 electronic total station. Surveys were designed to capture channel bed topography and bank foot, mid bank, and bank top elevations and floodplain topography. Channel survey points were arranged according to a paced grid of approximately 2 m longitudinally by 1 m cross sectionally in order to complement mesoscale hydraulic surveys. Resolutions were reduced to between 2 m and 5 m spacing on the flood plain.

Visualisation of the resulting topographic data using Triangulated Irregular Networks (TINs) created in ArcGIS 8.3 demonstrates the variation in both planform and morphology between sites (Figure 2.4). Reach photographs in Plate 2.1 provide further detail. The Oakley Hall reach is relatively straight and is characterised predominantly by a pool-glide morphological sequence. Approximately 50 m downstream from the end of the study reach, fallen riparian trees have created a large debris dam which ponds-back the flow, reducing water velocities and resulting in deposition of fine sediments upstream. Deposition of fines was particularly apparent within a riffle feature at the downstream end of the study reach, closest to the dam, where topographic and sedimentological characteristics of the riffle are subdued to the extent that the feature is more representative of a glide (see Chapter 4, Section 2 for field definitions of morphological features). Much of the reach is characterised by glide and run features punctuated by two small scour pools associated with lateral scour around riparian tree roots. Smaller localised bed scour was noted between the two main pools in association with flow deflection around a smaller root protrusion and beneath a fallen tree.

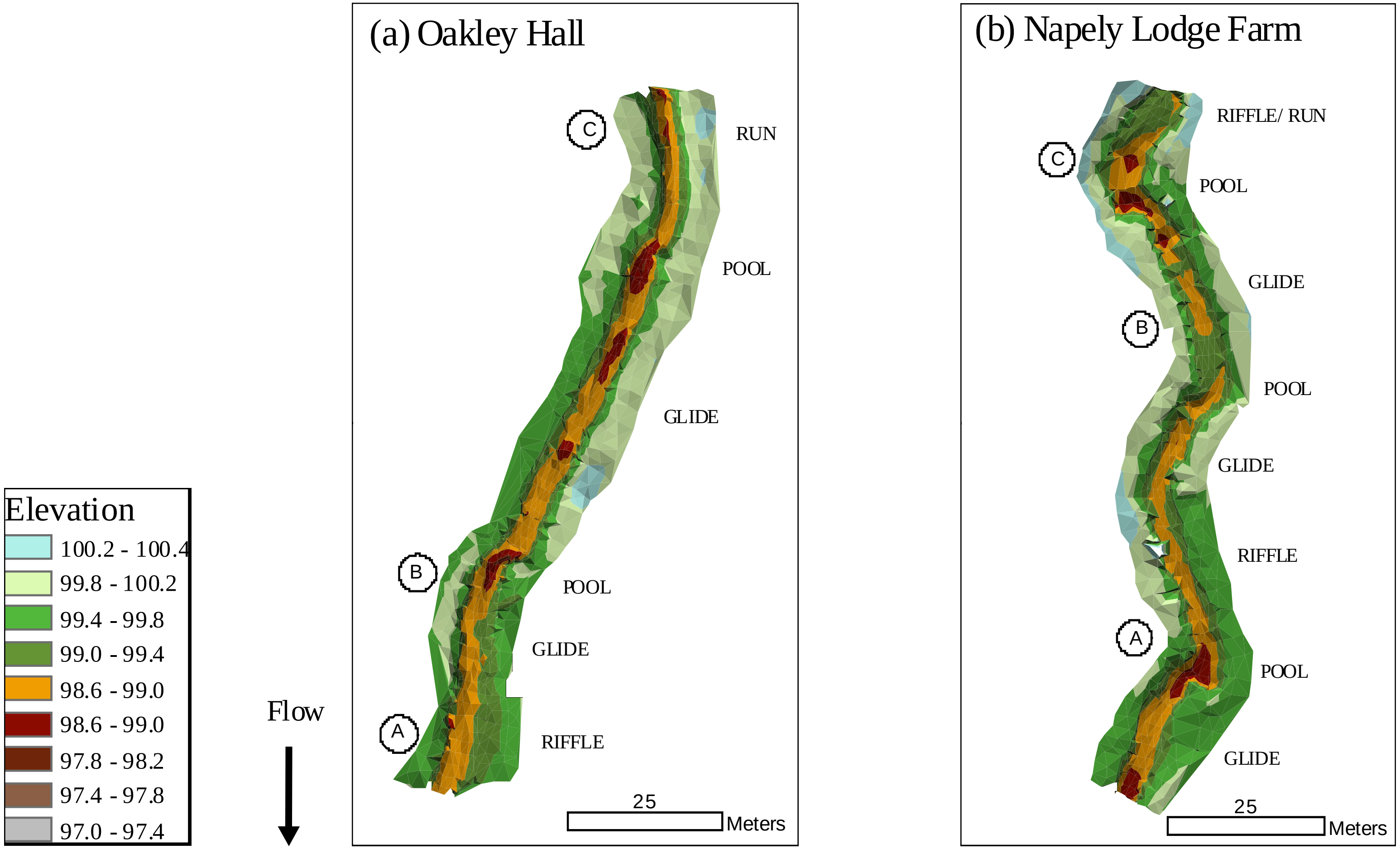


Figure 2.4 DTMs for (a) Oakley Hall and (b) Napely Lodge Farm study reaches created using Triangulated Irregular Networks (TINs) in ArcGIS 8.3. Channel and floodplain elevations were obtained by topographic survey using a Leica Geosystems TCR 307 electronic total station. Circled letters denote the location of reach photographs in Plate 2.1.

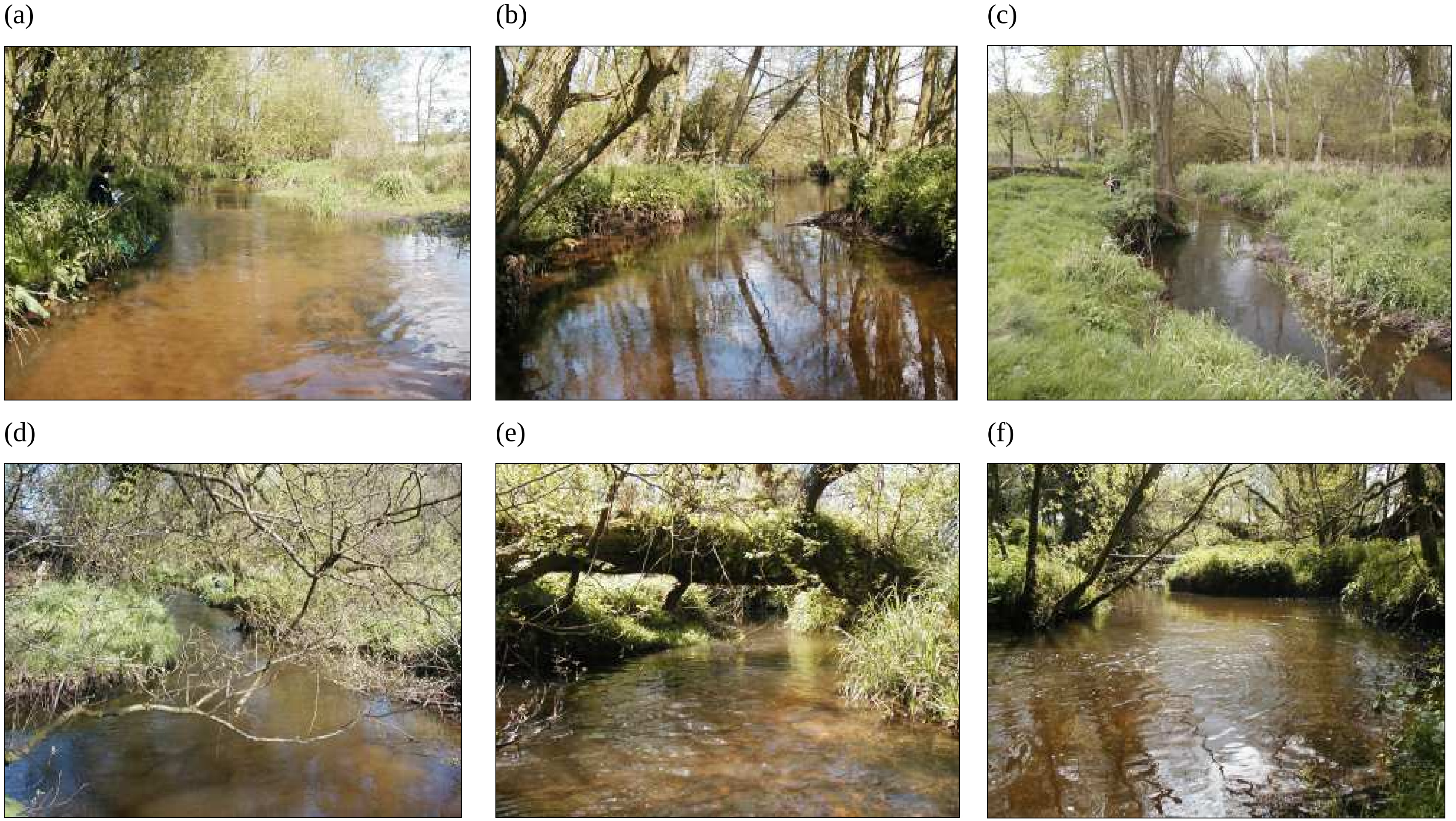


Plate 2.1 Study reach photographs for Oakley Hall (a to c) and Napely Lodge Farm (d to f) taken on 03/05/05 under discharge conditions of 0.27 m^3s^{-1} at Oakley Hall and 0.26 m^3s^{-1} at Napely Lodge Farm.

The reach at Napely Lodge Farm is more sinuous and is characterised by a more pronounced riffle-pool morphology. The channel morphology comprises one obvious riffle feature characterised by coarse bed material and significant disturbance to the water surface, plus several more subtle gravely features. Two large scour pools are associated with prominent backwater zones, and glides occupy some transitional areas between pools and riffles. A steeper gradient creates a coarser substrate across much of the channel compared to Oakley Hall, resulting in some gravel armouring of the sandy substrate and thus a more stable bed as noted previously by Emery (2003).

The small particle size of sand permits sediment transport wherever flow velocities equal or exceed 0.3 ms^{-1}, and thus sediment transport is virtually constant in sand-bed reaches (Simons and Simons, 1987). Consequently, although higher flow conditions are responsible for channel-moulding sediment transport events, near-constant saltation and low intensity suspension result in continual modification of sand bedforms (LaPoint, 1996). Sand bedforms are more prominent at Oakley Hall where the longer glide sections are characterised by small sand ridges extending laterally across the channel, creating an additional roughness element intermediate between grain roughness and larger-scale form roughness associated with riffle-pool bedforms. Further detail on particle size characteristics is provided in the following section.

2.3.4 Sedimentology

Gravel, sand and marginal silts were sampled at each site. Where visual observations revealed spatial variations in size distributions of gravel categories, several samples were taken. For instance, both pebble-gravels and granular gravels were sampled within the riffle, and an additional gravel sample was taken from glides. Samples (2-3 kg) were collected in bags held downstream of the sample area in order to ensure that the finest fraction was not lost downstream. Subsequent laboratory analysis of particle size distributions for gravel, sand and silt samples involved filtering off excess water, oven-drying, and dry-sieving down to a sieve size of 4Ø (0.06 mm). Sub-samples of the < 1 mm fraction were treated with hydrogen peroxide to remove organic matter and analysed in a Beckman LS Particle Size Analyzer. The coarser cobble fraction was sampled according to a grid sampling design based on Wolman's (1954) method. A sample grid of approximately 0.5 m x 0.5 m squares was paced across the channel, producing a sample spacing of several grain diameters in order to avoid serial correlation of the sample as a result of the tendency for similarly sized clasts to imbricate against one another (Church *et al.*, 1987). The longest (a), intermediate (b) and shortest (c) axes were measured and particles returned to the riverbed.

Particle size distributions may be described by percentiles derived from cumulative mass curves (Bridge, 2003). These were generated by the Particle Size Analyzer for silt samples, and derived from cumulative mass curves for the coarser samples (Figure 2.5). Table 2.3 presents the D_{50} and D_{90} for each substrate category, denoting the grain diameter associated with the 50th and 90th percentiles respectively. All gravel samples show bi-modal distributions, suggesting that a 'framework' of gravel-sized clasts (>2 mm) is supported by a finer 'matrix' of sand particles 0.125 mm to 2 mm in diameter (Church *et al.*, 1987). The relative size of particles in each substrate category varies between sites. For instance, silts and cobbles are generally finer at Napely Lodge Farm, while the sand fraction and riffle-gravel is coarser. This suggests some variation in 'absolute' particle size characteristics of the same biotopes even within the same river segment, although the variation may be partly attributed to variations in the spatial organisation of substrate types at each site. Most significantly, cobbles were associated with the riffle at Napely Lodge Farm but the run biotope at Oakley Hall. While cobble ‘shape’ is generally disc-like for both samples (Figure 2.6a and b), frequency distributions for particle sphericity emphasise the different hydraulic environments associated with cobbles at each site. Oakley Hall reveals a negatively skewed distribution compared to the positive skew at Napely Lodge Farm which suggests higher levels of sphericity. Particle sphericity is strongly related to the mode of sediment transport (Richards, 1982), suggesting some variations in transport mechanisms between the higher energy riffle at Napely Lodge farm compared to the run at Oakley Hall. However, this may also reflect the overall higher energy conditions at the former created by a steeper channel gradient.

2.3.5 Hydrology

Hydrological data from a gauging station at Ternhill, located approximately 13 km downstream of the study sites, and the records from pressure transducers installed on the Oakley Hall reach provide both longer- and shorter term hydrological contexts for the field surveys. Figure 2.7a presents the mean daily flow record at Ternhill for a 33-year period (1972 to 2005), which suggests several scales of variation. The mean daily discharge at Ternhill does not fall below 0.2 m^3s^{-1} for the period and reaches a maximum of over 14 m^3s^{-1} during one of the flood events. The annual fluctuation around the median is associated with higher flows in the winter and spring and lower flows in the summer and autumn periods. Within the higher-flow period for each year, several short-duration high magnitude events occur which often reach discharges greater than three times the median for the entire period. Extremely high magnitude

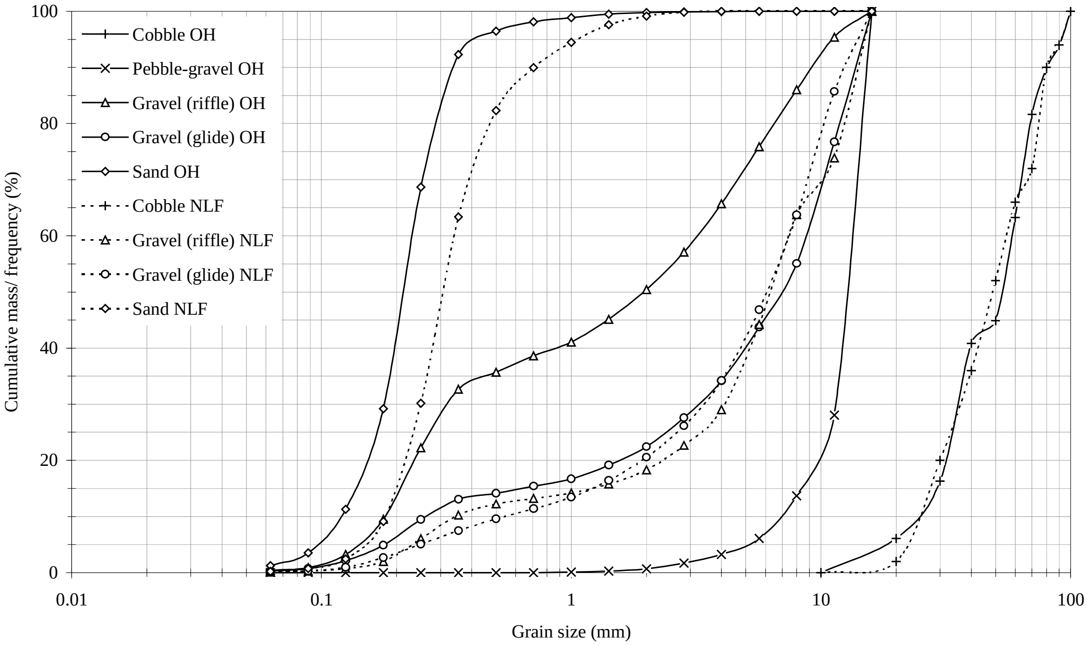


Figure 2.5 Grain size distributions for sieved sediment samples from Oakley Hall (OH) and Napely Lodge Farm (NLF).

Site	Sample	D_{50} (mm)	D_{90} (mm)
Oakley Hall	Silt	0.18	0.29
	Sand	0.22	0.34
	Gravel (glide)	7.00	16.00
	Gravel (riffle)	2.00	9.10
	Pebble-gravel	13.00	16.00
	Cobble	54.00	80.00
Napely Lodge Farm	Silt	0.06	0.18
	Sand	0.31	0.70
	Gravel (glide)	6.00	12.50
	Gravel (riffle)	6.20	14.50
	Cobble	49.00	80.00

Table 2.3 Particle size characteristics for Oakley Hall and Napely Lodge Farm.

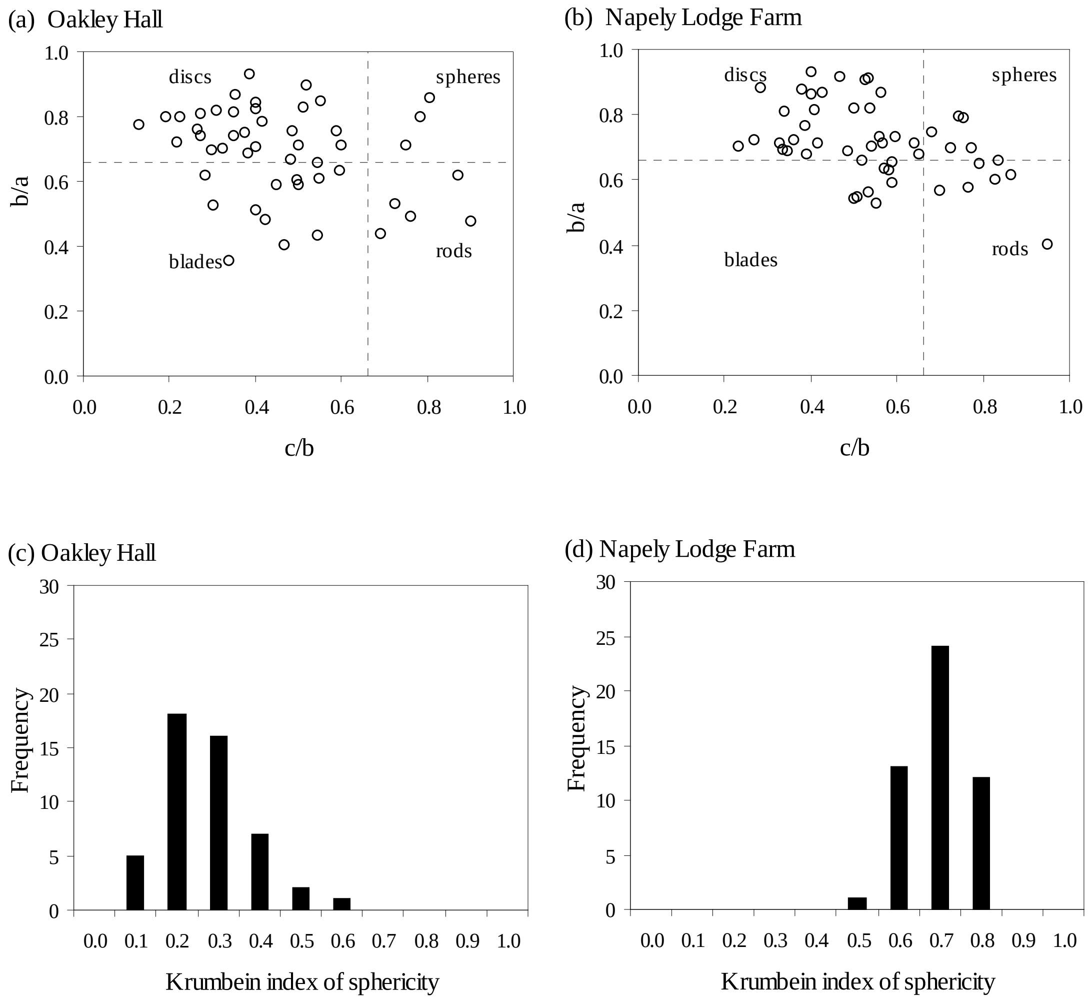


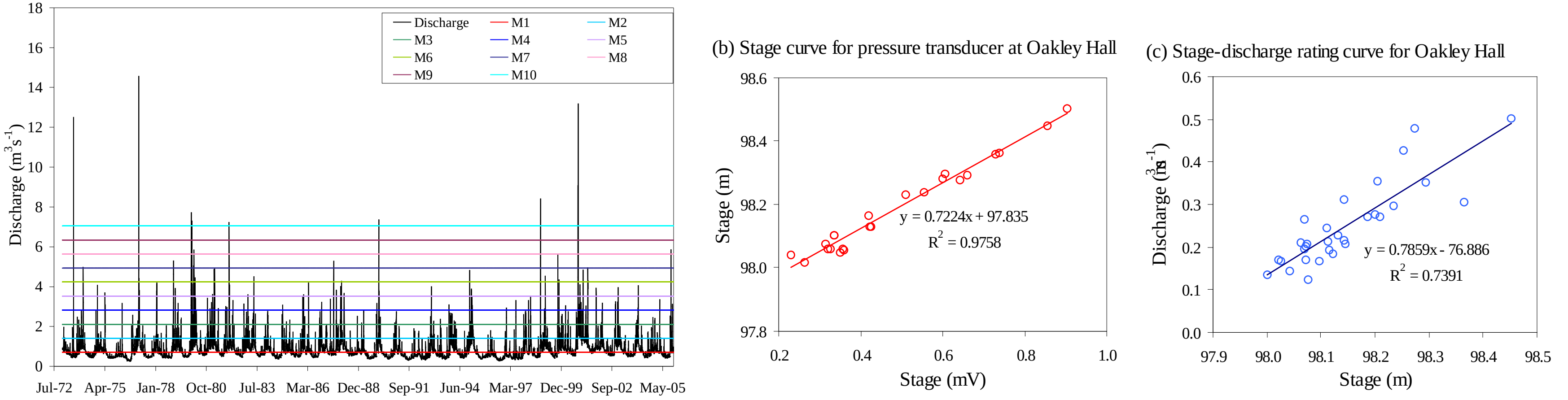
Figure 2.6 (a and b) Particle shape for cobble samples as calculated from particle axis ratios according to the Zingg classification (Richards, 1982) and (c and d) particle sphericity for cobble samples according to the Krumbein index of sphericity (Richards, 1982).

events associated with discharges over ten times the median value are observed to occur seven times within the record, generally during the winter period, with an average interval of approximately 5 years. The more frequent disturbances suggest modifications (through scour and redistribution of sediment) to the physical habitat structure of the channel several times per year which are likely to result in a reorganisation of the biotic community (Milner, 1996; Biggs *et al.*, 2005).

Three Druck PDCR 1830 pressure transducers (PTs) were installed at Oakley Hall in 2003 as part of the NERC-LOCAR project NER/T/S/2001/00930 and were maintained for the duration of the field study period in order to provide a hydrological context for field surveys. The pressure transducers provide a measure of river stage by measuring the pressure of water above a sensor positioned within a stilling well in the channel. Pressure transducers were connected to Campbell Scientific CR10X dataloggers programmed to sample at an interval of 30 s and store a 15-minute average. Pressure transducers were located at the upstream end of the study reach, and approximately 60 m and 150 m downstream, the final pressure transducer being located approximately 30 m beyond the downstream end of the study reach.

Output data from the pressure transducers is in the form of millivolts which was converted to a measure of water elevation (above an arbitrary datum) using a linear regression of millivolts readings against measured stage heights (Figure 2.7b). Mean daily discharge was then calculated using a linear regression of measured discharges obtained at PT2 (using a SonTek Handheld FlowTracker, see Chapter 4, Section 4.2.2) against pressure transducer stage readings for PT2 (Figure 2.7c). Stage, discharge and

(a) Mean daily flow for the Tern at Ternhill 1972 - 2005



(b) Stage curve for pressure transducer at Oakley Hall

(c) Stage-discharge rating curve for Oakley Hall

(d) Mean daily flow for the Tern at Oakley Hall 2003 - 2005

(e) Flow exceedance curves for the Tern at Ternhill and Oakley Hall (2003-2005)

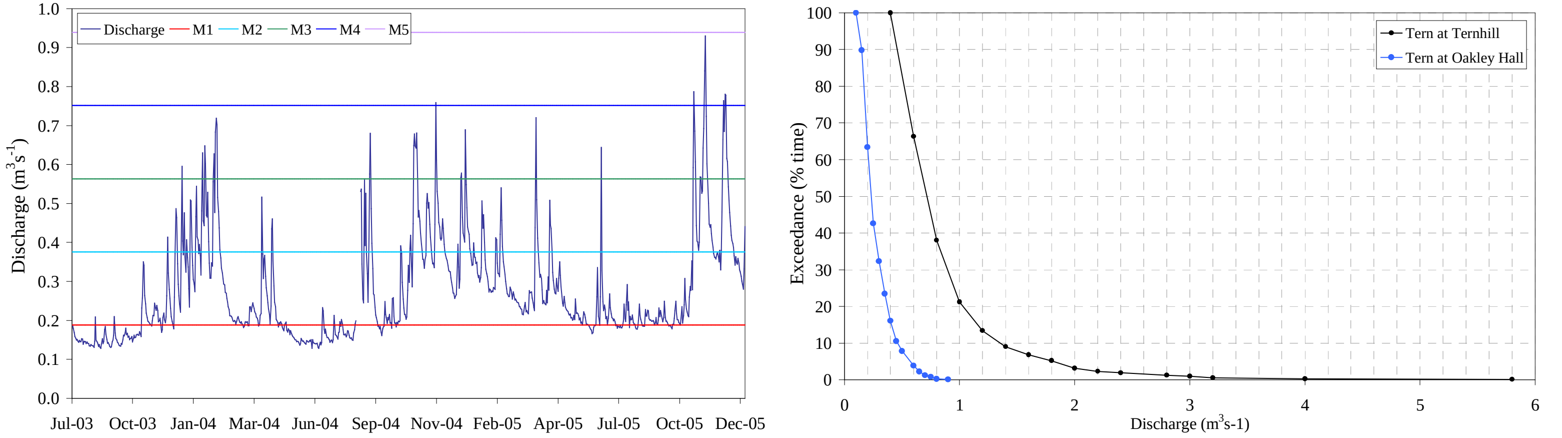


Figure 2.7 (a) Mean daily flow at Ternhill for the period 1972-2005 compared to multiples of the median discharge, (b and c) estimation of discharge from pressure transducer stage readings (above an arbitrary datum), (d) mean daily flow at Oakley Hall for the period July 2003-December 2005 compared to multiples of the median discharge and (e) flow exceedance curves for the Tern at Ternhill compared to Oakley Hall for the period 2003-2005.

Site	Survey	Date	Discharge (m^3s^{-1})	Stage (m)	Exceedance (2003-2005 period)
Oakley Hall	River Habitat Survey	28th May 2004	0.17		
	Topographic survey	24th/ 25th January 2005			
	RiverSurveyor velocity survey	27th/ 28th April 2005	0.27/ 0.28	98.21/ 98.20	39%
	Mesoscale habitat survey	19th/ 20th July 2005	0.17/ 0.17	98.07/ 98.07	79%/ 96%
		7th/ 8th March 2005	0.21/ 0.22	98.30/ 98.14	63%/ 60%
	Fine sediment pin survey	28th August 2004			
		28th January 2005			
		20th April 2005			
		4th July 2005			
	Microscale velocity surveys	20th July 2005	0.17	98.07	96%
		8th March 2005	0.28	98.14	39%
	Sediment transfer experiments	2nd June 2005	0.19	98.11	68%
		25th July 2005	0.23	98.13	54%
Napely Lodge Farm	River Habitat Survey	25th July 2004	0.17		
	Topographic survey	26th/ 27th January 2005			
	RiverSurveyor velocity survey	25th/ 26th April 2005	0.23/ 0.24	98.25/ 98.25	55%/ 47%
	Mesoscale habitat survey	21st/ 22nd July 2005	0.16/ 0.15	98.19/ 98.20	90%/ 91%
		9th/ 10th March 2005	0.25/ 0.22	98.25/ 98.25	43%/ 59%
	Fine sediment pin survey	28th August 2004			
		28th January 2005			
		21st April 2005			
		4th July 2005			
	Microscale velocity surveys	22nd July 2005	0.15	98.20	91%
		10th March 2005	0.22	98.25	57%
	Sediment transfer experiments	3rd June 2005	0.18		78%
		26th July 2005	0.24	98.21	56%

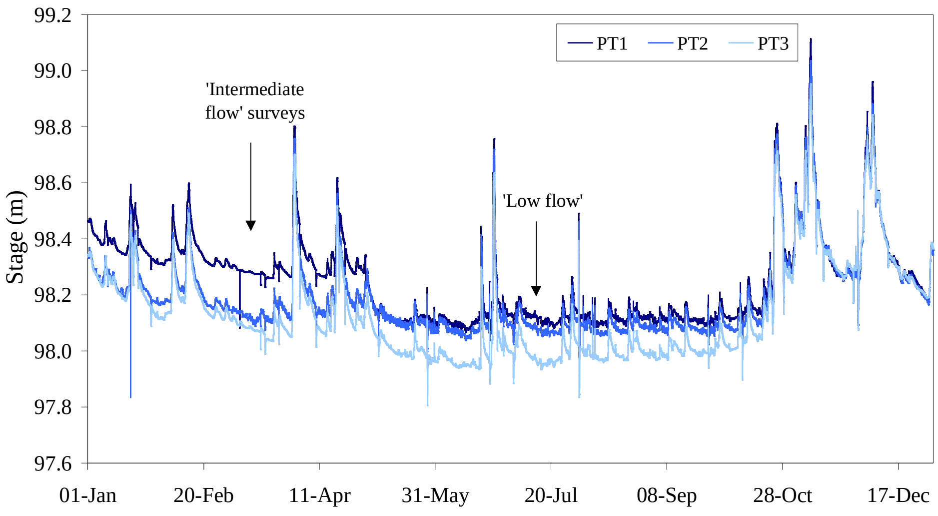
Table 2.4 Flow stage (above an arbitrary datum), discharge and exceedance statistics for each field survey.

exceedance statistics derived from these records provide the hydrological context for each field survey (Table 2.4).

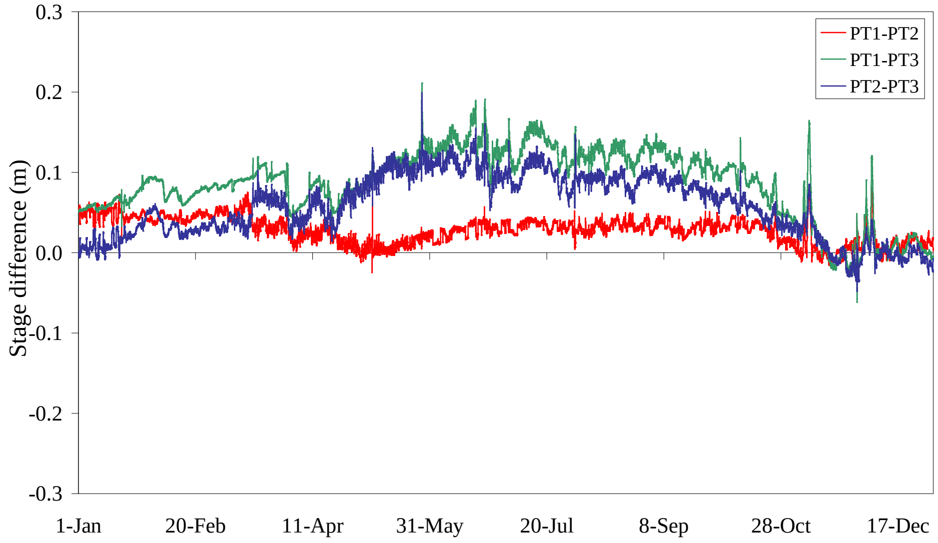
Figure 2.7d presents the mean daily flow record for PT2. Discharges do not exceed 1.0 m^3s^{-1} for the duration of the instrumentation period (2003-2005), but exhibit a similar annual cycle associated with higher flows in the winter and spring periods as observed for the Ternhill record. The highest floods for the period, however, do not exceed five times the median value. Flow exceedance curves for Ternhill and Oakley Hall (Figure 2.7e) for the same period suggest a much steeper curve for the Oakley Hall site compared to the Ternhill station further downstream. This suggests a 'flashier' regime for the study sites (Bridge, 2003), reflecting higher connectivity between hillslopes, floodplain and channel in the upper catchment compared to further down the valley where the effects of anthropogenic activity result in detachment of the stream from its surrounding floodplain. The study sites are located within the headwaters of the Tern catchment, where extensive un-drained valley-bottom wetlands are likely to increase the responsiveness of the channel to flood events, compared to further downstream where the river is channelised and the floodplain more extensively drained. This creates a different hydrological disturbance regime for the study sites compared to lower reaches, which may have a significant influence on biodiversity since the level and intensity of disturbance is important in controlling the ecological balance between colonisation and competition (Townsend *et al.*, 1997).

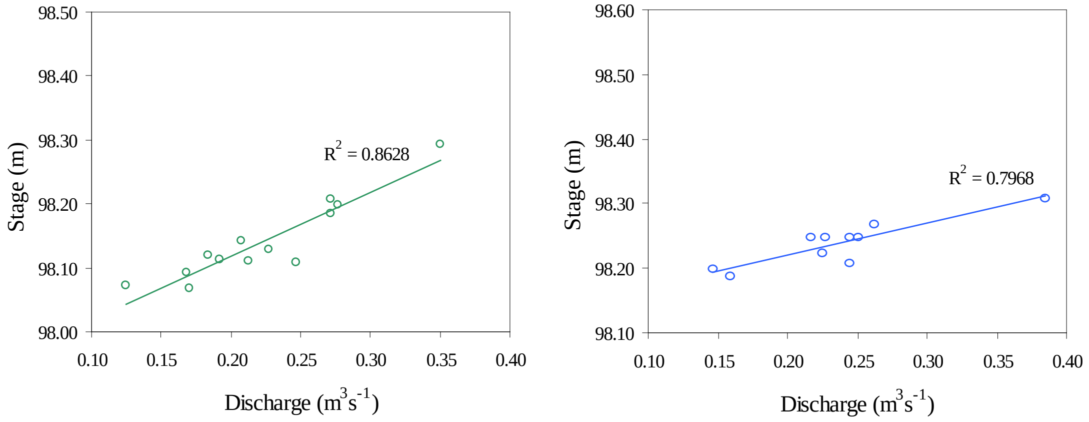
Hydrological data for the principal study season (January to December 2005) are presented in Figure 2.8. The period includes a relatively dry winter, but a pronounced summer low flow period is apparent between May and October (Figure 2.8a). Winter,

(a) Pressure transducer records for Oakley Hall 2005 field season



(b) Stage difference between pressure transducers at Oakley Hall 2005 field season





(c) Stage-discharge curve for Oakley Hall

(d) Stage-discharge curve for Napely Lodge Farm

Figure 2.8 (a) Flow stage (above an arbitrary datum) at Oakley Hall for the principal study period (January-December 2005), (b) stage difference between pressure transducers, and (c and d) stage-discharge curves for both sites for the same period.

spring and autumn periods are characterised by both higher average flows and greater incidence of flood events, creating a seasonal variation in the frequency of hydrological disturbance. During the low flow period, the difference in stage between PT1 and PT3 and PT2 and PT3 (Figure 2.8b) increases by approximately 0.05 m suggesting a homogenisation of water surface slope during periods of increased discharge when the effects of bedform controls such as riffles and pools are drowned out (Emery *et al.*, 2003). Additionally, the convergence and divergence of water surface elevations throughout the reach may reflect seasonal variations in flow resistance associated with the growth of instream vegetation (Gurnell *et al.*, 2006).

Relationships between stage and discharge reflect the differences in channel width and vegetation cover between the two study sites (Figure 2.8 c and d). More data are available for Oakley Hall due to the longer monitoring period associated with LOCAR installations. However, the data suggest a steeper stage-discharge curve for Oakley Hall, reflecting the narrower channel which creates greater increases in stage with discharge compared to the wider channel at Napely Lodge Farm. This may be amplified by the ponding of flow at the downstream end of the reach and the greater vegetation cover observed at Oakley Hall which creates increases in stage by increasing channel resistance and reducing flow velocities (Gaudet, 1974).

2.3.6 Habitat features

In order to provide an overview of the principal habitat features present, a rapid reconnaissance of the physical structure of each site was carried out in the form of River Habitat Surveys (RHS). The RHS field methodology records channel substrate, habitat features, vegetation types, bank features and modifications at ten equally spaced ‘spot-checks’ throughout a 500 m survey reach. This information is then supplemented by a ‘sweep-up’ checklist in order to account for infrequent features not occurring at spot-checks, and cross-section measurements of channel dimensions at one representative location (Raven *et al.*, 1997; Fox *et al.*, 1998). Surveys were carried out under low flow conditions at Oakley Hall and Napely Lodge Farm in May and July 2004 respectively. RHS survey reaches were determined by access: at Oakley Hall the RHS site incorporated the study reach and extended an additional 380 m downstream, while at Napely Lodge Farm the survey reach extended 360 m upstream and 20 m downstream of the principal study section.

A summary of the principal habitat features at each site is provided in Table 2.5. Observations of land-use within the river corridor are consistent with the coarser resolution data derived from satellite images (see inset in Figure 2.3a): both sites are predominantly characterised by a mixture of improved and unimproved grassland, woodland and wetland. A higher proportion of pools compared to riffles is noted at the ponded Oakley Hall reach, while Napely Lodge Farm is characterised by a similar number of pools and riffles suggesting a more organised pseudo-cyclic bed topography (Richards, 1976). Both sites are characterised by several habitat features of special interest (e.g. wet woodland, reed banks), however, and the high connectivity between the channel and surrounding riparian corridor creates a range of habitats associated with riparian tree growth (woody debris, tree roots, overhanging boughs).

RHS data may also be used to provide an indication of both habitat ‘quality’ and the level of human modification. Habitat Quality Assessment (HQA) scores are based on features considered to be of importance to wildlife and allow comparison between

	Feature	**Oakley Hall**	**Napely Lodge Farm**
Dimensions and influences	No. riffles	1	6
	No. pools	5	5
	No. unvegetated point bars	0	0
	No. vegetated point bars	0	3
	No. weirs	1	0
	No. bridges	1	1
	Bankfull width (m)	5.6	4.5
	Water width (m)	4.05	4.2
	Water depth (m)	0.28	0.12
	Features of special interest	Debris dam, leafy debris, fringing reed bank, quaking bank, marsh, flush	Debris dam, leafy debris, fringing reed bank, wet woodland, marsh
	Nuisance species	Giant hogweed, Himalayan balsam	Giant hogweed, Himalayan balsam
	Major impacts	Litter, sewage	Litter, sewage
Sweep-up	Land-use (left bank)	Improved/ semi-improved grassland/ pasture (extensive), broadleaf/ mixed woodland, wetland	Improved/ semi-improved grassland/ pasture (extensive), broadleaf/ mixed woodland, wetland
	Land-use (right bank)	Rough/ unimproved grassland (extensive), Broadleaf/ mixed woodland, wetland	Tall herb/ rank vegetation (extensive) Broadleaf/ mixed woodland, wetland
	Extent of trees	Occasional clumps	Semi-continuous/ occasional clumps
	Associated features	Shading of channel, overhanging boughs, exposed bankside roots, underwater tree roots, fallen trees, large woody debris	Shading of channel, overhanging boughs, exposed bankside roots, underwater tree roots, fallen trees, large woody debris
HMS		4	1
HMS class		‘Predominantly unmodified’	‘Semi-natural’
HQA		60	65

Table 2.5 RHS data for Oakley Hall and Napely Lodge Farm obtained by field surveys conducted in May and July 2004.

rivers of similar type, while Human Modification Scores (HMS) are based on the extent of structural alterations to the channel such as reinforcement and resectioning, providing a measure of artificial modification (Raven *et al.*, 1998b). Napely Lodge Farm is associated with lower levels of modification and a higher HQA score, suggesting that the site may be considered 'semi-natural', while Oakley Hall is associated with a lower HQA score and a 'predominantly unmodified' status which reflects a higher incidence of modifications including bank reinforcements and a small weir.

Both sites are associated with a relatively high proportion of fine sediments (sand and silt) resulting from the underlying soft geology. The high inputs of sand and silt and lower slopes associated with sandstone geologies create enhanced levels of silting in sandstone streams, which often extends further upstream compared with rivers cut into more resistant rocks (Haslam, 1978). However, RHS spot-check data suggests that Oakley Hall is associated with a comparatively higher proportion of fine sediments and slower flow conditions than Napely Lodge Farm (Figure 2.9a and b) which again emphasises the ponded nature of the reach.

Due to the high mobility of fine substrates, vegetation types with general preferences for stable substrates (e.g. mosses) and low turbidity levels (e.g. submerged macrophytes) are uncommon in sandy reaches. Instead, marginal emergent herbaceous vegetation such as *Myosotis scorpiodes* and *Veronica beccabunga* may thrive in silted margins and extend across the bed where low current velocities allow the encroachment of silts toward central channel areas (Haslam, 1978). While emergent (e.g. *Sparganium erectum*), amphibious (e.g. *Agrostis stolonifera*) and

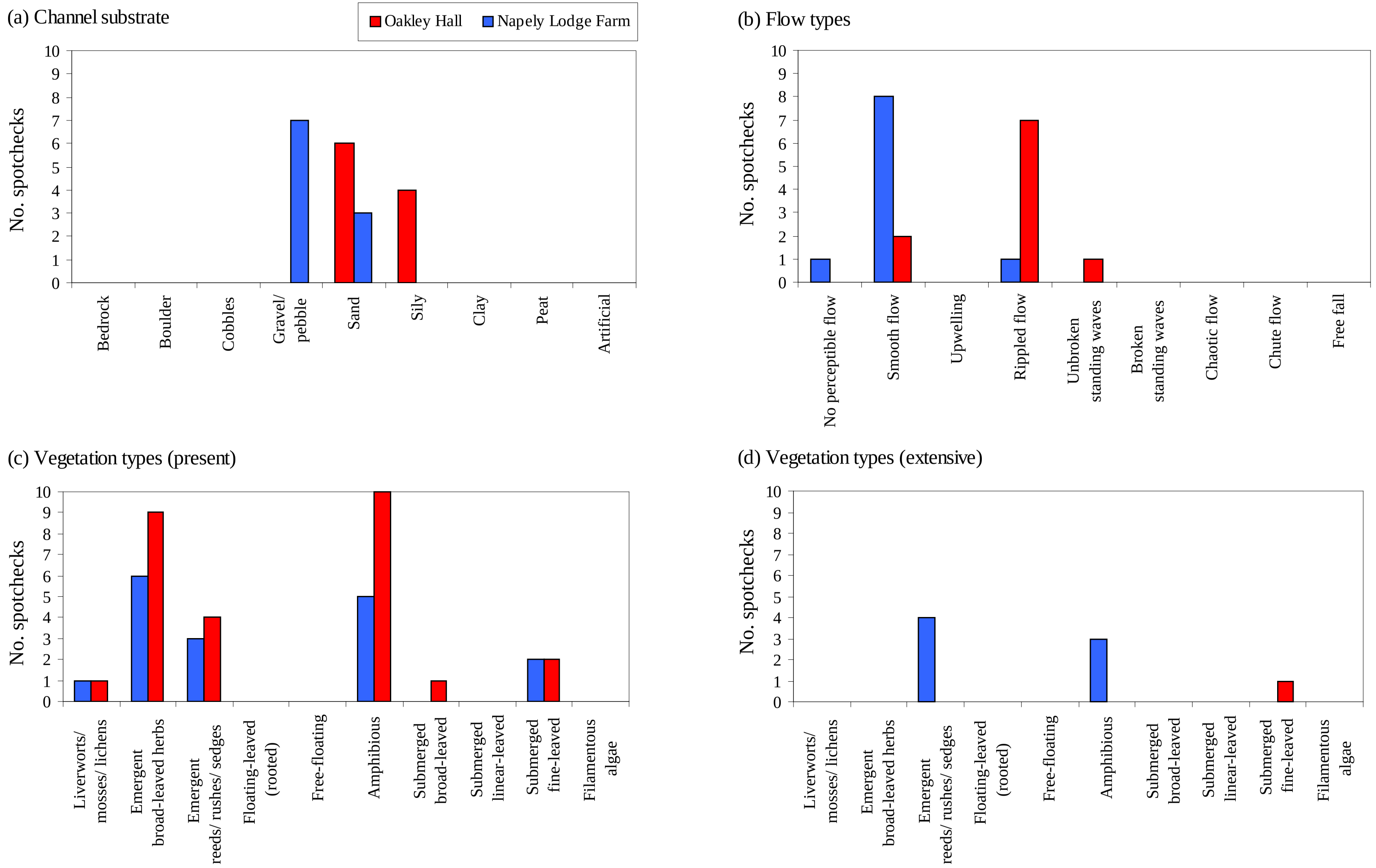


Figure 2.9 Channel substrate (a), flow types (b) and vegetation types (c and d) identified at RHS spot-checks during field surveys conducted in 2004.

(a) *Myriophyllum alterniflorum*

(b) *Sparganium erectum*

(c) *Phallaris arundinacea*

(d) Tree roots

(e) Trailing vegetation

(f) Small woody debris

Plate 2.2 Vegetation types and other organic habitats observed on the Tern study sites.

submerged (e.g. *Myriophyllum alterniflorum*) vegetation types (Plate 2.2) occur frequently at Napely Lodge Farm, they rarely account for over 33% of an RHS transect (Figure 2.9c and d). Extensive vegetation cover is generally restricted to emergent and amphibious species at Oakley Hall, although there is some extensive cover of submerged fine-leaved macrophytes at Napely Lodge Farm outside of the main study section. However, while vegetative habitat units are relatively sparse at both sites, other types of organic habitat were identified in abundance, particularly those associated with riparian tree growth such as small woody debris, leaf litter and protruding tree roots (Plate 2.2). The distributions of these habitats are explored further in Chapter 4.

CHAPTER 3 BIOTOPES AND HABITATS: TOWARDS AN IMPROVED CONCEPTUAL BASE

3.1 CHAPTER SYNOPSIS

This chapter details an attempt to improve the conceptual basis of mesoscale physical habitat characterisation as summarised in Clifford *et al.*(2006) and Harvey *et al.* (in Press). The first part of the chapter comprises a review and evaluation of the physical biotope concept based on the published literature, and demonstrates a requirement for ‘ecological validation’ of hydraulically or morphologically-defined biotopes. The second part of the chapter attempts to address this requirement by exploring correlations between surface flow types (used to indicate the presence of physical biotopes) and biologically distinct minerogenic and vegetative functional habitats, within a comprehensive national data set. An ecological ‘classification’ of flow types is derived from frequency distributions and statistically validated by two multivariate techniques, suggesting a hierarchical organisation of physical and functional habitat at the reach scale.

3.2 PHYSICAL BIOTOPES: IDENTIFICATION AND CHARACTERISATION

3.2.1 The biotope approach

Chapter 1 introduced some mesoscale habitat concepts and identified a transition within empirical ecohydraulics from species-level habitat assessments, to a more holistic approach focusing on the physical requirements of instream communities known as the ‘biotope’ approach. Such an approach is attractive to practical river applications for several reasons. First, the concepts are conducive to rapid visual surveys, providing a cost-effective solution to legislative requirements for habitat assessment and improvement, and have already been incorporated into the EA's River Habitat Survey (RHS) methodology (Raven *et al.,* 1997). Second, the approach offers a means of simplifying the complex interactions between flow, substrate and channel morphology at scales appropriate to management and restoration. Third, reconciliation of 'physical biotopes' with the ecological concepts of 'functional' or 'meso'- habitats offers a route to substantive interdisciplinarity within the field of ecohydraulics which has so far been undermined by a lack of standardised terminology and true integration of geomorphological and ecological concepts (Janauer, 2000). However, some methodological and theoretical issues require clarification for the full potential of the biotope concept to be realised. The following sections explore these issues in the context of previous studies in an attempt to improve the conceptual base of the physical biotope.

3.2.2 Theoretical and methodological issues

The terms 'biotope' and 'physical biotope' have been employed in ecohydraulics literature as a convenient means of describing common morphological habitat structures (e.g. riffle, run, pool, glide) at the sub-reach scale. From an ecological perspective, however, biotope definitions concentrate on *biological* organisation, for example:

> *'The species has a habitat but it does not have a biotope. The biotope harbours instead, a biotic community…The concept of the biotope belongs to the realm of synecology. It is a convenient term for the habitat of a biotic community'* (Udvardy, 1959: 726-727).

Thus, in ecological terms the habitat and biotope are distinguished according to ecological structure rather than physical properties. Consequently, in order to have ecological value, a biotope must be biologically distinct (Udvardy, 1959; Newson *et al.*, 1998a). However, the term ‘habitat’ or ‘physical habitat’ is frequently adopted in the literature in place of the ecological ‘biotope’ since it is readily understood by river managers (Harper *et al.*, 1998a). Geomorphological definitions promote the biotope as the ‘basic unit’ of instream physical habitat (Padmore, 1997c) representing differing combinations of hydraulic variables (generally velocity, depth and substrate) which constitute the abiotic environment of communities of organisms (Wadeson and Rowntree, 1994). How such broad definitions translate into practicable units of instream habitat is, however, unclear.

Field protocols for the identification of physical biotopes are based on the character of the water surface across channel cross sections. These assume ‘characteristic’ associations between physical biotopes and low flow stage ‘surface flow types’ (Table 3.1). From a geomorphological perspective, however, there are several concerns with these connections. First, although recent research shows a more complex picture involving flow intensification around obstacles (Clifford *et al.*, 2002b), increasing discharge is generally accompanied by an overall homogenisation of flow conditions across bedform controls, with larger areas of the channel characterised by similar, and higher, water depths and velocities (Clifford *et al.*, 2006). Variation in surface flow conditions is diminished, resulting in potential misidentification of the more temporally stable underlying morphological features, depending on the hydrological context of the survey. At high discharges, for instance, both deadwater zones and

Surface flow type	**Description**	**Code**	**Associated physical biotope**
No perceptible flow	No net downstream flow – a floating object placed in the water remains stationary	NP	Pool, Deadwater
Smooth boundary turbulent	Perceptible downstream movement is smooth (no eddies).	SM	Glide
Upwelling	Heaving water as upwellings break the surface – secondary flow evident as vertical and horizontal eddies.	UP	Boil
Rippled flow	No waves, but general flow direction is downstream with a disturbed rippled surface.	RP	Run
Unbroken standing waves	Upstream facing wavelets which are not broken.	UW	Riffle
Broken standing waves	White-water tumbling must be present.	BW	Rapid, Cascade
Chaotic flow	A mixture of at least three rough flow types.	CF	Any of the below physical biotopes
Chute flow	Low curving fall in contact with substrate.	CH	Cascade (step)
Free fall	Clearly separates from the back wall of vertical features	FF	Waterfall

Table 3.1 Surface flow types and their low flow stage associations with physical biotopes.
Source: Environment Agency (2003) Newson *et al.* (1998a)

riffles may exhibit the same surface flow behaviour as a ‘deep run’ (Newson *et al.*, 1998a). It is thus possible to distinguish between surface flow types and physical biotopes on the basis of stage-dependency, since flow types are stage-dependent and hence spatio-temporally unstable, whereas morphological features can be considered relatively stable at time scales up to around 10 years (Schumm and Lichty, 1965).

Second, surface flow conditions and underlying morphologies may show high cross sectional variation. Consequently, the transect-level surveys often employed in biotope assessments can overlook ‘secondary’ biotopes and marginal features of ecological importance (Padmore, 1998). Third, certain surface flow types are ‘characteristic’ of more than one morphological feature. No perceptible flow, for example, may be associated with both pools and deadwaters; broken standing waves with both rapids and cascades; and chaotic flow with a range of physical biotopes (Table 3.1). This was hydraulically quantified by Padmore (1997a) who identified ‘shallow’ and ‘deep’ areas of both rippled flow and no perceptible flow, suggesting that very different habitats may be represented by the same surface flow conditions.

Relationships between flow types and physical biotopes are therefore complex, reflecting the multiple and dynamic interactions between channel hydraulics and morphology, and hence casting some doubt on the use of flow types as a proxy for physical biotopes in visual surveys. Therefore for purposes of clarity, the data sets used in this Chapter refer to surface flow types, or ‘flow biotopes’ for brevity, and inferences on the channel morphologies and ‘physical biotopes’ associated with these flow features are made retrospectively following the analysis.

3.2.3 Biotope characterisation: a review of previous approaches

Initial attempts at objectively identifying physical biotopes focused on the classification of riffle and pool units according to undulations in bed topography (Richards, 1976; O'Neill and Abrahams, 1984). This has since been expanded to include variations on the basic riffle-pool structure (e.g. rapids, cascades, runs, glides). Characterisation has also incorporated the hydraulic variables of velocity, depth and substrate since they are relatively easy to quantify, are simpler to predict than biological factors, and have direct relevance to instream biota through the provision of habitat (Garcia de Jalon, 1995). For instance, while invertebrate distributions are influenced by a variety of biotic and abiotic factors operating over a range of spatial scales, the combined effect of flow velocity, water depth and substrate size may be considered particularly significant at the meso- and microscales of river systems (Quinn and Hickey, 1994; Swann and Palmer, 2000; Figure 3.1).

Early studies identified broad combinations of velocity, depth and substrate for a range of sites, and often related these to basic units of channel morphology such as riffles and pools. Thus, Bisson *et al.* (1981) identified characteristic hydraulic ranges for riffles, rapids, cascades, glides and various types of pools which were shown to provide different types of habitat for different fish species. Davis and Barmuta (1989) provide a classification of flow types based on the interaction between flow and substrate which create different types of habitat for biota and may be related to certain channel features (Table 3.2). Since the 1990s, however, biotope characterisation attempts have generally taken one of two broad methodological approaches.

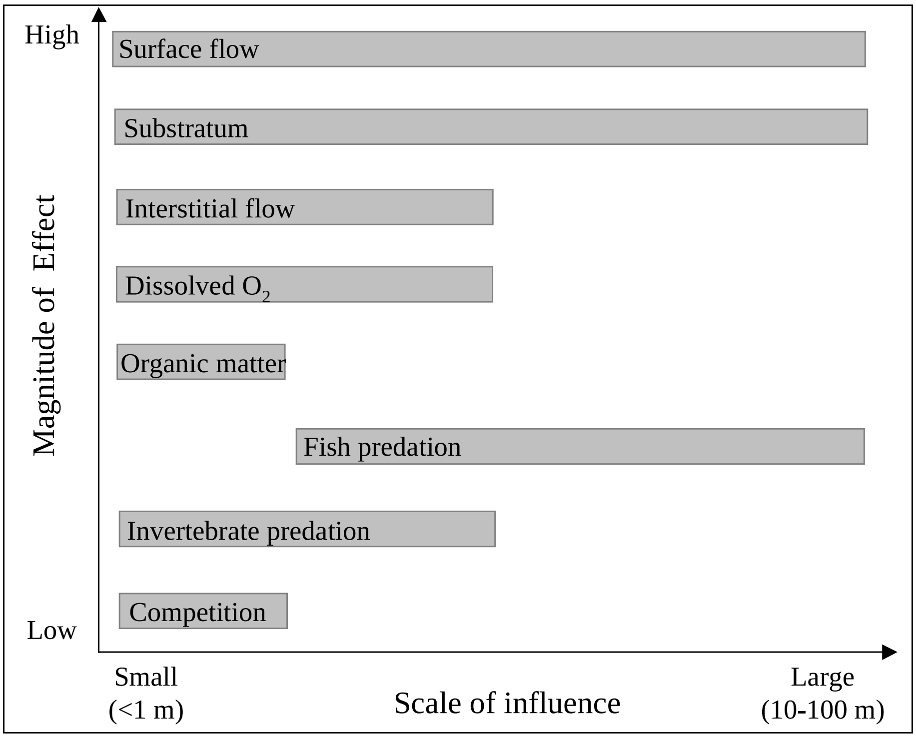


Figure 3.1 Spatial scale of influence and strength of factors influencing stream invertebrate distributions, modified from Swan and Palmer (2000: 117).

Flow type	Description	Biological implications	Channel feature
‘Hydraulically smooth’ flow	Occurs over fine sediments or flat bedrock surfaces where the roughness height is less than the thickness of the laminar sublayer	Homogeneous flow environment – biological forces will be the primary influence on species distributions.	Glides
‘Isolated roughness’ flow	Roughness elements are spaced far apart so that vortices created in the wake behind each element are dissipated in the space between elements.	Patchy habitat structure - different surfaces of the same rock provide different habitats due to the creation of horseshoe vortices.	Individual rocks
‘Wake interference’ flow	Distance between substrate elements is approximately equal to the length of the wake generated by each element. Considerable interference occurs between wake vortices creating high local velocities.	High turbulent stresses at the stream bed, less patchy and more homogeneous than isolated roughness flow.	Riffles
‘Quasi-smooth’ or ‘skimming’ flow	Roughness elements are spaced closely together so that flow skims across the crests of particles and fills the spaces between elements with much slower water containing stable eddies.	Two habitats are created: high velocities across the top of substrate elements and low velocities within the crevices.	Pebble- and cobble-bottomed runs

Table 3.2 Flow types resulting from the interactions between flow and substrate, their biological implications and associated channel features. Source: Davis and Barmuta (1989)

The first approach involves the quantitative measurement of hydraulic parameters within physical biotopes, which are visually identified according to surface flow characteristics. Most studies incorporate some measurement of velocity and depth, but fewer include substrate size as a hydraulic variable, despite the influence of substratum on habitat provision for aquatic plants (Boeger, 1992), benthic invertebrates (Quinn and Hickey, 1994; Swan and Palmer, 2000) and fish (Garcia de Jalon, 1995). Measured hydraulic parameters and derived ratios such as Froude number (a dimensionless ratio of streamwise velocity (U) and depth, $Fr = U / \sqrt{gd}$) are then examined for their power in discriminating between biotopes.

Froude number is used to determine whether the flow is subcritical and tranquil (Fr <1) or supercritical and rapid (Fr >1) and has been identified by several authors as the hydraulic variable most 'successful' at discriminating between biotopes (Jowett, 1993; Wadeson, 1994; Padmore, 1997a). However, the Froude ranges occupied by different physical biotopes are associated with some overlap in values (Newson *et al.*, 1998a), which increases when data are compared between different sites (Clifford *et al.*, 2006), suggesting limited transferability. A re-evaluation of data published in Newson *et al.* (1998a) data reveals substantial overlap in Froude ranges between certain flow types (Figure 3.2a; Clifford *et al.*, 2006). Some flow types even form a 'subset' of others for instance, the Froude range for smooth boundary turbulent flow plots entirely 'within' that of rippled flow.

While this overlap reflects the fact that biotopes form a 'continuum' from tranquil to more rapid environments (Jowett, 1993), it may also reflect some of the inadequacies of Froude in describing hydraulic conditions. Bivariate plots of velocity and depth by

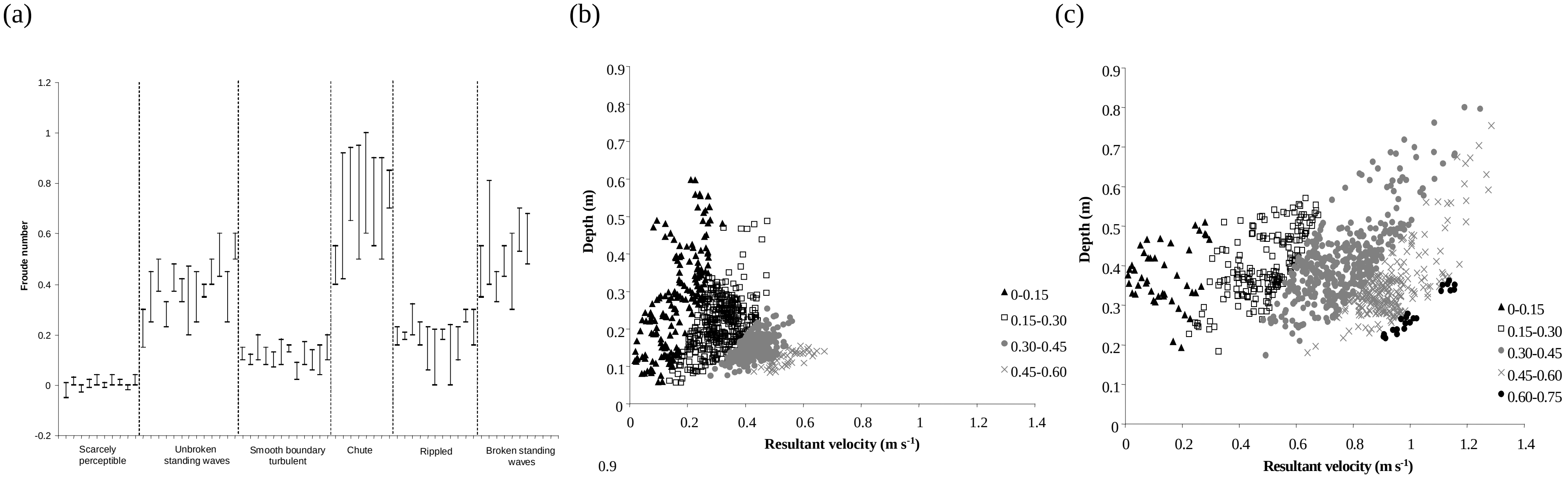


Figure 3.2 (a) Froude number ranges for flow biotopes identified by Newson *et al.* (1998a), and velocity-depth ranges for different Froude number classes for the River Cole, Birmingham at (b) low flow (discharge 0.34 m^3s^{-1}; 70% exceedance) and (c) high flow (discharge 1.49 m^3s^{-1}; 13% exceedance). Source: Clifford *et al.* (2006: 395, 405).

Froude number class for the River Cole, Birmingham (Figure 3.2b and c; *Clifford et al.*, 2006) demonstrate that Froude classes are aligned diagonally within the plot, encompassing a range of velocity-depth combinations which expands with discharge. Thus, very different combinations of velocity and depth may be associated with a similar Froude number, potentially masking variation between flow types and physical biotopes. Further analysis of these data demonstrate that these classes traverse morphological boundaries (riffle and pool; Clifford *et al.*, 2006) thus questioning the appropriateness of the ratio as a means of biotope characterisation.

More recently, an alternative and complementary geostatistical approach has been employed, focusing on the spatial characterisation of velocity fields without *a priori* assumptions concerning the existence of physical or flow biotopes (Clifford *et al.*, 2002a; Clifford *et al.*, 2002b; Emery *et al.*, 2003). These studies have highlighted the complexities of the hydraulic response of a reach to increasing discharge. The overall effect is a weakening of relationships between flow and morphology as stage rises, with obvious implications for both the identification and hydraulic characterisation of physical biotopes. At low flow, for instance, flow patterns appear ‘topographically-constrained’, i.e. velocity variation is closely related to bedform spacing (and hence physical biotopes). At higher discharges, however, hydraulic distinctions between riffles and pools are reduced and microscale flow intensification such as jetting and vortex shedding appears to become more significant (Clifford *et al.*, 2002a; Clifford *et al.*, 2002b). Further empirical work identified six sub-reach scale hydraulic habitat ‘clusters’ characterised by different responses to increasing discharge (Emery *et al.*, 2003). Different clusters were identified for riffle crest and riffle margins, channel margins, backwater and pool zones suggesting significant ‘within-biotope’ variations in hydraulics, which are similar to prefered fish habitats (Aadland, 1993), and emphasise the importance of channel margins as a distinct hydraulic ‘patch’. Furthermore, the amplitude of bedforms was shown to exert a significant influence on the hydraulic response of a channel to increasing discharge, stressing the complexity of morpho-hydraulic relationships.

Both of the approaches outlined above have in common the assumption that the hydraulic biotopes identified are of some ecological significance. While known relationships between physical parameters and biotic distributions suggest that this is likely, biological distinction must be demonstrated explicitly in order for biotopes to be considered of ecological value to river management (Newson *et al.*, 1998a). A practical and cost-effective means of exploring the ecological validity of the biotope concept is offered by a complementary ecological approach to habitat characterisation known as the ‘functional habitat’ concept, which is explored in the following section.

3.3 BIOLOGICALLY FUNCTIONAL HABITAT

3.3.1 Aquatic invertebrates and habitat functionality

Aquatic invertebrates are generally considered an appropriate biological focus for habitat studies. They provide a link between micro-organisms and larger vertebrates such as fish, which are commonly the target of management strategies (Kellerhals and Miles, 1996), and are greatly influenced by stream hydraulics throughout the river continuum (Statzner and Higler, 1986), thus providing a link between ecosystem structure and channel hydraulics. Additionally, invertebrates have the practical advantages of a well established taxonomy and lifecycles conducive to seasonal sampling regimes (Cummins, 1996), and their relatively sedentary nature means they are heavily influenced by local physical conditions (Metcalfe-Smith, 1996). An established literature acknowledges the role of both physical substrate and aquatic macrophytes in providing habitat for biota (Butcher, 1933; Hynes, 1970; Gregg and Rose, 1982; Newall, 1995; Biggs, 1996; Jowett, 2003). This has formed the basis of ecological approaches to the characterisation of instream habitat through the concept of ‘functional habitats’.

The functional habitats concept was developed by Harper *et al.* (1992) who identified a suite of sixteen organic and inorganic habitat units associated with distinct invertebrate assemblages from a more comprehensive list of ‘potential habitats’ readily identifiable from the riverbanks of three lowland streams in England. The habitats identified are associated with either substrate particle size, the morphology of aquatic plants, or the growth of riparian vegetation (Table 3.3), and appear relatively portable across catchments, despite variations in disturbance regimes and water quality. The habitats are associated with various biological ‘functions’, (e.g. by providing oviposition sites, food sources, and shelter from flow or predation) which traverse species boundaries and hence move the focus away from target species towards a more community-level approach. The authors suggest that these functional habitats forge a link between organisms and the physical processes operating within the river channel (Harper and Everard, 1998). Although a need remains for rigorous field testing, the approach has shown promise both as an indicator of the type and extent of habitat change within degraded reaches (Harper *et al.*, 1998a), and as a post-project appraisal tool in rehabilitation projects (Harper *et al.*, 1998b).

Habitat type	Habitat	Biological function(s)
Habitats based on substrate particle size	Rocks	• 'Hygropetric zone' – thin film of water on the surface of bare rock provides habitat for small macroinvertebrates.
	Cobbles/ Gravel	• Hyporheic zone within interstitial spaces. Often includes finer sediment/ organic matter encouraging biodiversity. • Also provide fish spawning sites.
	Sand	• Usually species-poor, but can support large numbers of specialised smaller invertebrates. • Accumulations around obstructions such as woody debris can become more stable and biologically richer.
	Silt	• Silted pools provide a detritus-rich habitat for macroinvertebrates which is stable for much of the summer.
Habitats based on the morphological characteristics of aquatic plants	Trailing vegetation/ marginal plants	• Feeding, mating and oviposition zone for mature stages of otherwise aquatic invertebrates.
	Emergent macrophytes	• Passage to the surface for emerging insects • Attachment surface for filter-feeders • Oviposition sites
	Floating-leaved macrophytes	• Passage to the surface for emerging insects
	Submerged fine-leaved macrophytes	• Protection from predation and turbulence • Provide surface for periphyton growth and attachment of invertebrates.
	Submerged broad-leaved macrophytes	• Can act as extensions of the substrate, providing smooth surfaces for attachment and locomotion
	Moss	• Oviposition in faster flowing waters • Protection from predation and flow • Accumulate fine sediment and organic matter, providing physical substrate and food
	Macroalgae	• Food source for grazers • Case material for some chironomids • Refuge from predation • Oviposition sites
Habitats based on riparian terrestrial vegetation	Roots	• May provide important habitat for specialised and rare species, but under-sampled.
	Leaf litter	• Direct food source for shredders • Site for product and capture of fine particulate organic matter • Can act as an extension of the physical substrate – particularly important in finer sediments
	Woody debris	• Direct use by borers • Increases channel stability.

Table 3.3 Minerogenic, vegetative and detrital habitats and their principal biological functions, from Harper *et al.* (1995).

3.3.2 Linking biotopes and functional habitats

Strong relationships between flow, substrate and instream vegetation suggest a potential for linking functional habitats with physical biotopes, providing a hydraulic context for the former and adding ecological value to the latter. However, minerogenic habitats (i.e. channel substrate types), and vegetative habitats respond to flow conditions in different ways. While channel substrate may be considered most strongly dependent upon current velocity through the entrainment and transport of particles, aquatic macrophytes are influenced by a more complex array of flow related factors, including, for instance, the effects of depth and turbidity on light availability which is particularly important for submerged species (Hynes, 1970). Despite this, stream velocity (and related factors such as turbulence) is generally considered of great significance to macrophytes both directly through the effects aeration and nutrient replacement on plant metabolism and mechanical damage to leaves and stems (Westlake, 1967; Fox, 1996), and indirectly through controls on the channel substrate (Carling, 1992).

Various authors have explored the relationships between ecology and channel hydraulics by linking plant species or morphologies with channel substrate and flow properties. Earlier attempts are generally descriptive, identifying broad ‘slow’, ‘moderate’ and ‘fast’ velocity zones associated with substrate types and plant morphologies (Table 3.4 and Table 3.5). For example, Haslam (1978) linked individual species distributions with visually identified ‘flow types’ which approximate the surface flow type categories used by the EA in RHS, Butcher (1933) included substrate as a predictor of plant morphologies and French and Chambers (1996)

Hydraulic class	**Macrophytes**
(a) ‘Very fast’ current, rocky substrate	Mosses, macroalgae
(b) ‘Fast’ current, stony substrate	Plants with strong stems and small leaves, or woody or tough rhizomes
(c)‘Moderate’ current, gravel substrate	Similar to (b), but potentially more diverse and abundant.
(d) ‘Slow’ current, sandy substrate	Plants with fibrous roots or matted rhizomes which exhibit a rapid growth.
(e) ‘Very slow’ current, silty substrate	Similar to (d) but more abundant, and dominated by plants with small and very abundant roots.
(f) ‘Negligible current’, mud substrate	Vegetation similar to pond or lake shore: erect reeds and plants similar (e).

Table 3.4 Descriptive hydraulic classes and associated macrophytes identified by Butcher (1933)

Hydraulic class	**Macrophytes**
‘Negligible flow’ (e.g. canals and fen dykes)	Free-floating and tall emergent species.
‘Slow flow’ (Plants hardly move)	Emergent reeds
‘Moderate flow’ (Trailing plants clearly move and water surface is slightly disturbed)	Submerged, fine-leaved macrophytes.
‘Fast flow’ (Trailing plants move vigorously and the water surface is markedly disturbed)	Submerged, fine-leaved macrophytes, mosses.

Table 3.5 Descriptive hydraulic classes and associated macrophytes identified by Haslam (1978)

quantified slow, moderate and faster velocity ranges for different macrophytic communities.

More recently, the focus has shifted to the hydraulic preferences of functional habitats rather than individual species, and has explicitly incorporated physical biotopes either by visual assessment or using hydraulic proxy indicators. For instance, Kemp *et al.* (1999) examine the velocity-depth distributions associated with the suite of functional habitats identified by Harper *et al.* (1995) and although a significant amount of 'overlap' between habitats is observed, some broad relationships are identifiable. Submerged fine-leaved macrophytes, mosses, cobbles and gravel were found to correlate with shallow, fast-flowing riffle zones and submerged broad-leaved macrophytes and sand correlated with slower and deeper marginal riffle and run zones. Silt and emergent macrophytes were generally found within slow-flowing shallow pools and floating-leaved macrophytes with deeper pools while marginal plants were associated with the shallowest and slowest-flowing marginal locations. A further analysis employed Froude number as a quantitative descriptor of different physical biotopes which were compared with the distribution of functional habitats (Kemp *et al.*, 2000). However, the Froude number appears able to discriminate only between broad 'low' Froude habitats (silt, roots, trailing vegetation, marginal plants, leaf litter, emergent macrophytes, floating-leaved and submerged broad-leaved macrophytes) and 'high' Froude habitats (rocks, cobbles, gravel, sand, submerged fine-leaved macrophytes, moss and macroalgae), although habitats within the second class form a gradient of increasing Froude number.

Thus, in a similar way to physical biotopes (Section 3.2), functional habitat categories appear to be associated with a large overlap in hydraulic parameters such as Froude number (Clifford *et al.*, 2006). While part of this overlap may again be attributed to the inadequacies of Froude as a hydraulic descriptor, it is also likely to reflect species-specific variations in hydraulic 'preferences' within functional habitat categories. For instance, *Ranunculus fluitan*s and *Myriophyllum alterniflorum* are both classified as 'submerged, fine-leaved macrophytes', but while the former shows relatively clear preferences for fast flowing rivers and stable substrates, the latter is tolerant of a broad range of conditions from standing waters to slowly or rapidly flowing streams and rivers (Preston and Croft, 2001). As a result, the cumulative range of hydraulic parameters associated with the amalgamated 'submerged fine-leaved macrophytes' category will be broad.

While neither physical biotope nor functional habitat categories appear easily delimited by specific ranges of hydraulic parameters, the two phenomena may still reveal correlations at a broader scale. 'Mapped' flow types and physical biotopes themselves may provide a more appropriate scale of investigation, identifying *relative* changes in physical conditions within a river reach at scales of interest to river inventory, rehabilitation and appraisal. Preliminary attempts at this type of analysis have been made by Newson *et al.* (1998a) using data on selected functional habitats derived from a subset of the RHS database, and by Harper *et al.* (2000) using finer-resolution data from four surveyed reaches. Some differences in the flow type frequency distributions associated with each habitat are observed, allowing some tentative inferences to be made concerning the broad flow type 'preferences' of certain habitats. Thus, 'slower' flow types (no perceptible flow) are linked with silt, tree roots, trailing vegetation and marginal and emergent plants;

‘intermediate’ flow types (smooth boundary turbulent and rippled flow) with sand, gravel and submerged macrophytes; and ‘faster’ flow types (unbroken standing waves) with cobbles and mosses.

The remaining part of this chapter expands on these preliminary studies by seeking correlations between flow types and functional habitats within the extensive national data set provided by the RHS database. The analysis also provides an opportunity to evaluate the data derived from rapid RHS field surveys in the context of habitat inventory, assessment, design and appraisal requirements.

3.4 A NATIONAL DATA SET

3.4.1 Data extraction

The RHS database V 3.34 provides a comprehensive national data set of habitat features which can be used to assess relationships between channel hydraulics (in the form of surface flow types) and functional habitats. Flow type and functional habitat data is recorded within the ‘spot-check’ component of the RHS field survey, which comprises visual observations at ten equally spaced cross-sectional transects (‘spot-checks’).

Derivation of flow type and functional habitat data for each spot-check location within RHS V 3.34 required a significant amount of database manipulation due to the structure of the database. An initial process of data ‘cleaning’ involved the removal of all spot-checks with missing or invalid data, those characterised by artificial substrates and those where turbid flow conditions or visual obstructions prevented inspection of instream habitat features. This reduced the available data set from a theoretical 159, 480 observations from 15, 984 different 500 m reaches, or ‘sites’, to 108, 979 spot-checks from 12, 715 sites.

In order to focus the investigation on ‘natural’ relationships between habitat components, the EA’s Human Modification Score (HMS) system was also used to eliminate data from sites which have experienced significant anthropogenic disturbance. The HMS system was developed by the EA as an analysis tool for expressing the levels of human modification to the channel and banks in order to facilitate inter-site comparisons (Environment Agency, 2000; Table 3.6). A data set of ‘semi-natural’ spot-checks was obtained by extracting sites with HMI scores < 3, and a data set of ‘heavily modified’ spot-checks was obtained by extracting sites with HMI scores > 20 (Table 3.7).

Surveyed RHS sites have been used to create a typology of UK rivers based upon certain map-derived variables (altitude, slope, distance from source and altitude of the source) which were found to correlate strongly with most habitat features (Jeffers, 1998a). A multivariate Principal Components Analysis (PCA) transformed these original variables into two axes which may be used to describe the macroscale characteristics of a particular site. The PCA ‘scores’ are presented in Figure 3.3 for the entire data set of all reference sites, the semi-natural data set and the heavily modified data set. The scatterplots reveal that while semi-natural sites are associated with a similar range of typologies as the entire database, there is a slight skew towards upland and montane locations and higher energy conditions. In contrast, heavily modified sites reveal a skew towards lowland environments. This reflects the susceptibility of lowland reaches to both long-term

HMS Score	**Descriptive category of channel**
0	Pristine
1-2	Semi-natural
3-8	Predominantly unmodified
9-20	Obviously modified
21-44	Significantly modified
45 or more	Severely modified

Table 3.6 Habitat Modification Score (HMS) system categories for RHS data as developed by the Environment Agency (2000).

Data set name	**Criteria**	**Number of records**	**Number of sites**
‘Raw’ spot-checks	None	158440	15844
All sites	Valid entries for flow type and functional habitat categories	108979	12715
Semi-natural	HMI<3	40832	4682
Heavily modified	HMI>20	22000	2635

Table 3.7 Criteria and characteristics of data sets derived from the RHS database.

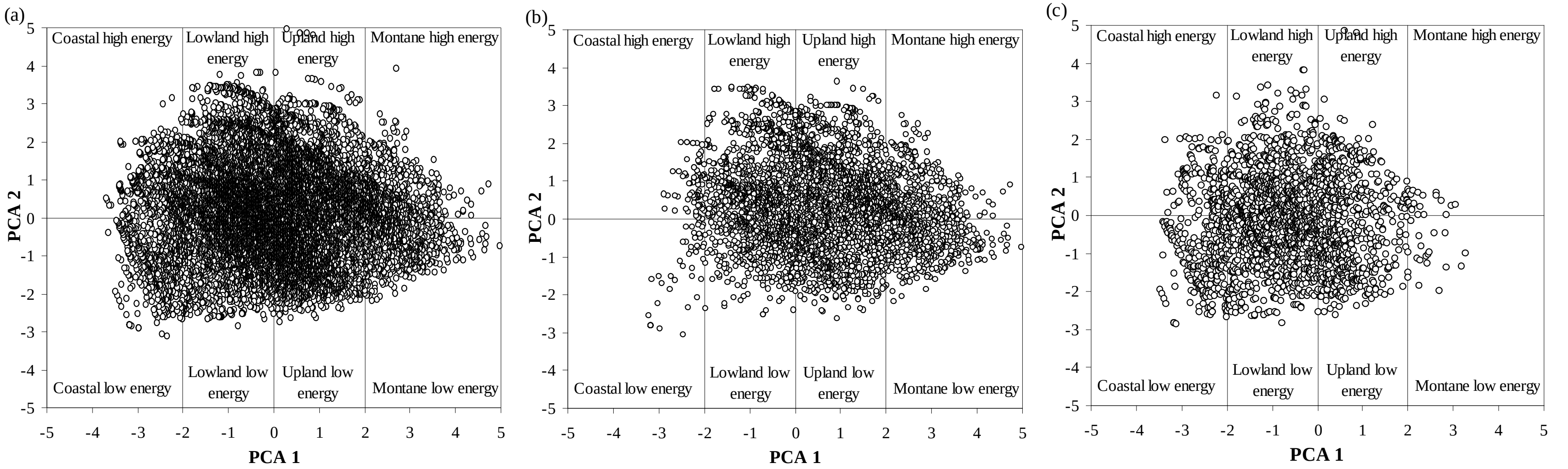


Figure 3.3 Data set characteristics for (a) all sites, (b) semi-natural sites and (c) heavily modified sites. The Environment Agency's typology is based on a Principal Components Analysis (PCA) using the variables of site altitude, slope, distance from source and altitude of source. PCA 1 represents a transition from low altitude, low slope ('coastal') sites, to high altitude, high slope ('montane') sites. PCA 2 represents a transition from low energy to high energy environments based on distance from source and altitude of the source.

indirect anthropogenic impacts associated with land use change and direct modifications to the channel itself for flood defence and water resource management.

3.4.2 Variable extraction

Derivation of flow type data from the database was relatively straightforward since RHS explicitly records the 'dominant' surface flow type (that occupying 50% or more of the channel width) across 1 m wide cross sectional 'transects' at each spot-check location (Figure 3.4). Only one entry is permitted per spot-check and where two flow types each occupy 50% of the channel, only the faster flow type is recorded. Minerogenic habitats and vegetative functional habitats are not recorded explicitly on field survey forms, but it was possible to adapt the data for the purpose and derive 12 of the 16 functional habitats identified by Harper *et al.* (1995) from observations of channel substrate and vegetation types (Table 3.8).

In a similar way to surface flow types, the 'dominant' channel substrate is assessed across a 1 m wide cross sectional transect at each spot-check, using the substrate particle size categories identified by Wentworth (1922). Organic functional habitat categories based on riparian vegetation (woody debris, tree roots and leaf litter) are recorded only within the 'sweep-up' section of the survey, and cannot be directly linked to surface flow type observations made at individual spot-checks. These habitats are therefore excluded from the analysis. However, it was possible to derive data for macrophytic functional habitats from spot-check assessments of channel vegetation types. RHS allows a variety of aquatic plant morphologies to be recorded as either 'present' (between 1% and 33% cover) or 'extensive' (>33% cover) across a wider cross sectional transect, extending 4.5

Functional habitat	Code	RHS categories
Rocks	BR	Boulder, bedrock
Cobbles	CO	Cobbles
Gravel	G	Gravel, pebble-gravel, pebbles
Sand	SA	Sand
Silt	SI	Silt
Roots	R	Not recorded as part of spot-checks
Trailing vegetation	TV	Amphibious
Marginal plants	MP	Not recorded as part of spot-checks
Leaf litter	LL	Not recorded as part of spot-checks
Woody debris	WD	Not recorded as part of spot-checks
Emergent macrophytes	ME	Emergent broad-leaved herbs, emergent reeds, rushes & sedges
Floating-leaved macrophytes	MF	Floating-leaved (rooted), free-floating
Submerged, fine leaved macrophytes	MSF	Submerged fine-leaved
Submerged, broad-leaved macrophytes	MSB	Submerged broad-leaved, submerged linear-leaved
Mosses	M	Bryophytes and lichens (includes liverworts, mosses and lichens)
Macroalgae	MA	Filamentous algae

Table 3.8 Derivation of functional habitat categories from RHS data.

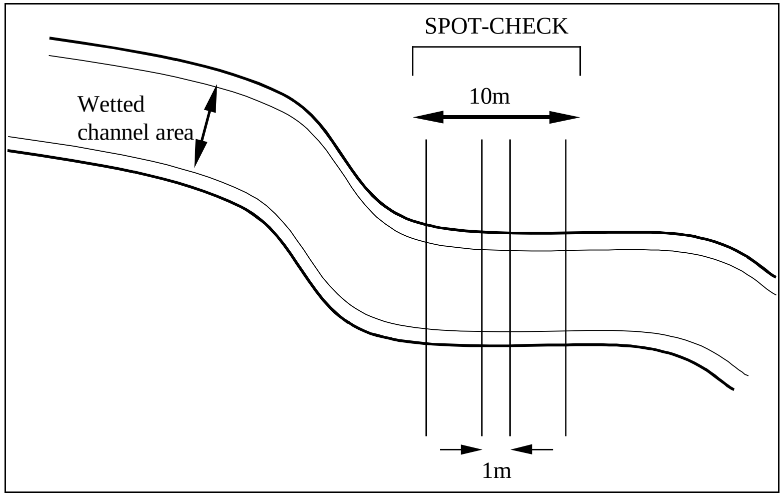


Figure 3.4 Dimensions of RHS spot-check attributes used in analysis, Environment Agency (2003: 1.4).

m either side of that used for flow type and substrate assessments (Figure 3.4). Due to the differences in spatial scales of assessment, analysis was restricted to vegetation types occurring ‘extensively’ at spotchecks. Derivation of functional habitat data required some amalgamation of RHS categories (Table 3.8) and it should be noted that the RHS definition for ‘emergent macrophytes’ also encompasses the ‘marginal plants’ habitat identified by Harper *et al.* (1995).

3.5 FLOW TYPES AND FUNCTIONAL HABITATS IN THE UK

3.5.1 National frequency distributions

Figure 3.5 presents the national frequency distributions of flow types and functional habitats for semi-natural sites. Several points are worthy of note.

Certain flow types and functional habitats occur far more frequently in the national data set than others. In terms of flow types, for instance, over 65% of spot-checks are characterised by smooth boundary turbulent or rippled flow types while the ‘faster’ flow types (broken standing waves, chute flow, and free fall) cumulatively account for just 10% of the distribution. The prominence of smooth boundary turbulent flow and rippled flow suggest a high incidence of ‘transitional’ morphological units such as glides and runs which is significant because such transitional units are frequently overlooked in habitat studies in favour of more physically prominent features such as riffles and pools. The low sample numbers of unbroken standing waves and no perceptible flow suggest that riffles and pools occur relatively infrequently compared to the intervening transitional run and glide units. However, particularly for pools, this may reflect the localised nature of features, which may not necessarily account for over half the channel width and will thus be overlooked at spot-checks.

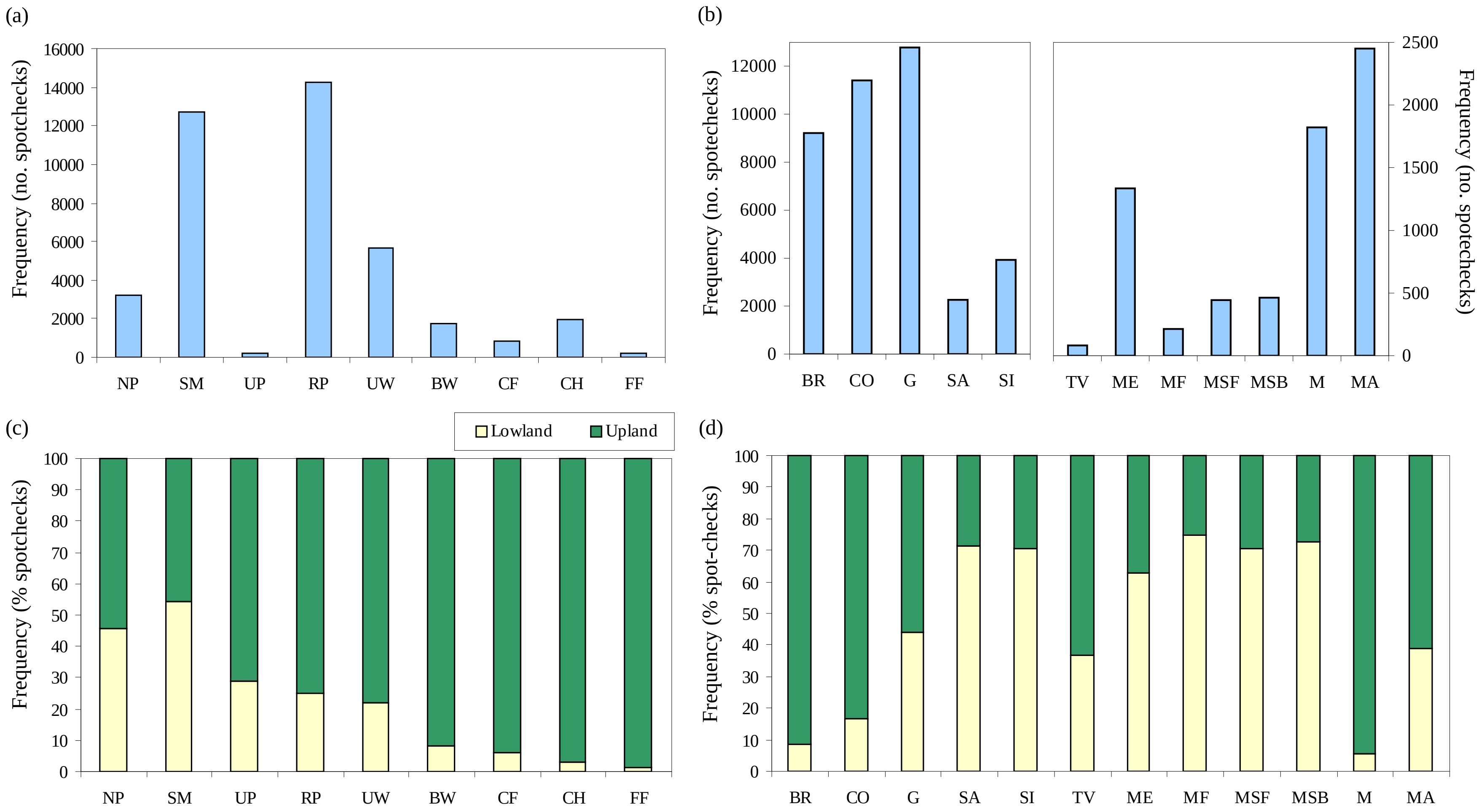


Figure 3.5 National frequency distributions for (a) flow types and (b) functional habitats, and percentage of observations of each flow type and habitat associated with upland and lowland settings (c and d) for semi-natural sites. See Table 3.1 (p. 53) and 3.8 (p. 63) for flow type and functional habitat category codes.

This methodological issue also applies to upwelling due to the relatively localised nature of associated ‘boil’ features. In contrast, the low frequency of ‘chaotic flow’ (which represents a combination of at least three of the ‘faster’ flow types) suggests that rougher flow environments are often dominated by a single flow type.

For functional habitats, minerogenic categories are necessarily associated with much higher sample numbers compared to vegetative categories, due to the ubiquity of substrate and the more spatially restricted nature of aquatic vegetation which is dependent upon climatic, chemical and biological factors in addition to flow (Fox, 1996). Minerogenic and vegetative categories are therefore plotted on separate axes in order to improve comparability. Of the minerogenic habitats, coarser substrates (gravel, cobbles, and rocks) dominate the national distribution, and sand and silt account for significantly fewer observations, reflecting the higher proportion of higher energy upland sites within the semi-natural data set and the dominance of gravel substrates in intermediate reaches. Of the vegetative habitats, macroalgae and mosses occur most frequently in the data set, reflecting the high proportion of coarse substrates available for attachment (Giller and Malmqvist, 1998). Emergent macrophytes also occur relatively frequently, while submerged and floating-leaved species are associated with significantly fewer observations.

The extremely low frequency of trailing vegetation (83 spot-checks) is likely to reflect analysis protocols which selected only ‘extensive’ occurrences of vegetation types at spot-checks. The marginal nature of trailing vegetation, which is rooted in the bank or margins but trails the water surface, will mean that this category occupies over 33% of a spotcheck only in narrow channels with high riparian connectivity. This low sample number creates problems for analysis. However, this habitat is likely to be less appropriate for comparisons with flow types compared to other habitat categories, since distributions are likely to be more highly correlated with the structure of the riparian zone rather than flow velocities and water depths within the channel. Trailing vegetation is retained in the analysis at this exploratory stage but interpretation is limited.

Figure 3.5 c and d plot the proportion of spot-checks for each flow type and functional habitat which are classified as ‘lowland’ (including coastal) and ‘upland’ (including montane) by the EA’s PCA-based river typology. For the surface flow types, a distinct increase in the proportion of upland locations is associated with the transition from ‘slower’ to ‘faster’ flow types. Functional habitats reveal a more complex pattern, but suggest that coarser substrates, mosses, macroalgae and trailing vegetation show stronger correlations with upland environments, while finer substrates and vascular plants are predominantly associated with lowland reaches. These findings are consistent with the fining of channel substrate from river source to mouth associated with a combination of particle abrasion, channel gradient and sediment sorting (Richards, 1982), and the known preferences of different aquatic vegetation types (Hynes, 1970; Haslam, 1978). In the following section, these relationships are explored further in the context of macroscale landscape controls on habitat features.

3.5.2 Macroscale controls on mesoscale habitat features

Hierarchical classifications of instream habitat stress the importance of linkages between different scales within river systems, such as the influence of catchment-scale controls on reach-scale habitat structure (Frissell *et al.*, 1986; Naiman *et al.*, 1992).

Map-derived variables included in RHS V 3.34 allow some exploration of the macroscale controls on mesoscale habitat features.

Figure 3.6 presents boxplots for altitude, slope and distance of the site from the river source for flow type categories. The ranges of values observed for different flow types suggest that most flow types can persist in a range of environmental contexts. However, the median values reveal a trend of increasing altitude and slope with the transition from ‘slower’ to ‘faster’ flow types, consistent with lowland and upland preferences identified in the previous section. Furthermore, increasing median values are accompanied by larger interquartile ranges, suggesting that faster flow types may persist in a wider range of environmental contexts while slower flow types are more clearly restricted to lower energy environments. The distance from source plots confirms that faster flow types are associated with source-proximal locations while slower flow types are found within a wider range of locations along the river continuum. Figure 3.7 summarises this information using scatterplots based on PCA data from the EA’s typology, revealing a ‘tightening’ of preference ranges for upland locations and a tendency for higher energy reaches with the transition from slower to faster flow types.

Relationships can be assessed for functional habitats in Figure 3.8 and 3.9. For minerogenic habitats, a trend of decreasing median values and interquartile ranges is observed with decreasing particle size. This reflects the restriction of finer sediments to lower energy conditions farther from the river source, while coarser substrates show a tendency towards higher energy locations and are restricted to source-proximal

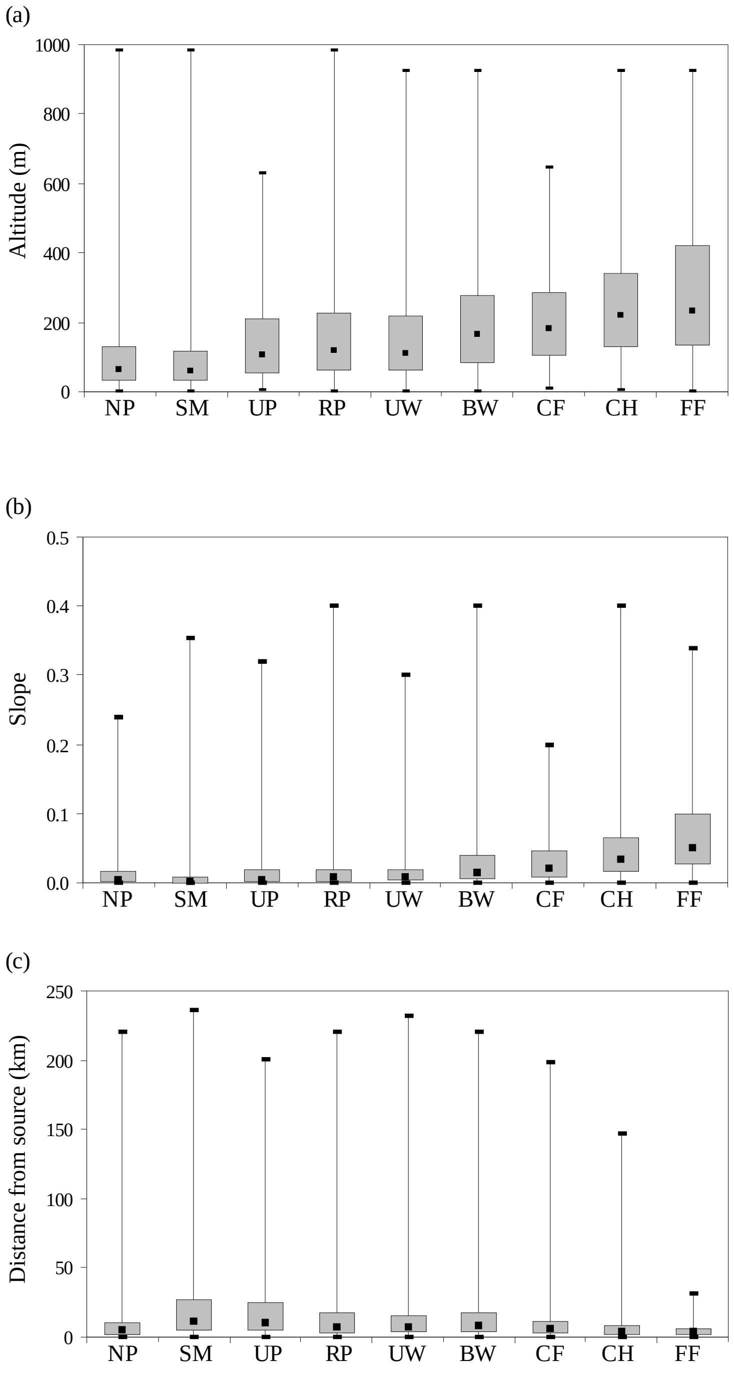


Figure 3.6 (a) Altitude, (b) slope and (c) distance from source ranges, interquartile ranges and median values for flow biotopes within semi-natural sites. See Table 3.1 (p. 53) for flow type category codes.

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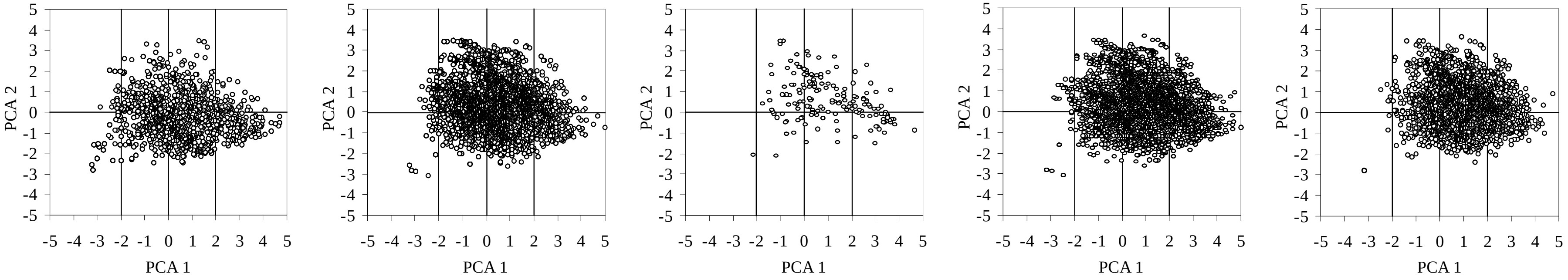
(a) No perceptible flow (b) Smooth boundary turbulent (c) Upwelling (d) Rippled flow (e) Unbroken standing waves



(f) Broken standing waves (g) Chaotic flow (h) Chute flow (i) Free fall

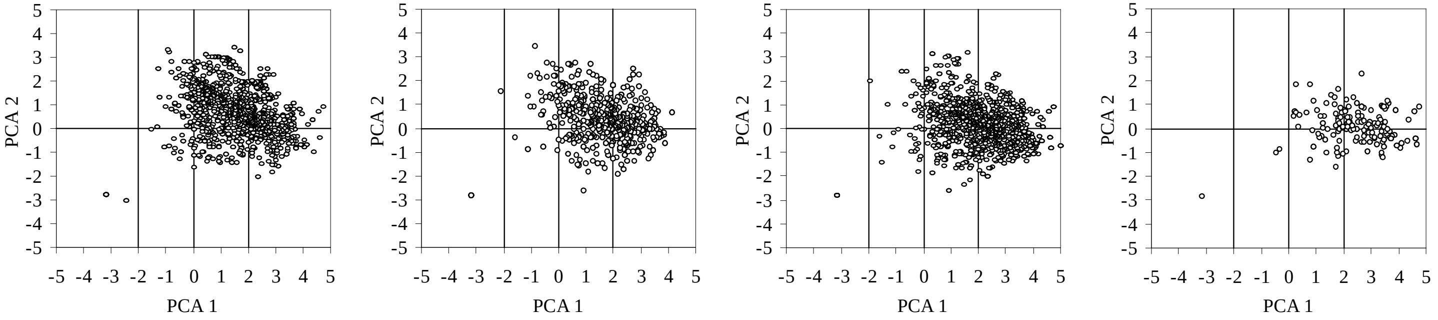


Figure 3.7 Distributions of site PCA scores for each flow biotope category.
PCA 1 represents a transition from low altitude, low slope (‘coastal’) sites, to high altitude, high slope (‘montane’) sites.
PCA 2 represents a transition from low energy to high energy environments based on distance from source and altitude of the source.

locations. Vegetative habitats demonstrate varied preferences for energy conditions (e.g. associated with altitude and slope) and certain locations along the river continuum (associated with distance from the river source). Mosses, for example, are generally restricted to upland locations and show a preference for higher energy conditions, while the majority of observations of emergent macrophytes are associated with lowland reaches but reveal an approximately equal distribution between high and low energy conditions. Macroalgae appear relatively unrestricted in location but show a tendency for higher energy environments, and submerged broad-leaved macrophytes suggest a preference for lowland high energy reaches. Submerged fine-leaved macrophytes show a relatively strong preference for high energy conditions, but these may be associated with both lowland and upland locations while the low sample numbers for trailing vegetation and floating-leaved macrophytes limit interpretations.

3.5.3 Habitat response to physical degradation

Figure 3.10 compares flow type and functional habitat frequency distributions for semi-natural sites with heavily modified sites in an attempt to explore the response of mesoscale habitat features to physical degradation. Increases in the proportion of no perceptible flow and smooth boundary turbulent flow accompanied by reductions in faster flow types for degraded sites suggest a homogenisation and overall ‘slowing’ of flow conditions consistent with the effects of direct channel modifications such as abstraction and impoundment, and the reduced turbulence associated with artificial substrates and channelisation (Hynes, 1970).

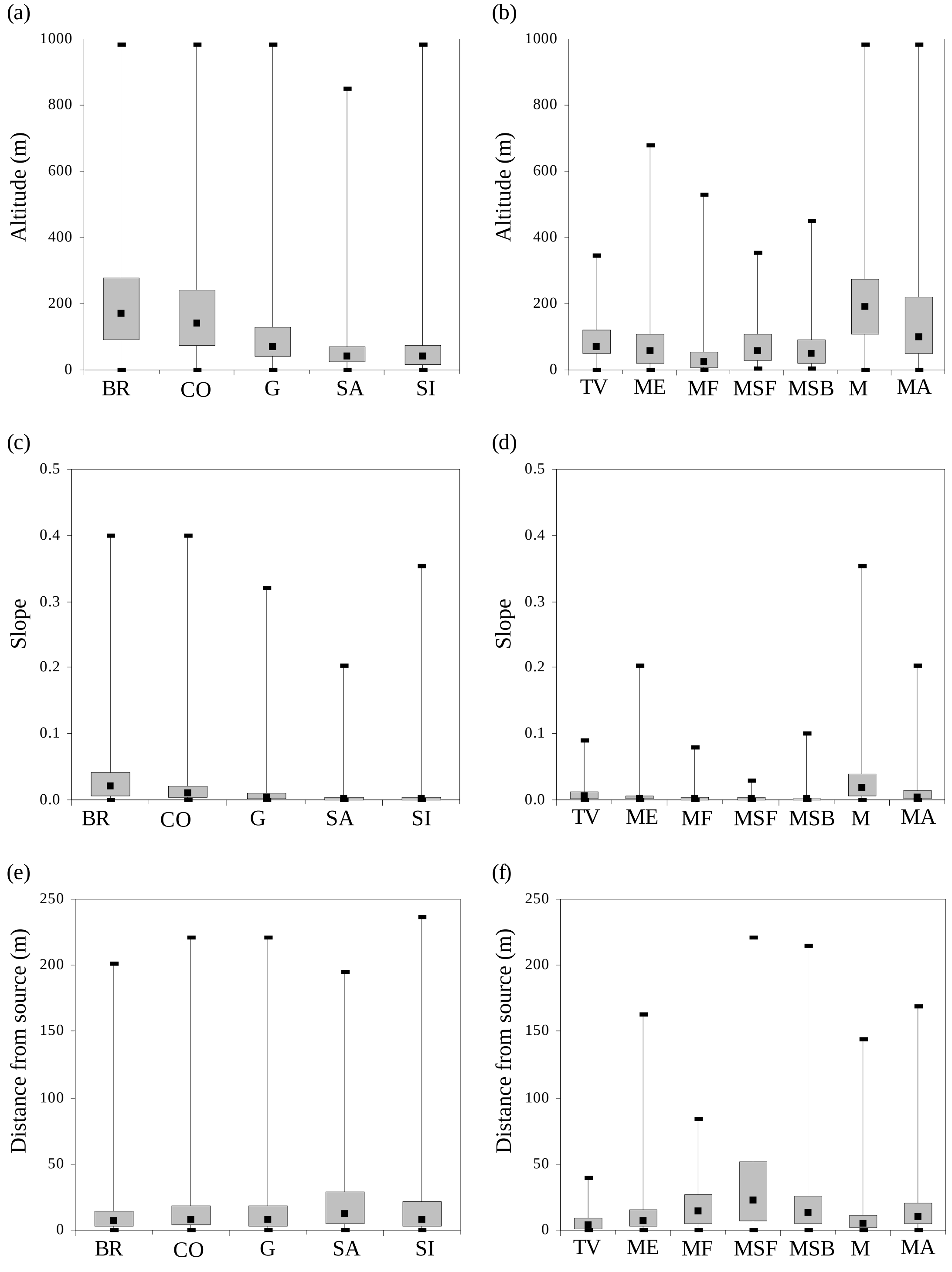


Figure 3.8 Altitude, slope and distance from source ranges, interquartile ranges and median values for minerogenic functional habitats (a, c and e) and vegetative functional habitats (b, d, and f). See Table 3.8 (p. 63) for functional habitat category codes.

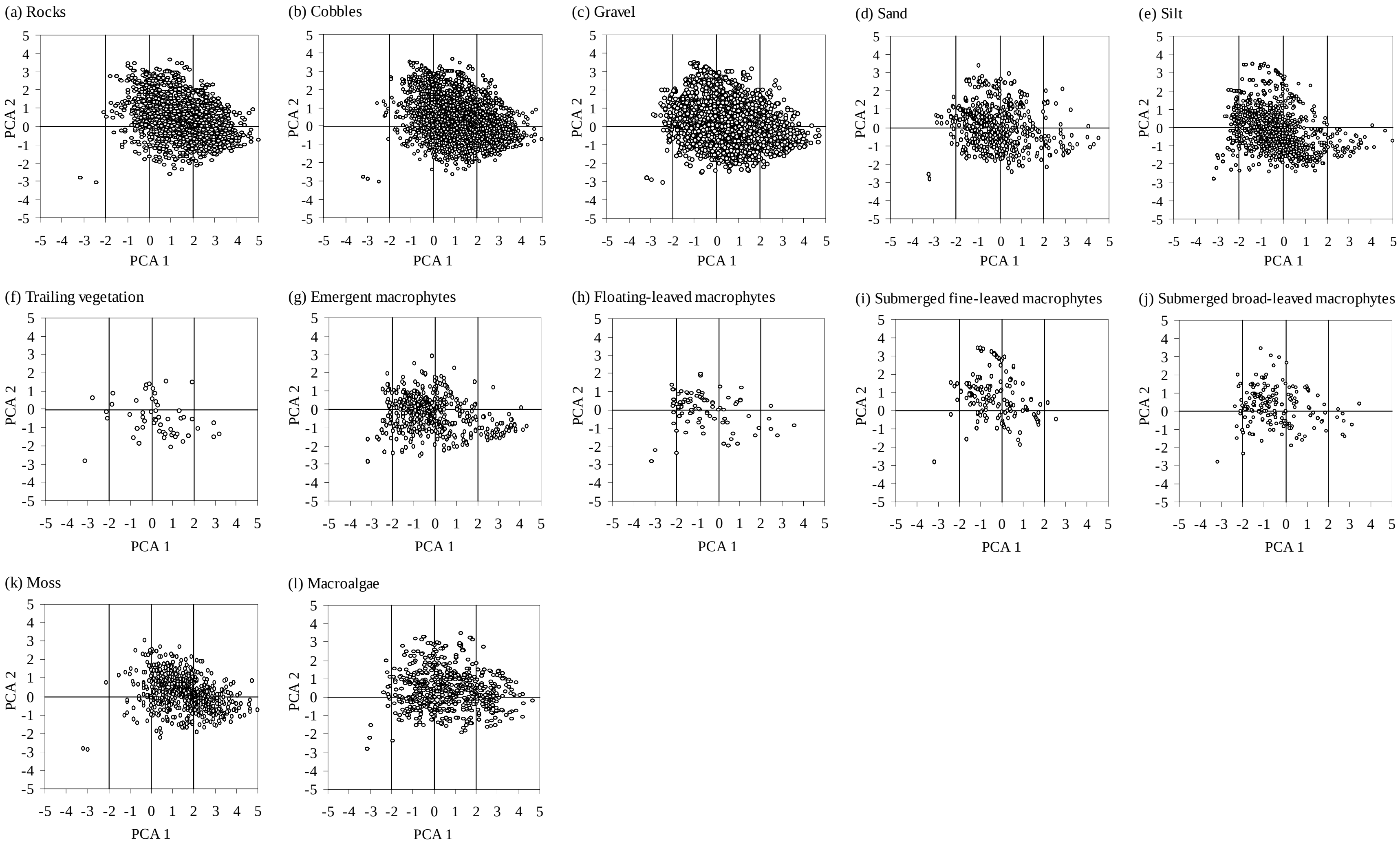


Figure 3.9 Distributions of site PCA scores for each functional habitat category (see Figure 3.7 for explanations of PCA axes).

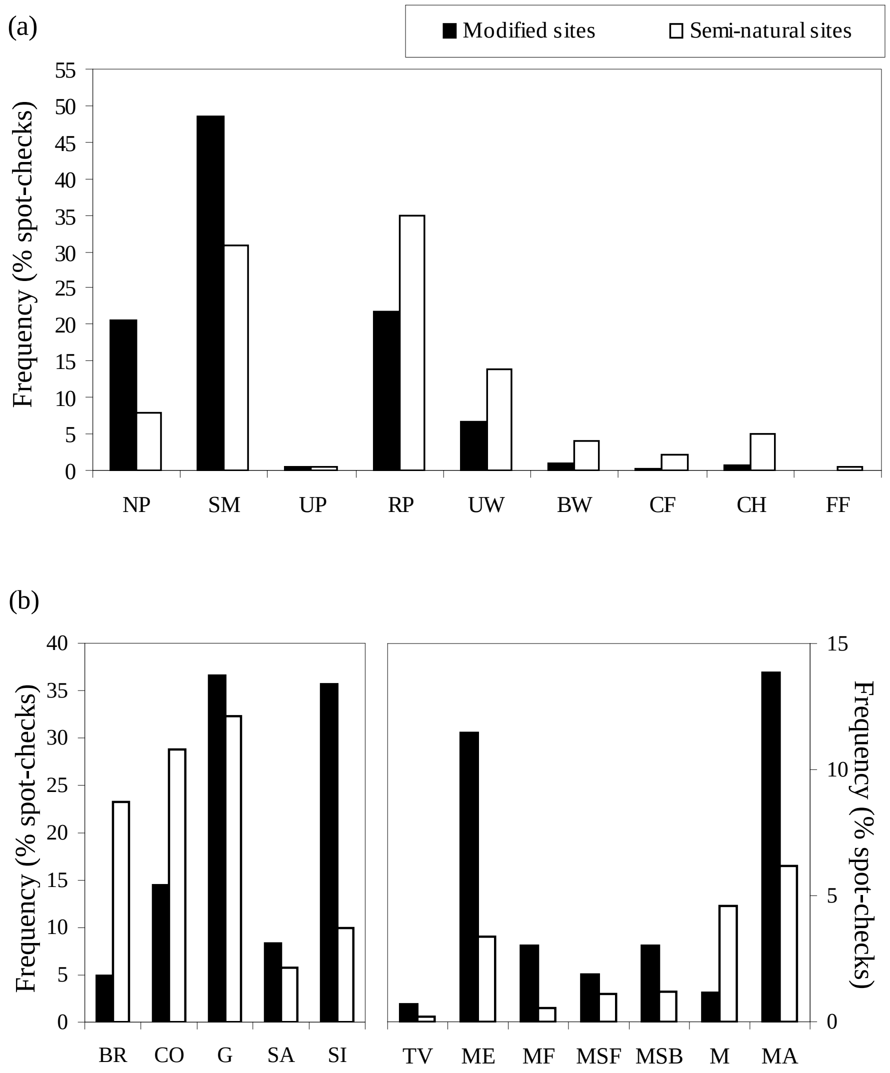


Figure 3.10 Comparison of national frequency distributions of (a) flow types and (b) functional habitats within semi-natural and heavily modified reaches. See Table 3.1 (p. 53) and 3.8 for flow type and functional habitat category codes.

This slowing of flow within the heavily modified sites is predictably accompanied by a fining of substrate calibre within the minerogenic habitats (Figure 3.10b), reflecting the reduced competence of flows in degraded reaches. All vegetative habitats (except for mosses) show a proportional increase within degraded reaches. The reduction in frequency of moss cover reflects the strong preferences of moss species for high current velocities and very stable, coarse substrates (French and Chambers, 1996), conditions which are likely to be lost as a result of physical degradation. Furthermore, reduced turbulence in many modified channels inhibits aeration of the water with atmospheric carbon, an important environmental requirement for mosses which are unable to utilise bicarbonate carbon sources (Fox, 1996).

The most significant increases in vegetative habitat frequency for degraded sites are associated with emergent macrophytes and macroalgae, followed by submerged broad-leaved and floating-leaved macrophytes. Prolific growth of various types of macrophytes and macroalgae has been associated with neglected canalised reaches and siltation (Butcher, 1933), impoundments (Ridley and Steel, 1975) and overwidened or ponded reaches (Kemp *et al.*, 1999), as well as chemical degradation through nutrient enrichment (Hynes, 1970; Whitton, 1975). These increased frequencies of extensive vegetation cover may therefore reflect a higher incidence of ‘choking’ of channels and an alteration of the competitive balance between different species (Demars and Harper, 1998; Marks and Power, 2001), and are unlikely to reflect increased biodiversity since the frequency distribution becomes dominated by a smaller number of habitats. This suggests an overall dominance of certain habitats, namely emergent macrophytes and macroalgae, the former of which has been associated with fewer microhabitats for meiofauna compared to other plant morphologies (Newall, 1995).

However, more detailed interpretations are complicated by the differences in response of similar plants to various types of channel modifications (Jansson *et al.*, 2000).

3.6 TOWARDS AN ECOLOGICAL CLASSIFICATION

The following sections explicitly explore the ‘co-occurrence’ of flow types and functional habitats in order to assess relationships between the two phenomena at the national level across a range of sites within the ‘semi-natural’ data set of reference sites.

3.6.1 Co-occurrence of flow types and functional habitats

Figure 3.11 presents the flow type frequency distributions for each functional habitat category, which may be used to assess the flow type ‘preferences’ demonstrated by each habitat within the national data set. All functional habitats are found in association with at least five different flow types, suggesting that singular connections between habitats and flow biotopes do not exist. Furthermore, the modal flow type category reveals little variation across functional habitat categories. Rippled flow represents the modal flow type for rocks, cobbles, gravel, mosses and trailing vegetation, and smooth boundary turbulent flow represents the modal flow type for the remaining habitats (sand, silt, macroalgae, and emergent, floating-leaved and submerged macrophytes).

The relatively broad ‘scatter’ across flow types can be partly attributed to the survey resolution which may overlook more localised associations between flow types and functional habitats. However, distributions may also reflect the influence of non-flow related factors on the distributions of functional habitats. For instance, tolerance of

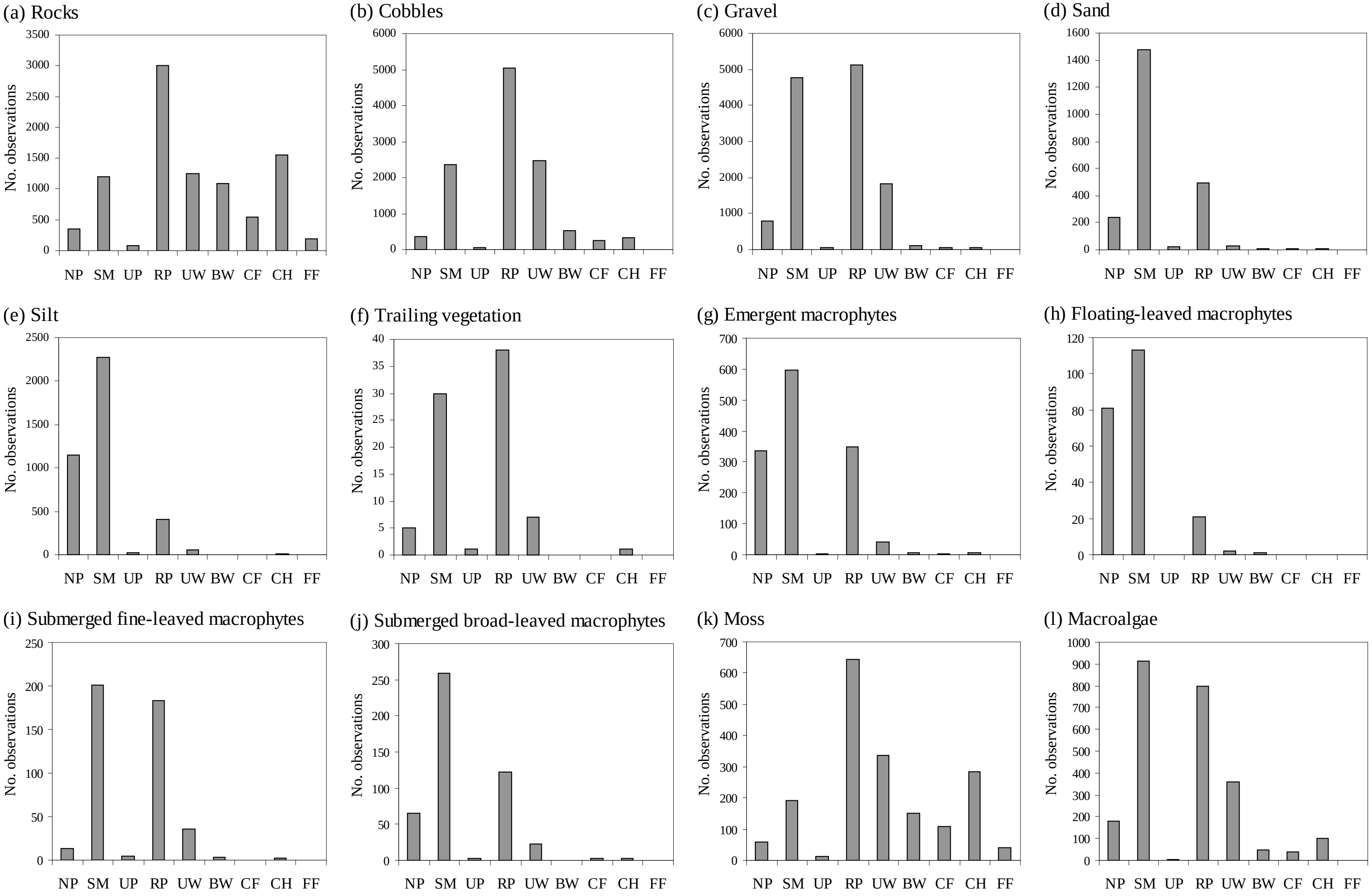


Figure 3.11 Flow type frequency distributions for each functional habitat category for semi-natural sites. See Table 3.1 (p. 53) for flow type category codes.

abiotic factors is just one of three principal determinants which govern the colonisation of macrophytic vegetation at a particular site: biotic interactions and dispersal characteristics also play important roles in determining the geographical distribution of a species (Fox, 1996). Furthermore, non-hydraulic abiotic factors such as light and water chemistry are also important factors for aquatic macrophytes (Westlake, 1975; Giller and Malmqvist, 1998). Relationships between macrophytes and flow biotopes may be further complicated by a complex system of feedbacks between aquatic plants and channel hydraulics. For instance the growth of instream vegetation influences the surrounding physical environment by increasing roughness and reducing velocities (Gaudet, 1974; Watson, 1987). However, while velocities within vegetation stands may decrease, channelling of flow in adjacent areas can create high velocity ‘threads’, thus significantly altering the flow field (Gregg and Rose, 1982; Cotton *et al.*, 2006; Gurnell *et al.*, 2006).

While local flow conditions exert a significant influence on minerogenic habitat distributions through the control on sediment transport (Carling, 1992), both macroscale landscape controls such as catchment geology, and microscale factors such as the growth of aquatic macrophytes, also bear a significant influence on substrate composition within a particular reach (Fox and Raven, 1996; Sand-Jensen, 1998).

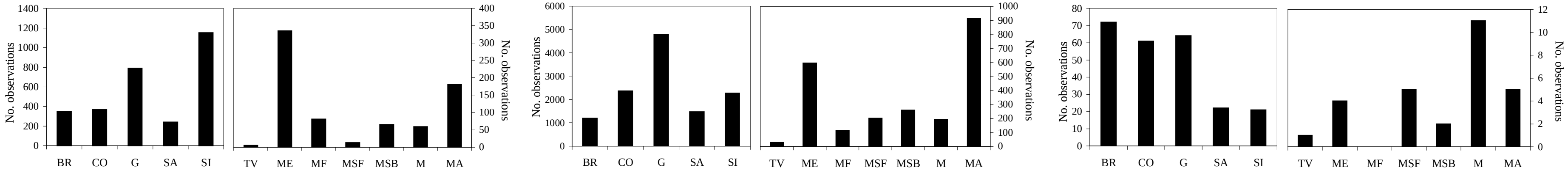
However, some trends within frequency distributions are apparent at a broader level, which may be considered particularly significant in the light of complexities introduced by the extraneous factors described above. Within the minerogenic habitats, for instance, decreasing particle size is associated with a ‘tightening’ of frequency distributions towards slower flow biotopes, reflecting the tighter environmental ranges identified for finer substrates in the previous section. Of the vegetative habitats, a distinction is noted between mosses and macroalgae which are frequently associated with a range of flow types, and the vascular plants which reveal stronger preferences for two or three 'predominant' flow types. Proportions of flow types indicate certain flow type 'preferences', for instance floating-leaved macrophytes are associated with a higher proportion of no perceptible flow while submerged fine-leaved vegetation is associated with a higher proportion of rippled flow. Frequency distributions show similarities with observations by Harper *et al.* (2000) on four river reaches, but lower proportions of both slower (e.g. no perceptible flow) and 'faster' (e.g. unbroken standing waves) flow biotopes are noted for the RHS data, perhaps reflecting the coarser transect-level RHS survey resolution compared to the 1 m^2 cells in Harper *et al.* (2000).

Overall, slower to intermediate flow types correlate most strongly with the majority of habitats, while faster flow types are associated with low frequencies for all habitat categories except for moss and rocks. 'Reversing' the analysis and examining the frequencies of functional habitats associated with each flow type category (Figure 3.12) demonstrates this clearly: the transition from slower to faster flow types is associated with a decrease in the number of associated functional habitats. These data also provide information on the functional habitats associated with the faster flow types, which account for only very low sample numbers in Figure 3.11. For instance, while free fall and chute flow account for a relatively low number of the total observations of rocks, moss and macroalgae, this combination of functional habitats constitutes the majority of habitat provision at spot-checks characterised by free fall and chute flow.

(a) No perceptible flow

(b) Smooth boundary turbulent

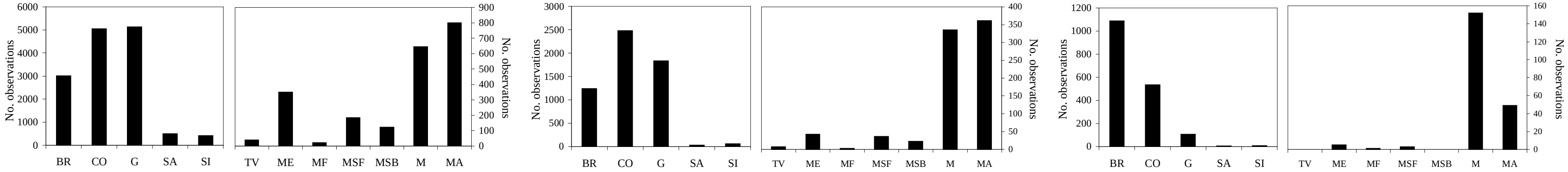
(c) Upwelling



(d) Rippled flow

(e) Unbroken standing waves

(f) Broken standing waves



(g) Chaotic flow

(h) Chute flow

(i) Free fall

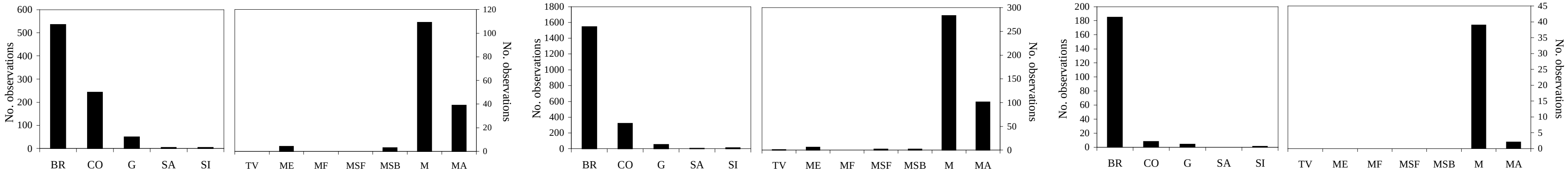


Figure 3.12 Functional habitat frequency distributions for each flow type category. See Table 3.8 (p. 63) for functional habitat category codes.

Since the functional habitat concept was developed on lowland UK reaches (Harper *et al.*, 1992), it is unsurprising that functional habitat distributions correlate most strongly with slower to intermediate flow types characteristic of lower-energy features such as riffles, runs, pools and glides rather than rougher flow types associated with waterfalls and rapids. Rocks and mosses, and to a lesser extent cobbles and macroalgae, are the exception since these habitats may also occur within higher-energy flow environments where they may constitute the principal functional habitats.

However, while most habitats demonstrate some ‘preferences’ for certain flow types, correlations appear to lie at a relatively broad level as identified by Clifford *et al.* (2006), relating to ‘assemblages’ of flow types rather than individual categories and thus suggesting that some form of data reduction or amalgamation is appropriate.

3.6.2 A preliminary classification

The previous section identified that most habitats were generally associated with a combination of two or three flow types. Flow type frequency data for each functional habitat was therefore examined in order to identify the number of flow types required to explain over 50% of the observations for each habitat (Figure 3.13). The 50% threshold is exceeded by one flow type for sand, silt and floating-leaved macrophytes, but a second must be introduced for gravel, cobbles, trailing vegetation, macroalgae, moss and emergent and submerged macrophytes. A third flow type must be introduced to explain over 50% of the distribution for rocks, and additionally the use of three flow types explains over 60% of the variance for all habitats.

Focusing on the three ‘predominant’ flow types for each functional habitat provides and indication of the assemblages of flow types which correlate most strongly with each habitat. For all habitats, these assemblages incorporate some combination of a total of five flow types (no perceptible flow, smooth boundary turbulent flow, rippled flow, unbroken standing waves and chute flow) which are typically associated with pools, glides, runs, riffles and cascades respectively. Using these relationships, a preliminary ‘ecological classification’ of flow type assemblages was produced, based on the preferences of different functional habitats (Figure 3.14).

Three ‘classes’ of flow types are derived which indicate the reach-scale morphological preferences of functional habitats. Class one comprises the ‘roughest’ combination of flow types, chute flow, unbroken standing waves and rippled flow, and can be considered to represent higher-energy step-pool morphologies. Class two includes smooth boundary turbulent flow, rippled flow and unbroken standing waves and is interpreted to represent riffle-pool morphologies. Class three is associated with a ‘slower’ assemblage of flow biotopes comprising no perceptible flow, smooth boundary turbulent flow and rippled flow which indicate glide-pool morphologies. Thus, although the methodological and theoretical issues outlined in section 3.2 prohibit reliable singular connections between flow types and physical biotopes, *suites* of functional habitats appear to correlate with *assemblages* of flow biotopes which broadly correspond to certain reach-scale morphologies (taking into account slight variations from the ‘typical’ low flow states).

Within these broader assemblages, suites of functional habitats show different ‘preferences’ for certain flow biotopes according to the order of dominance of

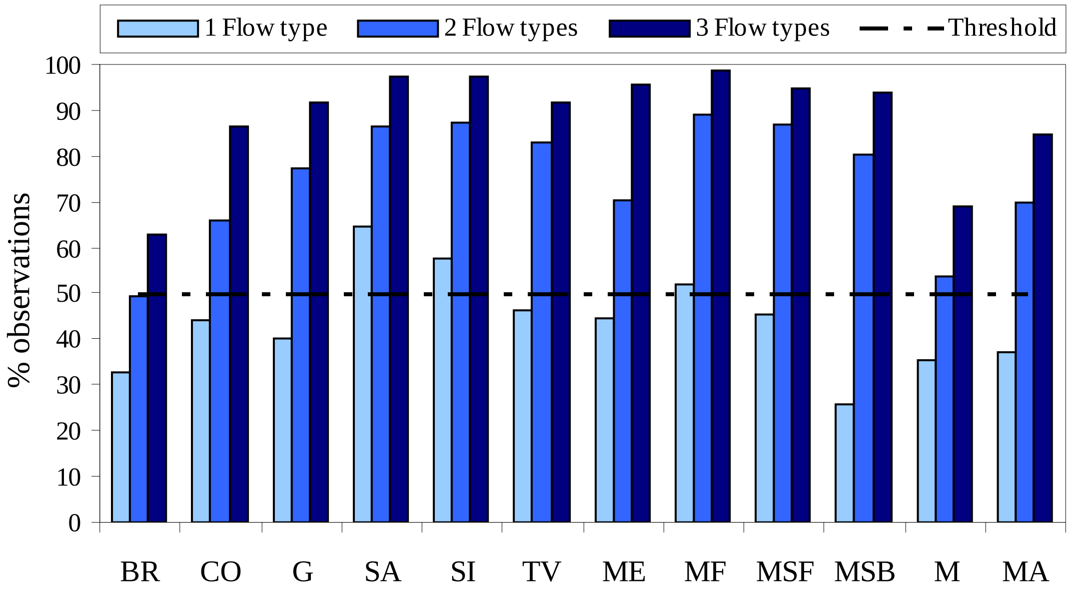


Figure 3.13 The percentage of observations of each functional habitat which is accounted for by one, two and three flow types. See Table 3.8 (p. 63) for functional habitat category codes.

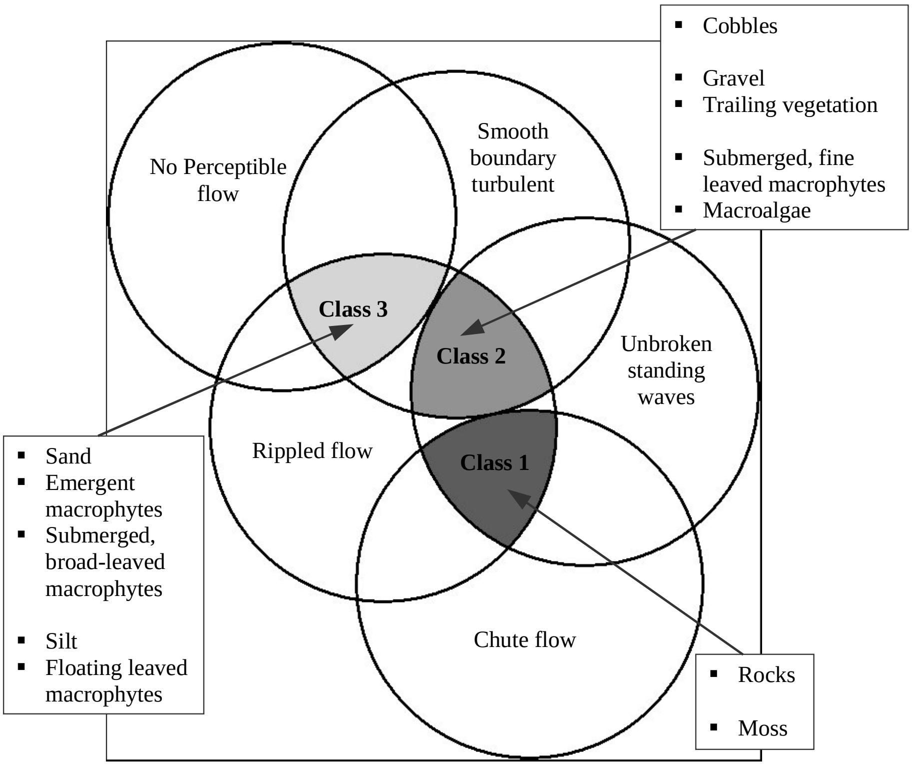


Figure 3.14 Venn diagram to illustrate relationships between assemblages of flow types and suites of functional habitats. Different combinations of three out of a total of five common flow types may be linked with suites of functional habitats.

individual flow types within frequency distributions (Table 3.9). These preferences may reflect the influence of hydraulics at smaller-scales within and between morphological units. Within class one, mosses are more frequently found in close proximity to unbroken standing waves, while rocks are more frequently associated with chute flow. However, proportions of chute flow and unbroken standing waves are very similar for both habitats (see Figure 3.11), suggesting that amalgamation of these two subclasses may be appropriate, and that rocks and mosses may occur ubiquitously within step-pool cascades. Class two differentiates between ‘faster’ riffle zones associated with the highest frequency of unbroken standing waves which are characterised by cobbles (class 2A), and marginal riffle or run areas dominated by rippled flow and associated with gravel and trailing vegetation (2B). Higher proportions of smooth boundary turbulent flow in class 2C may represent transitional zones (e.g. glides or runs) which are characterised by higher proportions of submerged fine-leaved macrophytes and macroalgae. Glide-pool reaches (class three) may be subdivided into glide or run zones associated with a higher frequency of rippled flow and sand, emergent and submerged broad-leaved macrophytes (3A), and pool habitats associated with a higher proportion of no perceptible flow, silty substrates and floating-leaved macrophytes (3B).

Sub-classes within the preliminary classification combine vegetative and minerogenic functional habitat categories, highlighting the complex interactions between vegetation, substrate calibre and flow. Substrate type is an important environmental factor influencing macrophyte distributions, and groupings identified support known macrophytic preferences: mosses depend upon the substrate stability provided by large boulders, the dense horizontal roots of submerged fine-leaved macrophytes require

	Flow biotope class	Flow types (order of dominance)	Functional Habitats
Step-pool	1A	Rippled flow Chute flow Unbroken standing waves	Rocks
	1B	Rippled flow Unbroken standing waves Chute flow	Mosses
Riffle-pool	2A	Rippled flow Unbroken standing waves Smooth boundary turbulent	Cobbles
	2B	Rippled flow Smooth boundary turbulent Unbroken standing waves	Gravel Trailing vegetation
	2C	Smooth boundary turbulent Rippled flow Unbroken standing waves	Submerged, fine-leaved macrophytes Macroalgae
Glide-pool	3A	Smooth boundary turbulent Rippled flow No perceptible flow	Sand Submerged, broad-leaved macrophytes Emergent macrophytes
	3B	Smooth boundary turbulent No perceptible flow Rippled flow	Silt Floating-leaved macrophytes

Table 3.9 Classification of flow types according to functional habitat ‘preferences’ for three principal flow types. Habitats are grouped into sub-classes according to the order of dominance of flow types within frequency distributions.

gravels for anchoring, and emergent and floating-leaved plants with long deep roots require finer grained sands and silts (Haslam, 1978).

However, the preliminary classification shown in Figure 3.14 is based upon simple observations of frequency distributions and requires statistical validation. While the categorical nature of the data set imposes some limitations on analysis, it is possible to apply two contrasting statistical techniques to test the integrity of the classification.

3.6.3 Statistical validation

Statistical validation of the classification involved two stages. An analysis of the variation between functional habitats in terms of flow types was performed using a Principal Components Analysis (PCA), and subsequently, habitats were objectively grouped according to the similarity of their flow type frequency distributions using agglomerative Hierarchical Cluster Analysis (HCA). The two techniques complement each other, since PCA provides a depiction of the overall phenetic structure of the data set, and cluster analysis provides a good fit if tight clusters actually occur in the data set (Rohlf, 1970).

i) Principal Components Analysis

PCA is a linear ordination method which reduces the dimensionality of a data set containing a large number of variables. It does this by linearly transforming the original, (potentially correlated) variables (*p*) into a new set of uncorrelated variables ('principal components') which maximise the original variance (Dunteman, 1989). PCA may be based on a covariance matrix or a correlation matrix (standardised covariance matrix) of the original data. The matrix may then be expressed geometrically, as a series of vectors, with each row of the matrix providing the co-ordinates of the end point of a vector (Davis, 2002). These vectors are known as 'eigenvectors' in matrix algebra, and represent the 'principal components' in a PCA. Most of the variance can often be accounted for by a small number of principal components, and commonly only the first two are analysed. PCA was performed in Canoco 4.0 using a frequency matrix of the co-occurrence of functional habitats and flow types.

To test the appropriateness of PCA for the data set (Leps and Smilauer, 2003), a Detrended Correspondence Analysis (DCA) was performed on the frequency matrix in order to ensure that the maximum gradient length of the data (in standard deviation units of species turnover, SD), was below 3. Axis one demonstrated a maximum gradient length of 2.099 SD and therefore PCA was appropriate. Analysis focuses on the first two principal components of the PCA since these account for 98% of the variance in functional habitats.

The PCA bi-plot for axes one and two is presented in Figure 3.15a and illustrates the variance in functional habitats (represented by vectors) according to the distribution of flow biotopes (represented by points). Vectors on the bi-plot represent increasing frequencies of functional habitats towards the arrowhead, and flow biotopes situated towards the end of these vectors are highly correlated with those habitats. Flow biotopes situated at distal locations in the bi-plot may be projected onto habitat vectors at right angles to assess the strength of correlations. Thus, for instance, free fall, chaotic flow and upwelling are rarely observed within the data set and therefore plot as negative scores suggesting weak correlations with all 12 functional habitats. The angle between arrows is a measure of correlation between functional habitats, so that

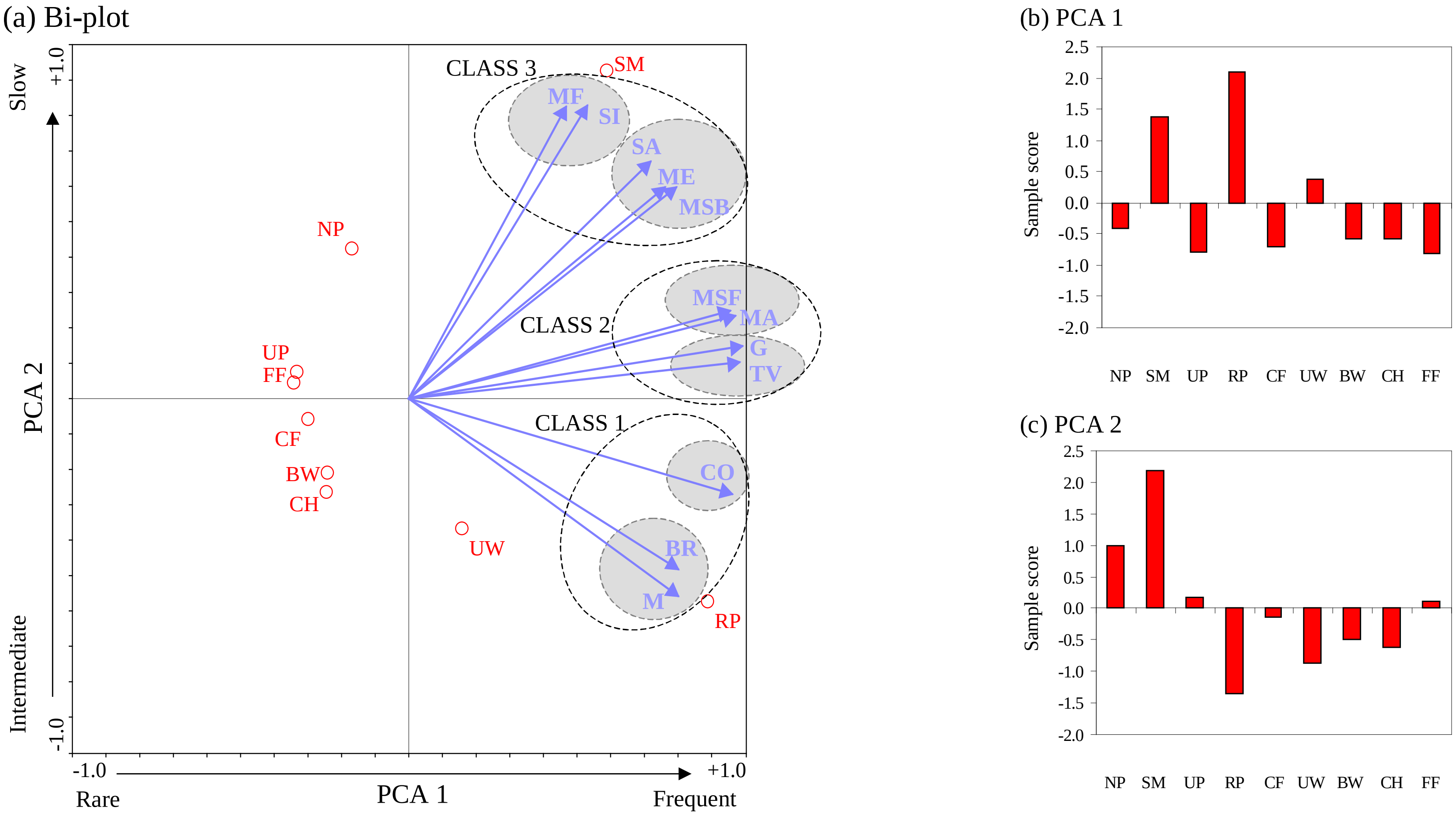


Figure 3.15 (a) PCA bi-plot showing correlations between flow types (represented by circles) and functional habitats (represented by vectors) for the semi-natural data set. (b) and (c) plot the flow type sample scores for PCA axes 1 and 2 respectively. See Table 3.1 (p. 53) and 3.8 (p. 63) for flow type and functional habitat codes. Dotted lines are superimposed on the bi-plot to highlight the clustering of functional habitat vectors.

closely spaced habitat vectors are associated with similar flow biotope frequency distributions, while perpendicular arrows show zero correlation between habitats, and angles at 180^o would represent negative correlations.

The diagram is strongly dominated by principal component one, which captures 86.4% of the variation in functional habitats, while axis two contributes just 11.6%. This may, however be a reflection of the data set characteristics, since flow biotopes are part of a continuum, rather than representing distinct environmental variables, and therefore variance may reasonably be expected to be concentrated along an axis reaching from 'faster' to 'slower' flow biotopes. Variable loadings, or flow type 'sample scores' presented in Figure 3.15b and c allow further interpretation of the 'meaning' of axes one and two. Axis one appears to represent a transition from rare flow types (upwelling, chaotic flow, broken standing waves, chute flow and free fall) associated with negative loadings, to the most commonly occurring flow types (smooth boundary turbulent, rippled flow and unbroken standing waves) associated with positive loadings, reflecting the overall frequencies of flow types. Axis two suggests a transition, within the more commonly occurring flow biotopes, from 'intermediate' flow types (unbroken standing waves and rippled flow) associated with stronger negative loadings to 'slower' flow types (no perceptible and smooth boundary turbulent flow) associated with positive loadings.

Thus, intermediate flow types such as unbroken standing waves and rippled flow exert a strong influence upon functional habitat vectors located within the bottom right quarter of the diagram, while habitats falling in the upper right quadrant of the bi-plot show stronger positive correlations with slower smooth boundary turbulent and no perceptible flow types. Furthermore, while no habitats show significant correlation with the rarer (negatively scored) flow types, they demonstrate a parabolic distribution within the bi-plot suggesting that ‘intermediate’ flow types are more common than both slower and faster flow types.

The sequencing and spacing of habitat vectors corresponds with the preliminary classification proposed in section 3.6.2. Functional habitat vectors are grouped into ‘clusters’ which broadly correlate with the suites of habitats outlined in Figure 3.14 and Table 3.9. Since the PCA uses frequency data for all flow biotopes, these results suggest that the classification system based on the three most predominant flow types associated with each functional habitat provides an accurate representation of the overall characteristics of the data set. The only exception is the sequencing of moss and rocks which is reversed in the PCA plot, with moss showing slightly stronger correlations with faster flow types. However, the overall characteristics of flow type frequency distributions for these two habitats are almost identical: both habitats are characterised by very similar proportions of ‘secondary’ flow biotopes (chute flow and unbroken standing waves), reinforcing the suggestion in Section 3.6.2 that amalgamation of these two habitats may be appropriate in the classification scheme.

ii) Agglomerative Hierarchical Cluster Analysis

As a means of objectively verifying the ‘similarity’ of the functional habitat ‘clusters’ identified by the PCA, HCA was performed on the frequency matrix. HCA provides an objective means of identifying groups of similar objects without the requirement for an arbitrarily pre-defined number of clusters. Choice of clustering methods, however, is a relatively subjective practice and there are no universally accepted rules for selection of methods. However, average (or ‘weighted’) techniques focusing on pairs of objects with high similarity are often considered superior to simpler single-linkage methods (Everitt and Dunn, 2001).

The hierarchical clustering process begins with each ‘object’ (in this case functional habitats) as a separate ‘cluster’. Clustering then proceeds through a number of steps, merging pairs of functional habitats with the highest similarities until the similarity matrix is reduced to dimensions of 2 x 2 (Davis, 2002). Outputs take the form of an agglomeration schedule, detailing the steps taking during the clustering process, and a dendrogram (branched diagram) whose ‘distortion’ may be assessed through computation of a cophenetic correlation coefficient. The correlation coefficient compares correlations derived from the dendrogram with actual correlations between habitats identified from a similarity matrix to provide a measure of the distortion of original relationships in the data introduced by imposing a hierarchical structure on the data set (Everitt and Dunn, 2001). Coefficients greater than 0.95 may be considered to represent acceptable levels of distortion, whereas coefficients around 0.6 and 0.7 may suggest that the data set is not characterised by a system of nested clusters (Rohlf, 1970). HCA was performed on the frequency matrix in SPSS 14.0 using the average linkage (weighted) within-group clustering method, which uses the Pearson correlation coefficient as a measure of the similarity between pairs of objects.

The agglomeration schedule is provided in Table 3.10 and reveals that the pairs of habitats associated with the most similar flow biotope frequency distributions were gravel and macroalgae, followed by sand and submerged broad-leaved macrophytes. Pairs with the next highest levels of similarity were then linked, connecting gravel with submerged fine-leaved macrophytes and trailing vegetation. Step six connects moss and rocks together, and seven links sand with emergent macrophytes. At this stage, correlation coefficients are still greater than 0.95 and therefore linkages may be considered acceptable representations of the structure of the data set (Rohlf, 1970).

These linkages create an initial level of clustering in the dendrogram associated with the highest levels of similarity (Figure 3.16). Five clusters of functional habitats are identified which show broad correspondence with the class subdivisions identified in Section 3.6.2. Moss and rocks, cobbles, and silt and floating-leaved macrophyte clusters correlate strongly with relationships identified in Figure 3.14 and Figure 3.15. However, gravel and trailing vegetation, and macroalgae and submerged leaved macrophytes are combined to form a single cluster, masking the variations in flow biotopes observed in section 3.6.1. Fusion of these categories in the dendrogram may reflect the near-equal proportions of rippled flow and smooth boundary turbulent flow associated with these habitats, suggesting a potential amalgamation of classes 2A and 2B from Table 3.9. Further field investigation would aid understanding of these relationships.

Sand and submerged broad-leaved macrophytes form a different cluster to that occupied solely by emergent macrophytes, exposing a different relationship to the PCA which suggests emergent and submerged broad-leaved macrophytes are more similar to each other than to sand in terms of flow type frequencies. This reflects some subtle variations in the frequency distributions of these habitats: sand and submerged broad-leaved macrophytes show similarly low proportions of ‘secondary’ flow biotopes, whereas the secondary flow types of no perceptible flow and rippled flow account for relatively high proportions of emergent macrophyte observations,

Stage	Cluster Combined		Correlation coefficient
	Cluster 1	Cluster 2	
1	G	MA	0.989
2	SA	MSB	0.989
3	SI	MF	0.985
4	G	MSF	0.984
5	G	TV	0.980
6	BR	M	0.975
7	SA	ME	0.956
8	CO	G	0.938
9	SA	SI	0.926
10	BR	CO	0.839
11	BR	SA	0.699

Table 3.10 Agglomeration schedule for Hierarchical Cluster Analysis on flow type and functional habitat frequency matrix.

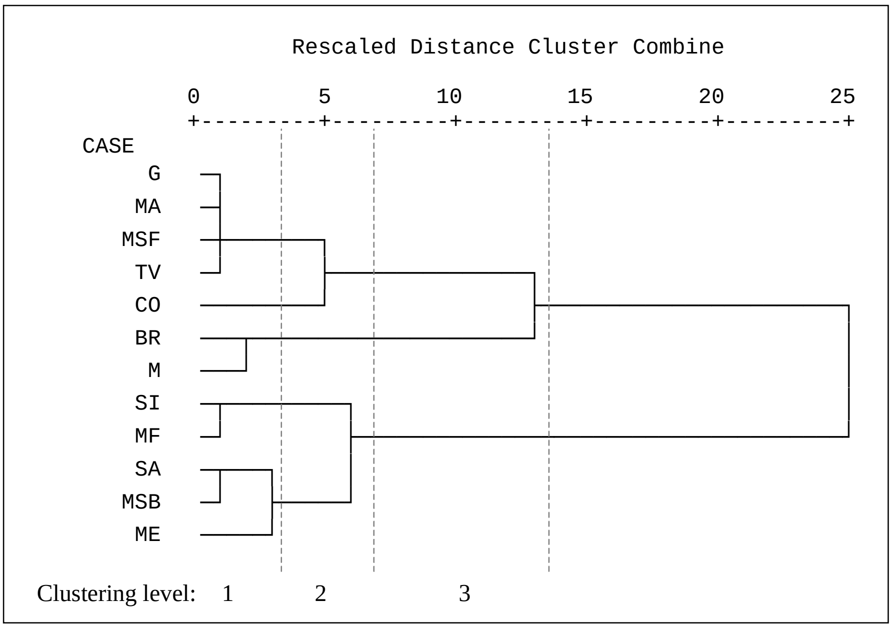


Figure 3.16 Dendrogram presenting the results of the hierarchical cluster analysis on functional habitat and flow type frequency data. Dotted lines are superimposed onto the dendrogram to highlight the two principal levels of clustering which correspond to the classes and subclasses identified in Table 3.9.

despite overall dominance of smooth boundary turbulent conditions (see Figure 3.11).

The dendrogram represents a nested hierarchy of clusters, however, and a second level of clustering may be identified which corresponds accurately with classes one, two and three presented in Figure 3.14. This level of clustering is achieved through steps eight and nine in the agglomeration schedule, and since correlation coefficients are still above 0.9 at this stage, the integrity of relationships may be considered relatively strong. The third level of the hierarchy is associated with steps ten and eleven in the agglomeration schedule, both of which show significantly higher levels of distortion suggesting that these clusters may be disregarded since relationships between habitats are not consistent with the hierarchical structure imposed on the data.

3.7 DISCUSSION AND CONCLUSIONS

The review and appraisal of mesoscale habitat concepts presented in the first sections of this chapter highlight the theoretical and methodological issues associated with the application of the ‘physical biotope’ concept to the characterisation of instream habitat. It is suggested that the complex relationships between channel hydraulics and morphology cast some doubt upon the integrity of using surface flow types to identify physical biotopes. This, in conjunction with the limitations of certain hydraulic parameters, may partially explain the relatively limited success of biotope characterisation attempts to date. Furthermore, previous approaches fail to explicitly address the ecological function of physical biotopes, focusing instead on hydraulic characterisation.

Although a need remains for rigorous field-testing of the concept, ‘functional habitats’ potentially offer a practical means of adding biological value to physical biotopes. While preliminary investigations have identified that functional habitats demonstrate certain ‘preferences’ for velocity-depth combinations and surface flow types, only tentative connections have been made directly between functional habitats and physical or flow biotopes. The second part of this chapter provides a comprehensive investigation of the relationships between functional habitats and surface flow types using an extensive national data set derived from the EA’s RHS database in an attempt to explore the ecological validity of physical biotopes.

Examination of the national distribution of habitat features emphasises that certain flow types and functional habitats occur more commonly than others, reflecting the natural organisation of habitat along the river continuum (Vannote *et al.*, 1980), where certain habitats are restricted to headwater locations while others occur throughout the catchment. This is supported by the macroscale environmental ‘preferences’ of flow types and functional habitats which show some distinctions between lower energy lowland reaches and higher energy upland environments, although the majority persist in a range of environmental contexts. ‘Slower’ flow types are generally associated with tighter ranges of altitude and slope conditions while ‘faster’ flow types show larger ranges associated with a variety of environmental contexts. This may reflect the differences between biotopes associated with bedrock (falls, steps, pools) where channel morphology is determined principally by geologic controls, and those associated with alluvial channels (riffles, pools, runs, glides) where morphology depends upon sediment supply and transport capacity (Wadeson, 1994).

While the principal data set deals only with semi-natural reaches, a limited assessment of mesoscale habitat response to physical degradation can be made by comparison with heavily modified reaches. Overall, channel modifications appear to induce a slowing of flow conditions and fining of channel substrates, consistent with known physical effects of modifications such as impoundments, abstraction and channelisation. Vegetative habitats, however, reveal a more complex response. Most categories show some increases in cover, but this is unlikely to reflect increases in biodiversity since the distributions are generally dominated by large frequencies of specific habitats which are able to tolerate harsh environmental conditions but provide fewer microhabitats for biota and may raise instream biomass to nuisance levels.

The frequency of co-occurrence of functional habitats and flow types was assessed to identify whether direct links can be made between the two phenomena. Distributions reveal a relatively complex picture at first glance, which is attributed to a combination of methodological limitations, such as survey resolution and data types (McEwen *et al.*, 1997; Padmore, 1997a), and theoretical considerations, such as the influence of extraneous factors on habitat distributions. However, some broad trends are apparent which may be considered relatively strong in the context of these issues. Exploration of frequency data and the application of two contrasting multivariate statistical techniques reveal that three principal flow types cumulatively account for the majority of variation for each flow type. Functional habitat ‘preferences’ for certain flow types are organised into *assemblages* of flow types indicative of step-pool, riffle-pool and glide-pool reach-scale morphologies, providing some level of ecological validity to the biotope concept. Within these, however, habitats show certain preferences for rougher or more tranquil zones suggesting some sub-reach scale variation. The classification shows broad correlation with functional habitat preferences for different velocity and depth combinations (Kemp *et al.*, 1999), with a similar flow type data set obtained from a subset of RHS (Newson *et al.*, 1998a), and with the results of field surveys at finer spatial resolutions (Harper *et al.*, 2000).

Figure 3.17 presents a conceptualised nested hierarchical system of mesoscale habitat encompassing morphological, hydraulic and biologically functional habitat components within the context of wider macroscale environmental preferences of flow types and habitats derived from the database. Reach-scale morphological units and their respective flow type assemblages are organised along an energy gradient from high to low altitude and slope conditions in conjunction with distance from the river source. Within these assemblages, suites of functional habitats show preferences for hydraulically 'rougher' and more tranquil zones, although the low amplitude of steps and alternating pools in step-pool cascades (Bisson *et al.*, 1981) suggests that moss and rocks will be relatively ubiquitous within such reaches.

The classification emphasises the strong interrelationships between flow, substrate and vegetation, raising the issue that minerogenic and vegetative functional habitats are influenced by different extraneous factors and are associated with significantly different spatial distributions, perhaps suggesting that they should be recorded and analysed as separate habitat features. The classification requires further field validation, particularly at smaller spatial scales to account for the shortcomings of RHS survey resolutions and in order to explore microscale habitat structure. These

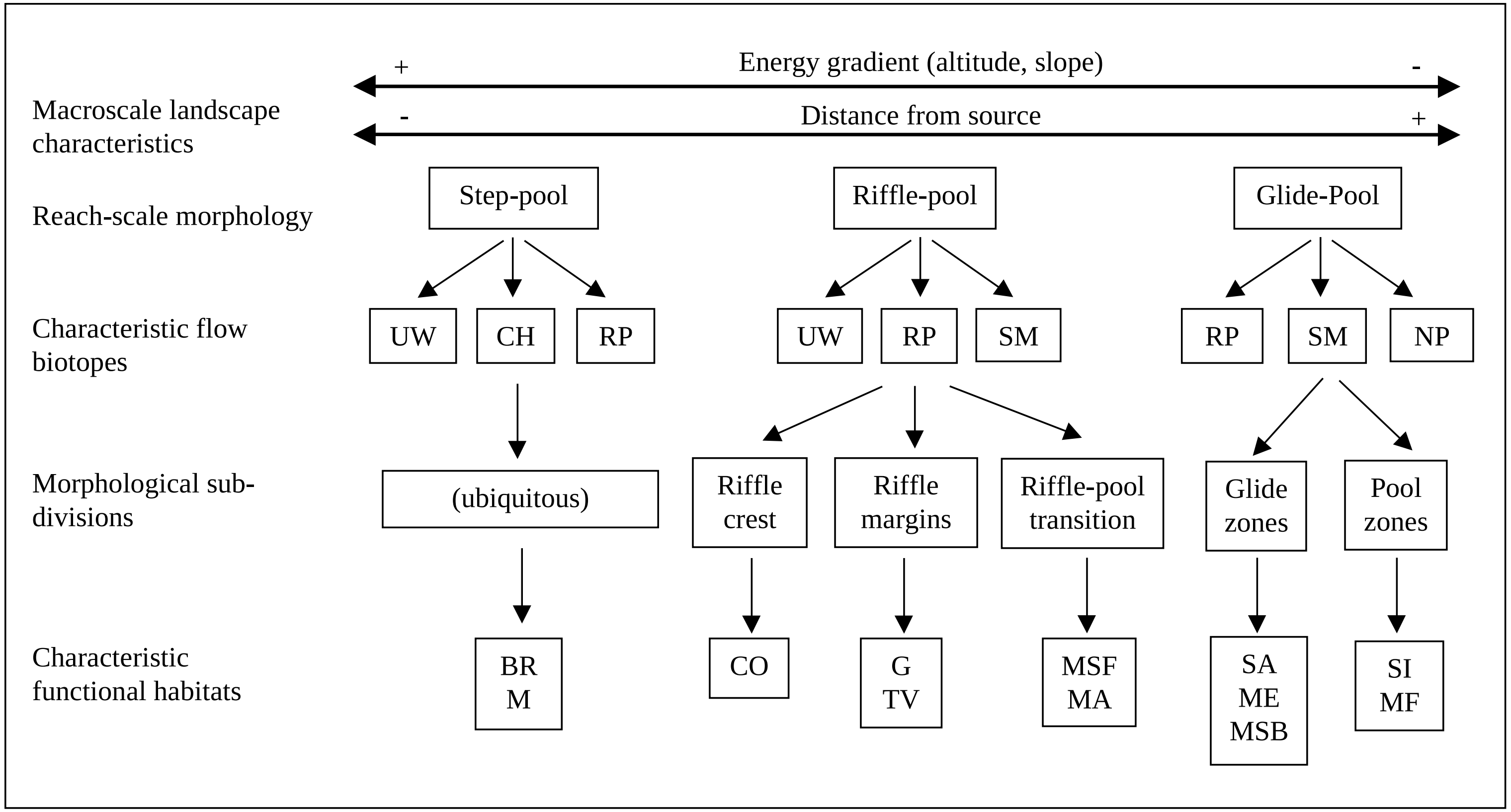


Figure 3.17 Hierarchical linkages between channel morphology, surface flow types and functional habitats in the context of wider macroscale environmental variables.

issues are addressed in the following chapters which undertake an intensive analysis of mesoscale and microscale physical habitat at selected field sites.

While the analysis highlights some limitations of RHS output data, these must be viewed in the context of the low-cost and high geographical coverage such surveys afford, and their ability to explicitly record rare and unique factors and levels of human modification allowing evaluation of the quality status of national water resources. Alternative methods based on more detailed field surveys form the focus of Chapter 4.

CHAPTER 4 A FIELD APPLICATION OF MESOSCALE HABITAT CONCEPTS: THE RIVER TERN

4.1 CHAPTER SYNOPSIS

This chapter explores the mesoscale organisation of physical and biological habitat within two contrasting reaches of the River Tern, Shropshire. A range of habitat parameters reveal characteristic ‘patch’ and ‘ribbon’ structures at each site. These are associated with variations in heterogeneity of the physical structure of the channel, and emphasise the significance of bedform controls on habitat organisation. The hydraulic characteristics of different physical biotopes and surface flow types form a continuum from more ‘tranquil’ to ‘rougher’ environments but fail to demonstrate distinct hydraulic ranges. However, an objective multivariate analysis of velocity, depth and substrate identifies physical habitat clusters which are associated with variations in velocity and depth distributions and are consistent with the location of visually identified physical biotopes. Analysis of the output data from rapid field assessments highlights the influence of both survey resolution, hydrological context and seasonal timing of surveys on results in terms of both ‘physical’ and ‘functional’ habitat units.

4.2 EXPLORING PHYSICAL HABITAT AT THE MESOSCALE

4.2.1 Research challenges

Results presented in Chapter 3 suggest that relationships between physical biotopes, surface flow types and functional habitats exist at relatively broad scales. However, several research challenges must be addressed before the physical biotope can be considered a physically robust and ecologically functional unit of stream habitat.

The objective identification of biotopes still represents a significant challenge for field surveys, partly resulting from confusion over terminology (Wadeson, 1994). Chapter 3 also outlined some concerns regarding the use of surface flow types as a means of physical biotope identification, but these issues require further examination in order to identify the effects of complex morpho-hydraulic relationships on survey outcomes. Furthermore, while it has been acknowledged that coarser survey resolutions neglect more marginal habitats, the effect of survey scale on various other biotopes remains to be explored.

Further examination of the hydraulic character of physical biotopes will improve understanding of their ecological purpose in terms of the type of habitat they create. However, most studies to date have identified large levels of overlap in hydraulic ranges between different biotopes, and furthermore, the discriminatory ‘success’ of different hydraulic parameters varies according to the combinations of biotopes tested (e.g. Jowett, 1993). These issues can be explored using the two complementary methodological approaches outlined in Chapter 3 (Section 3.2.3): (i) hydraulic characterisation of visually-identified units and; (ii) objective statistical identification of biotopes from high resolution hydraulic surveys.

Most contemporary physical biotope studies focus on variations in velocity and depth between biotopes but few incorporate channel substrate as a hydraulic variable despite its strong influence on the distributions of aquatic macrophytes, invertebrates and fish (Hynes, 1970; Gorman and Karr, 1978; Fox, 1996; Beisel *et al.*, 2000). Furthermore, the interrelationships between flow, substrate and vegetation types identified in

Chapter 3 require field testing at smaller spatial scales in order to explore the extent to which functional habitats may be ‘mapped’ onto physical biotopes.

This chapter comprises a series of field ‘tests’ on two contrasting reaches of the River Tern, Shropshire (see Chapter 2, Section 2.3 for site details) in an attempt to address some of these outstanding challenges and improve the conceptual basis of the physical biotope.

4.2.2 The field studies

Rapid field surveys of hydraulic parameters, substrate and channel vegetation types were carried out at relative ‘low’ and ‘intermediate’ flow stages (see Chapter 2, Section 2.3.5 for discharges and exceedences). Sampling resolution and study reach length were designed in an attempt to allow maximum data capture under steady discharge conditions. In practice, each survey took a little over one day to complete, but stage variations over the duration of each surveying period may be considered negligible.

The field surveys addressed the following key questions:

1. *Do physical biotopes correspond to the sub-reach scale organisation of bed topography and surface flow characteristics?*
2. *How does the spatial resolution of habitat assessments influence survey outcomes?*
3. *Can functional habitats be ‘mapped’ onto physical biotopes at the sub-reach scale?*
4. *Can physical biotopes be adequately described by simple hydraulic parameters such as velocity, depth and substrate?*

i) The field survey methods

Surveys were carried out according to a grid system, in order to avoid the subjective placement of sample transects according to visually identifiable hydraulic variation (Padmore, 1997a). A rectangular grid was devised with dimensions of 2 m in the streamwise direction by 1 m cross-stream, in order to ensure significant cross sectional detail and capture several morphological transitions (Figure 4.1).

ii) Measured parameters

Each cross sectional transect was subdivided into 1 m^2 ‘cells’ (Figure 4.1). At the centre of each cell, point measurements were made of water depth and three-dimensional current velocity at 0.6 of the water depth from the surface. Surveying began at the downstream extent of the study reach and continued upstream systematically in order to minimise bed disturbance (Wright *et al.*, 1981). Across each transect, measurements were taken 0.5 m from the waters edge at the left bank and then at 1 m intervals across the channel, ensuring that an additional measurement was taken 0.5 m from the right bank if not captured automatically.

Velocity was recorded using a SonTek/YSI Flowtracker handheld Acoustic Doppler Velocimeter (ADV®) with a 3D side-looking probe sampling at 1 s intervals and calculating a 30 s average for streamwise (U), cross stream (V) and vertical (W) velocity components. The ADV probe is designed to provide two-dimensional functionality (U and V) to water depths as low as 0.02 m, but in practice, irregular bed material and microtopography generally restricted two-dimensional measurements to water depths greater than 0.07 m and three-dimensional measurements to depths greater than 0.11 m.

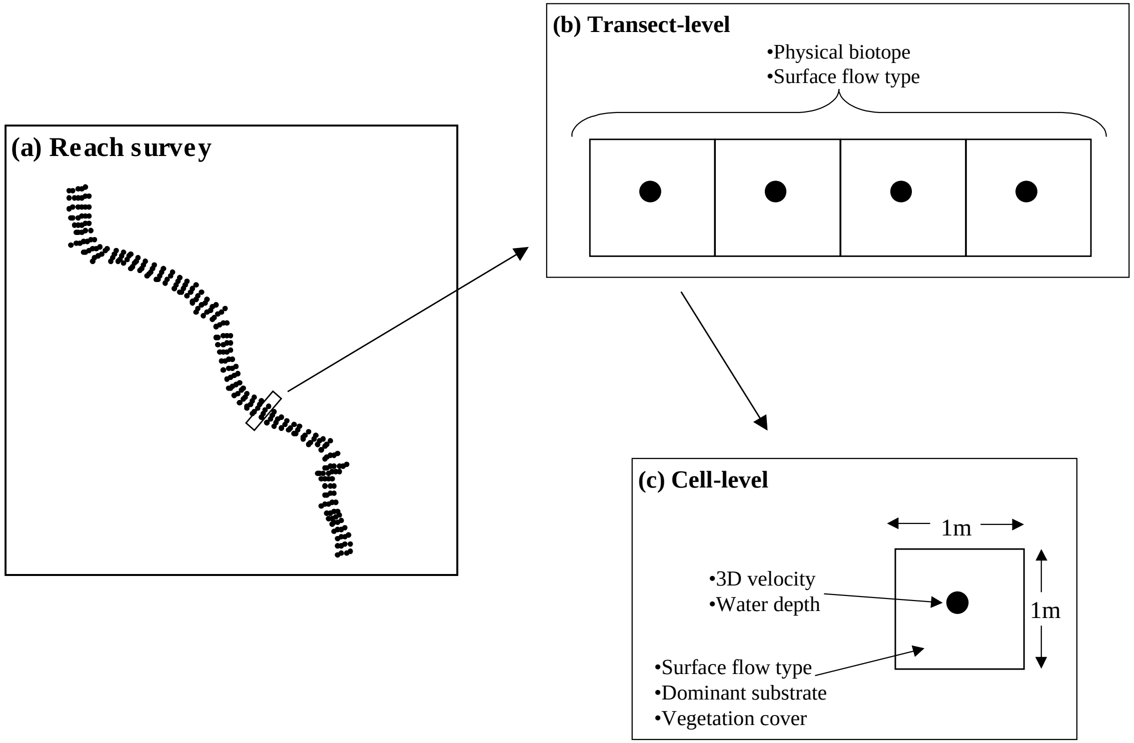
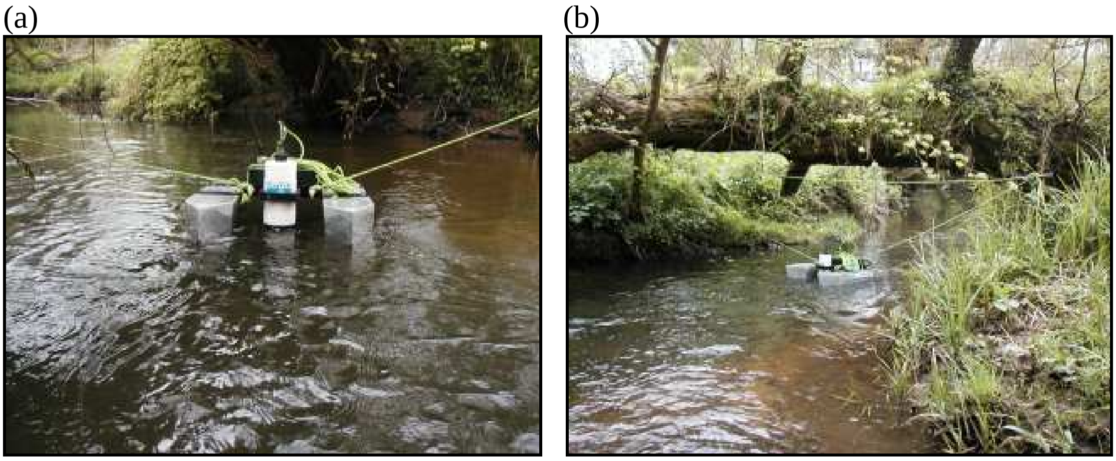


Figure 4.1 (a) Distribution of velocity sample points throughout the reach, demonstrated for Napely Lodge Farm, which are sub-divided into cross sectional transects in order to assess physical biotopes and surface flow types at the transect-level. Each transect is further sub-divided into $1m^2$ cells in order to sample velocity and depth and record surface flow types, dominant substrate and vegetation cover.

Acoustic Doppler velocimetry uses the Doppler shift principal to measure the change in frequency between an acoustic signal which is transmitted from the probe, reflected by particulate matter within the sampling volume, and subsequently detected by each of the three receivers (SonTek/ YSI Inc, 2002). The calculated speed at which particulate matter travels through the sampling volume is considered a safe representation of the water velocity, although the signal-to-noise ratio (SNR) provides an indication of measurement reliability. Acoustic Doppler velocimetry has the advantage, over conventional electromagnetic current meters (EMCMs), of velocity measurement in three dimensions. Since the sampling volume is remote from the sensor head, it is also associated with reduced flow interference, although ADV representation of turbulent flow structures has yet to be investigated fully (Lane *et al.*, 1998). Handheld velocimeters do, however, present challenges for flow gauging at high unwadable discharges which are often of interest to river scientists (Brookes, 1995b). Velocity was therefore measured in a second way using a remote ADV velocity profiler for comparison with the two main FlowTracker velocity surveys. The SonTek/YSI ‘RiverCat’ integrated catamaran system (Plate 4.1) provides high-resolution velocity and depth ‘profiles’ and may be towed across the channel, offering a potential solution to velocity measurement at high discharges. The RiverCat uses a ‘bottom-track’ system to measure the speed and direction of the vessel and subsequently correct the straight line distance across a channel cross section (SonTek/ YSI Inc., 2005). Three-dimensional velocity is measured within ‘cells’ throughout the water column and used to calculate a discharge value for each vertical ‘profile’ and for the entire cross section (Figure 4.2). A 3.0 MHz RiverSurveyor System was hired during April 2005 in order to field-test the sampling capability and data output. The system was tethered to a line and towed across the channel, recording velocities at a


(a)

(b)

Plate 4.1 Field deployment of the RiverCat velocity profiler in March 2005.

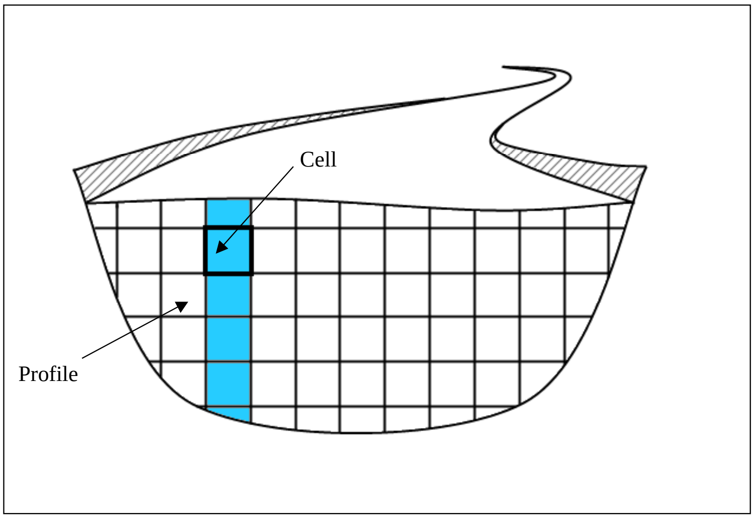


Figure 4.2 RiverCat sampling structure for a channel cross section.

cell resolution of 0.15 m. A 'blanking distance' of 0.2 m below the sensor head is excluded from the profile, and therefore a minimum depth of 0.35 m was required to produce a profile with one 'valid' cell.

iii) Biotope and habitat classification

Each transect was assigned to a physical biotope category (riffle, pool, run or glide) based on a visual assessment of flow and substrate character following the RHS field guidance (Environment Agency, 2003) and the Bisson *et al.* (1981) classification (Table 4.1). The 'dominant' surface flow type for each transect, often used as a proxy for physical biotopes, was identified separately according to the definitions provided in Chapter 3 (Table 3.1) in order to evaluate the robustness of connections between morphology and flow types.

However, since transect-level classification of flow types and physical biotopes can overlook important marginal or secondary biotopes which may be of ecological importance (see Chapter 3, Section 3.2.2), each 1 m^2 cell within a transect was assigned to a flow type category individually to supplement the transect-level classification (Figure 4.1). Minerogenic and vegetative habitats were recorded separately for each 1 m^2 cell according to categories in Table 4.2 and 4.3 in order to capture the character of the substrate within cells where vegetation cover exceeded 100%.

Physical biotope	**Description**
Riffle	Shallow water depths Moderate to swift flowing Moderate to pronounced turbulence Gravel, pebble or cobble substrate Distinctly disturbed water surface
Run	Intermediate water depths Generally fast-moving water with rippled surface but no other major features of turbulence Often associated with a high velocity feature (e.g. riffle or rapid) upstream or a narrowing of the channel.
Glide	Intermediate water depths Water moves effortlessly as smooth flow; only careful inspection reveals the turbulence. Associated with fine substrates and bedrock.
Pool	Deep water depths Generally slow velocities, and back currents may be present Should occupy most of the wetted width

Table 4.1 Descriptions used to classify physical biotopes observed on the River Tern from Environment Agency (2003) and Bisson *et al.* (1981)

Substrate	Code	Notes
Rocks	BR	Includes boulders and bedrock > 256 mm
Cobbles	CO	>64 mm
Gravel	G	> 2 mm
Sand	SA	> 0.125 mm
Silt	SI	< 0.125 mm

Table 4.2 Substrate categories used for field surveys, from Kemp *et al.* (2000)

Functional habitat	Code	Notes
Roots	R	
Trailing vegetation	TV	
Marginal plants	MP	
Leaf litter	LL	
Woody debris	WD	
Emergent macrophytes	ME	
Floating-leaved macrophytes	MF	
Submerged fine-leaved macrophytes	MSF	Includes fine and dissected leaves
Submerged broad-leaved macrophytes	MSB	Includes strap-like leaves
Mosses	M	
Macroalgae	MA	

Table 4.3 Functional habitat categories (organic) used for field surveys, from Kemp *et al.* (2000)

4.3 IDENTIFICATION OF PHYSICAL BIOTOPES

This section addresses the first research question posed in section 4.2.2 by exploring different methods of biotope identification using assessments of morphology and surface flow types. Quantitative methods, based on statistical variation in bed topography and fine sediment distributions, are employed in addition to more subjective assessments of surface flow types. This allows some evaluation of the complexities of the relationships between surface flow character and underlying morphology.

4.3.1 Morphological assessments

i) Topographic identification of biotopes

Topographic data for each reach were examined in order to identify whether physical biotopes at the study sites can be defined by undulations in bed topography (see Section 3.2.3). However, even along short reaches, the longitudinal gradient of the channel can exert a strong influence on bed elevations, often amplifying topographic lows in downstream sections and topographic highs within upstream sections of a reach. In order to improve the detection of sub-reach scale fluctuations in bed topography, the longitudinal gradient was extracted by fitting linear trends to the topographic data. While second or third order polynomial trends may be required for longer stream segments to account for the logarithmic nature of river long profiles, linear trends are generally considered suitable for short reaches (Richards, 1976).

Linear trends were fitted to the extracted channel centreline and thalweg of each site for comparison (Figure 4.3). While Napely Lodge Farm conforms with the expected

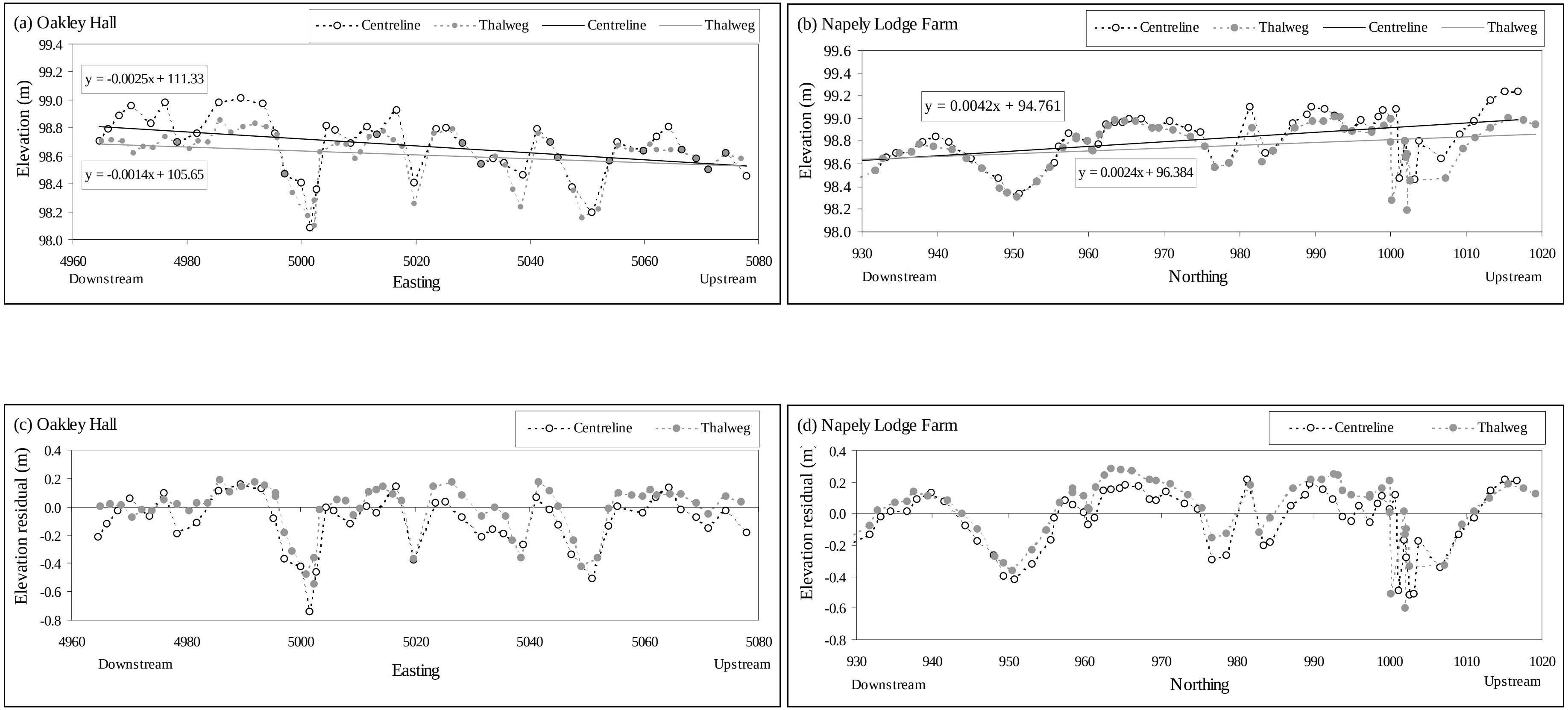


Figure 4.3 Raw channel centreline and thalweg elevations fitted with linear regressions for (a) Oakley Hall and (b) Napely Lodge Farm. (c) and (d) plot the detrended residual elevations in which riffles may be interpreted as positive values and pools as negative values after Richards (1976). For Oakley Hall bed elevations show a linear increase downstream, contrary to the expected trend of reductions in elevation downstream, reflecting siltation as a consequence of ponding of flow by debris at the downstream extent of the reach.

pattern of longitudinal decreases in bed elevations with distance from the river source, Oakley Hall shows the reverse relationship, with an overall increase in bed elevations downstream. This may simply reflect a topographic undulation superimposed on the logarithmic long profile of the river, but in this case it may alternatively expose the effects of ponding by debris dams further downstream, resulting in siltation at the downstream end of the study reach. Figure 4.3c and d plot the elevation residuals from the reach-scale trends for thalweg and centreline profiles. Negative residuals from the reach-scale trend suggest topographic lows (pools) while positive residuals suggest topographic highs (riffles; Richards, 1976). Pseudo-cyclic oscillations in bed topography along the reach are more pronounced at Napely Lodge Farm where similar proportions of riffles and pools were observed (see Section 2.3.6) and the amplitude of variations in bed topography is more marked. At Oakley Hall, two pools are identifiable at Eastings of approximately 5000 and 5050, but topographic highs are less obvious, reflecting the dominance of glides rather than riffles in intra-pool distances.

Residuals from the centreline trend were used to create Triangulated Irregular Networks (TINs) in ArcGIS 8.3, allowing visualisation of reach-scale topography. TINs create topographic surfaces by connecting sample points using a mesh of triangles. Linear interpolation is then performed along the edges of triangles, but the original data collected at sample locations are retained in the mesh (Petrie, 1990). While original triangulation procedures were associated with excessive execution times and were susceptible to error, these issues have since been overcome and Delauney triangulations using ‘Thiessen’ polygons are now a popular choice of algorithm for geomorphological applications (Moore *et al.*, 1993; Lane *et al.*, 1994).

The topographic visualisations are presented in Figure 4.4 (a and b) and can be compared to the distribution of physical biotopes identified visually in the field using the definitions in Table 4.1 (highlighted by rectangles). At Oakley Hall, the two scour pools are clearly identifiable from TIN visualisations, and two smaller areas of localised scour within the main glide zone are associated with protruding tree roots and a fallen tree. Glide, riffle and run areas are characterised by different levels of cross sectional variation in elevations. Within the run there are clear differences between higher elevations at the channel margins and lower values along the centreline; within the glide, bed elevations are more patchy; and within the riffle, scour is greater towards the right bank. At Napely Lodge Farm, residual elevations clearly identify distinctive pool and riffle features, and cross sectional variation in elevations appears less significant.

Figure 4.4c and d classifies residual elevations into positive (riffle) and negative (pool) groups in order to investigate whether such simple topographic classifications of physical biotopes correspond with visually identified features (rectangles). At Oakley Hall the ‘pool’ class (residual elevation < 0 m) extends longitudinally through all physical biotopes while the ‘riffle’ class (residual elevation > 0 m) is generally associated with channel margins, reflecting the greater cross-sectional, rather than longitudinal, variation in physical structure. At Napely Lodge Farm, elevations demonstrate a more ‘patchy’ distribution, suggesting that longitudinal variation exceeds cross sectional variation. Pool and riffle/ run areas are clearly distinguished by topography, but some localised scour within riffle and glide units is classified as ‘pool’.

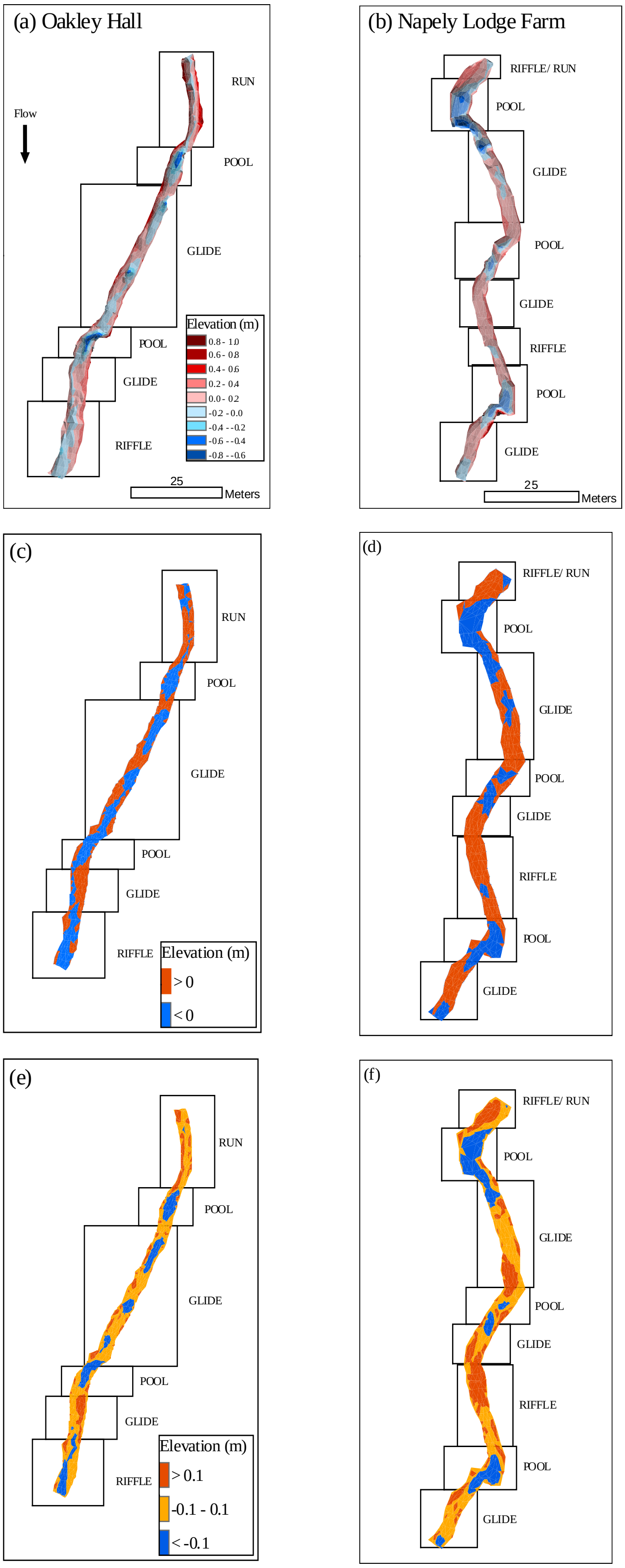


Figure 4.4 TIN visualisations of residual channel elevations for (a) Oakley Hall and (b) Napely Lodge Farm. In (c) and (d) elevation residuals are classified into positive and negative values, and in (e) and (f) a 'transitional' class (-0.1-0.1 m) is incorporated to account for transitional glide and run biotopes. Rectangles mark the physical biotopes identified visually in the field at low flow stage.

Since transitional ‘run’ and ‘glide’ biotopes have been associated with certain hydraulic characteristics (Jowett, 1993) and are therefore considered to provide a specific type of habitat for aquatic biota (Bisson *et al.*, 1981), the topographic classification was adjusted to include an additional ‘transitional’ biotope class. Figure 4.4e and f plot visualisations for the adjusted classification whereby ‘pools’ are described by residuals lower than -0.1 m, ‘transitional’ run or glide units by residuals between -0.1 and 0.1 m and ‘riffles’ by residuals greater than 0.1 m. For Oakley Hall, this results in much of the channel being classified as ‘transitional’, a relatively accurate representation of the observed morphological structure which is dominated by glides. In contrast, at Napely Lodge Farm pools are clearly identifiable, the highest elevations are principally associated with riffles, and most glide zones are classified as ‘transitional’.

Residual elevations from the TIN surfaces were then linearly interpolated to a regular 2 m^2 grid in order to calculate the approximate proportions of ‘riffle’, ‘transitional’ and ‘pool’ topographic classes at each study site. These data are presented in Figure 4.5 for comparison with the proportions of the surveyed channel area associated with different physical biotopes as identified visually at low flow. Visual observations of ‘run’ and ‘glide’ biotopes are amalgamated into a ‘transitional’ class for comparability with grid data. The proportions of the channel occupied by the different topographic classes for the grid data are very similar to visual observations of physical biotopes at low flow stage. However, Figure 4.5e demonstrates that discrepancies between visual observations and interpolated grid classifications are more significant in terms of percentage change within riffle and pool biotopes, which occupy a smaller proportion of the channel area compared to the transitional class.

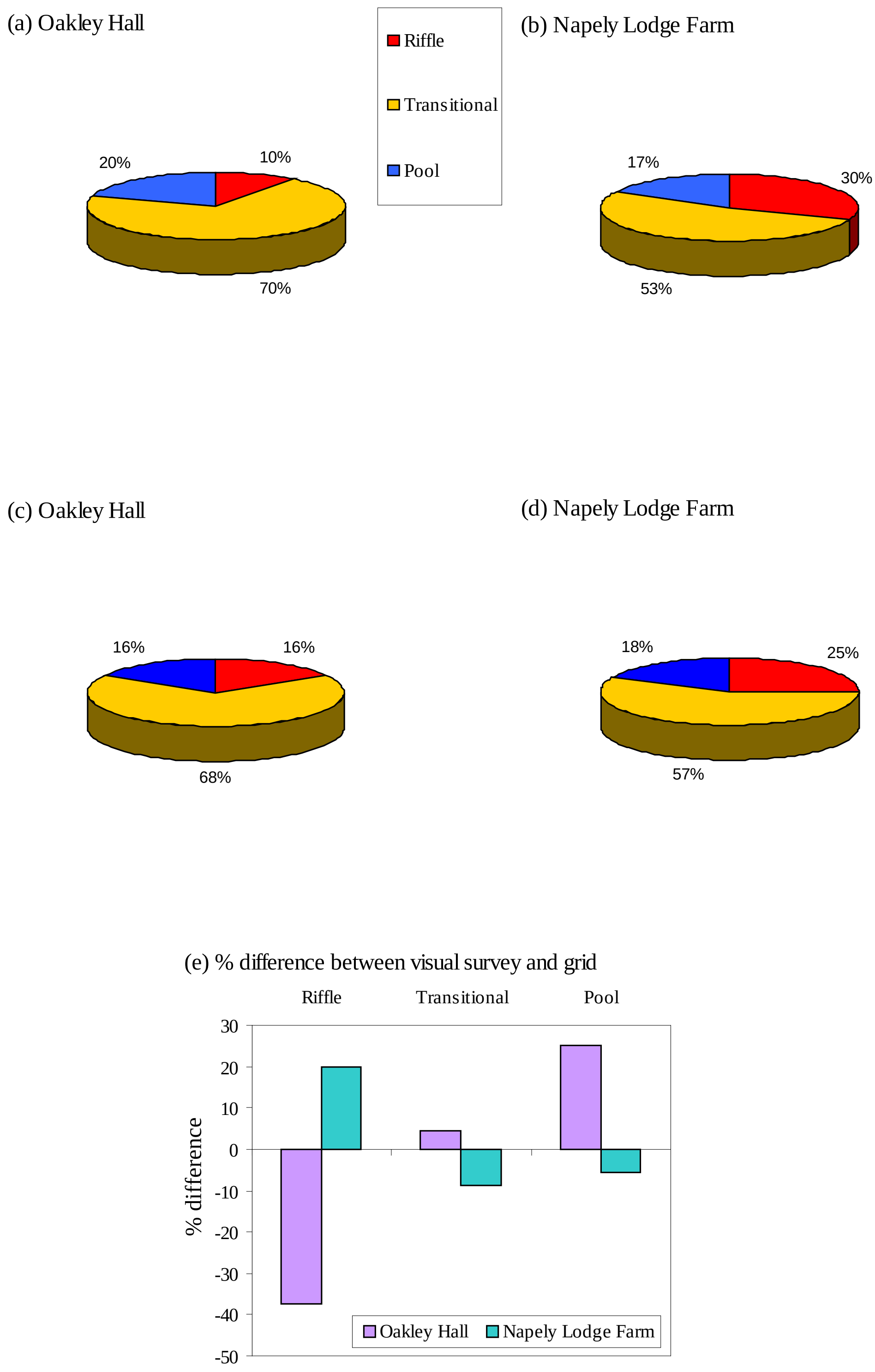


Figure 4.5 (a) and (b) present the proportion of channel area occupied by 'biotopes' derived from interpolated topographic residuals at each site, which can be compared to those visually identified at low flow stage (c and d). (e) plots the difference (% change) between visual surveys and gridded residual elevation data derived from TINs.

The proportion of the channel area occupied by each biotope class also varies between the two study sites. The 'transitional' topographic class accounts for 70% of the channel area at Oakley Hall compared to 50% at Napely Lodge Farm, although both sites are characterised by a significantly higher proportion of transitional biotopes compared to the 11% observed by Bisson *et al.* (1981) for North American streams. Both interpolated grids and visual survey data suggest that a higher proportion of the channel area is occupied by pools at Oakley Hall, and by riffles at Napely Lodge Farm, reflecting the ponding of flow at the former and a more typical pseudo-cyclic riffle-pool structure at the latter. Thus, not only do different physical biotopes occupy different proportions of the channel area, but these proportions vary between sites of different habitat 'quality' (see Section 2.3.6). This has implications for rapid habitat quality assessments such as RHS, which does not record biotope proportions, (Environment Agency, 2003) and for the resolution of such surveys, particularly regarding the spacing of sample transects, since the probability of capturing different biotopes using a stratified sampling strategy will vary between sites.

ii) Spatial organisation of bed topography

The spatial organisation of bed topography within a reach can be explored statistically by calculating the semivariance. Bed topography represents a spatially continuous or 'regionalised' variable whereby the elevations of samples closer together are more similar than for those located further apart (Davis, 2002). The semivariance can be used to describe the nature of this spatial dependence by comparing the characteristics of pairs of samples located at various distances apart:

$$\gamma h = \sum_{i}^{n-h} (x_i - x_{i+h})^2 / 2n$$ **Equation 4.1**

Where x_i represents a measurement of the regionalised variable (bed elevation), X, taken at location i, x_{i+h} is another measurement take h intervals away, n is the number of samples and n-h is the number of comparisons between pairs of points.

The experimental semivariogram is used to express the average semivariance for successive lag intervals of distance between samples, and is associated with a characteristic form (Figure 4.6). Samples located progressively further apart become less similar (associated with increasing semivariance) until at some point the variance stabilises (at the 'sill'). The 'range' refers to the distance at which the sill is reached and reflects the spatial range over which the variable exhibits statistical variation (Clifford *et al.*, 2002b). Failure of the semivariogram to pass through the origin is termed the 'nugget effect' and suggests that significant variation in the variable occurs over distances shorter than the sampling interval. Semivariograms were computed for bed elevations using a lag width of 2 m (approximating the sampling interval) in Surfer 8 (Golden Software Inc.). Semivariograms were plotted for 20 lags (a distance of 40 m) following Clifford *et al.* (2002a) in order to incorporate several morphological transitions and avoid introducing error associated with low sample numbers at higher lags.

Figure 4.7 presents the semivariograms for bed topography at each site. A 'nugget effect' is identified at both sites, suggesting that significant variation occurs at scales smaller than the average sampling interval (< 2 m), reflecting the influence of microtopography. Oakley Hall is associated with higher overall semivariance, which may be associated with the higher cross sectional variation in bed elevations observed in Figure 4.4a. In contrast, Napely Lodge Farm demonstrates a stronger spatial

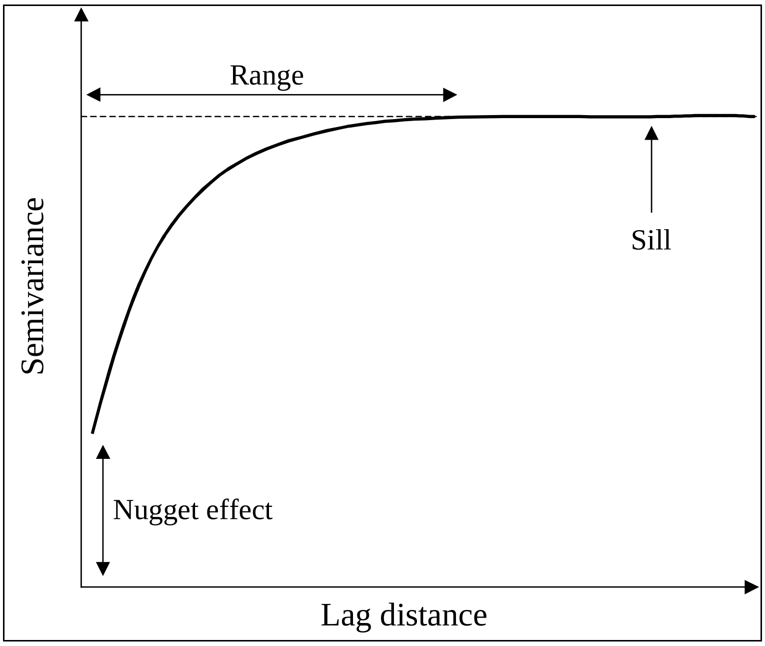


Figure 4.6 Characteristics of the experimental semivariogram.

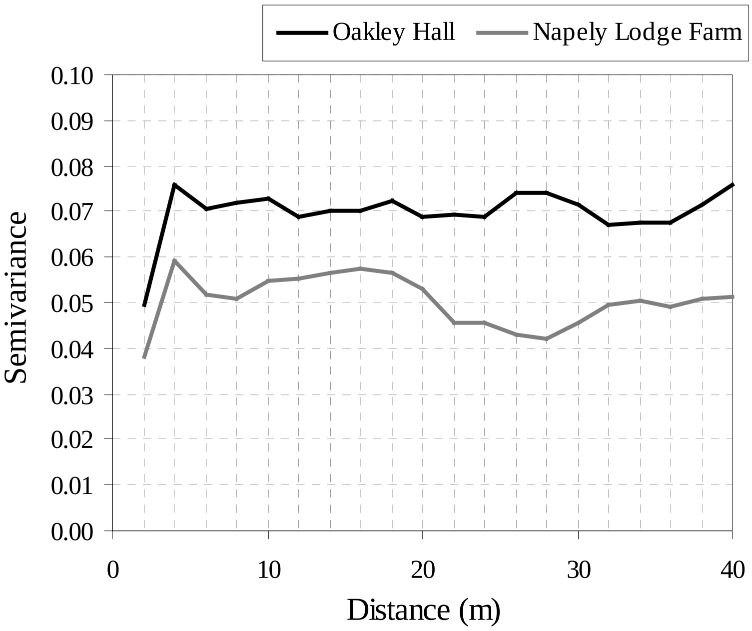


Figure 4.7 Semivariograms of channel bed elevation for Oakley Hall and Napely Lodge Farm calculated for a total of 20 lags using a lag interval of 2 m.

dependence of topography and a reduction in semivariance at a lag distances between 20 m and 30 m. This distance approximates the spacing of riffles and pools at Napely Lodge Farm (see Figure 4.5), suggesting a more organised bed topography which is strongly related to the occurrence of physical biotopes.

iii) The distribution of fine sediment

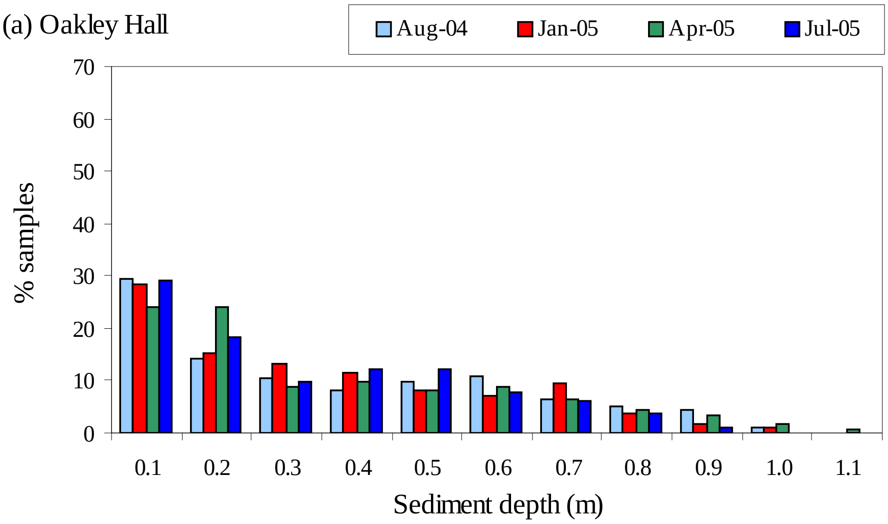
Accumulations of fine sediment can create more localised variations in bed topography superimposed onto the reach-scale undulations in bed elevations associated with the positioning of bedforms. Gravel-bed channels commonly contain fine sediments within the voids of framework gravels, but where the supply of fines exceeds the storage capacity of the voids, fine sediments can occur in surficial patches (Lisle and Hilton, 1992). While this has been noted particularly for pools (Lisle and Hilton, 1999), the high volumes of fine sediment derived from the sandstone geology underlying the upper Tern catchment create large patches of fine sediment which constitute a significant component of the bed structure throughout the study reaches. Fine sediment distributions influence the ecological condition of the hyporheic zone with implications for fish spawning and provision of refugia for invertebrates (Dole-Olivier *et al.*, 1997; Matthaei *et al.*, 1999), but have so far been largely overlooked in biotope studies.

In order to quantify the spatio-temporal distribution of fine sediment distributions at the two study sites, four ‘pin-surveys’ of fine sediment depth were undertaken over a 12 month period following the methodology of Lisle and Hilton (1992). Three locations across each transect within the sampling grid were sampled for fine sediment depth, incorporating points 0.5 m from each bank, plus channel centreline locations. At each sample point, a 3 mm diameter copper pin was pushed into the riverbed with consistent force until abrupt changes in resistance were encountered as the pin came into contact with the underlying coarse substrate (Lisle and Hilton, 1992). The depth of fine sediment was recorded as the distance between the surface of the channel bed and the first contact with coarse substrate.

Figure 4.8 plots the frequency distributions of fine sediment depth for each survey at each field site. The deepest fine sediment accumulations are observed at Oakley Hall, where over 40% of samples for all four surveys are associated with sediment depths greater than 0.3 m and the deepest recorded accumulation was over 1.0 m. At Napely Lodge Farm, the steeper gradient imposes a greater restriction on the accumulation of fine sediments. Less than 10% of samples are associated with values greater than 0.3 m and sediment depths do not exceed 0.6 m. It is also worthy of note that most of the deepest fine sediments were not associated with pools as some studies suggest (Keller, 1971; Lisle and Hilton, 1992), but instead were generally associated with accumulations of silt and sand at channel margins and within glides.

The fine sediment frequency distribution for Oakley Hall is bi-modal for the two summer surveys (August 2004 and July 2005), suggesting a higher proportion of deeper sediment accumulations in the summer months. This may reflect the lower base flows and reduced frequency of flood events during summer months (see Section 2.3.5) resulting in lower levels of bed disturbance and scour of fine sediments. However, the seasonal growth of aquatic macrophytes is also likely to increase sediment deposition through a combination of direct physical trapping of particles and by increasing in frictional resistance, leading to reductions in flow velocity and a

(a) Oakley Hall



(b) Napely Lodge Farm

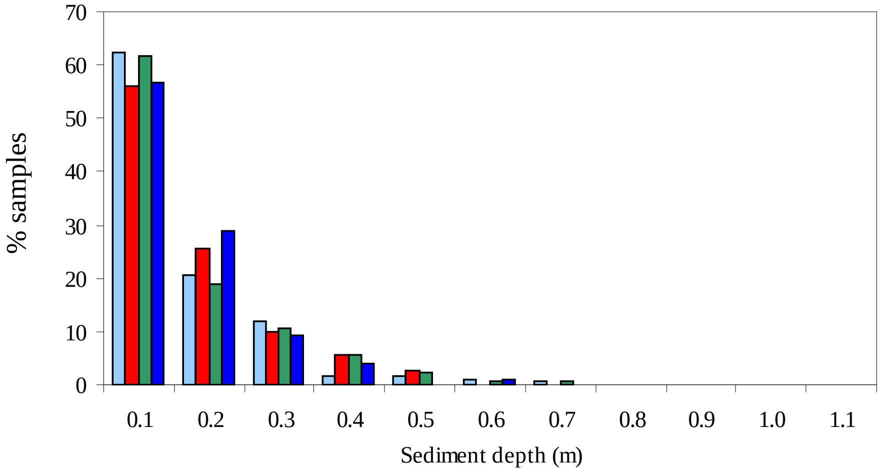


Figure 4.8 Frequency distributions for fine sediment depth at each site for each of the four pin surveys.

higher fall-out rate of particles from suspension (Gaudet, 1974; Sand-Jensen, 1998). Since bimodal summer distributions are observed only at Oakley Hall, where aquatic vegetation was more abundant (see Section 4.4), this factor seems significant in increasing summer sediment depths. This interaction between vegetation and the composition of the bed material introduces an element of seasonality to physical habitat organisation, creating temporal variability at timescales greater than the discharge-dependency of morphohydraulic behaviour, and emphasising the complexity of relationships between the biotic and abiotic components of the instream environment.

In order to explore the spatial patterns of accretion and degradation of fine sediments at the study sites, TIN visualisations of the change in fine sediment depth between sequential surveys were produced in ArcGIS 8.3 (Figure 4.9). Positive values represent accretion of fine sediment (‘fill’) and negative values degradation (‘scour’). Patterns of scour and fill are relatively patchy at both sites, revealing a complex ‘mosaic’ structure similar to observations by Matthaei *et al.* (1999) for New Zealand rivers. However, closer inspection reveals some suggestion of a reversal in scour and fill between surveys: areas dominated by accretion for one survey are often associated with degradation during the subsequent period and vice versa.

Figure 4.10 plots the cumulative scour and fill for the entire study reach (a and b) and for each physical biotope as identified visually at low flow (c and d) in order to quantify this feature for the sampled channel area. Each survey is associated with near-equal proportions of scour and fill for the entire study reach at both sites,

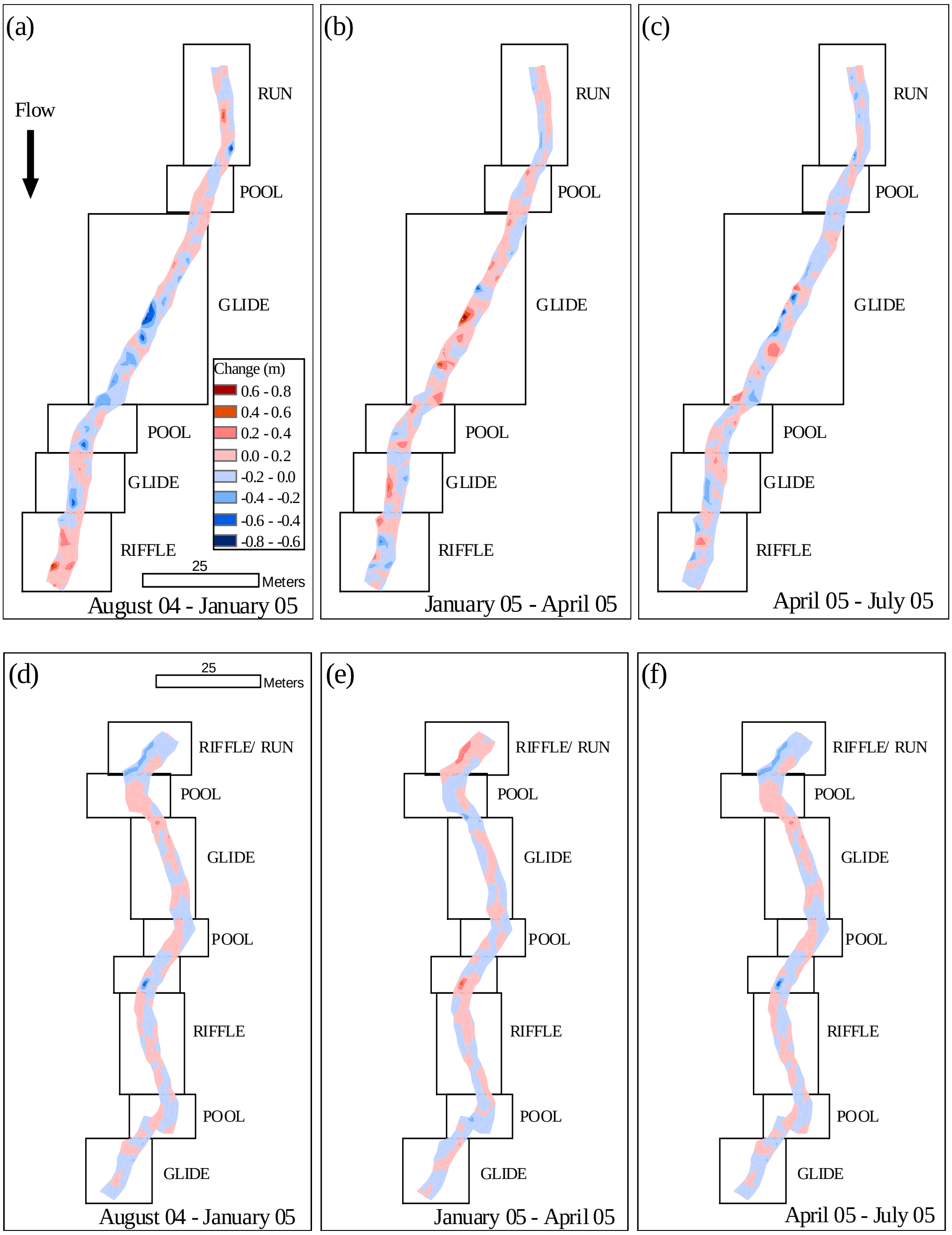
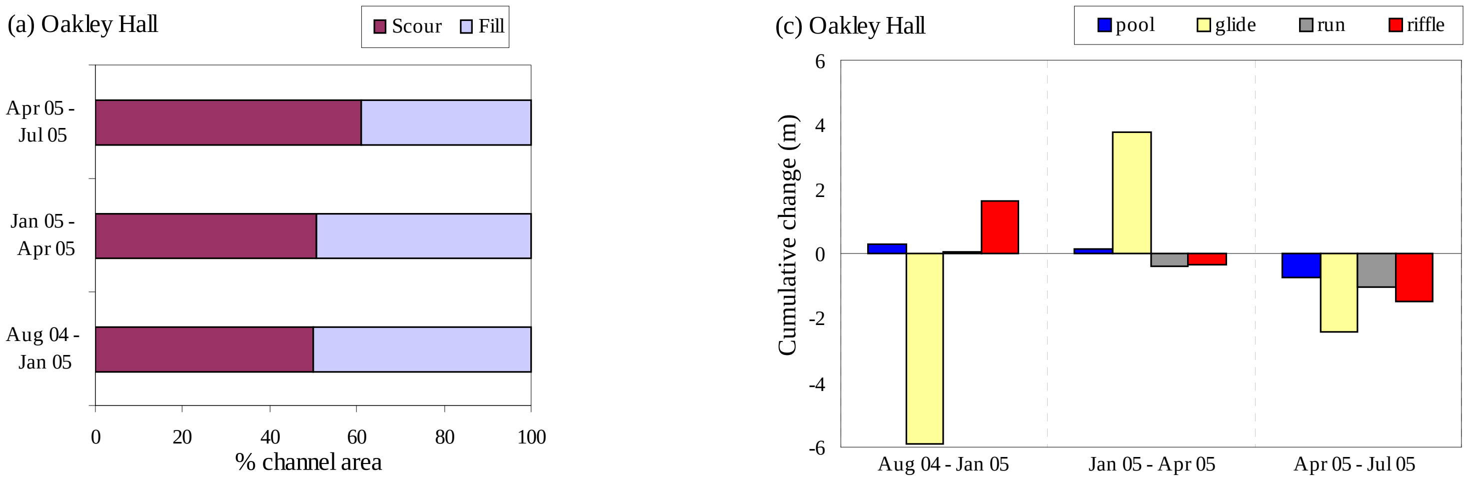


Figure 4.9 Change in sediment depth between surveys for Oakley Hall (a to c) and Napely Lodge Farm (d to f).



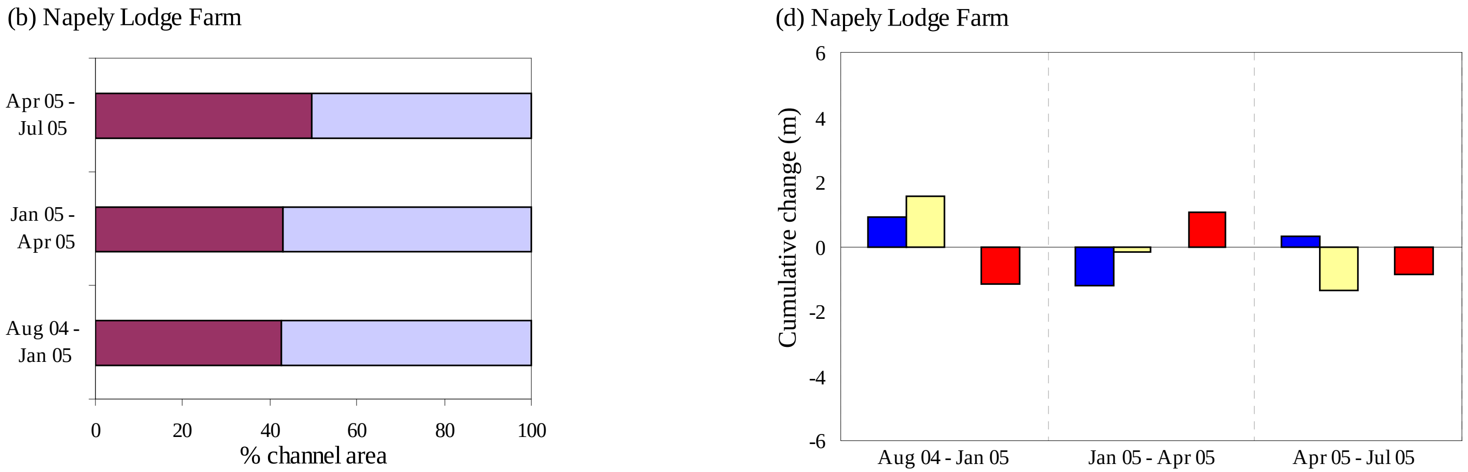


Figure 4.10 Percentage of the channel area associated with scour and fill between surveys calculated from a 2 m interpolated grid for (a) Oakley Hall and (b) Napely Lodge Farm. Cumulative change in sediment depth between surveys for each biotope (measured samples only) is plotted in (c) for Oakley Hall and (d) for Napely Lodge Farm.

suggesting that sediment supply is approximately in equilibrium with losses downstream. However, individual physical biotopes show some variations between surveys and the nature of these variations differ between sites. At Oakley Hall, both riffle and pool fill during the autumn/winter period (August 2004 – January 2005), and scour during the spring/summer period (April– July 2005) while very little change is noted for winter/spring (January - April 2005). The largest changes in fine sediment depth are associated with the glide which is characterised by cumulative scour in autumn/winter and spring/summer compared to cumulative fill in winter/spring. Interestingly, this pattern associates cumulative scour with the season of highest macrophyte cover which may be expected to induce fill through sediment trapping. However, significant sediment accumulations may be highly localised within and around vegetation stands (Sand-Jensen, 1998), which is reflected in the biomodal summer distributions in Figure 4.8. Some deep, but localised accumulations may therefore persist around vegetation despite scour over large portions of the channel associated with the influence of flood events within the inter-survey period (of which there are two between April and July 2005 - see Section 2.3.5).

At Napely Lodge Farm there is greater evidence of systematic seasonal reversals in scour and fill patterns between riffle and pool. In the autumn/winter period the pool fills while the riffle scours; winter/spring is characterised by the reverse relationship; and spring/summer shows a return to the original state. Interpretation of the causal processes associated with these patterns is limited since shorter-term change within these broader periods (for instance in response to individual flood events) is unknown. However, the results do suggest a seasonal variation in the sorting of fine sediments between riffle and pool units similar to patterns identified for individual flood events (Keller, 1971) which may relate to the hydrological regime.

The dynamics of fine sediments within the study reaches highlight the complex array of factors influencing sediment transport at the mesoscale. In particular, the combination of seasonal growth of instream vegetation and both seasonal and event-specific hydrological variation introduces a temporal variability in physical habitat intermediate between the stage-dependency of biotope hydraulics and longer-term variations in channel morphology and planform.

4.3.2 Surface flow type assessments

Surface flow characteristics are often used as a proxy for physical biotopes (Padmore, 1997a), but deviations from the ‘typical’ relationships identified between the phenomena can introduce significant error to field studies (see Chapter 3, Section 3.2.2). In an attempt to examine the nature of these variations, Figure 4.11 explores the occurrence of different flow types, assessed at both the ‘transect-level’ and the ‘cell-level’ (see Section 4.2.2) for different physical biotopes.

Several points are worthy of note. First, for each reach and flow stage, each physical biotope category is associated with at least two different flow types when assessed at both scales, and most biotopes are associated with a larger range of flow types when assessed at the cell level, suggesting significant cross sectional variations in hydraulics. However, while no single linkages between flow types and physical biotopes are identifiable, a transition from predominance of ‘slower’ (no perceptible flow, upwelling and smooth boundary turbulent flow) to ‘faster’ (rippled flow and

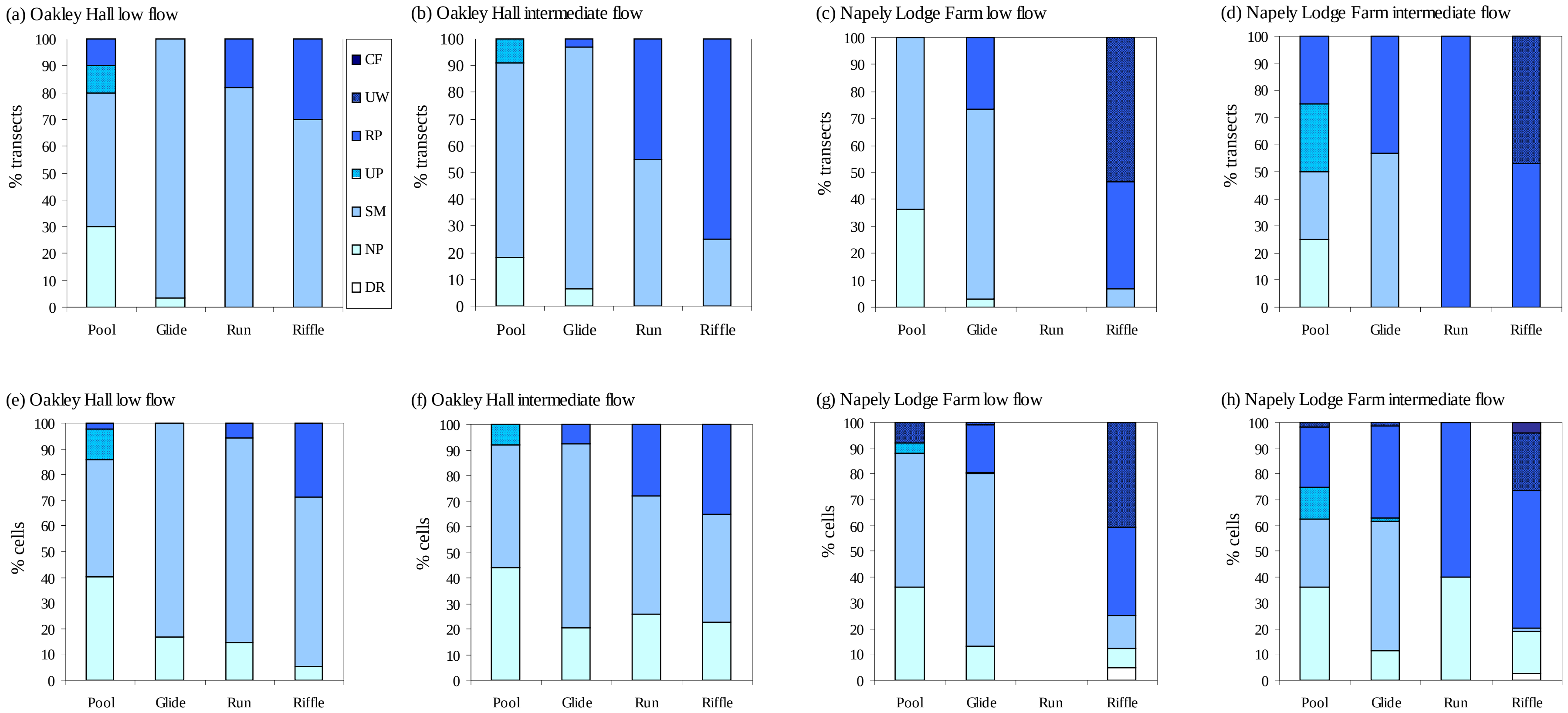


Figure 4.11 Occurrence of surface flow types within each physical biotope for each site and flow stage assessed at the transect-level (a to d) and the cell-level (e to h). For flow type category codes, see Table 3.1 (p. 53).

unbroken standing waves) flow types is observed from pool, to glide, to run, to riffle biotopes. This is more pronounced at Napely Lodge Farm compared to Oakley Hall, suggesting that the amplitude of bedform structures (see Section 4.3.1) bears an influence on the hydraulic characteristics of biotopes.

Second, different biotopes show different levels of conformity with the ‘characteristic’ relationships identified between physical biotopes and surface flow types at low flow stages. For pools, the ‘characteristic’ flow type, no perceptible flow, accounts for less than 40% of observations when assessed at either scale. The remaining observations are associated with a combination of smooth boundary turbulent flow, upwelling and rippled flow suggesting significant within-biotope hydraulic variation. Furthermore, the percentage area of pools occupied by no perceptible flow is reduced at the higher flow stage as velocities increase through the pools and faster flow types become more prominent. In contrast, riffle areas reveal greater correspondence with the ‘characteristic’ unbroken standing waves flow type, although this is only the case for Napely Lodge Farm since siltation of the riffle feature at Oakley Hall means it is more glide-like in nature. Glide biotopes show the strongest overall correspondence with the ‘characteristic’ smooth boundary turbulent flow, particularly at Oakley Hall where glides are more prominent features (Section 4.3.1).

Third, different physical biotopes demonstrate different responses to increasing discharge in terms of surface flow types, and the same biotopes demonstrate different responses between sites. For instance, pools at Oakley Hall appear to become more homogeneous in terms of surface flow types with increasing stage, while pools at Napely Lodge Farm are characterised by a wider range of flow types. This is likely to reflect the more subdued pool morphologies at Oakley Hall which mean that with increasing stage, pools quickly become more glide-like. At Napely Lodge Farm, however, pools are more prominent features associated with larger channel bends, and flow obstructions such as root wads resulting in an intensification of flow conditions at the higher stage as backwater zones are enlarged and thalweg velocities increase. At Oakley Hall, the riffle feature is associated with a higher proportion of rippled flow and a lower proportion of smooth boundary turbulent flow at the higher discharge, suggesting an increase in velocities. This is likely to result from a combination of faster flows under the higher discharge and less resistance from vegetation cover which was much more sparse in March than July within the riffle (See section 4.4). Riffle areas at Napely Lodge Farm become associated with a lower proportion of characteristic unbroken standing waves at the higher flow stage as rippled flow becomes more prominent, reflecting the lower levels of relative roughness associated with increased water depths.

These observations suggest that not only do physical biotopes within the two study reaches frequently fail to conform with ‘characteristic’ flow type relationships, but the response of surface flow type organisation to increasing stage varies both between different biotopes, and between the same biotopes at different sites. The adequacy of surface flow types as proxy for physical biotopes is therefore likely to be dependent on a range of site- and survey-specific factors including the amplitude of bedforms and the resolution and hydrological context of the survey.

4.4 THE EFFECTS OF SURVEY RESOLUTION

This section addresses the second research question posed in Section 4.2.2 by exploring the effects of survey resolution on output data in terms of both rapid visual assessments and measured hydraulic parameters.

4.4.1 Surface flow types

Deviations from the typical relationships between physical biotopes and surface flow types identified in the previous section may partly result from cross sectional variations in hydraulics which are not accounted for by transect-level sampling schemes (Padmore, 1998). Figure 4.12 (a to d) plots the proportion of the surveyed channel occupied by each surface flow type when assessed at the transect-level compared to the cell-level. Significantly, survey resolution has contrasting effects on different flow types.

Some flow types account for a higher proportion of the channel area when assessed at the cell-level compared to the transect-level, suggesting that these flow types are more localised in nature and therefore are frequently overlooked by transect-level surveys. No perceptible flow, for example, was frequently noted at channel margins, while dry areas were associated with exposed sand ridges and chaotic flow with accumulations of boulders and woody debris. In contrast, the more frequently occurring flow types (smooth boundary turbulent flow, rippled flow, and unbroken standing waves), occupy a smaller proportion of the channel area when assessed at the cell level. This reflects over-estimation by transect-survey since flow types may occupy only 50% of the channel width but are recorded as spanning the entire cross section.

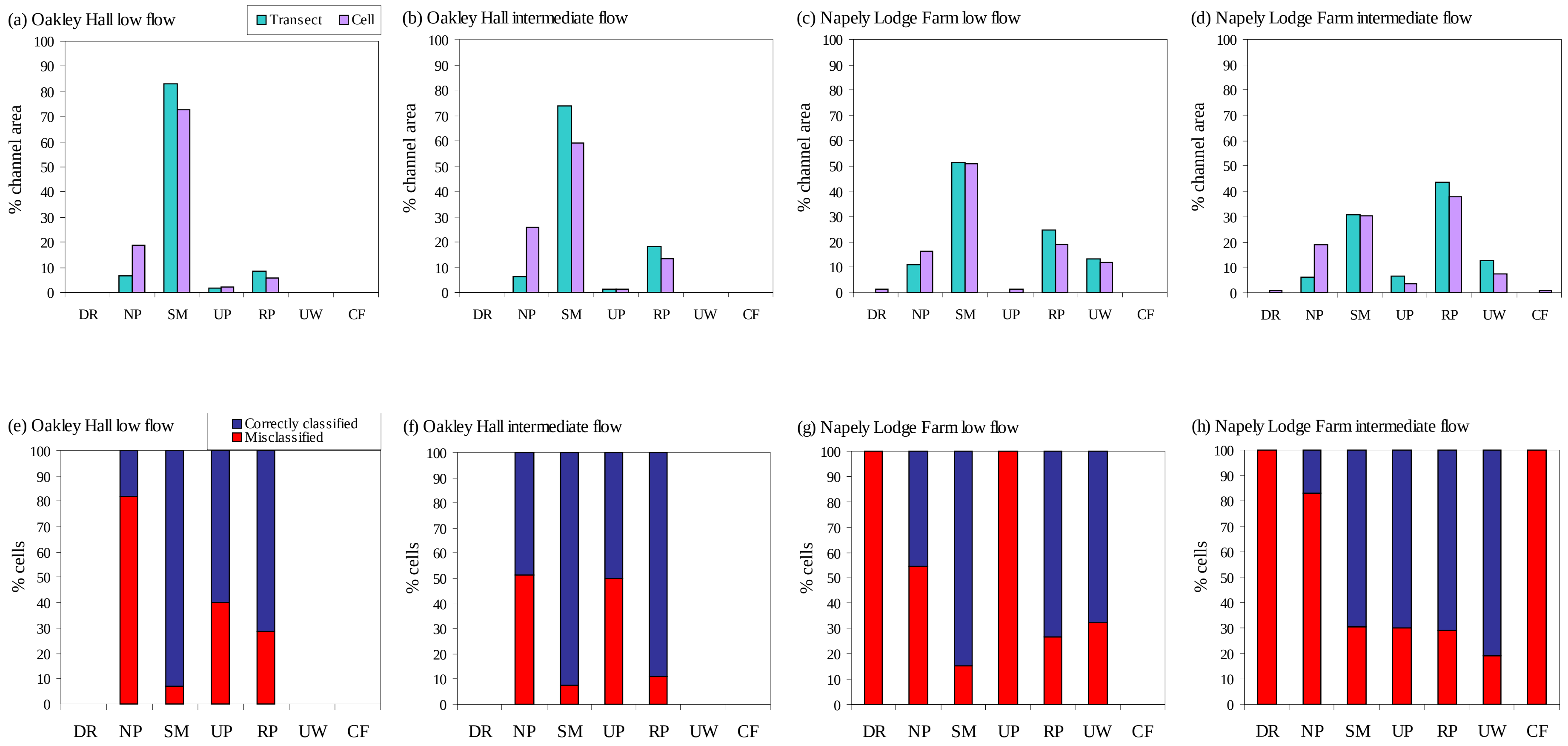


Figure 4.12 Percentage of surveyed channel area occupied by flow types when assessed at the cell-level compared to the transect-level for each site and flow stage (a to d) and level of misclassification of cell flow types by the flow type assigned to the entire transect for each site and flow stage (e to h).

These observations suggest a ‘misclassification’ of cells by transect-level flow type assessments, the nature of which varies between flow types (Figure 4.12). For example, smooth boundary turbulent flow is associated with the lowest levels of misclassification suggesting that it often occupies the majority of a cross section. No perceptible flow, upwelling and chaotic flow are associated with the highest levels of misclassification by transect-level survey, since they frequently occur as ‘marginal’ or secondary flow types. For some flow types, such as upwelling, the level of misclassification varies with flow stage, suggesting that certain flow types become more localised at different discharges, and therefore that survey outcomes will be influenced by the interaction of survey resolution and hydrological context.

Figure 4.13 explores the combinations of cell-level flow types recorded ‘within’ the different transect-level flow types in order to explore these variations in greater detail. At each site, each transect-level flow type is associated with at least two, and generally three different flow types assessed at the cell-level, reflecting the cross sectional diversity of flow types. Cross sectional complexity also appears to increase with stage, where a larger proportion of cells are associated with flow types other than that assigned to the transect as a whole. Part of this complexity is associated with the frictional effects of the banks which create small patches of no perceptible flow at channel margins, providing important flow refugia for aquatic organisms. Cells of no perceptible flow are more common at the higher flow stage suggesting that rather than being lost to faster flowing zones as discharge increases, some marginal zones may increase due to the incorporation of bank irregularities within the wetted width. However, this increase in habitat heterogeneity may be expected to decrease with further rises in stage as marginal habitats are lost to faster flow velocities.

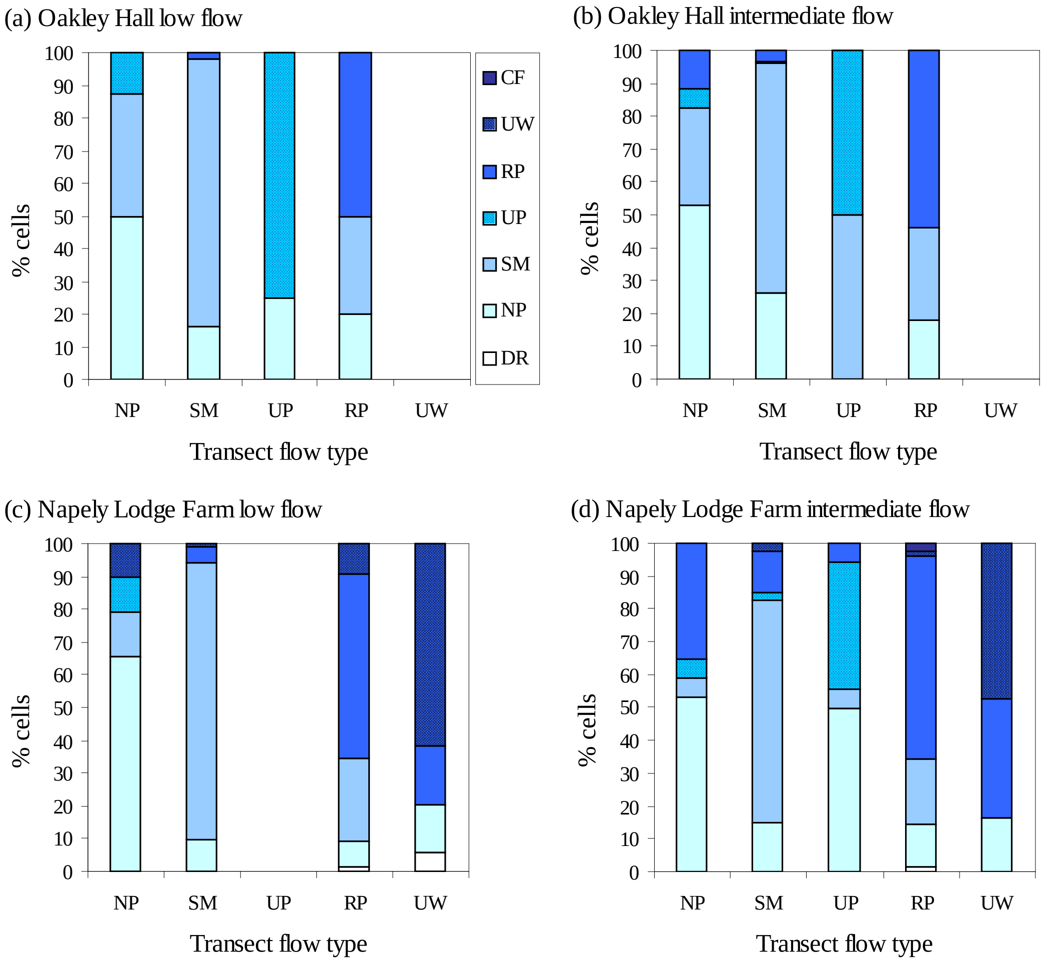


Figure 4.13 Proportions of different cell types associated with each transect-level flow type for each site and flow stage. See Table 3.1 (p. 53) for flow type category codes.

Figure 4.14 allows visual examination of the spatial organisation of surface flow types using plots produced in ArcGIS 8.3. The patterns observed are similar to those identified for bed topography. Longitudinal 'ribbons' of smooth boundary turbulent and rippled flow follow the centreline at Oakley Hall indicating low levels of streamwise variation compared to higher cross sectional variability associated with the frictional effects of channel margins. Napely Lodge Farm is again associated with a 'patchy' spatial organisation suggesting greater longitudinal variation in flow types which corresponds broadly with the organisation of bed topography and physical biotopes.

Visualisations also provide an indication of the changing 'shape' of flow types with increasing stage. When assessed at the cell-level, no perceptible flow is observed to extend along the channel margins at the higher flow stage, a trend which is overlooked by transect-level assessments. At Napely Lodge Farm, areas of smooth boundary turbulent flow contract with increasing stage, in conjunction with the longitudinal and cross sectional expansion of rippled flow within glide, pool and riffle biotopes and upwelling within the downstream pool. Additionally, unbroken standing waves appear to contract cross sectionally as marginal riffle areas are increasingly associated with rippled flow.

These observations suggest that variations in 'within-biotope' heterogeneity and response to increasing discharge mean that the accurate representation of field conditions by rapid survey may vary between different biotopes according to a combination of survey resolution and water level at the time of survey.

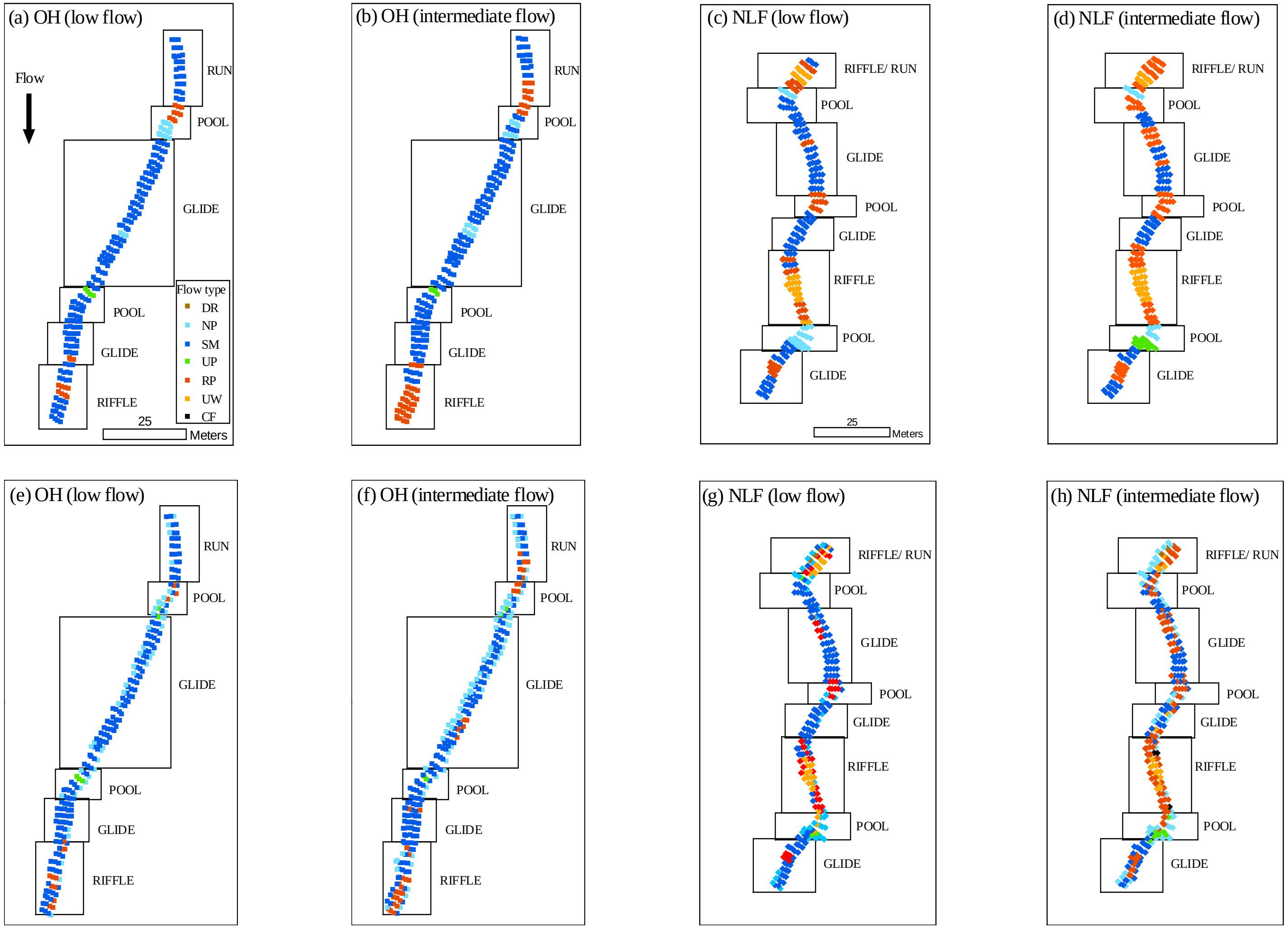


Figure 4.14 Visualisations of surface flow types assessed at the transect level (a to d) and cell-level (e to f) for each site at each flow stage.

4.4.2 Cross-sectional hydraulics

The previous section identified some significant cross sectional variations in surface flow types, with implications for coarser resolution field surveys. However, visual assessments of surface flow types only allow broad inferences to be made regarding underlying hydraulic conditions. Measured hydraulic parameters were therefore used in order to investigate the cross sectional variability in hydraulic behaviour within different physical biotopes in more detail.

Figure 4.15 plots cross section-averaged streamwise velocity and water depth against values measured within each individual cell for different physical biotopes at each site. Overall, the deviation of cell-level hydraulics from the cross section average is greatest at Oakley Hall for both velocity and water depth, reflecting the more significant cross sectional variations in bed topography and flow character identified in previous sections. An increase in scatter with flow stage is noted for Napely Lodge Farm, particularly for the velocity component consistent with the flow intensifications noted in Section 4.3.2. An intensification of velocity is observed for both positive values (downstream flow), reflecting an increase in velocities throughout much of the channel with flow stage, and for negative values (upstream flow) suggesting an intensification of rotational circulations within pool backwaters.

In addition to these more general variations between sites, some variations in the cross sectional hydraulic organisation of different physical biotopes are observed. Glide samples, for instance, are associated with the tightest distributions suggesting greater cross sectional hydraulic homogeneity. Riffles are associated with relatively tight distributions in terms of water depth, but greater variation in velocities, reflecting the

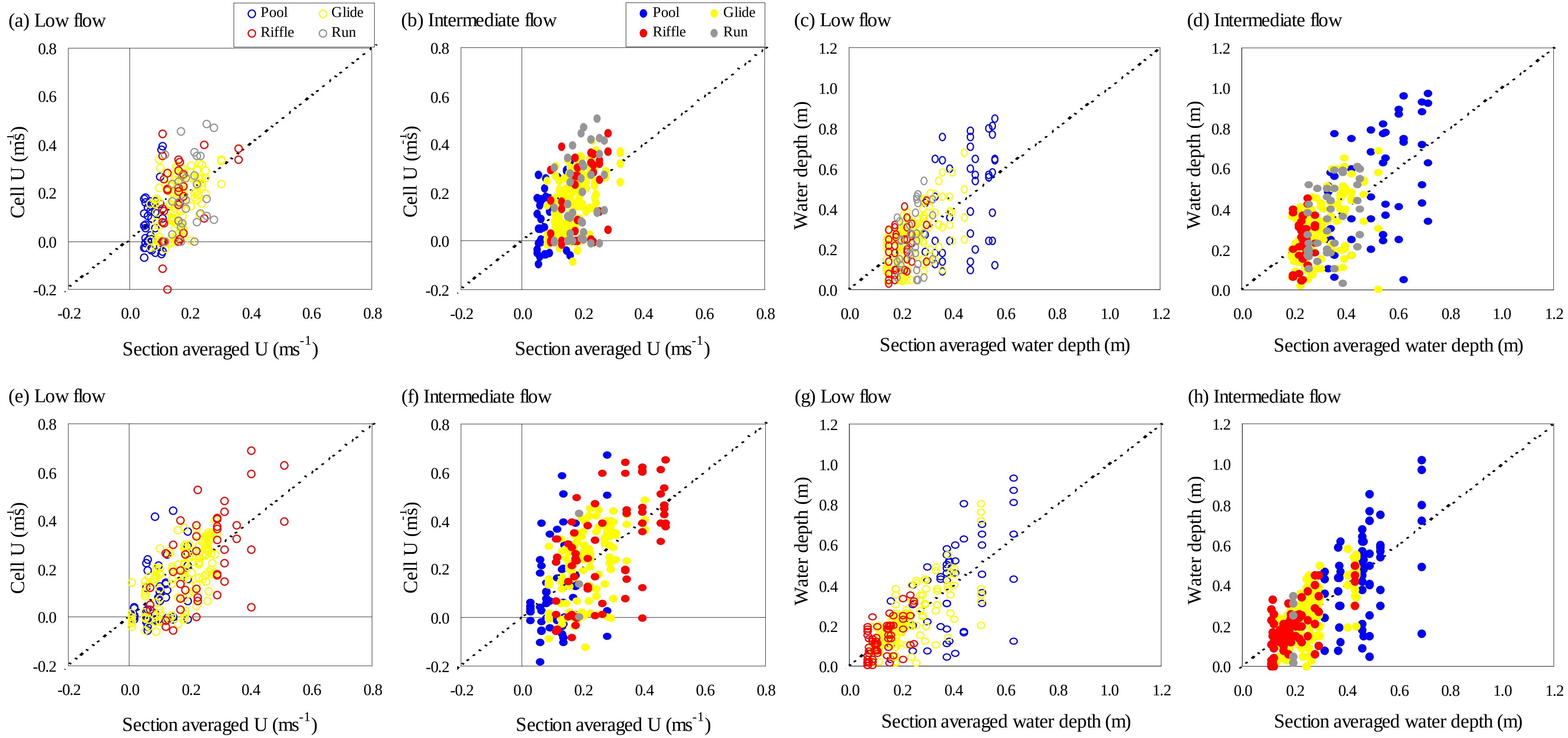


Figure 4.15 Comparison of cross section-averaged and cell-level streamwise velocities and water depths for each physical biotope at low and intermediate flow stage for Oakley Hall (a to d) and Napely Lodge Farm (e to h).

frictional influence of channel margins. In contrast, pools are associated with a tighter range of velocities but large cross sectional variations in water depth which incorporate shallow silted margins and deep mid-pool zones. Both of these characteristics are more pronounced for Napely Lodge Farm where variations in bed topography between physical biotopes are more marked (Section 4.3.1).

Cross sectional symmetry in velocity and depth characteristics may be examined for selected cross sectional profiles for different physical biotopes in Figure 4.16. The simpler channel morphology at Oakley Hall is manifest in greater cross sectional symmetry, particularly in terms of water depth. Profiles at Napely Lodge Farm appear less symmetrical with the exception of the riffle which is associated with relatively high levels of cross sectional symmetry in both velocity and depth. Surveys using half channel width transects for purposes of time- and labour-efficiency (e.g. Kemp *et al.*, 1999) may therefore overlook significant habitat heterogeneity where cross sectional asymmetry is pronounced.

‘Internal’ hydraulic complexity therefore appears to vary both in magnitude and nature between biotopes, supporting the suggestion in the previous sub-section that the effects of sampling resolution on the representation of field conditions will differ between biotopes.

4.4.3 Velocity profiles

The RiverCat profiler was deployed during April 2005 under similar discharge conditions to the ‘intermediate flow’ surveys conducted in March using the handheld FlowTracker. However, even at an ‘intermediate’ flow stage, many cross sections at

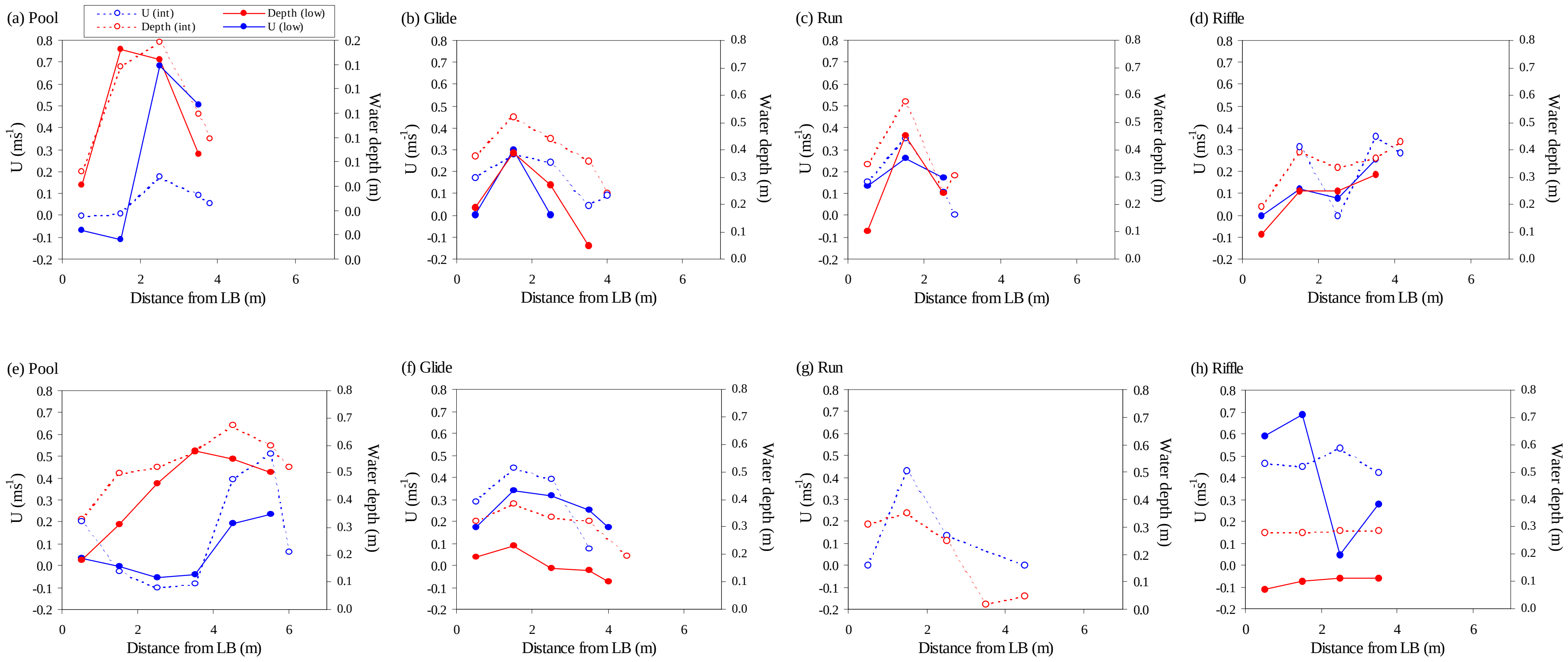


Figure 4.16 Cross sectional velocity and depth profiles from selected transects within each physical biotope at Oakley Hall (a to d) and Napely Lodge Farm (e to h).

the River Tern study sites were too shallow for RiverCat profiling. Where sampling was possible, depths rarely permitted sampling at greater than the minimum of two vertical cells required for data quality purposes (SonTek/ YSI Inc., 2005). Additionally, where bank profiles were particularly shallow, data capture was restricted to central channel areas due to reductions in water depths towards bank locations. This results in a skewing of the RiverCat data set towards higher water depths and a consequent loss of the lower velocity samples representative of marginal areas. This is demonstrated in Figure 4.17 where velocity and depth frequency distributions for each reach derived from RiverCat profiles are compared with data collected using the handheld FlowTracker survey.

While the RiverCat appears unsuitable for sampling in narrow or shallow channels, the equipment does allow very high resolution sampling in deeper channels and incorporates a vertical dimension by sampling cells through the water column as well as in the streamwise and cross stream directions. Vertical and cross sectional velocity variation can then be simultaneously examined for each profiled cross section. Figure 4.18 demonstrates the type of visualisation possible using RiverSurveyor 4.30 (SonTek Software). The small number of vertical cells captured limits interpretation, but some qualitative information can be derived for different biotopes. Pools, for example, are associated with a higher velocity ‘core’ and some cross sectional asymmetry in the depths and velocities of marginal areas. This is particularly significant for the Napely Lodge Farm pool which demonstrates a large, relatively deep backwater zone towards the right bank (RB) and a shallower profile at the left bank (LB). Slower margins are also detectable within the two glide transects, but this is less obvious for the riffles where faster velocities extend further towards the banks.

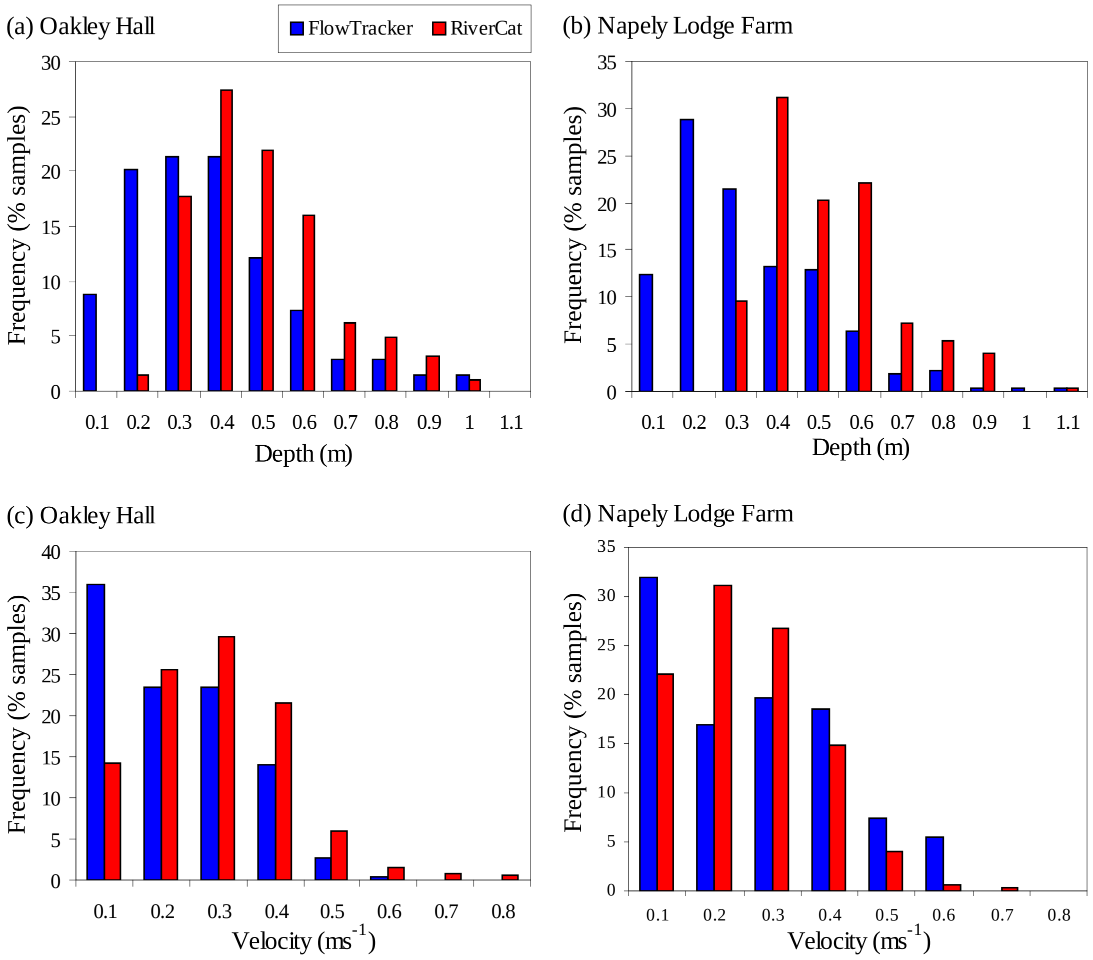


Figure 4.17 Frequency distributions for water depth (a and b) and velocity (c and d) for each site comparing data sets derived from the RiverCat with those obtained using the Handheld FlowTracker.

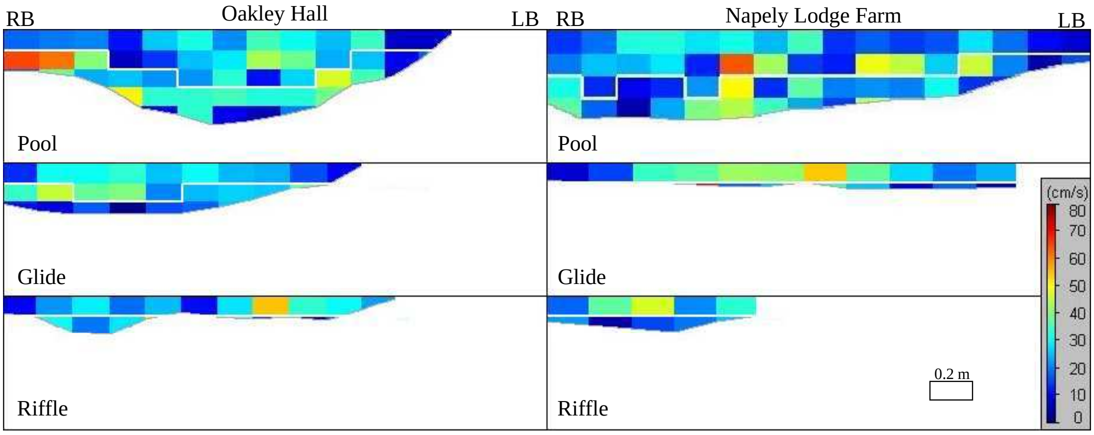


Figure 4.18 Selected RiverCat cross section profiles for physical biotopes at Oakley Hall and Napely Lodge Farm (facing upstream). White line represents the boundary between measured and interpolated (near-bed) cells.

These variations are explored more quantitatively for the pool at Napely Lodge Farm in Table 4.4 and Figure 4.19. Velocities derived from the individual cells visualised in Figure 4.18 reveal a wide range of values and a high coefficient of variation (0.53) emphasising the high levels of heterogeneity (Table 4.4). Figure 5.19a compares individual cell velocities to the mean for the entire cross section. Over 60% of cells fall beyond +/- 20% of the mean value, suggesting that section-averaged values will not provide a representative description of hydraulics within the pool. Furthermore, vertical variation between cells within the same profile appears more significant within the central part of the pool, compared to the margins reflecting the influence of complex secondary circulations.

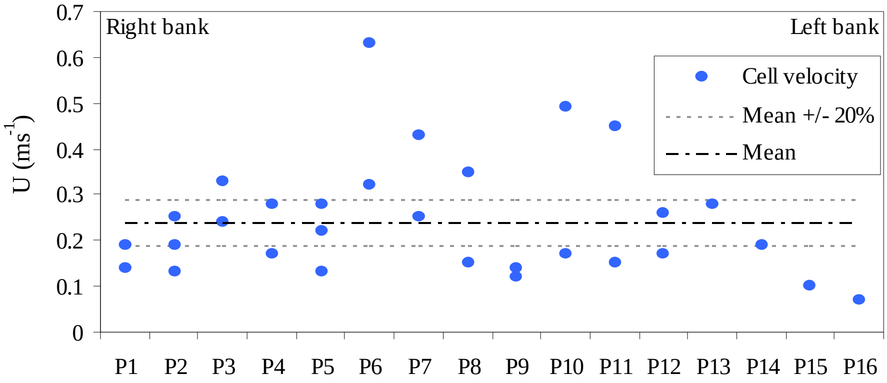
Figure 4.19b plots the cross sectional variation in velocity (as residuals from the cross section mean) for cells closest to the water surface. Even at the same relative depth within the water column, variation in cell velocities with respect to the cross section mean is significant. Velocities fall below the cross sectional mean at channel margins reflecting the frictional effects of banks, but also demonstrate some variability within central channel areas associated with the thalweg and pool backwaters. Thus, assessment of ‘suitable’ habitat for a particular organism based on a single measurement within a transect, or on spatially averaged values may therefore be particularly problematic for the more ‘complex’ physical biotopes.

This type of velocity profiling represents a significant technological development of direct relevance to biotope studies since it allows exploration of channel hydraulics in three dimensions: streamwise, cross stream and vertical. Most biotope studies concentrate only on streamwise and cross stream variations in physical structure, but

Statistics	**Velocity (ms^{-1})**
Average	0.24
Minimum	0.07
Maximum	0.63
Range	0.56
Standard deviation	0.13
Coefficient of variation	0.53
Proportion of samples within 20% of mean	37%

Table 4.4 Velocity statistics for a single RiverCat cross section through the pool at Napely Lodge Farm.

(a) Velocity variation about the pool mean



(b) Velocity variation about the pool mean at the water surface

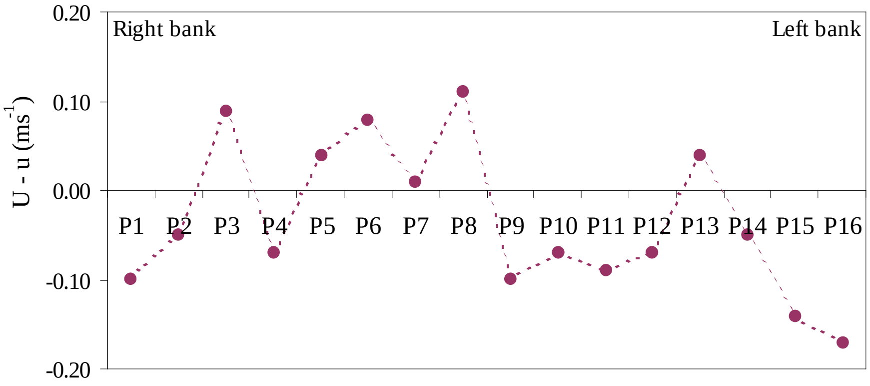


Figure 4.19 (a) Velocity variation throughout the pool cross section with respect to the section-averaged mean and (b) variation about the mean for velocities near the water surface.

high resolution velocity profiling may provide an efficient means of capturing variation in the vertical dimension (through the water column) with the potential for investigating the three-dimensional structure of different biotopes.

4.5 PHYSICAL BIOTOPES AND FUNCTIONAL HABITATS

Chapter 3 identified some broad correlations between functional habitats and physical biotopes, providing some ecological validity to the biotope concept. In the following section, relationships between functional habitats and physical biotopes are explored at finer scales in an attempt to identify whether functional habitats may be ‘mapped’ onto physical biotopes.

4.5.1 Functional habitat distributions

The functional habitats identified by Harper *et al.* (1995) may be subdivided into inorganic (substrate types) and organic (aquatic plants, and habitats associated with riparian vegetation) categories. Due to the ubiquitous nature of substrate and the more localised spatial distribution of vegetation types, the two types of habitat were assessed and analysed separately.

In order to explore the spatial distribution of minerogenic habitats in relation to physical biotopes, visualisations of channel substrate were produced in ArcGIS (Figure 4.20). Substrate composition varies little between surveys for each field site, highlighting the more temporally stable nature of minerogenic habitats compared to the seasonal changes in vegetation cover. At Oakley Hall, substrate types demonstrate the same longitudinally homogeneous ribboning structure identified for bed topography and surface flow types in previous sections, and do not reveal any

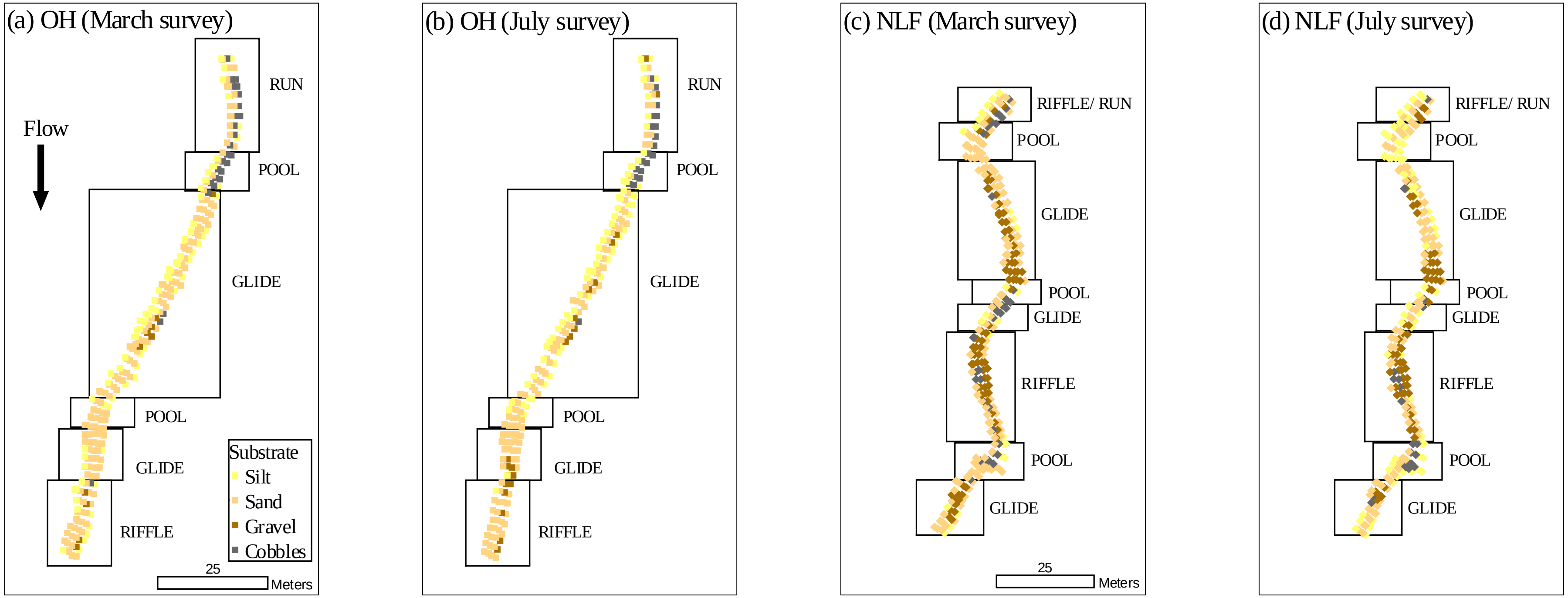


Figure 4.20 Spatial distribution of channel substrate types (minerogenic functional habitats) for each site in March and July 2005.

consistent associations with physical biotopes. Channel margins are generally characterised by silt, and glide and riffle zones are predominantly associated with sand punctuated by patchy shoals of gravel. The pools are characterised by silt and sand in marginal areas, but accumulations of cobbles were found within some mid-pool locations in contrast to observations of finer sediments in pools by Keller (1971) and Lisle and Hilton (1999). These coarser particles are likely to be transported only during the higher magnitude flood events and may have become trapped in pools as flow competence is reduced on the declining limb of the flood.

At Napely Lodge Farm, substrate composition is patchy, consistent with the spatial organisation of topography and flow types, and substrate types show greater variation between biotopes compared to Oakley Hall. The main riffle is characterised by gravel, while glides are associated predominantly with sand and some gravely shoals. Some mid-pool zones are associated with cobble substrates as observed at Oakley Hall, but the more pronounced planform and cross sectional asymmetry of pools at Napely Lodge Farm produce a higher proportion of finer substrates within the large backwater zones consistent with observations by Milne (1982).

Similar visualisations were produced for the organic vegetation types (Figure 4.21 and 4.22). In general, the non-macrophytic, detrital organic habitats associated with riparian vegetation (roots, leaf litter, woody debris) reveal little variation between surveys. However, the distribution of macrophytic vegetation types varies significantly between the start of the growing season (March survey) and the peak of the growing season (July survey). Overall, macrophytic vegetation cover increases at both sites between the surveys, although significant in-channel vegetation cover is

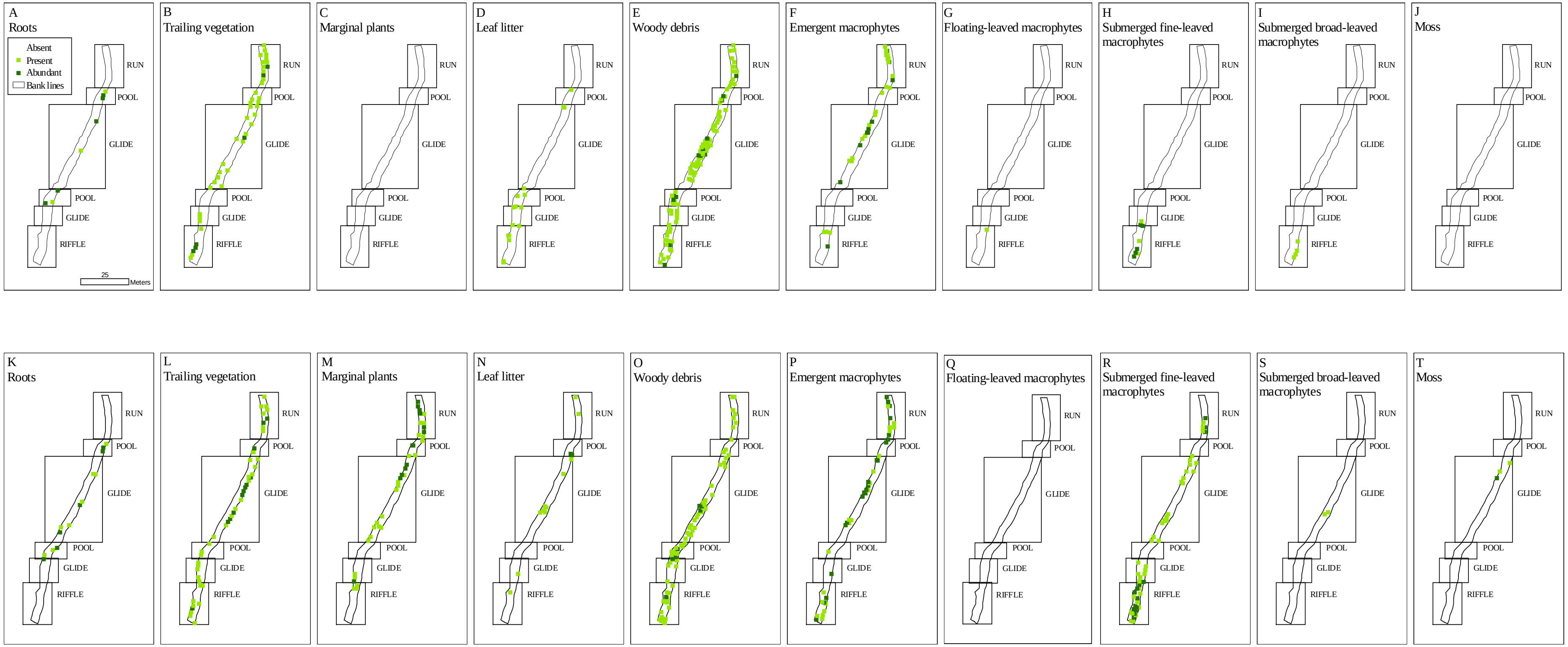


Figure 4.21 Organic functional habitat distributions for Oakley Hall in March (A to J) and July (K to T) 2005.

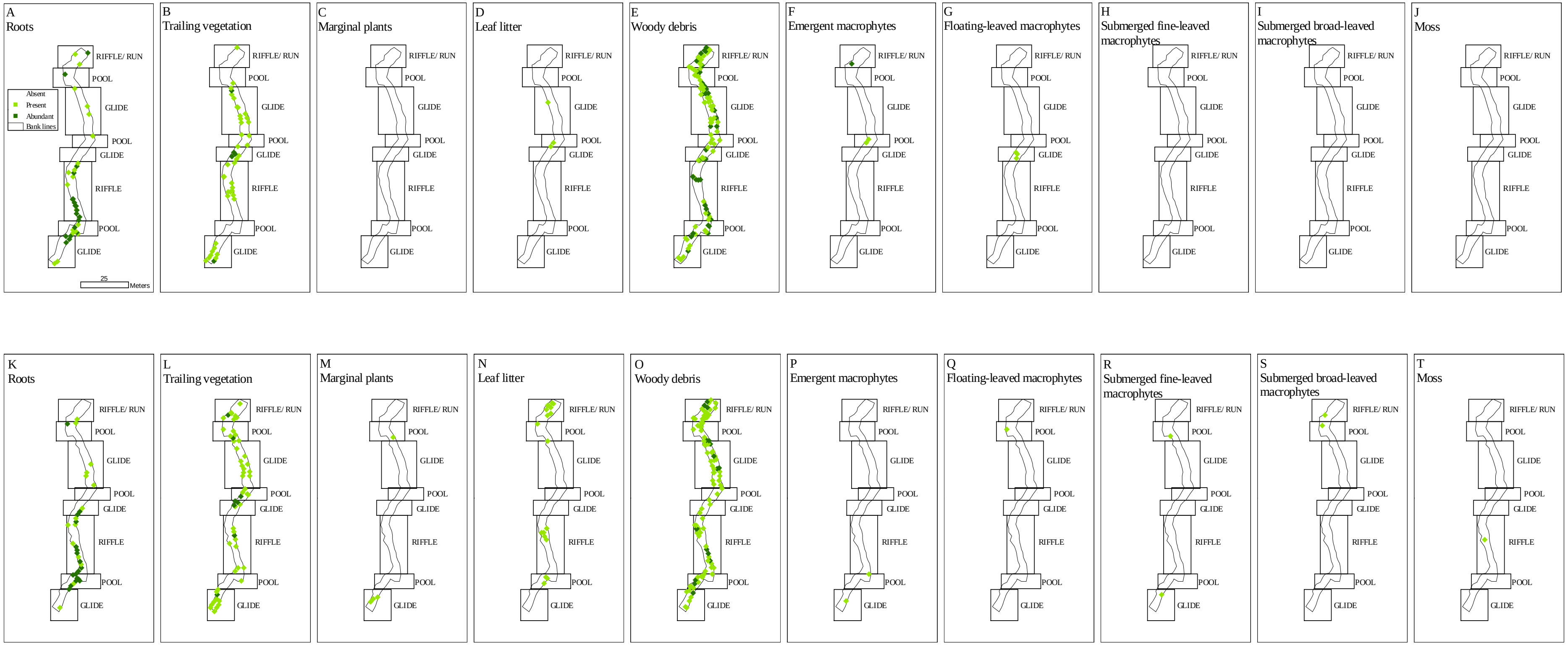


Figure 4.22 Organic functional habitat distributions for Napely Lodge Farm in March (A to J) and July (K to T) 2005..

restricted to Oakley Hall. Two general observations are of particular importance.

First, the magnitude of seasonal change in cover varies between different vegetation types. Most notably, emergent macrophytes show only a moderate increase in cover compared to large increases in marginal plants and submerged fine-leaved macrophytes between surveys, particularly at Oakley Hall. Second, different organic habitat categories demonstrate different spatial distributions which can be described as either ‘patchy’, ‘linear’ or spatially ‘unrestricted’. Roots, leaf litter and submerged fine-leaved macrophytes are associated with a relatively patchy spatial distribution. For submerged fine-leaved macrophytes, this reflects a general preference for shallower areas with coarser substrates for rooting (Fox, 1996), restricting the habitat to riffle locations and gravely shoals within glides at the study sites. Roots are associated with the intrusion of riparian trees into the channel at scour pool locations while leaf litter is predominantly trapped around obstacles such as woody debris. In contrast, trailing vegetation, emergent macrophytes and marginal plants are concentrated along channel margins and are therefore associated with a more linear spatial distribution. Although these vegetation types are found within all biotopes, they appear most abundant within glide units. Small woody debris was observed in abundance at both sites due to the high connectivity between the channel and wooded riparian corridor (< 1 m), and appears relatively unrestricted spatially.

Thus, organic functional habitats may be considered within the context of a two-dimensional matrix of occurrence traits based on seasonal variation and spatial distribution (Table 4.5) which have implications for field surveys and correlations with physical biotopes. The matrix suggests that some of the more ‘patchy’ organic

		SPATIAL DISTRIBUTION		
		LINEAR	**PATCHY**	**UNRESTRICTED**
SEASONAL CHANGE IN COVER	**SMALL**	Trailing vegetation	Roots	Small woody debris
	MODERATE	Emergent macrophytes	Leaf litter	
	LARGE	Marginal plants	Submerged, fine-leaved macrophytes	

Table 4.5 Spatio-temporal distributional characteristics of organic habitats identified on the River Tern.

habitats may map more readily onto physical biotopes while others may be restricted to channel margins but can occur within several different biotopes. These characteristics also suggest that seasonal timing, survey resolution and river size (particularly for marginal habitats) will influence results of rapid visual assessments of habitat features, possibly accounting for some of the observed scatter in the relationships identified in Chapter 3.

4.5.2 Functional habitats, flow types and physical biotopes

In order to explore the correlations between physical and functional habitat at the two study sites, Principal Components Analysis (PCA) was performed on frequency matrices of functional habitats and flow types or physical biotopes in Canoco 4.0 in the same manner as the PCA used in Chapter 3. Only vegetation recordings classified as ‘extensive’ (>30% cover of a 1 m^2 cell) were used in the analysis and data for both sites were combined due to the low sample numbers at Napely Lodge Farm. Three PCA runs were performed on the low flow data set and on the intermediate flow data set in order to assess the relationships between functional habitats and: (i) surface flow types assessed at the transect-level; (ii) surface flow types assessed at the cell level; and (iii) physical biotopes (assessed at the transect-level).

Detrended Correspondence Analysis (DCA) for each data set identified axis 1 gradient lengths below three, meaning that PCA is an appropriate statistical technique for the data (Leps and Smilauer, 2003). For each PCA run, axes 1 and 2 account for over 98% of the variance in functional habitat distributions and therefore analysis focuses on these. Variable loadings for axes 1 and 2 for each data set are provided in Figure 4.23, allowing interpretation of the meaning behind the two axes. For all plots, axis 1

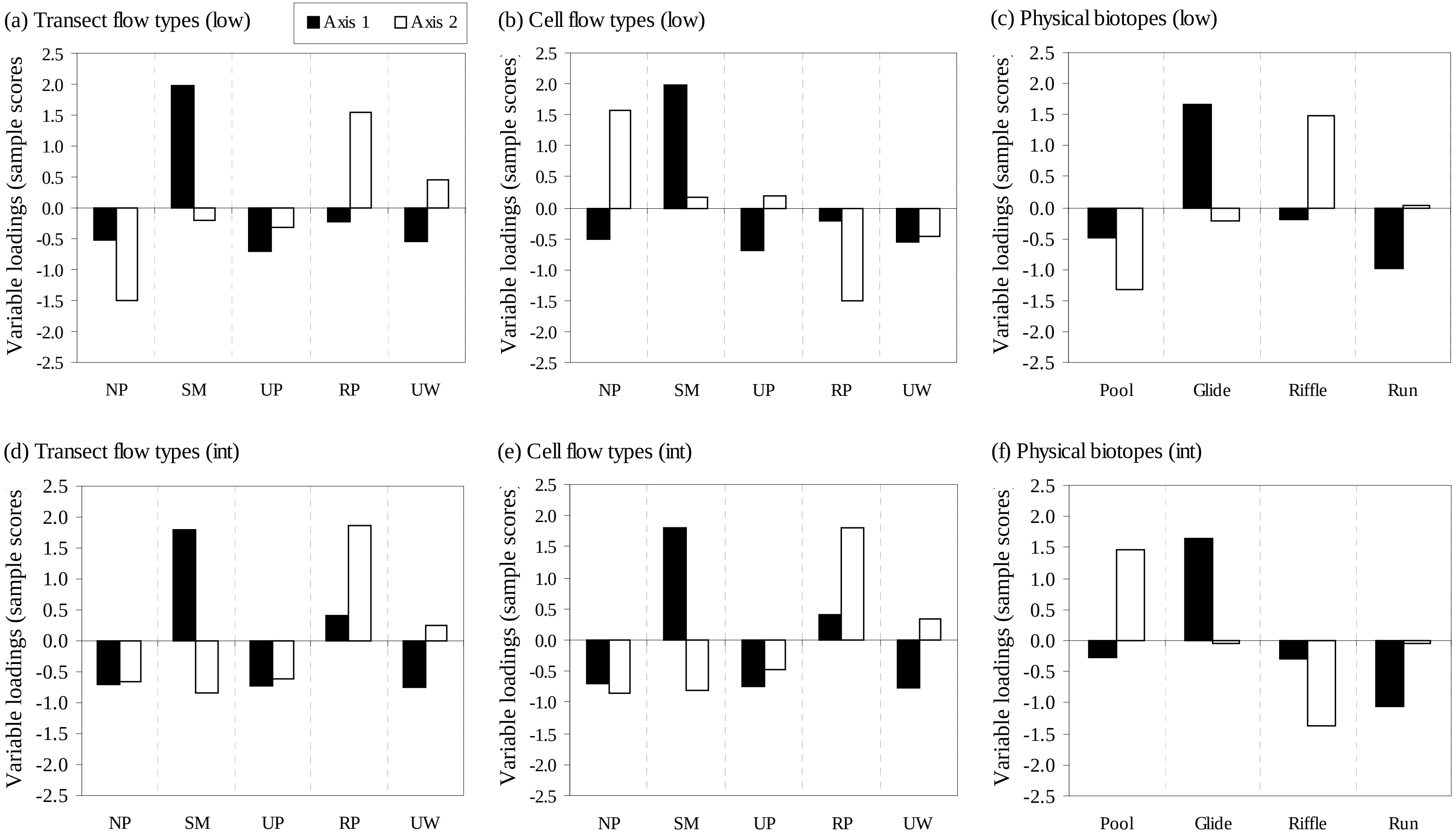
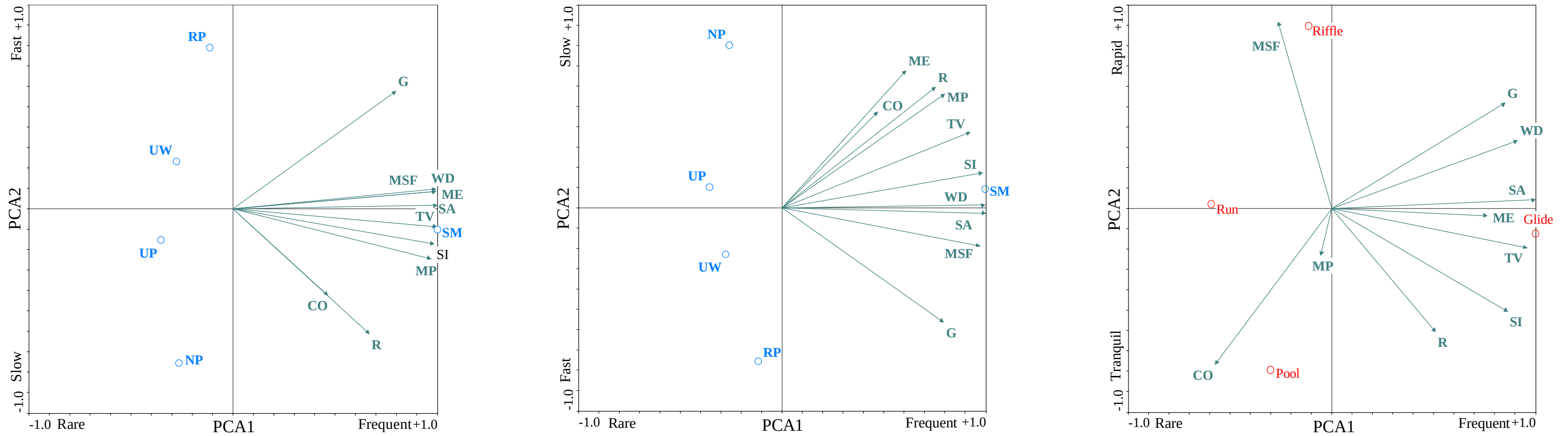


Figure 4.23 PCA axis variable loadings for PCAs performed on functional habitats and transect-level flow types (a and d), cell-level flow types (b and e) and physical biotopes (as visually identified at the transect-level; c and f) at low and intermediate flow stages. See Table 3.1 (p. 53) for flow type category codes.

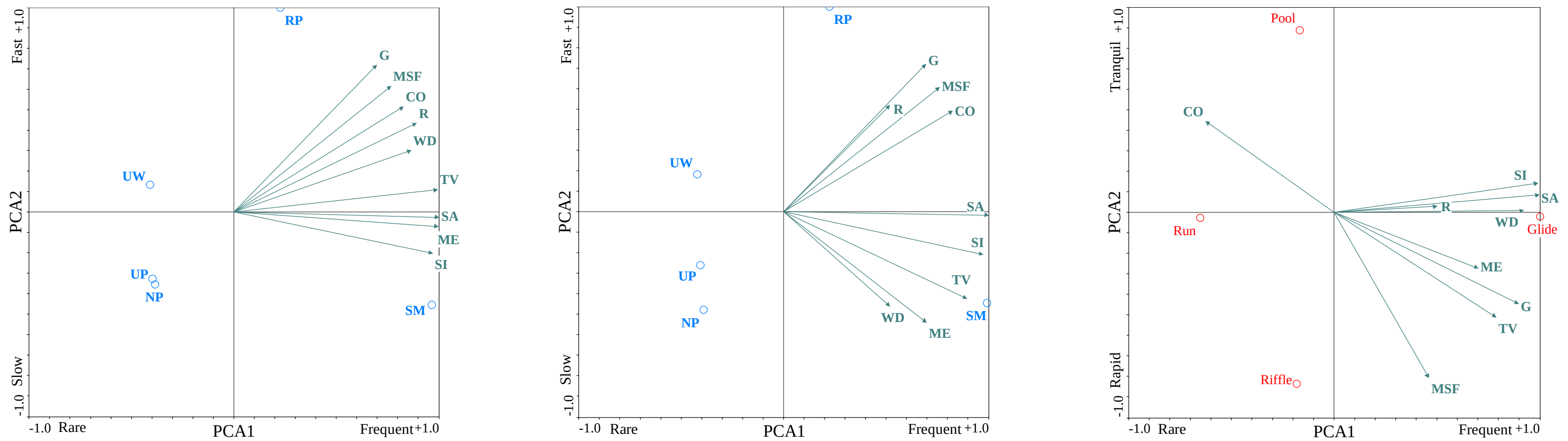
may be considered to represent a transition from frequently occurring flow types (smooth boundary turbulent and rippled flow) or physical biotopes (glide), to rarer flow types (upwelling, unbroken standing waves) or biotopes (run, pool). For the flow type plots, the second axis appears to reflect the transition from slower (no perceptible flow) to faster (rippled flow) flow types similar to the results in Chapter 3. For physical biotopes, the second axis suggests a transition from more tranquil pool biotopes, to transitional glide and run units, to hydraulically 'rougher' riffle environments.

PCA bi-plots are presented in Figure 4.24. Circles represent flow types or physical biotopes, and vectors represent functional habitats. Bi-plots show very similar arrangements for both transect- and cell-level assessments of surface flow characteristics (Figure 4.24 a, b, d and e): plots are strongly dominated by smooth boundary turbulent flow at low flow, with all habitat vectors showing strong correlations with that flow type. At the intermediate discharge, the faster rippled flow type exerts a stronger influence on functional habitat distributions, but there is still little differentiation between habitats on the grounds of flow types.

Overall, differentiation between habitats is less clear than that observed for the national data set analysed in Chapter 3. This is likely to reflect a combination of factors including the smaller spatial scale of assessment (1 m^2 cells) and the size of the sample (which encompasses just two study reaches and will inevitably include less variety than the large national data set examined in Chapter 3). Furthermore, the sequencing of habitat vectors varies both between surveys and between survey resolutions, suggesting that correlations are dependent upon both the type of



(a) Transect flow types (low) (b) Cell flow types (low) (c) Physical biotopes (low)



(d) Transect flow types (int) (e) Cell flow types (int) (f) Physical biotopes (int)

Figure 4.24 PCA bi-plots illustrating the relationships between functional habitats and transect- and cell-level surface flow types and physical biotopes. Flow types or physical biotopes are represented by circles and functional habitats by vectors. See Table 3.1 (p. 53) and 3.8 (p. 63) for flow type and functional habitat category codes.

measurement and the hydrological context of the survey. Physical biotopes provide greater differentiation between functional habitats compared to surface flow types (Figure 4.23 c and f), although the glide exerts a strong influence on the diagrams in a similar way to smooth boundary turbulent flow. Correlations between habitats and biotopes also show less variation between flow stages compared to the flow type plots, reflecting the stage-dependency of flow types and the more temporally stable nature of physical biotopes (Wadeson, 1994).

4.6 HYDRAULIC CHARACTERISATION OF PHYSICAL BIOTOPES

While the previous sections have identified that physical biotopes demonstrate some broad associations with morphology and flow conditions, clear hydraulic distinctions between surface flow types and/ or physical biotopes remain to be demonstrated. The following sections address the fourth research question posed in Section 4.2.2 first by exploring the reach-scale hydraulic organisation of the study reaches and subsequently through two complementary methodological approaches to biotope characterisation outlined in Chapter 3 (Section 3.2.3). The first examines the hydraulic character of subjectively identified physical biotopes and surface flow types following the approach taken by Padmore (1997a), Jowett (1993) and Wadeson (1994), while the second approach focuses on an objective multivariate characterisation of sub-reach scale physical habitat in line with more recent work by Clifford *et al.* (2002a), Clifford *et al.* (2002b), and Emery *et al.* (2003).

4.6.1 Reach-scale hydraulics

Frequency distributions of three-dimensional flow velocity and water depth at low and intermediate discharges provide an overview of reach-scale hydraulics at each field site (Figure 4.25). Frequency distributions for all three velocity components (streamwise, cross stream and vertical) are more leptokurtic for the Oakley Hall site, suggesting a more spatially homogeneous velocity field. Cross-stream and vertical velocities are also very low, reflecting the smooth boundary turbulent conditions which were observed to dominate the reach. Napely Lodge Farm is associated with a more obvious shift to higher streamwise velocities at the intermediate discharge which is accompanied by an intensification of cross stream and vertical velocities. In contrast to the more complex response of flow velocities, water depths show a systematic increase with discharge at both sites.

The spatial organisation of velocity and depth characteristics may be assessed statistically using semivariograms in a similar way to bed topography (see Section 4.3). Figure 4.26 presents semivariograms for the three velocity components and water depth using a lag interval of 2 m. Several points are worthy of note. All semivariograms are associated with a 'nugget effect' suggesting that flow variation at microscales associated with individual clasts and microtopography is not accounted for by the sampling interval. Overall semivariance is lower for velocity compared to water depths, and cross stream and vertical velocities are associated with particularly low levels of semivariance and a horizontal approach to the sill, suggesting a lack of spatial organisation and a homogeneous velocity structure as identified from frequency distributions.

Semivariograms for the streamwise component are associated with higher overall levels of semivariance and some variations between sites and across flow stages. At Napely Lodge Farm, streamwise velocities demonstrate a more characteristic

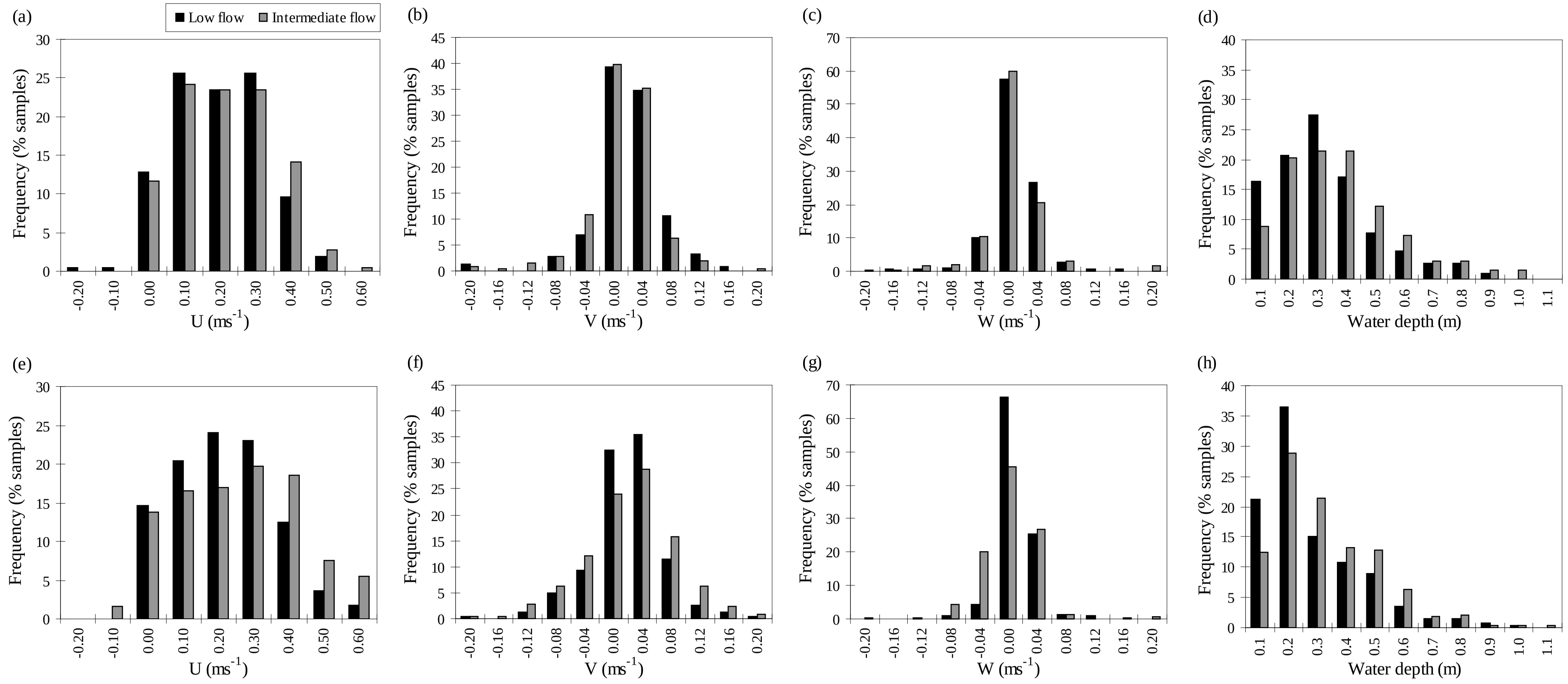


Figure 4.25 Frequency histograms for three-dimensional flow velocity and water depth for Oakley Hall (a to d) and Napely Lodge Farm (e to h) for low and intermediate discharges.

variogram shape at the lower flow stage. However, semivariance appears to decrease with increasing discharge, suggesting the development of a more homogeneous velocity structure as the effects of bedform controls are drowned-out (Clifford *et al.*, 2002a; Emery *et al.*, 2003). A similar situation is noted for Oakley Hall, but overall semivariance levels are lower suggesting that the velocity field is comparatively more homogeneous.

Semivariograms for water depth are associated with the highest overall levels of semivariance and most pronounced variogram form. This is perhaps to be expected, since water depths are more strongly controlled by bed topography and discharge, while velocity variation is also associated with flow obstructions and roughness elements of varying size (see Chapter 5). Greater evidence of spatial organisation in water depths is noted for Napely Lodge Farm where the semivariograms are characterised by an increase in semivariance up to lag intervals of approximately 18 m and a subsequent decline into the next riffle-pool couplet, suggesting a ‘containment’ effect of bedforms (Clifford *et al.*, 2002a). At both sites, overall semivariance is greater for the higher flow stage, in contrast to the homogenisation observed in velocities, possibly reflecting the incorporation of marginal areas with more irregular bank and bed structures into the wetted perimeter as stage rises. At Oakley Hall, a more typical range and sill form is noted for variograms. However, at the higher flow stage semivariance continues to increase throughout the 40 m lag distance, implying a reduction in spatial organisation perhaps related to the ponding of flow downstream by large woody debris.

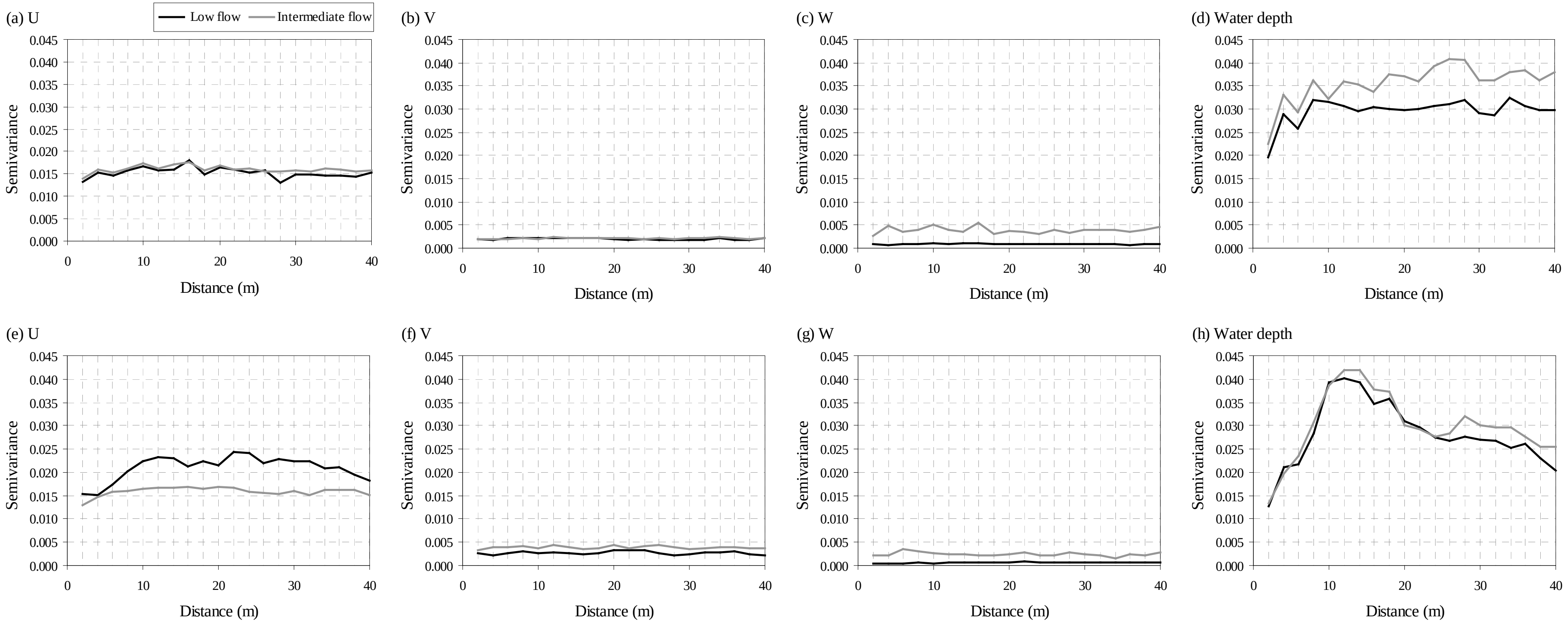


Figure 4.26 Semivariograms for three-dimensional flow velocity and water depth calculated for a total of 20 lags using a lag interval of 2 m for Oakley Hall (a to d) and Napely Lodge Farm (e to h) for each flow stage.

Spatial variation in streamwise velocity and water depth may be explored visually in Figure 4.27 using TINs produced in ArcGIS 8.3. The spatial homogeneity of velocities at Oakley Hall identified in Figures 4.25 and 4.26 is again manifest in the longitudinal 'ribboning' structure which results in little obvious differentiation between visually identified physical biotopes. At Napely Lodge Farm, the velocity structure exhibits a similar patchy distribution to that noted in previous sections, consistent with the higher levels of semivariance noted for Figure 4.26, although there is still some 'overlap' in velocities between physical biotopes. Patchiness is reduced to some extent at the higher flow stage as velocities along the thalweg become faster and more similar between biotopes, consistent with increased homogeneity resulting from the drowning-out of morphological controls. In addition to the intensification of flow along the thalweg, however, backwater zones associated with upstream flow in pools become larger and the magnitude of upstream flow is strengthened as discharge increases. The combined effect of these flow intensifications leads to an increase in cross sectional hydraulic variation, particularly within pools. These characteristics are particularly pronounced at Napely Lodge Farm where pool planform and topography was more marked, creating significant backwater areas associated with rotational circulations.

In contrast to velocity structure, water depths are associated with a relatively 'patchy' spatial organisation at both sites and show greater consistency with the organisation of physical biotopes within the channel, consistent with the variogram structures identified in Figure 4.26.

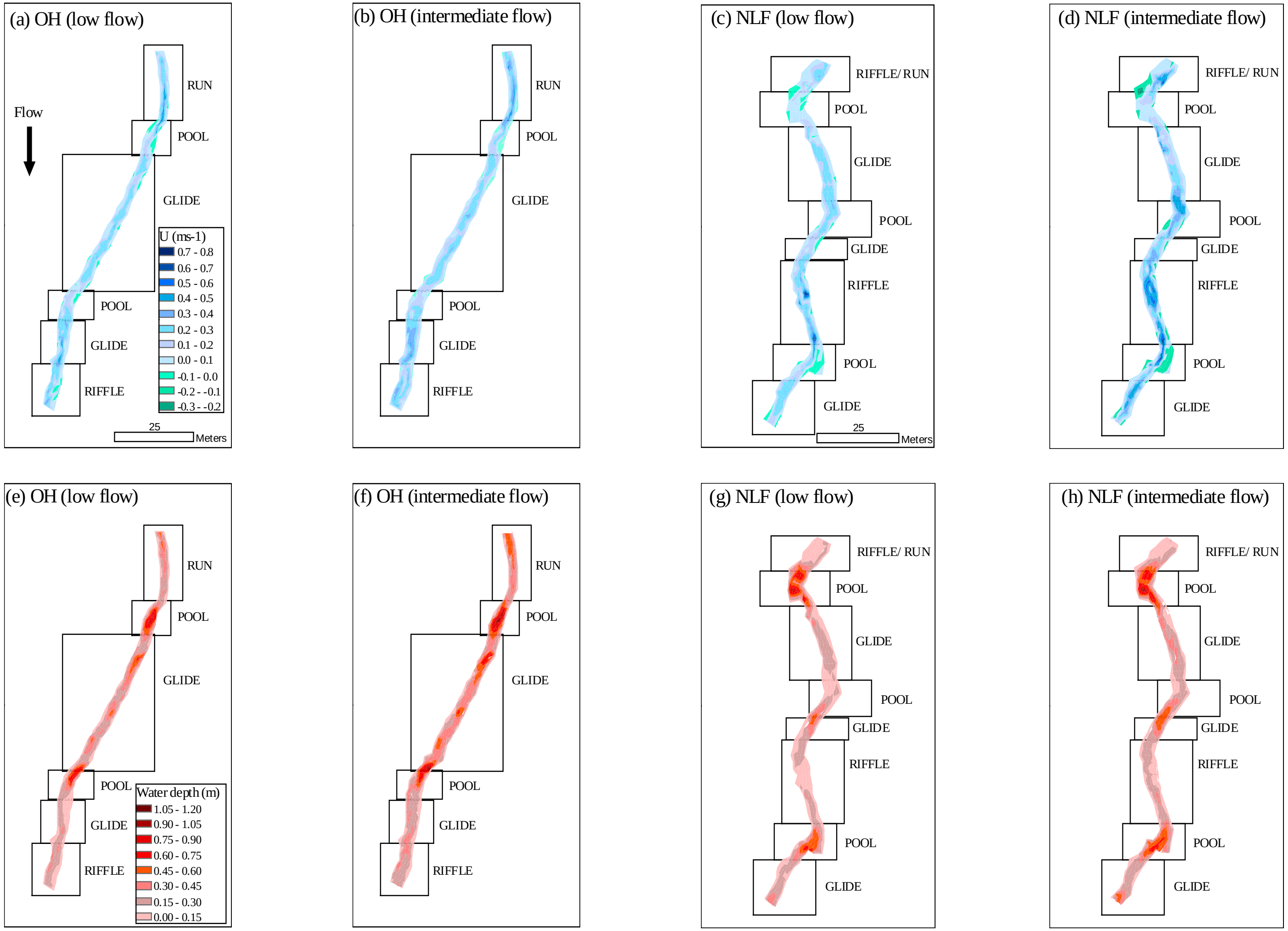


Figure 4.27 TIN surfaces for streamwise velocity (a to d) and water depth (e to h) for each site at low and intermediate flow stages.

4.6.2 The hydraulics of physical biotopes and surface flow types

In order to explore the hydraulics of biotopes and flow types more explicitly, the ranges of simple hydraulic parameters (velocity, depth and Froude number) were examined for each physical biotope and flow type category.

As introduced in Chapter 3, Froude number ($Fr = U/\sqrt{gd}$) is frequently used in biotope studies as a convenient means of simultaneously considering velocity and depth characteristics. Figure 4.28 plots the range, interquartile range and median Froude values for each physical biotope and surface flow type (for both transect-level and cell-level assessments) using box plots. A significant amount of overlap in Froude ranges and interquartile ranges is noted between categories. However, several general features are observed. Plots reveal a broad transition of increasing median values and ranges from more ‘tranquil’ biotopes (pool, glide) to hydraulically rougher run and riffle units consistent with the ‘continuum’ described by Jowett (1993). A similar pattern is noted for flow types with a transition from slower flow types (no perceptible flow, upwelling), through intermediate flow types (smooth boundary turbulent and rippled flow), to faster flow types (unbroken standing waves). Furthermore, slower biotopes and flow types are associated with ‘tighter’ ranges of Froude number compared to faster categories, consistent with similar patterns observed for larger scale ‘landscape’ variables such as slope and altitude in Chapter 3 (Section 3.5.2). Therefore both broad-scale and localised environmental ‘preferences’ of flow types are more specific for the slower biotopes than for faster biotopes which appear to persist in a wider range of environmental and hydraulic contexts.

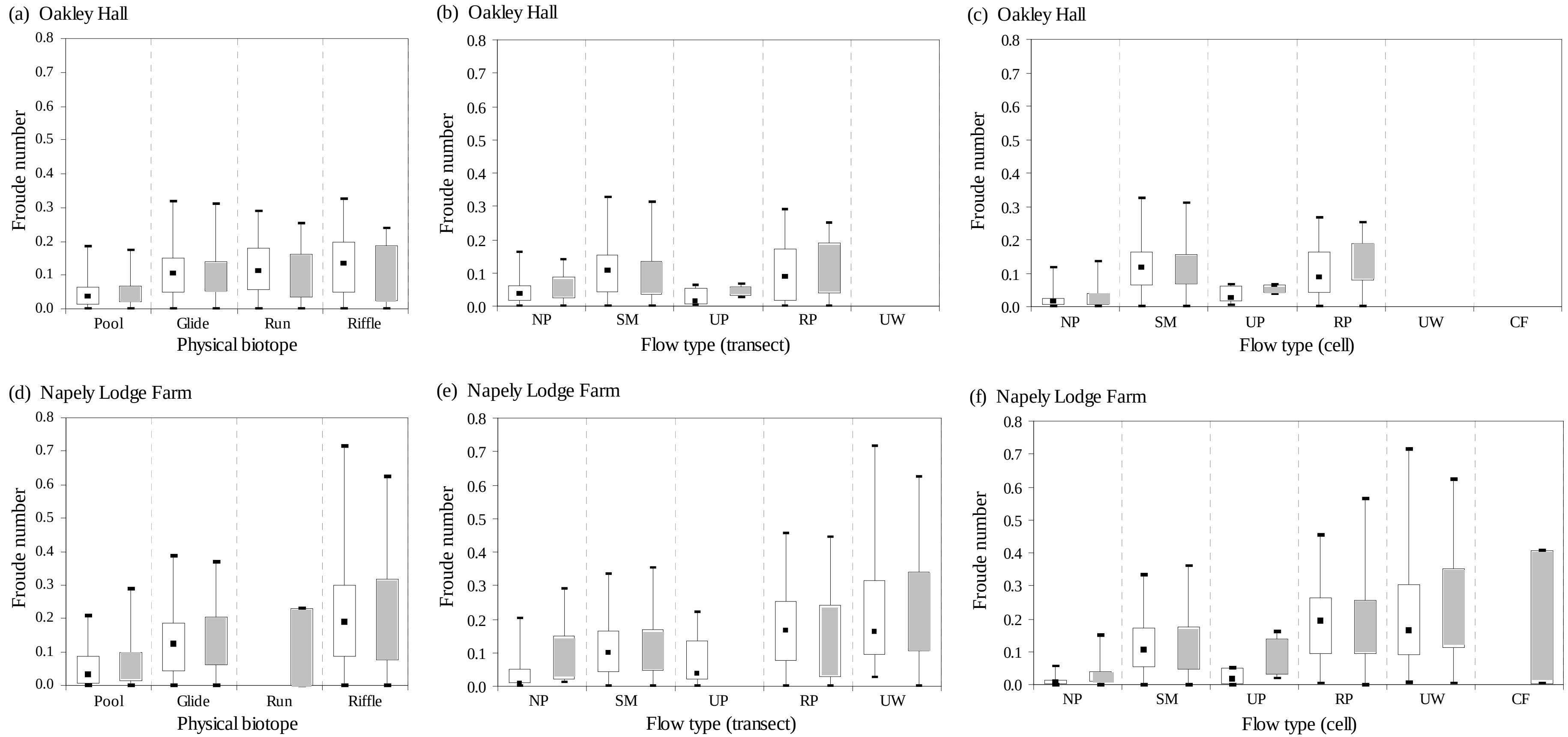


Figure 4.28 Froude number box plots for physical biotopes (a and d), transect-level flow types (b and e) and cell-level flow types (c and f). Boxes represent interquartile range, whiskers absolute range and points median values. White boxes represent low flow, grey boxes intermediate flow. See Table 3.1 (p. 53) for flow type category codes.

Froude ranges for flow types assessed at the transect-level are greater than those for flow types assessed at the cell level, reflecting the influence of cross sectional variations in hydraulics outlined in Section 4.4. Additionally, some flow types show more pronounced variations in Froude range and median values with increasing discharge. Slower flow types such as no perceptible flow and upwelling, for instance, show more pronounced increases in the range of Froude values compared to smooth boundary turbulent and rippled flow which are associated with a similar range of values across discharges. This may reflect localised intensification of flow conditions in certain parts of the channel, consistent with observations in previous sections, and suggests that relationships between surface flow characteristics and underlying hydraulics may be complex and dynamic. This feature is less obvious for physical biotopes, however, which show less variation in Froude values with stage, possibly suggesting that aggregate biotope hydraulics may be retained despite more localised flow variation at microscales ‘within’ physical biotopes.

However, as introduced in Chapter 3 (Section 3.2.3), the use of Froude number as a descriptor of hydraulic behaviour is associated with some limitations. In particular, since the Froude number is a dimensionless ratio, very different velocity and depth combinations of velocity and depth can produce similar Froude numbers, potentially obscuring hydraulic variation between biotopes. Velocity-depth distributions for physical biotopes and flow types are therefore plotted as bivariate scatterplots in Figure 4.29 for comparison.

Figure 4.29 (a) and (e) plot the velocity-depth ranges for binned Froude number classes for each site in order to demonstrate how similar Froude ranges are associated

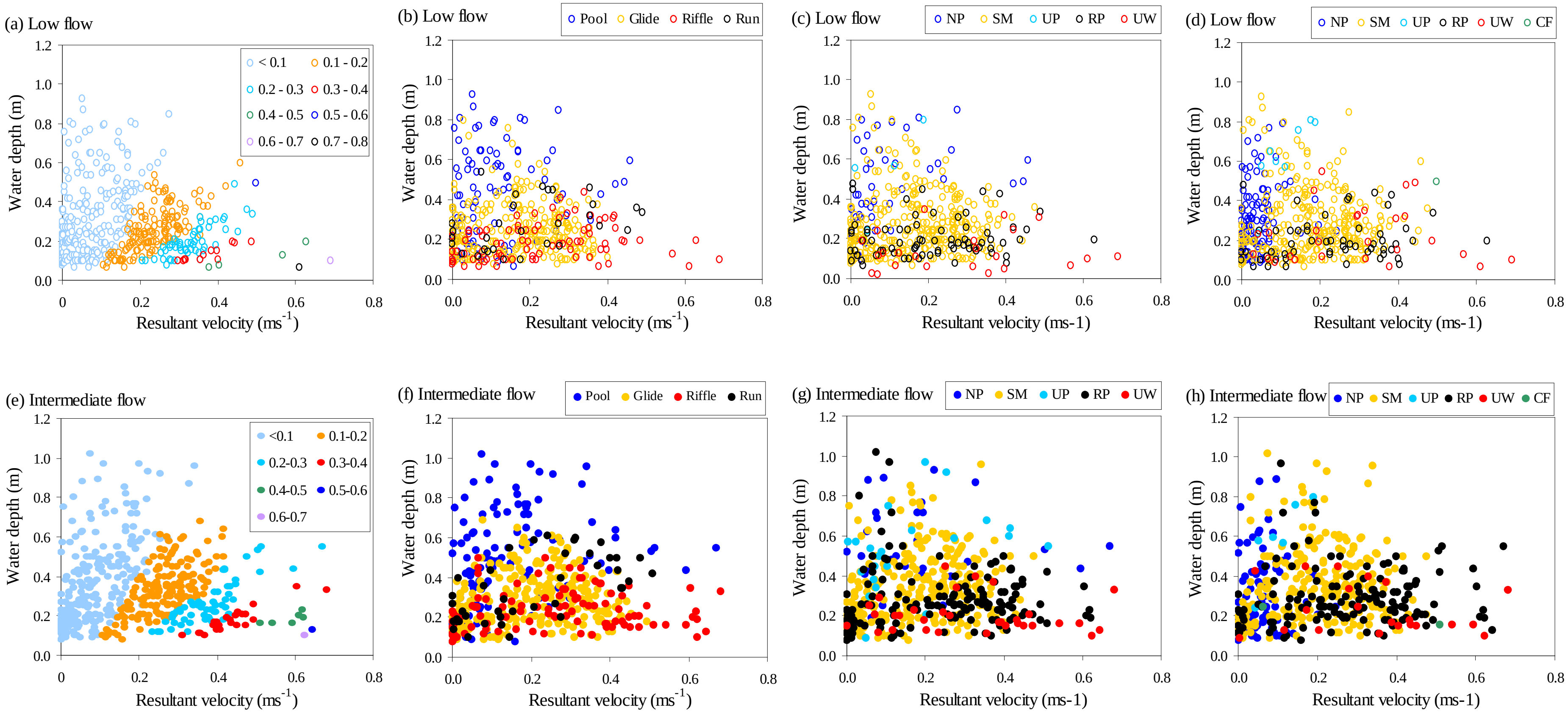


Figure 4.29 Velocity-depth distributions by flow stage (both sites) for different Froude number classes (a and e), and for different physical biotope (b and f), transect-level flow type (c and g) and cell-level flow type (d and h) categories. See Table 3.1 (p. 53) for flow type category codes.

with varied combinations of velocity and depth. Additionally, these ranges are observed to traverse the velocity-depth distributions of flow types and physical biotopes. Furthermore, significant scatter in velocity and depth values is observed across both physical biotope and flow type categories, which appears to increase with flow stage. This reduction in hydraulic 'coherence' of biotopes at the higher flow stage may be expected for physical biotopes as a result of the combined effect of flow intensification and drowning out of hydraulic controls. However, for flow types, this further emphasises the complex and potentially stage-dependent relationships between surface flow characteristics and underlying hydraulics identified previously from the Froude box plots.

However, distributions in Figure 4.29 do reveal some discrimination between physical biotopes and flow types on the basis of either velocity or water depth. In general, hydraulically 'rougher' physical biotopes (run, riffle) and flow types (rippled flow, unbroken standing waves) are associated with a range of velocities but are restricted to predominantly shallow zones. In contrast, 'slower' physical biotopes (pool) and flow types (no perceptible flow, upwelling) are associated with a wider range of water depths but are restricted to a relatively narrow range of low velocities (Figure 4.29). This creates some variations in the two-dimensional 'shape' of physical and flow biotopes in bivariate space. Distributions of faster biotopes and flow types are elongated along the velocity axis while distributions of slower biotopes and flow types are elongated along the depth axis. 'Intermediate' biotopes and flow types (glide and associated smooth boundary turbulent flow type) are associated with a more spherical distribution reflecting similar levels of variation in velocity and depth. These characteristics may have significance for species or lifestages which have stronger preferences for either velocity (e.g. in relation to swimming speeds) or water depth (e.g. in relation to cover associated with visibility).

These details are overlooked by the use of Froude number which identifies only a broad increase in values towards supercritical conditions with the transition from slower to faster flow types and physical biotopes. This emphasises the inadequacies of Froude as a hydraulic descriptor as introduced in Chapter 3 (Section 3.2.3), since very different velocity and depth combinations may be associated with a similar Froude values. Furthermore, the use Froude overlooks characteristic variations in the range of *either* velocity or depth for different physical biotopes.

The significant amount of overlap in velocity and depth characteristics between biotopes, however, suggests that additional hydraulic parameters are required for characterisation, assuming that biotopes are in fact hydraulically distinct. Relationships between flow, substrate and vegetation types identified in Chapter 3 suggest that substrate may be used as an additional variable for characterising physical biotopes and consequently predicting the distribution of vegetative functional habitats. To test this hypothesis, the following section employs multivariate statistical analysis to simultaneously consider velocity, depth and substrate in an attempt to objectively characterise physical habitat within the channel.

4.6.3 A multivariate approach

K-means cluster analysis was performed (using SPSS 14.0) initially on four separate data sets, one for each site at each flow stage. K-means clustering is an ‘arbitrary origin’ method of clustering which requires the specification of a number of initial cluster centres, to which observations are matched according to similarity. The attributes of each cluster centre are then recalculated as observations are added (Davis, 2002). An element of subjectivity is introduced into the analysis by the requirement for user-specification of the number of clusters, but this must be weighed against the shorter computation times for larger data sets compared to hierarchical clustering methods (see Section 3.6.3). Here, the selection of the number of cluster centres was based on work by Emery (2003) which identified that six clusters best described the hydraulic variation within two reaches, one of which included part of the Napely Lodge Farm study site itself. Furthermore six clusters corresponds to the maximum variation in surface flow character visually observed at the study sites (six flow types were identified in total at the cell-level), suggesting that this level of data reduction is appropriate.

Clustering was performed first using streamwise velocity (U), water depth and substrate category, and second by adding cross stream and vertical velocity components to the first set of variables in order to identify whether three dimensional velocity characteristics improve clustering outcomes. Data for each site and flow stage were clustered separately in order to allow for site-specific variations in physical habitat structure. The physical characteristics associated with each final cluster centre are provided in Appendix A. Table 4.6 summarises this information using descriptive terms for each cluster which refer to relative variations in velocity, depth and substrate characteristics described below.

Two clusters were consistently identified by all analyses: a ‘marginal’ cluster, relating to slow flowing areas of varying water depth characterised by a silty substrate, and a

Clustering variables	**Site**	**Flow Stage**	**Clusters**					
U Water depth Substrate	Oakley Hall	Low flow	Margins	Mid-pool	Pool margins	Glide	Riffle	Run
		Intermediate flow	Margins	Mid-pool	Pool margins	Glide	Riffle	Run
	Napely Lodge Farm	Low flow	Margins	Pool	Glide	Riffle margins	Riffle centre	Run
		Intermediate flow	Margins	Mid-pool	Pool margins	Glide	Riffle gravel	Riffle pebble
U V W Water depth Substrate	Oakley Hall	Low flow	Margins	Pool	Glide	Gravel shoal	Riffle	Run
		Intermediate flow	Margins	Mid-pool	Pool margins	Glide	Riffle	Run
	Napely Lodge Farm	Low flow	Margins	Mid-pool	Pool margins	Glide	Riffle gravel	Riffle pebble
		Intermediate flow	Margins	Pool	Glide	Riffle margins	Riffle centre	Run

Table 4.6 Habitat clusters identified for each data set using different clustering variables.

‘glide’ cluster associated with intermediate velocity and depth values and a sandy substrate. Pool biotopes were generally subdivided into a ‘mid-pool’ cluster associated with the greatest water depths and a cobble substrate (underlain by sand), and ‘pool margins’ characterised by comparatively shallower depths and a sandy substrate. At Oakley Hall, riffle and run biotopes were consistently identified by discrete clusters, while at Napely Lodge Farm, the lack of a significant run feature resulted in subdivision of riffle biotopes by the clustering algorithm with respect to either substrate or flow velocities for different data sets depending on flow stage and variables used.

Visualisation of the spatial distribution of clusters in Figure 4.30 allows some comparison with the distribution of visually identified physical biotopes (represented by labelled rectangles). At Oakley Hall, clusters identified from each analysis show broad consistency with observed channel morphology, but reveal high cross sectional variation in cluster membership reflecting the longitudinal ‘ribboning’ of habitat variables. At Napely Lodge Farm cross sectional variation is reduced, and ‘riffle’ and ‘glide’ clusters generally conform with observed physical biotope distributions. Pool biotopes, however, are associated with a variety of different multivariate clusters and are not clearly distinguished by the clustering algorithm at the low flow stage.

These observations suggest that clustering outcomes are sensitive to site-specific ‘microscale’ variations in hydraulics and are therefore unlikely to be transferable between different reaches. In order to test whether transferable clusters are identifiable between the two sites, clustering was performed on a ‘low flow’ data set

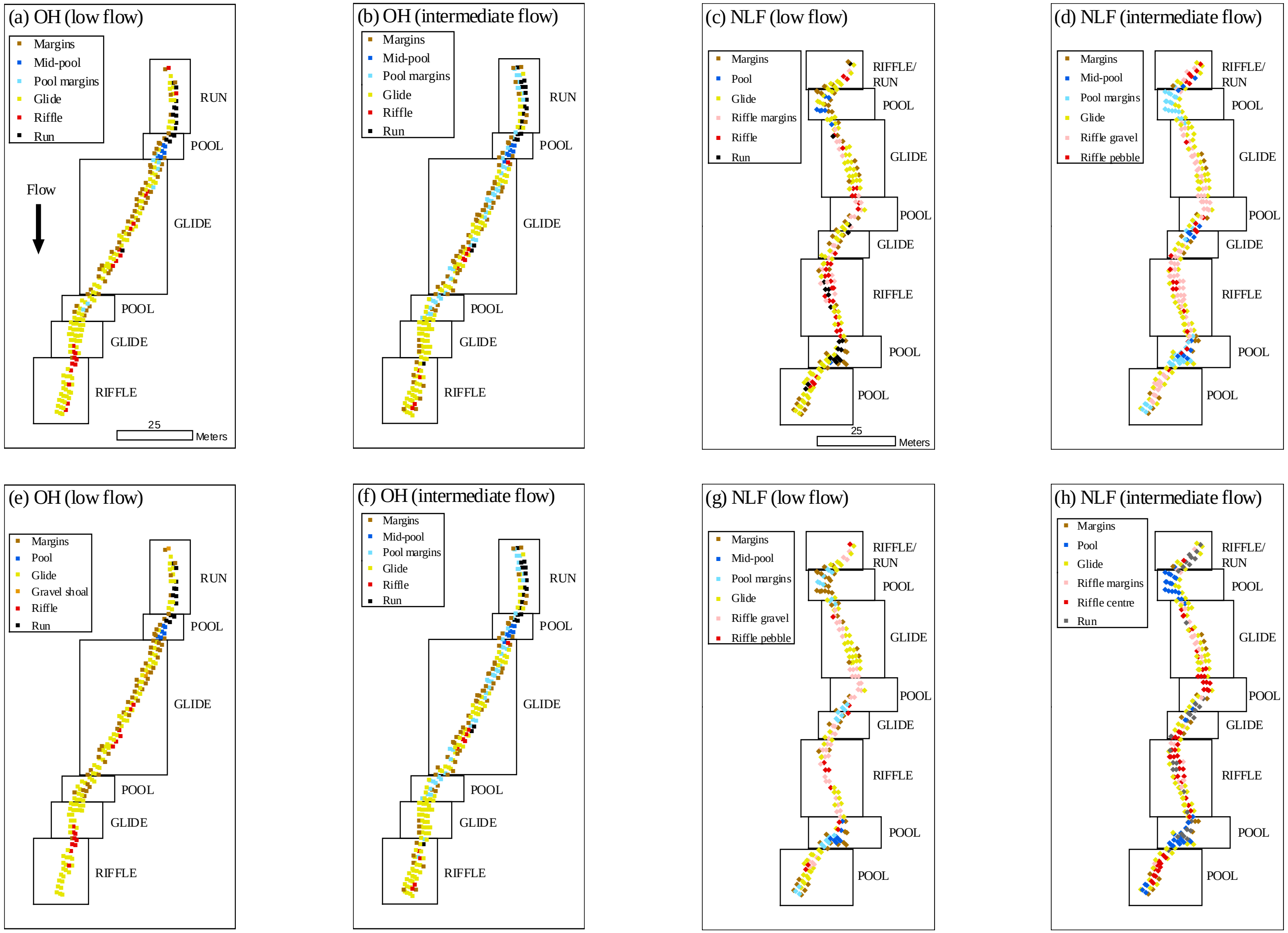


Figure 4.30 Spatial distribution of clusters performed on data sets for each site and flow stage individually using U, depth and substrate (plots a to d) and using U, V, W, depth and substrate (plots e to h).

combining data from both field sites and using the initial three variables of velocity, depth and substrate.

Cluster centre characteristics (Table 4.7) identify ‘marginal’, ‘mid-pool’, ‘pool margin’, ‘glide’, ‘run’ and ‘riffle’ clusters. The ranges of velocity and depth values derived from the data set for each cluster are presented in Figure 4.31. These ranges were used in conjunction with the appropriate substrate category to apply the low flow cluster characteristics to a combined intermediate flow data set and assess changes in cluster membership with increasing stage. This process identified some outlier samples which were not automatically allocated to a low flow cluster. Visual inspection of bivariate plots of the velocity-depth characteristics of these outliers revealed that some of these fell very close to cluster boundaries and these were consequently incorporated into the appropriate cluster. Those lying further beyond cluster boundaries were attributed to one of two additional clusters relating to ‘deep run’ and ‘deep glide’ zones associated with faster velocities and deeper water depths than the respective ‘run’ and ‘glide’ clusters identified at low flow.

Overall, consistency of clusters with observed morphology is improved for combined-site clustering (Figure 4.32). This suggests that the use of relatively ‘broad’ clusters, transferable between the two sites, represents an appropriate level of simplification of physical habitat structure. While the specific clusters identified are unlikely to transferable among a range of different sites, these observations do support the idea of broad ‘assemblages’ of habitat variables which are associated with some overlap in hydraulic ranges.

	Cluster centre characteristics		
Cluster	**U (ms^{-1})**	**Depth (m)**	**Substrate**
Margins	0.03	0.29	Silt
Mid-pool	0.12	0.61	Pebble
Pool margins	0.18	0.48	Sand
Glide	0.19	0.21	Sand
Run	0.19	0.22	Pebble
Riffle	0.27	0.21	Gravel

Table 4.7 Cluster centre characteristics for clusters derived from the combined low flow data set using velocity, depth and substrate variables.

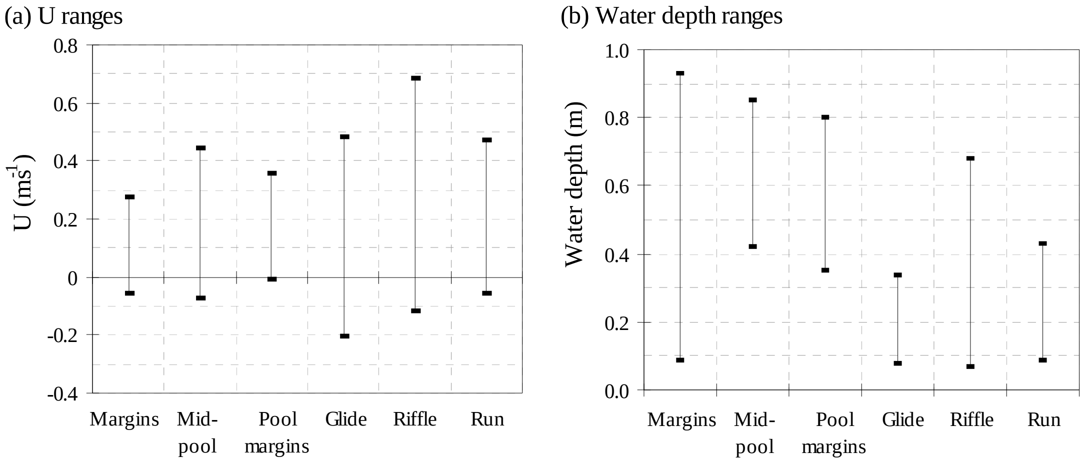


Figure 4.31 Velocity and depth ranges for clusters derived from the combined low flow data set using velocity, depth and substrate variables.

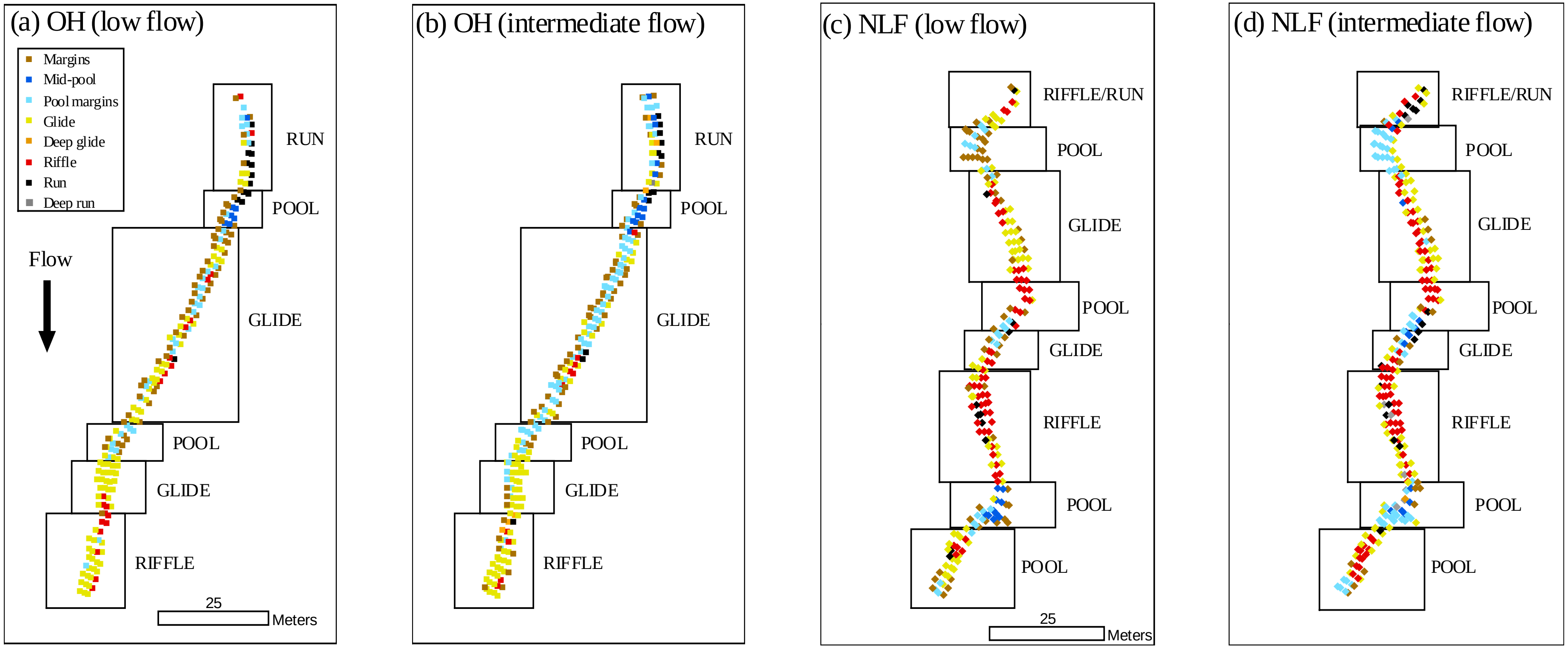


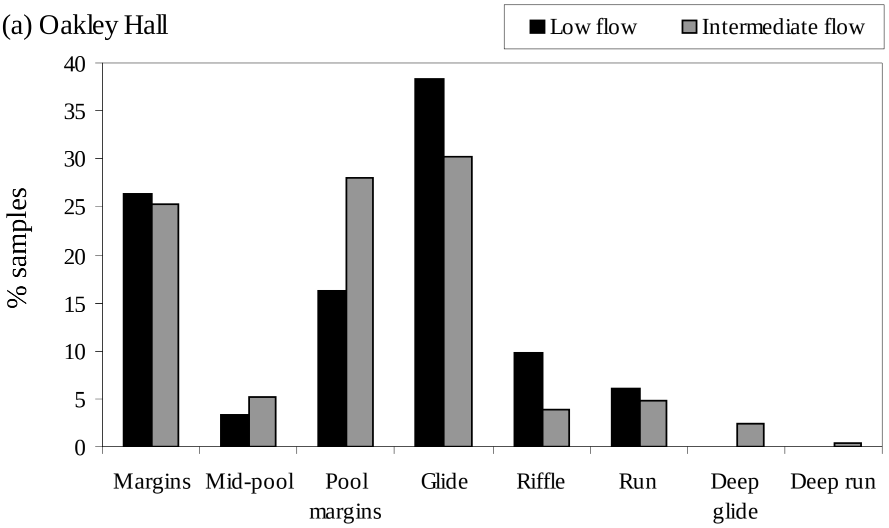
Figure 4.32 Spatial distribution of clusters based on velocity, depth and substrate variables which were calculated using a low flow data combining both study reaches. Cluster boundaries were then applied to the combined intermediate flow data set.

Some variation in the relative proportions of the channel area occupied by each physical habitat cluster is noted both between the two study sites, and with increasing flow stage (Figure 4.33). For instance while glide and riffle clusters occupy similar proportions of the channel at Napely Lodge Farm, glides account for more than twice the channel area occupied by riffles at the lower ‘quality’ Oakley Hall site (see Section 2.3.6). For Oakley Hall these characteristics are consistent with visual observations (Section 4.2.1), but for Napely Lodge Farm the clustering scheme classifies a much larger proportion of the channel as ‘riffle’ compared to visual observation of biotopes, suggesting some inconsistencies between the visual appearance and underlying hydraulics of biotopes.

Channel margins are also more prominent at Oakley Hall and show little variation with stage, compared to Napely Lodge Farm where the majority of marginal areas are lost at the higher discharge. At Oakley Hall large areas of the ‘glide’ biotopes behave more like ‘pool margins’ at the higher flow stage but this is less obvious for Napely Lodge Farm where biotopes remain relatively well ‘contained’ by the stronger bedform controls identified in Section 4.3.1 (Clifford *et al.*, 2002b). However, visualisations suggest increased complexity in the form of cross sectional variations in cluster membership (i.e. ‘patchiness’ at smaller scales), perhaps reflecting the flow intensification around obstacles and bedforms identified in previous sections.

The velocity, depth and substrate characteristics of each cluster maybe visualised using three-dimensional scatterplots (Figure 4.34). While substrate is necessarily restricted to a single plane for each cluster, there is some evidence of variations in the ‘shape’ of velocity-depth distributions for each cluster similar to those identified for

(a) Oakley Hall



(b) Napely Lodge Farm

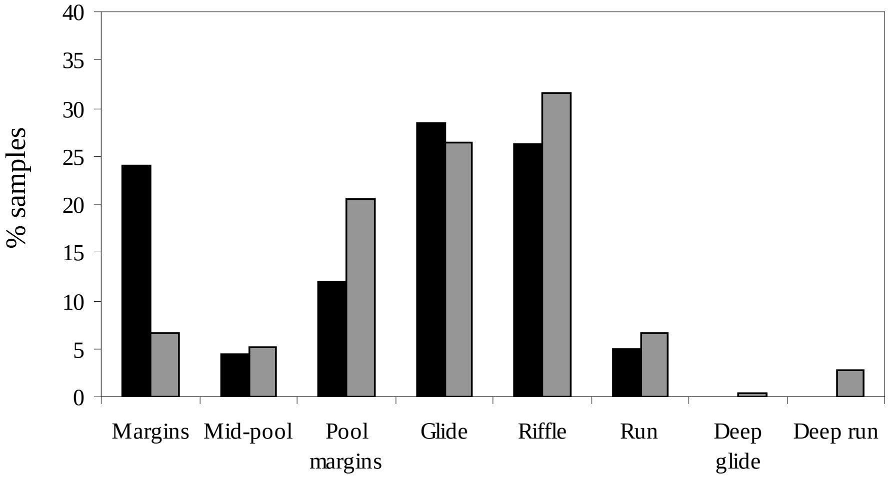


Figure 4.33 The proportion of the sampled channel area allocated to each cluster for each flow stage at (a) Oakley Hall and (b) Napely Lodge Farm.

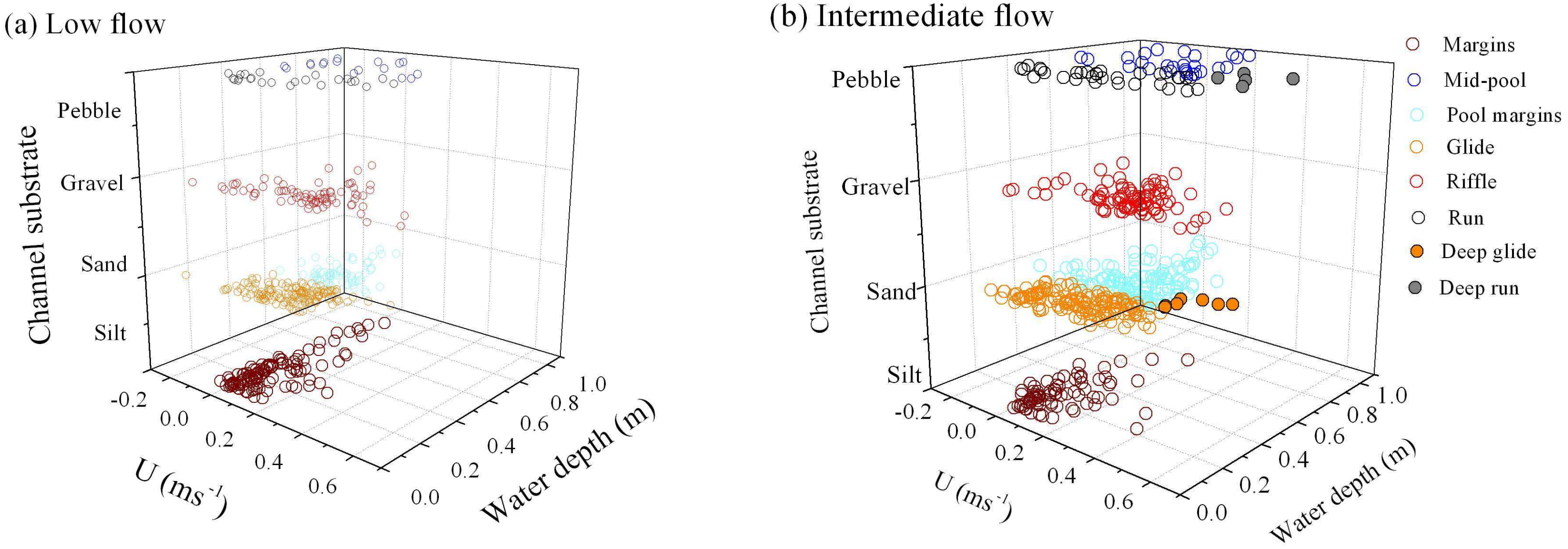


Figure 4.34 Velocity, depth and substrate characteristics associated with each statistically derived cluster for low flow (a) and applied to intermediate flow data (b).

physical biotopes and flow types in Section 4.6.2. The ‘marginal’ cluster, for instance, is associated with a wide range of depths but a narrow range of slow velocities, while ‘riffle’ and ‘pool margins’ clusters show similar ranges in velocity and depth. ‘Run’ and ‘glide’ clusters are associated with a range of velocities but are generally restricted to an intermediate range of water depths. Furthermore, some clusters reveal a change in two-dimensional ‘shape’ with increasing stage as frequency distributions are skewed towards a different range of velocity and depth values. For example, the marginal cluster loses many of the deeper samples at the higher flow stage, suggesting that only shallower areas are retained as low velocity refugia. In contrast, the riffle cluster becomes associated with a narrower range of water depths and the mid-pool cluster is associated with a much faster range of velocities reflecting the jetting effects of flow through the pools as discharge increases (Clifford and Richards, 1992).

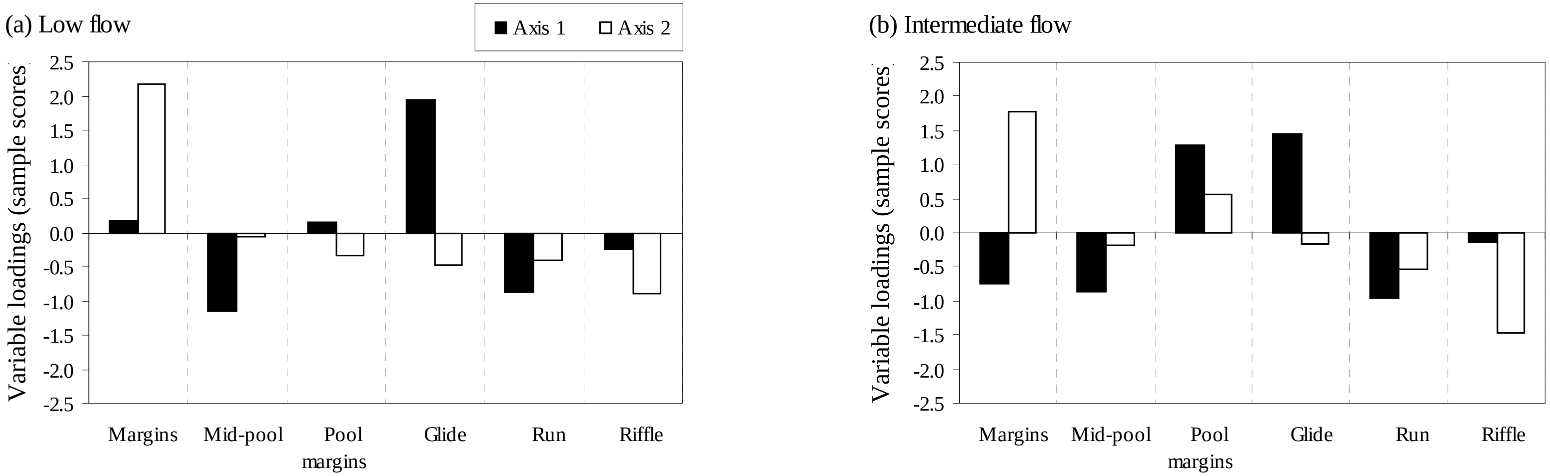
4.6.4 Physical habitat clusters, flow types and functional habitats

In order to explore the relationships between statistically-derived habitat clusters, surface flow types (assessed at the cell-level) and functional habitats (occupying > 30% cover of a 1 m^2 cell), Principal Components Analysis (PCA) was performed on low and intermediate flow data sets (combined for both sites).

In each case, PCA axes 1 and 2 cumulatively account for over 89% of the variance and represent a transition from ‘rare’ to ‘frequent’ and ‘tranquil’ to ‘rapid’ physical habitat clusters respectively (Figure 4.35). PCA bi-plots are presented in Figure 4.36 for each PCA run. Significantly, the flow type PCA reveals some contrasts with widely accepted relationships between flow types and morphology. No perceptible flow, for example, correlates strongly with channel margins rather than pool clusters, which are

(a) Low flow

(b) Intermediate flow



(c) Low flow

(d) Intermediate flow

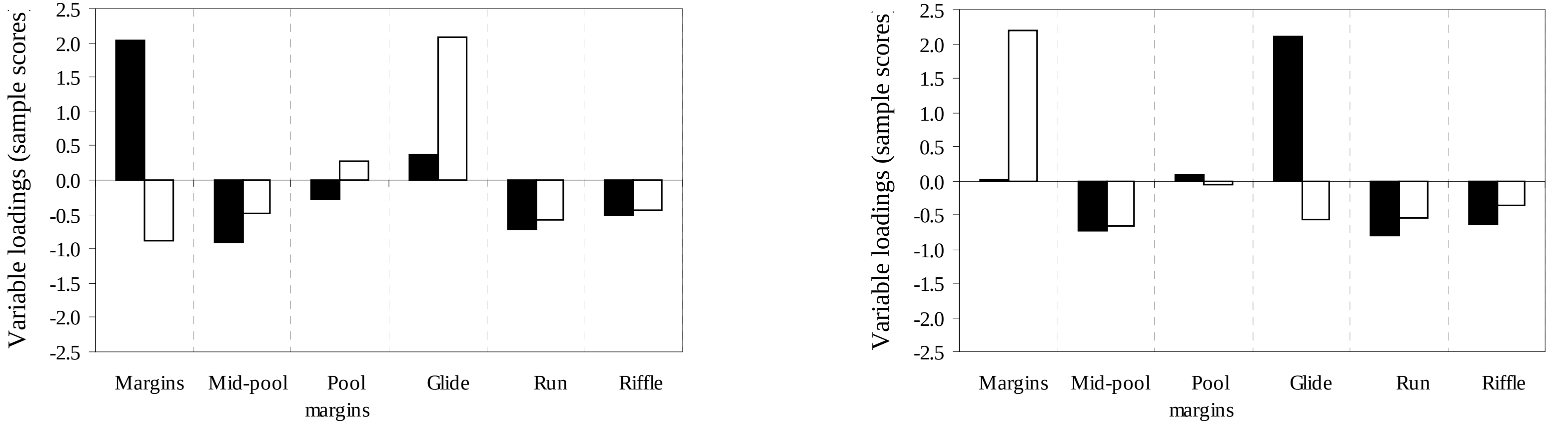
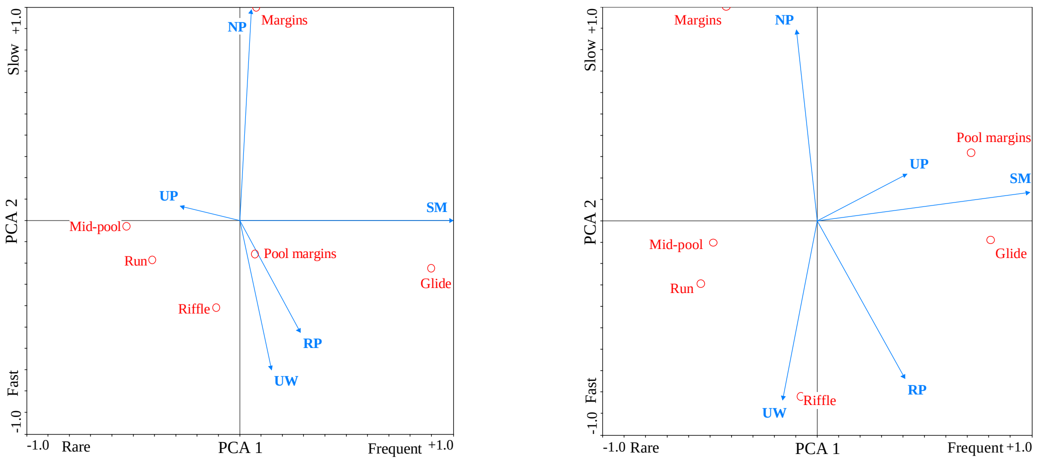
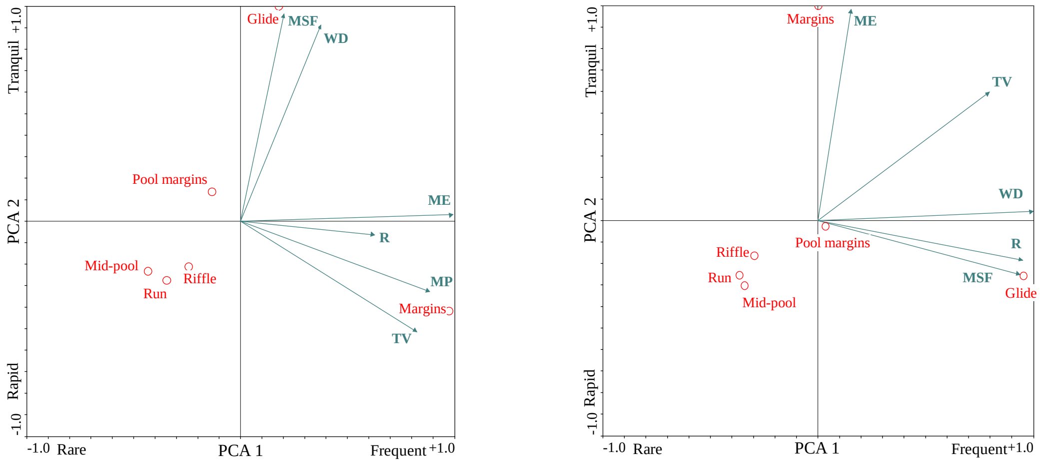


Figure 4.35 PCA axis variable loadings for PCA performed on habitat clusters and cell-level surface flow types (a and b) and habitat clusters and functional habitats (c and d).



(a) Low flow (b) Intermediate flow



(c) Low flow (d) Intermediate flow

Figure 4.36 PCA bi-plots illustrating the relationships between physical habitat clusters and flow types (a and b) and physical habitat clusters and functional habitats (c and d). Clusters are represented by circles, and flow types or functional habitats are represented by vectors. See Table 3.1 (p. 53) and 3.8 (p. 63) for flow type and functional habitat category codes.

instead associated with a combination of upwelling, smooth boundary turbulent and rippled flow (4.36a and b). In contrast, the glide cluster demonstrates a strong relationship with smooth boundary turbulent conditions and the riffle cluster with unbroken standing waves. Most of these relationships are maintained across flow stages, although a tendency for stronger correlations with faster flow types at the higher flow stage is noted for pool clusters, reflecting the intensification of flow conditions along the thalweg as noted in previous sections.

PCA performed on organic functional habitats and physical habitat clusters reveals that strong correlations between clusters and functional habitats are observed only for ‘glide’ and ‘marginal’ clusters: riffle, run and pool habitat clusters appear to support only minerogenic habitats at the two study sites investigated. Additionally, relationships are somewhat stage-dependent reflecting the spatial variations in cluster membership with increasing discharge. For instance, woody debris, roots and trailing vegetation correlate with the ‘marginal’ cluster at low flow but show stronger correlations with the ‘glide’ cluster at intermediate flow as some ‘marginal’ areas are lost to increased depths and faster flow velocities.

4.7 DISCUSSION AND CONCLUSIONS

This Chapter employs a range of methodological approaches in order to address four principal research questions as a means of field-testing the robustness and integrity of the biotope concept at the sub-reach scale.

Physical variables such as bed topography, velocity and water depth reveal some evidence of spatial organisation associated with the distribution of physical biotopes such as riffles and pools. However, differences in the amplitude of bed topography between the two study sites reflect a ‘bedform containment’ effect (Clifford *et al.*, 2002a; Emery *et al.*, 2003) which creates fundamental variations in the spatial organisation of a range of physical habitat variables. At Oakley Hall, the subdued bed topography and lack of a pronounced pseudo-cyclic riffle-pool morphology results in a homogeneous ‘ribbon-like’ physical structure where cross-sectional variation exceeds longitudinal variation. At Napely Lodge Farm, bedform amplitude is more pronounced and riffle and pool features are readily identifiable from undulations in bed topography. This creates a ‘patchy’ spatial organisation of physical habitats which is easier to reconcile with the concept of physical biotopes.

The complex relationships between bed topography and surface flow characteristics present challenges for the identification of physical biotopes in the field. Field data presented in this Chapter reveal significant deviations from the ‘characteristic’ relationships identified between physical biotopes and surface flow types. Importantly, channel margins, rather than pools, were associated with no perceptible flow and upwelling was associated with secondary circulations within pools rather than ‘boils’ (see Chapter 5, Section 5.4.1). These flow types were also more localised in nature than others, frequently occurring as marginal or ‘secondary’ biotopes at a particular cross section. The results of the cluster analysis further emphasise the importance of channel margins as a distinct hydraulic habitat unit. This is of great significance for transect-level survey resolutions which overlook marginal zones, despite their association with ecologically important microhabitats and refugia for aquatic biota.

Furthermore, relationships between certain flow types and physical biotopes are more spatially and temporally ‘robust’ than others. For example, glide biotopes appear to be relatively homogeneous features and show strong relationships with ‘characteristic’ smooth boundary turbulent flow conditions. In contrast, pools are associated with high levels of ‘internal’ heterogeneity, exhibiting significant hydraulic variation across the channel width and with varying discharge. These variations in the spatial and temporal ‘complexity’ of physical biotopes are explored in further detail in Chapter 5. The accurate identification of physical biotopes from simple physical parameters is therefore likely to be reliant on a combination of site-specific factors such as the amplitude of bedforms, the hydrological context of surveys, and the spatial resolution of the sampling design.

Physical biotope categories are associated with significant overlap in simple hydraulic parameters such as velocity, depth and Froude number but form a continuum from tranquil to rougher environments (Jowett, 1993). Slower biotopes and flow types are associated with a ‘tighter’ range of hydraulic conditions compared to faster categories, similar to patterns identified for broader-scale variables such as the altitude and slope of the reach (Chapter 3, Section 3.5.2). Biotopes derived from the cluster analysis do, however, show some broad associations with ranges of velocities and depths. Certain ‘slower’ biotopes (channel margins) are associated with tighter ranges of velocity but may be associated with a wider range of water depths, while ‘intermediate’ biotopes (glide, run, mid-pool) are associated with a limited depth range but a variety of velocity values and others (riffle, pool margins) are characterised by a similar range of velocity and depth values. Figure 4.37 illustrates how these characteristics form different two-dimensional shapes in bivariate space which may change shape or move with increasing flow stage according to variations in the frequency distributions associated with physical biotopes. This emphasises the suggestion in Chapter 3 that the most appropriate levels of simplification of aquatic habitat may relate to broad *assemblages* of features or habitat parameters, which reveal some overlap but provide a general description the local physical environment.

Sedimentological variables appear significant in characterising physical habitat at the sub-reach scale and are known to play a significant role in determining distributions of aquatic plants and invertebrates (Boeger, 1992; Quinn and Hickey, 1994). Substrate types show relatively strong conformity with the organisation of physical biotopes, particularly at Napely Lodge Farm, providing a third dimension to the physical characterisation of biotopes which has previously focused on velocity and depth. Furthermore, the distribution of fine sediments within the channel constitutes an additional sedimentological variable which has so far been neglected in biotope studies. Accumulation and scour of fine sediments is of particular significance to benthic biota through the condition of the hyporheic zone, and appears dependent on a combination of hydrological factors and seasonal vegetation growth. This complicates the relationship between the biotic and abiotic components of the instream environment and introduces an element of seasonal variation to the structure of physical habitat.

Organic functional habitats (both aquatic macrophytes and detrital organic habitats) demonstrate very different spatial distributions and significant variations in the magnitude of seasonal change in cover. This presents challenges for attempts to ‘map’ functional habitats onto physical biotopes for several reasons. First, some habitats,

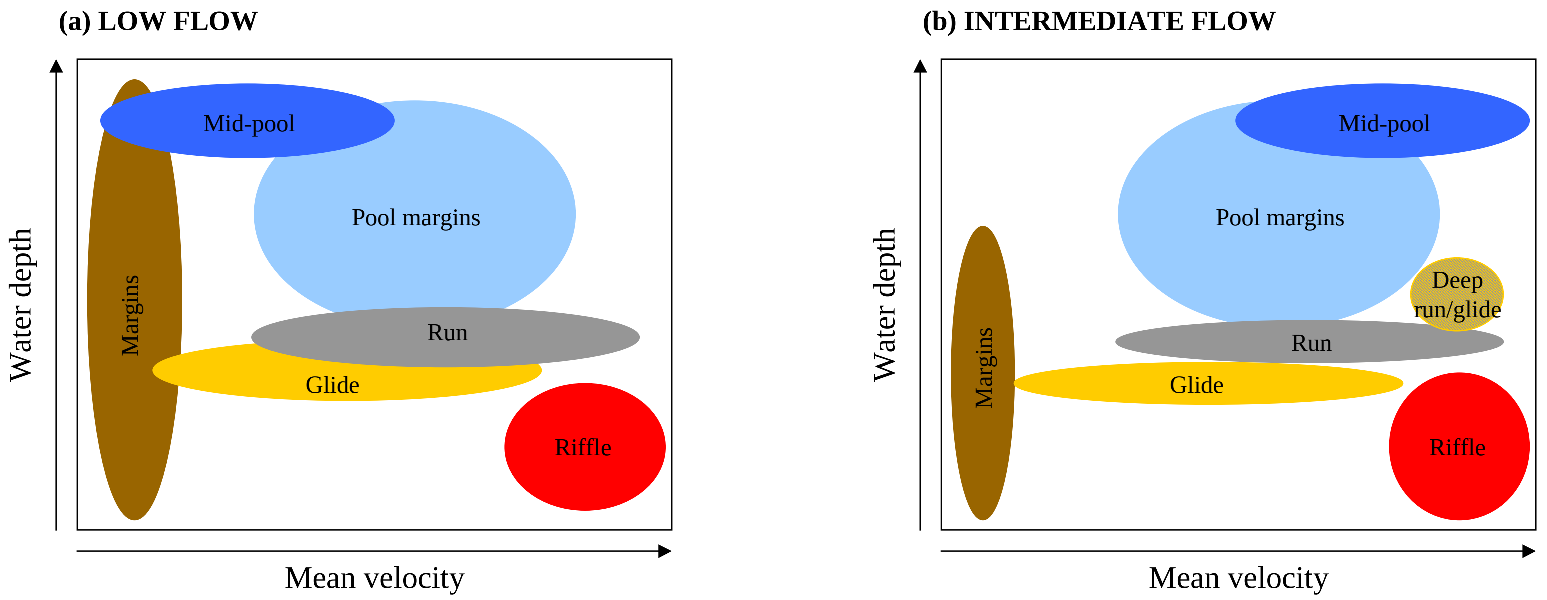


Figure 4.37 Conceptualised dynamic hydraulic character of physical habitat patches for the River Tern according to the velocity and depth frequency distributions of statistically derived clusters.

particularly those associated with ‘patchy’ distributions, may map more readily onto physical biotopes than other, more linearly distributed or ubiquitous habitats. Second, coarser survey schemes are likely to favour the recording of the ubiquitous or patchy habitats and under-represent the linear marginal habitats. Third, certain functional habitats are associated with significant seasonal variations in cover, while others vary little throughout the growing season, suggesting an influence of seasonal timing on survey outcomes. As a result, correlations between functional habitats and physical biotopes show significantly less distinct patterns than those identified for the national RHS data set in Chapter 3, suggesting that these relations may be most appropriate for the most prominent, or ‘typical’ features identified at relatively broad scales of assessment.

CHAPTER 5 BIOTOPE CHARACTERISATION AT THE MICROSCALE: TURBULENCE AND SEDIMENT TRANSPORT

5.1 CHAPTER SYNOPSIS

This chapter presents the results of a field investigation of the microscale hydraulics of selected physical biotopes from each of the two River Tern field sites. A combination of ‘first order’ (turbulent stresses and intensities), ‘second-order’ (turbulent event structure) and ‘third-order’ (autoregressive models and spectral signatures) hydraulic discriminators are employed in order to examine spatial and temporal variations within each physical biotope. While the discriminatory success of hydraulic parameters generally depends upon the combination of biotopes studied, some of the higher order turbulent properties appear more effective in characterising biotopes than simpler mean parameters. In addition to the absolute ranges of hydraulic parameters identified for each biotope, the type and level of ‘within-biotope’ heterogeneity constitutes an additional physical ‘characteristic’ which provides differentiation between biotopes.

5.2 ECOHYDRAULICS AT THE MICROSCALE

Flow variability is known to influence the structure of river ecosystems at a variety of spatial scales (Biggs *et al.*, 2005). Flood events occurring over time frames of years or months create large-scale disturbances that influence community composition, while lower magnitude variation over timescales of days influence biotic interactions, population densities and the physiological condition of biota. At microscales of minutes to milliseconds, however, processes associated with high frequency turbulent flow variation determine the supply of oxygen, nutrients and food which influence the growth and survival of individual organisms (Biggs *et al.*, 2005).

Characterisation of physical biotopes has generally attempted to discriminate between different physical biotopes using surveys of mean flow properties over various discharge ranges that provide a broad temporally- and often spatially-averaged representation of flow conditions. However, given that aquatic organisms are directly affected by localised channel hydraulics (both in terms of the physical force of flow on organisms and the distribution of sediments, nutrients and pollutants within the channel) the dearth of physical biotope research focused at the microscale reflects an obvious research priority.

5.2.1 The importance of the microscale

For benthic organisms, hydraulic parameters such as velocity and shear stress have direct physical impacts such as dislodgement, burial and abrasion (Carling, 1995), as well as indirectly influencing food availability and oxygen concentrations (Quinn and Hickey, 1994). In the fully turbulent outer flow zone, flow intensities and the organisation of turbulent structures are important for dispersal lifestages of benthic organisms (McNair *et al.*, 1997). The energy expenditure of filter feeding invertebrates and fish must match that of the hydraulic stress in order to maintain station within the flow (Giller and Malmqvist, 1998), and turbulence has been identified as a key factor influencing the energy costs associated with swimming for juvenile salmon (Enders *et al.*, 2003; Enders *et al.*, 2005). The suitability of habitat for different species will therefore be determined by both the abiotic environment and the swimming performance of the individual animal, which will vary between species (Katopodis, 1996).

At the reach-scale, as shown in Chapter 4, physical biotopes describe broad hydraulic environments. Thus, riffles are generally associated with higher hydraulic stresses approaching super-critical flow conditions, and pools with lower stresses and more tranquil conditions over much of the discharge range. However, investigations at smaller-scales have highlighted the effects of local microtopography and individual flow obstructions such as organic matter, rocks and root wads on the local flow environment. Sand ribbons and secondary current circulations have been shown to influence fish distributions (Tsujimoto, 1996) and large rocks can provide stability and shelter across flow stages, in addition to rearing habitat for certain species (Garcia de Jalon, 1995). Crowder and Diplas (2000) suggest that individual boulders can have a highly complex impact on the local flow environment by increasing local velocities, modifying velocity gradients and creating shelters and transverse flows. Often, the heterogeneity created by such structures is considered beneficial to biota, by providing habitats suitable for various life stages of organisms, and refugia from predation and disturbance. By contrast, some evidence has suggested that the reduced visual field associated with obstructions can have negative impacts on fish species (Kemp *et al.*, 2005), emphasising the complexity of relationships.

Specific types of microhabitat are also associated with the channel margins. Marginal features such as bank irregularities and overhanging vegetation can increase cover and provide some of the most important habitats for fish (Bisson *et al.*, 1981; Kellerhals and Miles, 1996) and native crayfish (Smith *et al.*, 1996). Marginal patches of low hydraulic stress which are retained across flow stages may create important refugia for invertebrates, enhancing the resilience of benthic communities to spates (Lancaster and Hildrew, 1993).

5.2.2 Turbulent boundary layers

A large volume of literature has developed on the causes and character of turbulence within the vicinity of a ‘wall’ or ‘boundary’ in laboratory flumes and under idealised conditions. Progress within the field of fluid dynamics since the mid-20th Century has given rise to theories of ‘turbulent bursting’ as an explanation for the existence of coherent flow structures within turbulent boundary layers (see Allen (1985) or Yalin (1992) for overview). Bursting theories suggest that the generation of turbulence is related to the break-up of streamwise ‘streaks’ of low momentum fluid within the viscous sub-layer (Kline *et al.*, 1967). As the streaks lift away from the boundary they are rapidly ejected into the outer flow (‘bursts’), which is followed by a compensatory inrush (‘sweep’) of outer flow fluid towards the bed which may then initiate the next burst (Figure 5.1a). Such interactions are intermittent in nature (Gordon, 1974; Lapointe, 1996) but have been shown to account for the majority of turbulence generation near the boundary (Lu and Wilmarth, 1973). While the effects of sweeps are generally confined to the region close to the boundary, the influence of bursts may extend throughout the boundary layer (Grass, 1971), perhaps even reaching the water surface as ‘boils’ (Roy *et al.*, 2004).

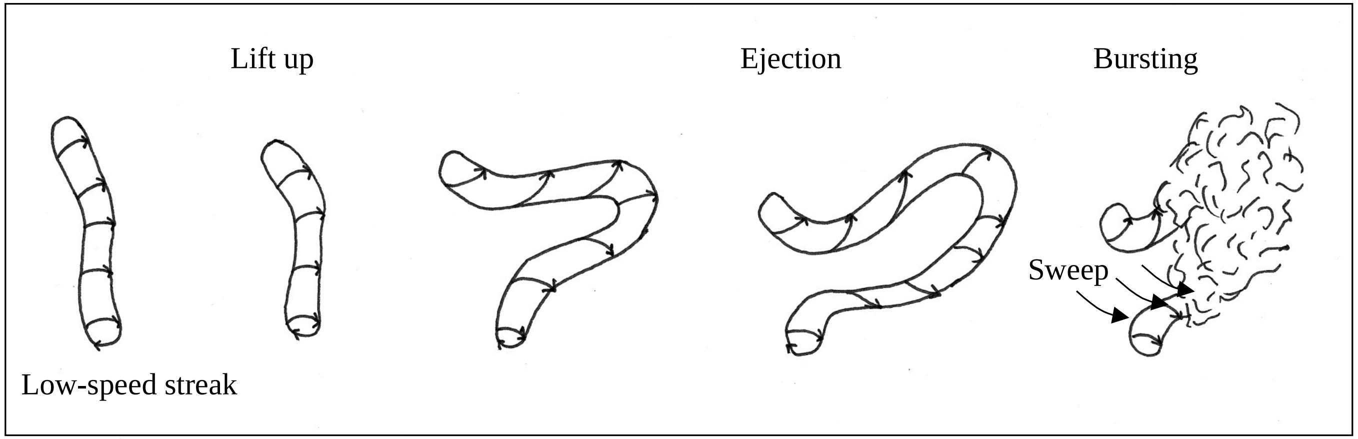
In geomorphological applications, research into the existence of similar turbulent structures has continued from the work of McQuivey (1973a; 1973b), through Clifford *et al.*, (1993a) and Ashworth *et al.*, (1996) at a variety of scales and for various potential applications. Generally this work supports initial findings but identified other sources of turbulent generation and a greater range of coherent flow structures. For instance, in many natural channels, the grain size of bed material is larger than computed estimates of viscous sublayer thickness. This suggests that streaks may be unable to form and turbulence generation may instead be related to the quasi-cyclical shedding of eddy structures from the lee of obstacles (Clifford *et al.*, 1992a; Clifford *et al.*, 1992b) (Figure 5.1b). Such obstacles may range in size from individual clasts to clusters of particles and larger scale bedforms, thus creating vortices of various sizes which may then interact and coalesce within the outer flow zone (Best, 1993). These developments are of particular importance in an ecohydraulics context in the light of recent bioenergetics work which has stressed the influence of turbulence on fish behaviour (Enders *et al.*, 2003).

Time series of field velocities monitored at high frequencies (c. 1 – 20 Hz) may be statistically analysed in terms of various turbulent properties. Such applications have identified variations in the character of flow structures between riffle and pool units (Clifford, 1996a), but these techniques have yet to be fully applied within the context of physical biotope characterisation. This chapter allows an assessment of the variations in turbulent properties and flow structures *within* and *between* selected physical biotopes in order to identify whether such 'higher-order' parameters provide better (or additional) discrimination compared to the more conventional mean flow values frequently employed in biotope studies.

5.2.3 Flow and suspended material

While the direct physical and biological impacts of turbulence are fundamental to the instream environment, the interactions between turbulence and the distribution of fine particulate matter suspended in the water column are also of great significance to the aquatic biota. Benthic invertebrates are exposed to direct impacts from suspended

(a) Turbulent bursting



(b) Vortex shedding generated by roughness elements

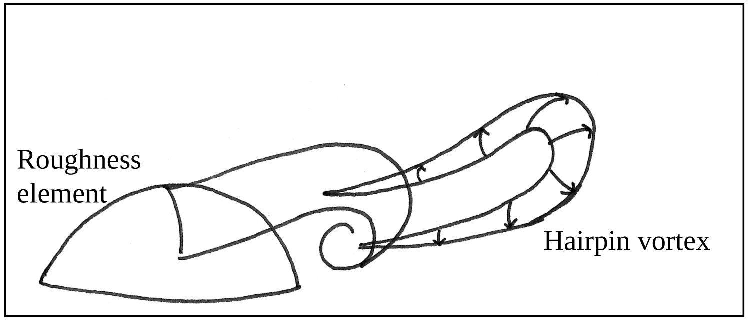


Figure 5.1 Turbulence generation in open channels: (a) the process of turbulent bursting, adapted from Allen (1985: Figure 6.15 p. 113) and (b) vortex shedding from roughness elements, adapted from Best (1993: Figure 3.11a p. 77).

material in the form of abrasion and burial, and by the reduction in suitable habitat caused by the smothering of interstices (Carling, 1995; Jowett, 2003). Short-term pulses of sediment can have a variety of effects on benthic invertebrates and riverine fishes. For instance, invertebrate drift in response to pulses can alter community structure, creating variations in food resources for larger vertebrates (Shaw and Richardson, 2001). In addition to direct impacts such as lower prey capture success rates due to vision impairment, and physiological stress, this will have implications for the growth and survival of fish (Shaw and Richardson, 2001). Accumulation of fine sediments within spawning gravels has a significant influence on interstitial flows and consequently on the oxygen supply rate to incubating salmonids (Sear *et al.*, 2004). Furthermore, where contaminants are adsorbed to the surface of particulate matter, biota may be directly exposed to the toxic effects of chemicals from anthropogenic sources (Greenberg *et al.*, 2002; Hose *et al.*, 2002).

While excess sediment is generally considered detrimental to many organisms, the distribution of nutrients, either in particulate form or adsorbed to minerogenic particles, is fundamental to survival. In unperturbed systems, the supply of food and nutrients represents the ultimate influence on invertebrate distributions (Cummins, 1975). Within all aquatic ecosystems, nutrients are taken up from the water column by biota, biologically processed and subsequently released, forming a continuous passage of nutrients through the food web known as ‘cycling’ (Newbold, 1992; Figure 5.2a). In lotic ecosystems, a spatial element to the cycling process is introduced by the unidirectional nature of the flow which means that the nutrient outputs from a cycle upstream form the inputs for cycling downstream (Giller and Malmqvist, 1998). This downstream ‘interdependence’ of cycling and transport of nutrients is known as nutrient ‘spiralling’ (Newbold *et al.*, 1983). The intensity of nutrient utilisation is indicated by the spiralling length (Figure 5.2b) which includes the distance travelled by a nutrient atom both in the water column (‘uptake length’) and within the biota (‘turnover length’) within a complete cycle (Newbold, 1992).

Spiralling lengths within a river reach are determined by a combination of abiotic factors, including local hydraulics and the frequency of spates, and biotic factors such as the mobility and uptake capabilities of different organisms, and have been shown to vary between scales of 10^0 m (Wotton, 1996) and 10^2 m (Newbold *et al.*, 1983). Faster current velocities may generally be associated with higher levels of downstream displacement, whereas slower velocities create ‘dead zones’ in pools and at channel margins where nutrients may reside for significant periods of time. In nutrient-limited reaches, transportation of nutrients in particulate form has a particularly important influence on the spiralling length (Newbold *et al.*, 1982). Transport pathways taken by fine particulate matter may therefore be indicative of the routes taken by food and nutrients. The final section of this chapter presents the results of a set of experiments designed to investigate whether different physical biotopes are associated with certain sediment (and hence nutrient and pollutant) transfer signatures and whether these exhibit evidence of stage-dependency.

5.3 VELOCITY TIME SERIES

5.3.1 Sampling design

High frequency velocity time series were recorded within selected physical biotopes under both ‘low’ and ‘intermediate’ flow stages (See section 2.3.5). Glide and pool biotopes were studied at Oakley Hall, and riffle and pool at Napely Lodge Farm (Plate

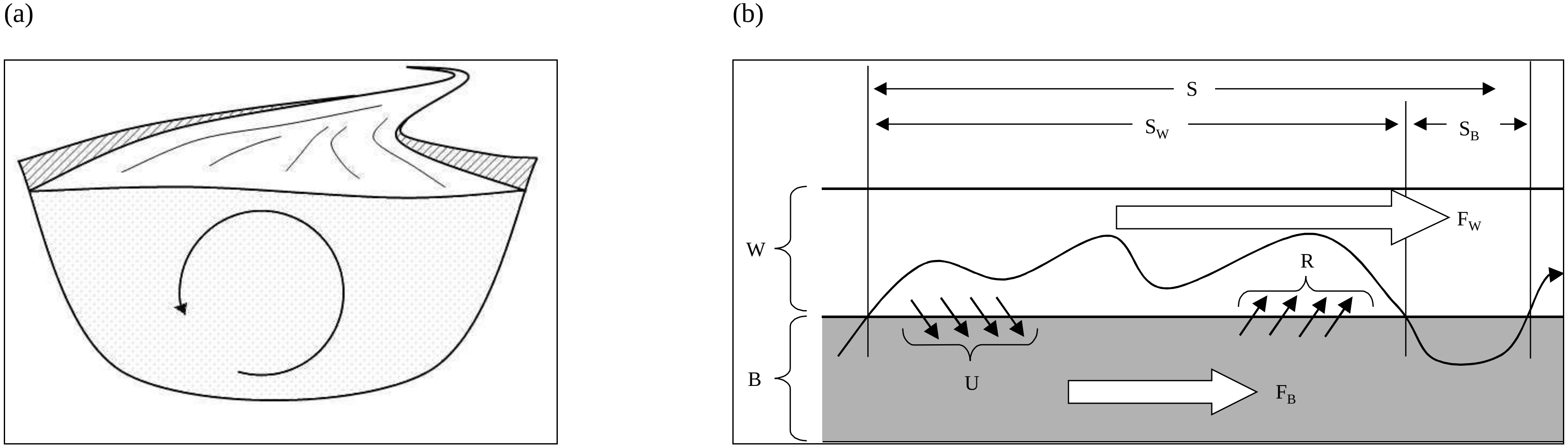


Figure 5.2 Nutrient cycling (a) and spiralling (b), modified from Newbold (1992)
In (b) nutrient spirally occurs within two compartments of the ecosystem: water (W) and biota (B).
S represents the spiralling length, the sum of the uptake length (S_W) and the turnover length (S_B), and can be calculated from the nutrient fluxes (FW and FB) and the exchange fluxes of nutrients between the biota and the water compartment (U and R).

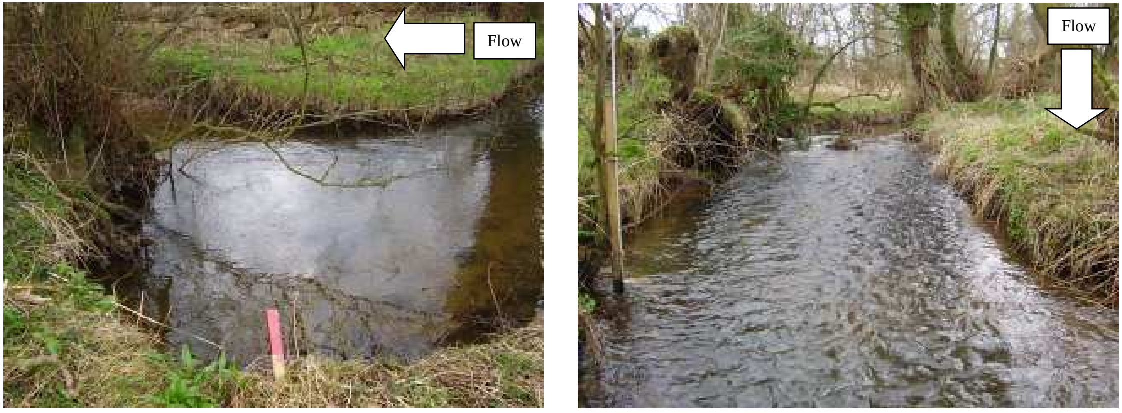
5.1). Measurements were taken at both 0.2 and 0.8 of the water depth (from the water surface) at 1 m intervals along a 5 m ‘longitudinal’ transect following the channel centreline, and along a cross sectional transect at the central point of the sample area (Figure 5.3).

A spherical-headed two-dimensional Valeport 802 Electromagnetic Current Meter (EMCM) modified for 16 Hz analogue output, was used in direct communications mode with a Campbell Scientific CR10X datalogger to allow high frequency logging of streamwise (U) and vertical (W) velocity. The EMCM uses two pairs of equi-spaced electrodes to simultaneously measure orthogonal velocity components (in this case U and W) by detecting the voltages induced by water passing through a magnetic field generated by the sensor (Lane *et al.*, 1993; Valeport Limited, 1998). Streamwise and vertical velocities were sampled simultaneously at 16 Hz for 30 s in order to assess turbulent fluctuations occurring during the common 30 s averaging period used for bulk flow properties. Clifford and French (1993b) identified turbulent structures with periods of around 5 s and smaller substructures with periods of approximately 1 s, while Kirkbride (1993) noted a 1 s to 10 s interval between turbulent bursting structures, suggesting that a 30 s interval should capture several repetitions of high frequency structures.

EMCMs are relatively robust and demonstrate a good frequency response and toleration of contamination (Clifford and French, 1993a). While spherical sensor heads have been associated with higher levels of instrument-related flow disturbance, the equal spacing of

(a) Pool, Oakley Hall

(b) Glide, Oakley Hall



(c) Pool, Napely Lodge Farm

(d) Riffle, Napely Lodge Farm

Plate 5.1 The physical biotopes selected for microscale field research at Oakley Hall and Napely Lodge Farm (Q = 0.22 m^3s^{-1})

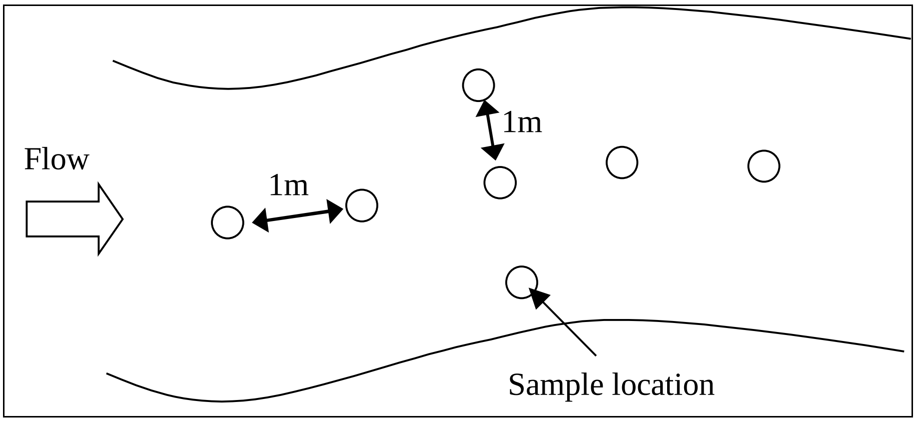


Figure 5.3 Sampling design for the microscale velocity surveys. Circles represent velocity sample locations where high frequency measurements were taken at 0.2 and 0.8 of the water depth from the surface.

electrodes avoids bias in the minimum detectable wavelength for the two velocity components (Lane *et al.*, 1993).

5.3.2 Data cleaning and detrending

It is common practice for any analysis of high frequency (temporal) data to proceed initially by visual inspection of time series of observations against time (Chatfield, 2004), both as a means of quality control and in order to examine the scales of variation within the data set (French *et al.*, 1993). Time series for streamwise (U) and vertical (W) velocity components (a total of 286 series) were produced using Origin Pro 7.5. These were inspected for: (i) abnormalities in the signal indicative of sensor corruption; and (ii) the existence of global or local non-stationarity in the mean and/or variance. Visual inspection highlighted apparent sensor-related errors for the W component at Napely Lodge Farm under low flow conditions. Values for W for these samples consistently demonstrate low levels of fluctuation within the range –0.35 to –0.4 ms^{-1} instead of the expected fluctuation either side of an approximately zero mean. Such values may indicate a strong localised downwelling, such as in the lee of an obstacle, but since this feature was observed for all series, it was attributed to an internal connection problem, and these series were excluded from analysis.

Time series also revealed the presence of extreme values in 33 U series where a small number of observations were associated with high magnitude values inconsistent with the overall character of the series. There are several possible explanations for the presence of such values and different methods of correcting errors are available, depending on the likely cause of the anomaly. It is possible that in some instances, anomalies may in fact represent the existence of intermittent high amplitude ‘events’ which may occur just once or twice in the sampled series but contribute significantly to the Reynolds stress (Gordon, 1974). However, sensor output is sensitive to corruption in the form of intermittent noise resulting from factors such as the passage of organic debris through the sampling volume, external magnetic fields, sensor cable movement or instability of sensor mountings (Clifford and French, 1993a; Lapointe, 1996) which may create anomalous values. For measurements in shallower parts of the channel, undulations in the water surface can create spikes in the time series where part of the sensor’s sampling volume is temporarily out of the water (Roy *et al.*, 2004). Many of the extreme values identified for this data set occurred at the start of series (generally within the first second) and were interpreted to reflect sensor set-up instabilities associated with, for instance, temperature adjustments and water bubbles. Removal of spikes considered to reflect sensor disruption later in the series is less straightforward, and in this instance, the method of ‘downweighting’ outlier values (Chatfield, 2004) to the next highest, or lowest, value was undertaken for observations in four series.

A more complex problem is encountered where the series exhibits non-stationarity in variance, manifest in short-term variations in the amplitude of fluctuations. This affected three of the 286 series. In some instances this may reflect sensor movement into and out of the influence of different upstream roughness elements or different parts of the velocity profile, although every effort was made to minimise mounting instability. Alternatively such characteristics may indicate the influence of isolated events such as movement of upstream bed material, or the intermittent effects of larger-scale flow circulations and therefore may reflect natural non-stationarity in channel velocities. In order to judge whether the non-stationarity exhibited by the three series were associated with measurement error or natural phenomena, U and W series were compared and the series examined in the context of surrounding samples. The characteristics were considered unlikely to represent sampling error and therefore the three series were left in their unmodified state with the acknowledgement that subsequent analysis may create anomalous results for these series.

Where a velocity series is steady, U and W velocity components may be decomposed into mean (u or w) and fluctuating (u' and w') parts simply by subtracting the series mean (Clifford and French, 1993b):

$$\text{(a)}\quad U = u + u' \qquad\qquad \text{(b)}\quad W = w + w' \qquad \textbf{Equation 5.1}$$

In series where turbulent fluctuations are superimposed onto a global trend, such as tidal variation, detrending is required and generally takes the form of a low order polynomial (French *et al.*, 1993). Although the steady flow conditions associated with this data set negate the need for global detrending, time-plots reveal the existence of local non-stationarity in most series, which takes the form of a low frequency fluctuating trend component. In fact, the majority of series exhibit variation at three different frequencies: higher frequency fluctuations with a period of ~1s; ‘intermediate’ fluctuations with a period of ~3-5s; and a low frequency trend component with a period of approximately ~10s or more. These are illustrated using an example series in Figure 5.4.

The two higher frequency components represent structures operating at near-turbulent scales, possibly reflecting complex interactions between roughness-shed vortices and burst-sweep structures (Clifford and French, 1993b) or the mixing and coalescence of vortices in the outer flow zone (Kirkbride, 1993). Assuming G. I. Taylor's substitution, that a sequence of events at a fixed point may be interpreted to represent the movement of an unchanging pattern of turbulence past that point (Reynolds, 1974), the low frequency component may be interpreted to represent flow structures up to several channel widths in size, possibly related to secondary circulations or vortex shedding from bedforms or large obstructions upstream. These features represent local non-stationarity outside of the turbulent range, and variance of the trend may dominate subsequent analyses of turbulent properties. For instance, Figure 5.5 illustrates the effect of local polynomial and linear non-stationarity on turbulent residuals by comparing residuals derived from polynomial and linear regressions with those derived by simple subtraction of the series mean. For the series characterised by the polynomial trend (Figure 5.5a), simple subtraction of the series mean creates turbulent residuals which amplify or subdue peaks and troughs within different parts of the velocity series (Figure 5.5c). For the series characterised by a linear trend (Figure 5.5b), turbulent residuals derived by simply subtracting the series mean are understated at the beginning of the series and exaggerated towards the end (Figure 5.5d).

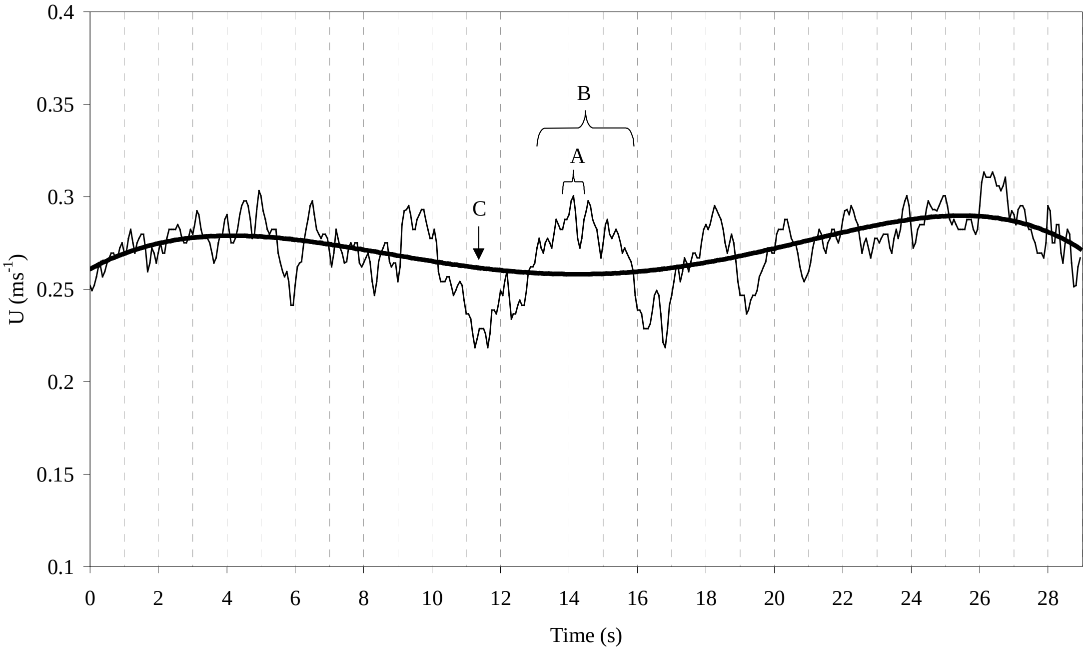


Figure 5.4 Example velocity series from the River Tern showing (a) high frequency (<1s) fluctuations, (b) intermediate (~3-5s) fluctuations and (c) slowly fluctuating trend (5^{th} order polynomial).

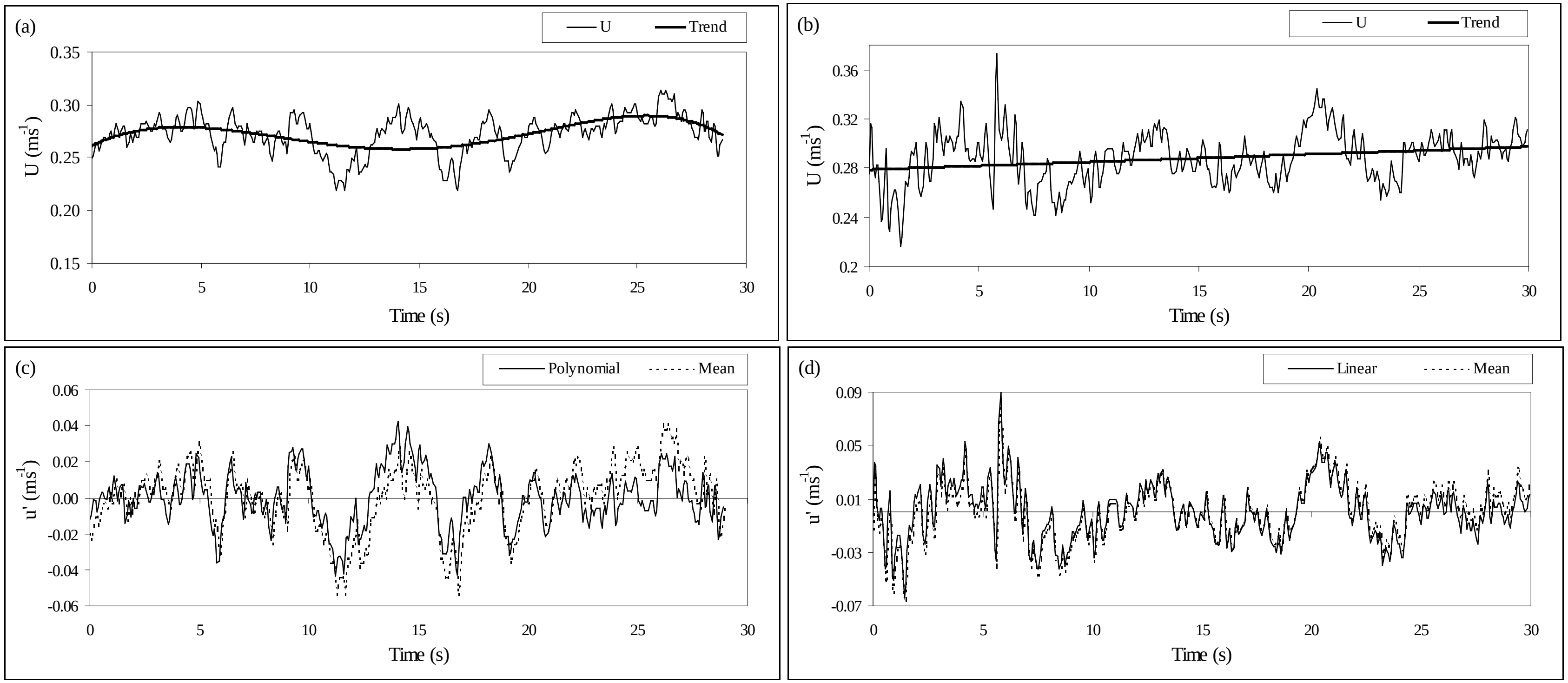


Figure 5.5 Velocity series detrending using (a) polynomial and (b) linear procedures. Resultant residuals are then compared to residuals derived by simple subtraction of the mean velocity (the dotted line) in (c) and (d). In (c), residuals from the mean are compared to those derived from the polynomial trend, and in (d) residuals from the mean are compared with those derived from the linear trend.

Series were therefore detrended by the fitting of linear or low order polynomial regressions, separating the high-frequency fluctuating ‘residual’ component from the slowly varying trend in the manner of Gordon (1974) and Clifford and French (1993b). Trend order was selected by visual assessment of goodness-of-fit, and restricted to a maximum of 5th order polynomials to ensure that turbulent properties were retained. For series with no apparent trend, turbulent residuals were derived by subtracting the series mean (u or w). Mean values computed for detrended series (u' and w') fall very close to zero (below 10^{-5} ms^{-1}) confirming successful removal of the trend component.

5.4 PHYSICAL BIOTOPES AND TURBULENT PROPERTIES

This section presents the results of an investigation of the turbulent properties of physical biotopes at the two River Tern study sites. This proceeds by analysis of simpler mean flow velocities, stresses and turbulence intensities, and subsequently employs increasingly more detailed analytical techniques in an attempt to explore ‘higher-order flow properties, such as the existence of coherent flow structures, which have so far been largely overlooked in biotope characterisation.

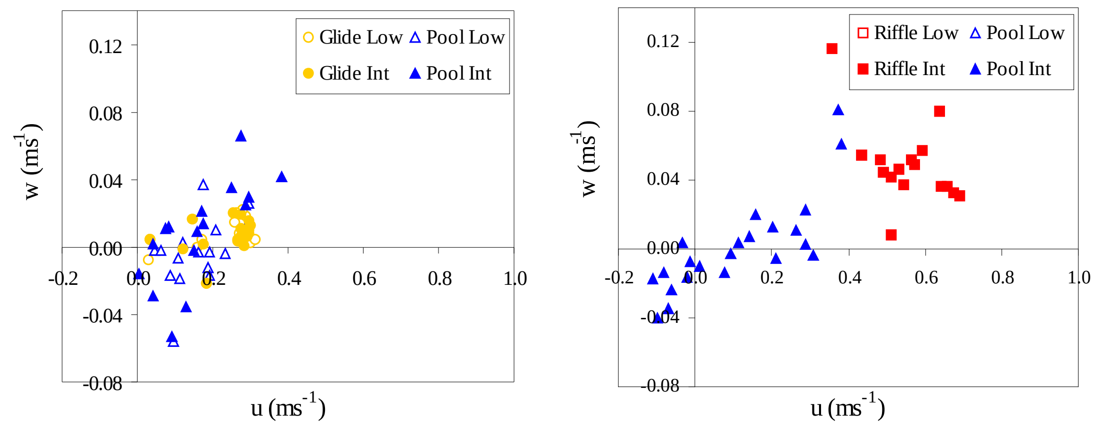
5.4.1 Average flow properties

i) Velocity and stress

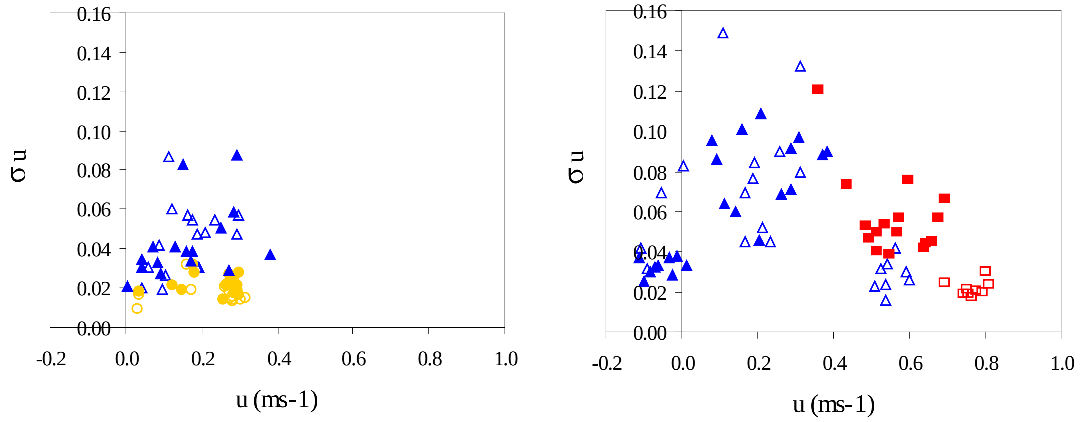
Mean flow velocity and stress properties are derived easily from field data and are often used in model calculations and the characterisation of flow conditions. The hydrodynamics of riffle-pool sequences have received a great deal of attention in the literature, particularly in terms of the mechanisms governing their stability and maintenance. Keller (1971) presented a ‘velocity reversal’ hypothesis as an explanation for observed variations in substrate character between riffle and pool units. The theory proposes that at low flow, near-bed velocities are higher within riffle units, and sediment transport is characterised by a winnowing of fine sediment into downstream pools where it becomes trapped. With increasing stage, near-bed velocities increase more rapidly within the pool and eventually exceed those within the riffle, resulting in a ‘reversal’ in velocity and shear stress. Beyond the reversal velocity, sediment transport is characterised by the movement of coarser gravels from the riffle, which are subsequently transported through the pool by high tractive forces associated with flow convergence, and deposited on downstream lower-competence riffles.

However, recent field studies have revealed a more complex cross-sectional response to increasing stage within riffle-pool couplets (Clifford and Richards, 1992), complicated by the identification of coarser substrates within pools (Milan *et al.*, 2001). Both field measurements and flow simulations have emphasised the role of flow routing through pools (Booker *et al.*, 2001) and the migration of velocity and stress gradients (Cao *et al.*, 2003; Wilkinson *et al.*, 2004) as opposed to the simpler divergent-convergent flow patterns suggested by Keller (1971).

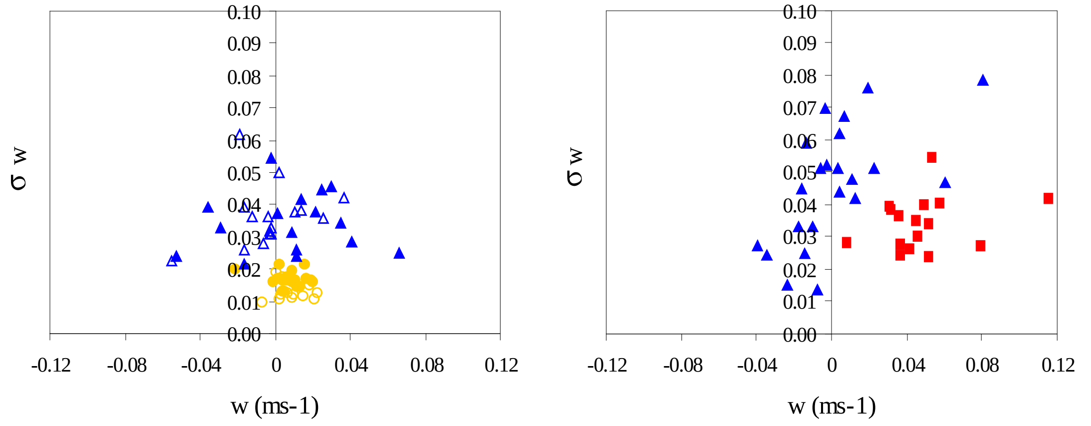
Mean velocity characteristics for the River Tern study sites derived from velocity time series are presented in Figure 5.6. Overall, the data reveal a broadly linear relationship between the streamwise and vertical velocity components (Figure 5.6 a and b), indicating that net uplift occurs where streamwise velocities exceed 0.3 ms^{-1}, consistent with observations of the entrainment of fines (Simons and Simons, 1987). Standard deviations for each of the velocity components reveal a systematic increase


(a) Oakley Hall

(b) Napely Lodge Farm


(c) Oakley Hall

(d) Napely Lodge Farm


(e) Oakley Hall

(f) Napely Lodge Farm

Figure 5.6 Mean streamwise and vertical velocity for (a) Oakley Hall and (b) Napely Lodge Farm at low and intermediate flow stages. In (c) and (d) the mean streamwise velocity is plotted against the standard deviation for each site, and in (e) and (f) the mean vertical velocity is plotted against the standard deviation for each site.

with their respective means (Figure 5.6 c to f) suggesting that stronger mean values amplify, rather than dampen the intensity of turbulent fluctuations (Clifford *et al.*, 1994). However, the mean flow characteristics do reveal some variations between physical biotopes.

The riffle at Napely Lodge Farm is associated with the highest streamwise velocities and net uplift. Velocities show a systematic decrease with increasing discharge, consistent with observations by Booker *et al.* (2001) of greater frictional contributions from banks, rather than the slower increase in competence identified by Clifford and Richards (1992). Standard deviations within the riffle, however, demonstrate a relatively complex relationship with mean parameters. For the streamwise component, standard deviations appear restricted by higher mean velocities, whereas deviations in the vertical component are amplified by higher mean values, perhaps reflecting intensification of flow around pebble clasts.

In contrast, the glide is associated with a slower and more restricted range of streamwise velocities that generally do not exceed 0.3 ms^{-1}, resulting in lower magnitude uplift compared to the riffle. Standard deviations are also restricted to a lower range of values than observed for both riffle and pool biotopes, suggesting lower turbulence intensities and a simpler flow structure. The pool biotopes are associated with the widest range of mean values and standard deviations, suggesting greater spatial variation. Vertical velocities show a stronger linear increase with mean values compared to riffle and glide biotopes, and a similar situation is noted for standard deviations, suggesting an intensification of flow conditions in faster flowing pool zones.

Variation in mean velocities *within* the different physical biotopes is explored in further detail in Figure 5.7 which simultaneously considers variation spatially (both longitudinally and cross sectionally), with relative depth of the sensor, and temporally (with varying discharge). The four biotopes are associated with different levels of variation in each of these dimensions, even in terms of the simple mean velocity parameters. The glide is associated with very high levels of 'internal' homogeneity, demonstrating very little variation in velocities spatially, with depth or across discharges. The riffle is also relatively homogeneous spatially, but shows some evidence of systematic variations in mean velocity with relative depth and increasing stage. At the intermediate flow stage, streamwise velocities within the riffle are consistently lower within the near-bed region reflecting the frictional effects of grain roughness elements which is also manifest in stronger vertical velocities indicative of flow intensification around pebbles (Buffin-Belanger and Roy, 1998).

In contrast, both pools are associated with significant within-biotope hydraulic complexity in the form of significant velocity variation spatially, temporally and with depth. This complexity is more pronounced for the pool at Napely Lodge Farm, which is associated with a more distinct planform and topographic structure (Plate 5.2), emphasising the strong control of channel morphology on biotope hydraulics as identified in Chapter 4. Variations with discharge and depth appear relatively unsystematic for both pools, but spatial variations in vertical and streamwise velocities within the pool at Napely Lodge Farm provide some information on secondary circulations. Spatial variations in vertical velocity suggest a transition from downwelling at the pool head and upwelling towards the pool tail which may

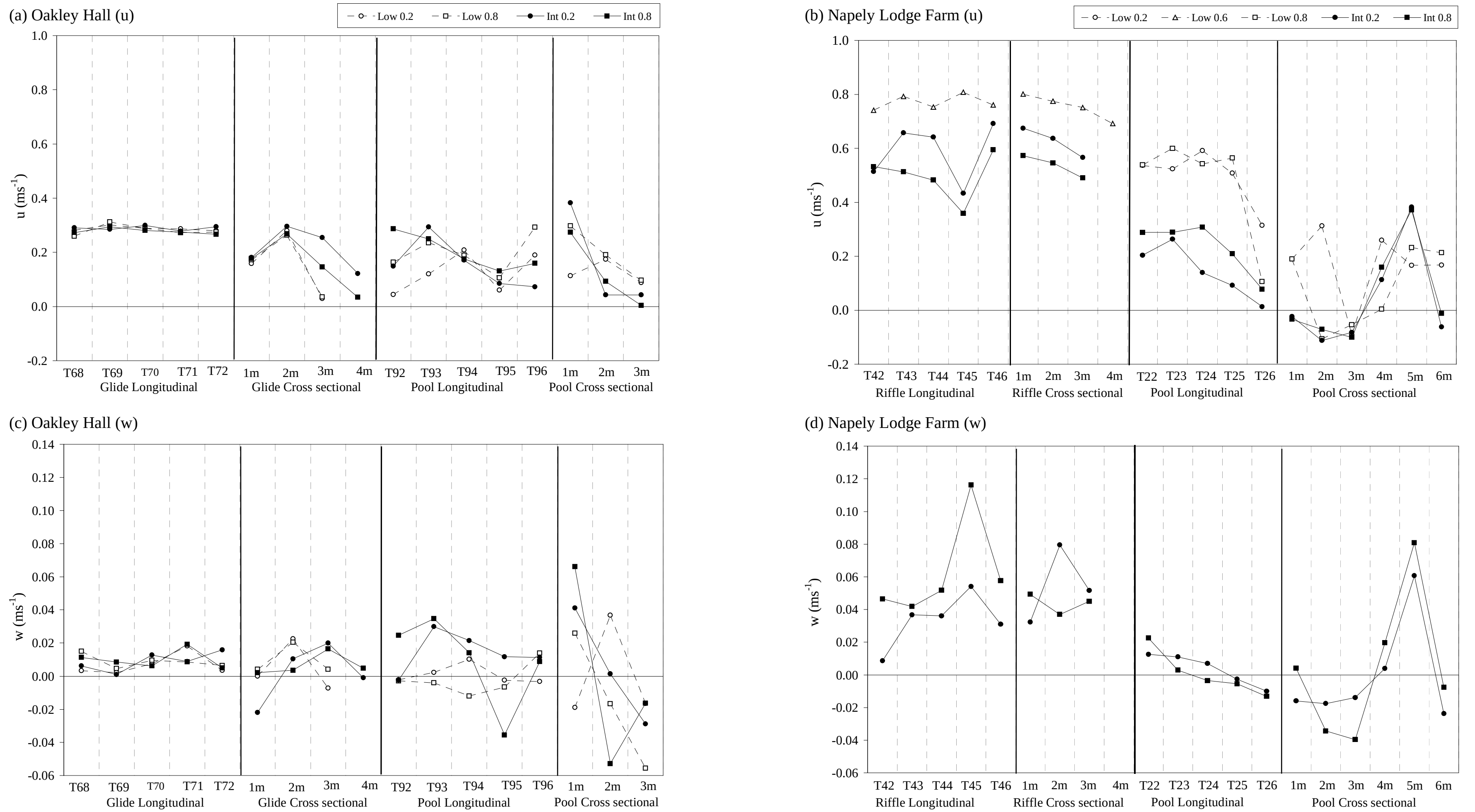


Figure 5.7 Mean streamwise velocity for (a) Oakley Hall and (b) Napely Lodge Farm, and vertical velocity (c and d) velocity by sample location according to depth of measurement and flow stage. Longitudinal measurements were located 1 m apart upstream along the channel centreline and are denoted by a numeric transect code (which increases upstream). Cross sectional measurements refer to the distance from the left bank.

(a) Oakley Hall (facing upstream)

Date: 08/03/2005 Q: $0.21 m^3 s^{-1}$

(b) Napely Lodge Farm (facing downstream)

Date: 03/05/2005 Q: $0.26\ m^3 s^{-1}$

Plate 5.2 Observed surface flow patterns within the pools at each site.

explain the observations of ‘upwelling’ flow type within mid-pool locations in Chapter 4. Vertical velocities also appear to intensify in the vicinity of the thalweg, located towards the right bank. A transition from negative to positive streamwise values across the channel width reflects the rotational flow circulations associated with the larger backwater zone towards the left bank (Plate 5.2b). Spatial variation is less systematic at Oakley Hall, but some flow intensification is observed towards the left bank in association with the intrusion of riparian tree roots.

The skewness of the turbulent residuals derived by detrending procedures outlined in Section 5.3.2 can provide further information on local hydraulics and sediment transport. Bagnold’s (1966) theory of sediment suspension requires that the residual upward turbulent stress must be in equilibrium with the suspended mass of grains, and thus positively skewed w' distributions can be considered indicative of favourable conditions for sediment entrainment (Leeder, 1983). Skewness values for all u' and w' series are presented in Figure 5.8. Most series are associated with minimal skewness, however some variations are noted both between sites and between physical biotopes. Oakley Hall reveals an overall tendency for negative skew towards lower magnitude fluctuations, reflecting the smooth boundary turbulent conditions which characterise the reach. In contrast, Napely Lodge Farm is associated predominantly with positive skew, suggesting higher flow intensities and more favourable conditions for sediment transport. Within the glide at Oakley Hall, there is some evidence of a reduction in residual upward stress with increasing discharge, in conjunction with increases within the pool.

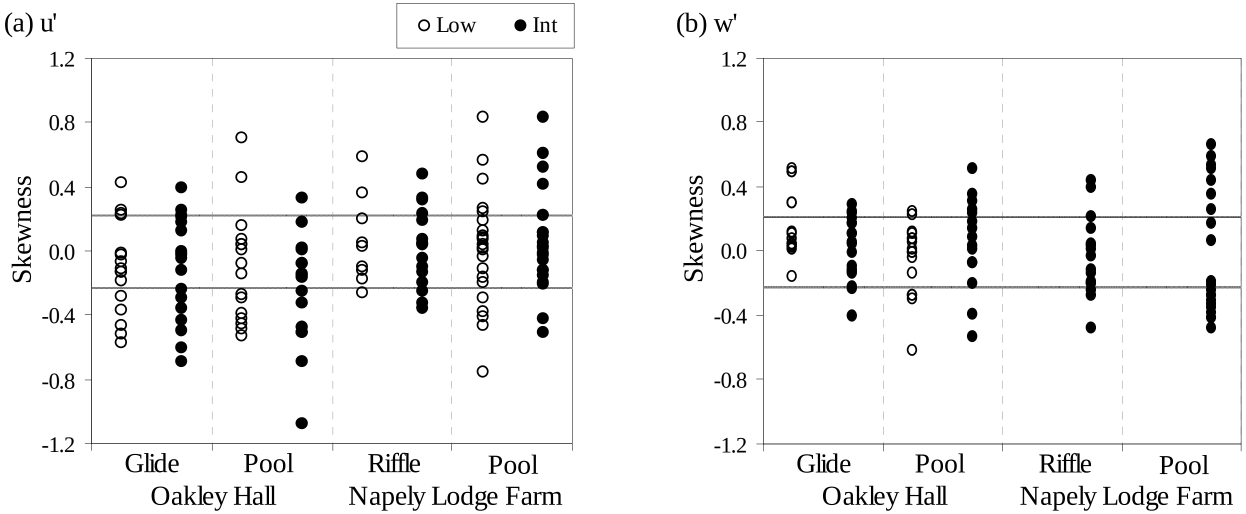


Figure 5.8 Skewness of the fluctuating components u' and w'. Horizontal dotted lines denote standard error of skew.

Turbulent stresses can be considered more explicitly by calculating the kinematic shear stress. Turbulent Reynolds stresses include twelve possible combinations of u' and w' components, but often the series-averaged kinematic shear stress (-u'w') is used as an overall descriptor (Duncan *et al.*, 1970). In addition to the influence on sediment entrainment and transport, the shearing force of water across the channel bed is of significance to benthic biota in terms of the energy required to resist detachment. Proportions of benthic invertebrates therefore demonstrate a spatial correlation with the distribution of shear stresses within the river channel (Merigoux and Doledec, 2004), and animals are known to seek lower-stress refugia in times of hydrological disturbance (Winterbottom *et al.*, 1997).

Kinematic shear stresses are plotted in Figure 5.9 in terms of both the series average and the average contributions from positive and negative stresses related to different turbulent ‘events’ which are explored in further detail in Section 5.4.2. The kinematic shear stress reveals some variation between biotopes in terms of overall values and scales of variation. The riffle at Napely Lodge Farm is consistently associated with negative shear stresses, reflecting a strong positive correlation between the streamwise and vertical turbulent residuals. This pattern differs from the tendency for large positive stresses that is generally expected as a consequence of large positive contributions to the shear stress from burst and sweep structures (Duncan *et al.*, 1970). This may suggest that burst-sweep processes are less significant within the riffle and instead turbulence generation is predominantly related to the shedding of vortices from the lee of clasts and pebble clusters.

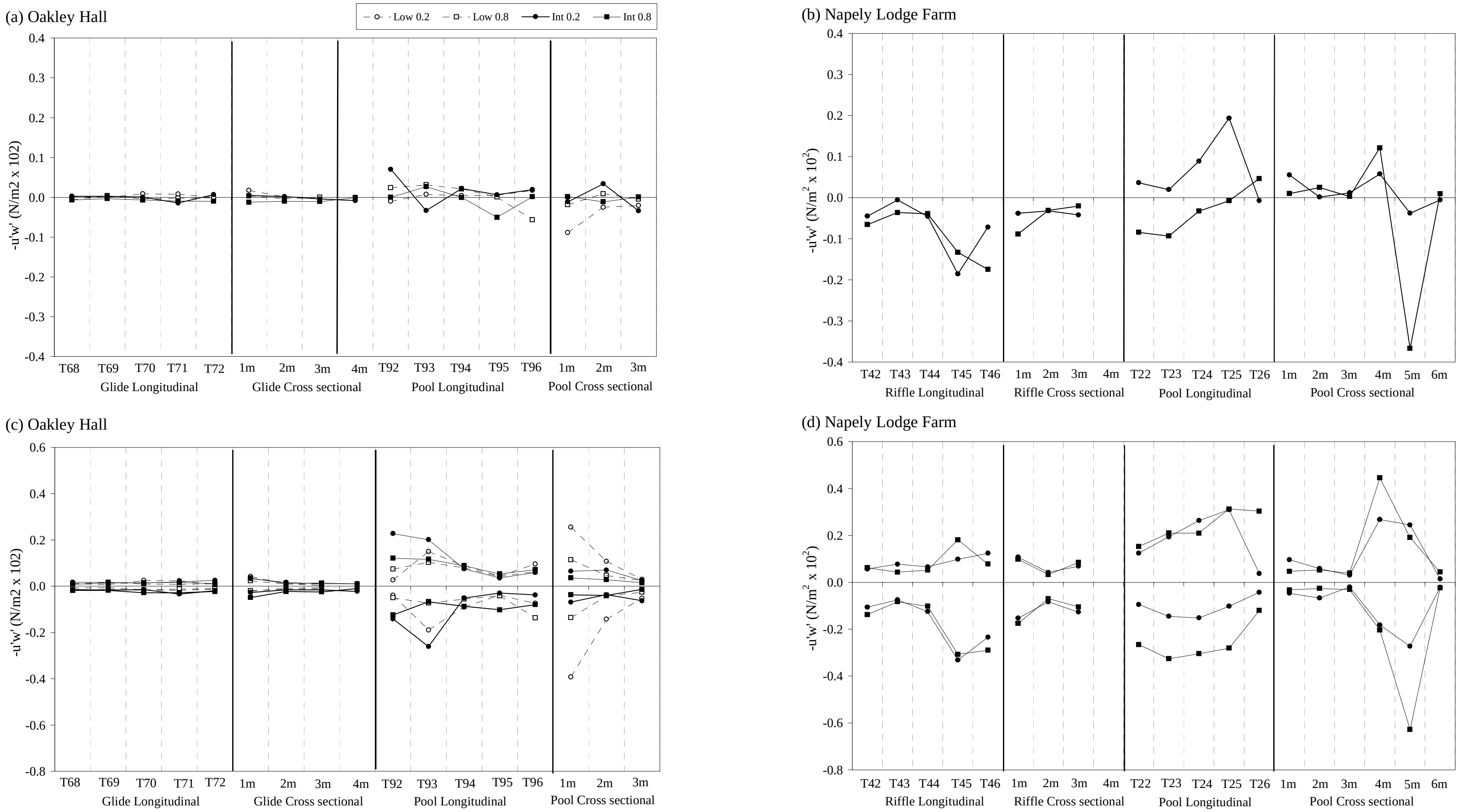


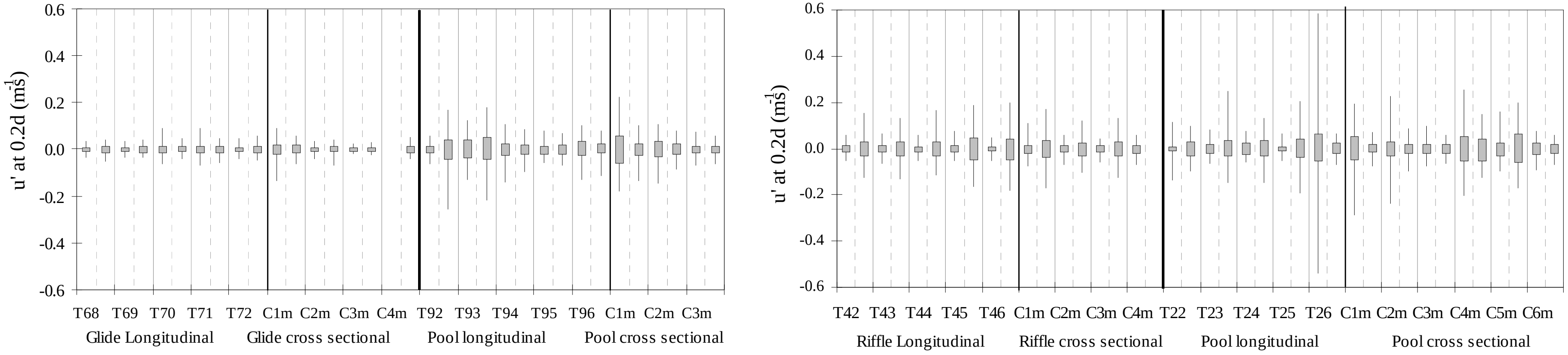
Figure 5.9 Series-averaged kinematic shear stress for (a) Oakley Hall and (b) Napely Lodge Farm, and separate positive and negative contributions to the shear stress (c and d) by sample location. Longitudinal measurements were located 1 m apart upstream along the centreline and are denoted by a numeric transect code (which increases upstream). Cross sectional measurements refer to the distance from the left bank.

Time-averaged kinematic shear stresses within the glide biotope are consistently very close to zero, reflecting approximately equal (and low magnitude) positive and negative contributions, and revealing very little variation spatially, with depth or with increasing discharge. Both pools are again associated with higher levels of internal variation which is more pronounced for the pool at Napely Lodge Farm. The pools are characterised by a combination of positive and negative average stresses, but separate positive and negative contributions suggest a tendency for higher magnitude stress associated with the location of the thalweg, and lower magnitude stresses within the backwater zone at Napely Lodge Farm.

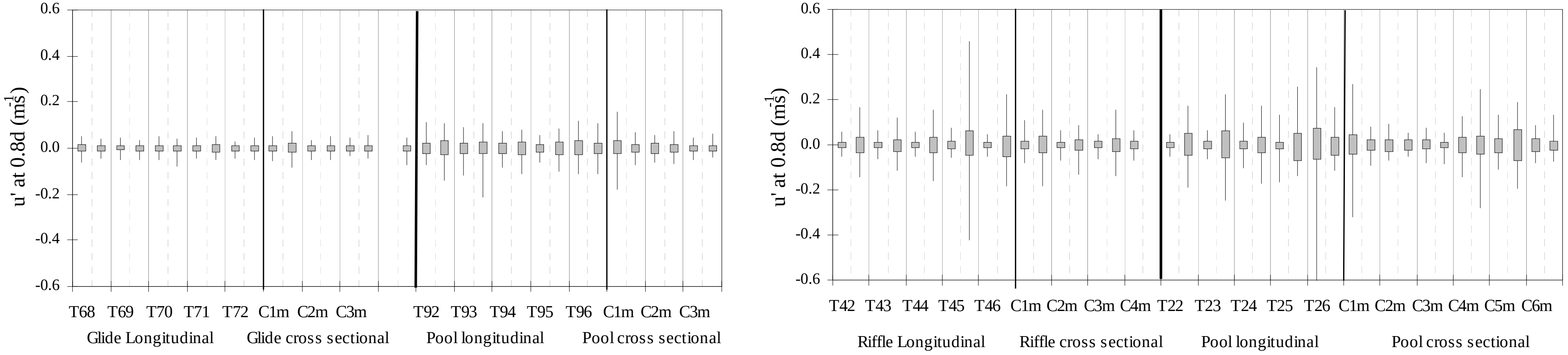
Both mean velocity and stress characteristics presented in this section support observations of complexity of hydraulic response to increasing stage (Clifford and Richards, 1992), particularly regarding the hydraulic organisation of pools, as opposed to the simpler reversal hypothesis suggested by Keller (1971). The following sections employ increasingly more ‘complex’ hydraulic parameters in order explore this further and attempt to improve the hydraulic characterisation of physical biotopes.

ii) Turbulence intensity

A preliminary indication of the intensity of the turbulent fluctuations may be gained from the absolute and interquartile ranges of the residual streamwise and vertical series (Figure 5.10 and 5.11). An overall increase in intensities can be identified with the transition from glide, riffle, to run biotopes. Once again, the glide is associated with the strongest spatio-temporal homogeneity of all biotopes, while the riffle is relatively homogeneous spatially, but demonstrates a pronounced increase in intensities with discharge. The pools are associated with the most pronounced spatial


(a) Oakley Hall

(b) Napely Lodge Farm

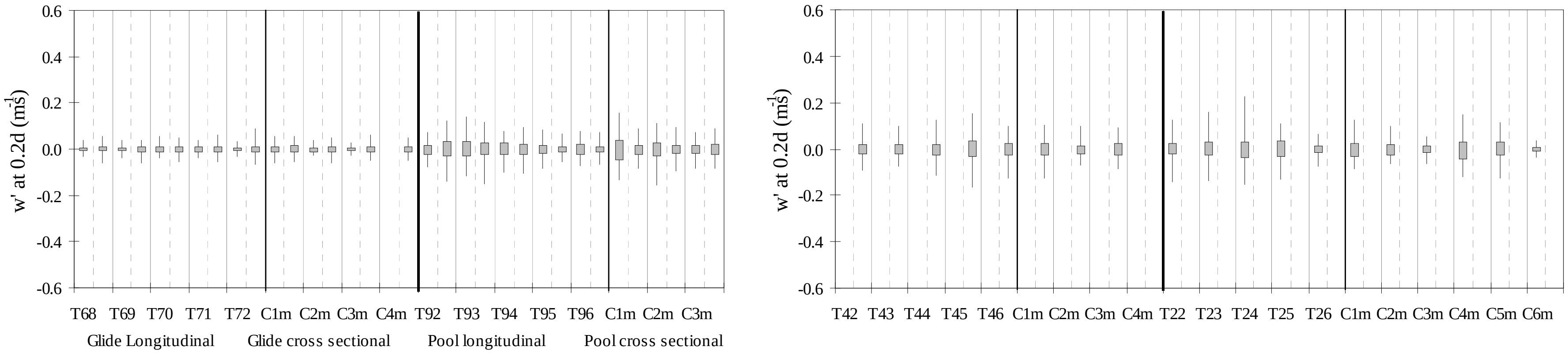

(c) Oakley Hall

(d) Napely Lodge Farm

Figure 5.10 Boxplots for u' series showing median, interquartile range and absolute range of values within each series. Dotted grey gridlines separate low flow (left hand boxes) and intermediate flow (right hand boxes) for each sample location. At Napely Lodge Farm low flow samples are 0.6d on both plots.

(a) Oakley Hall

(b) Napely Lodge Farm



(c) Oakley Hall

(d) Napely Lodge Farm

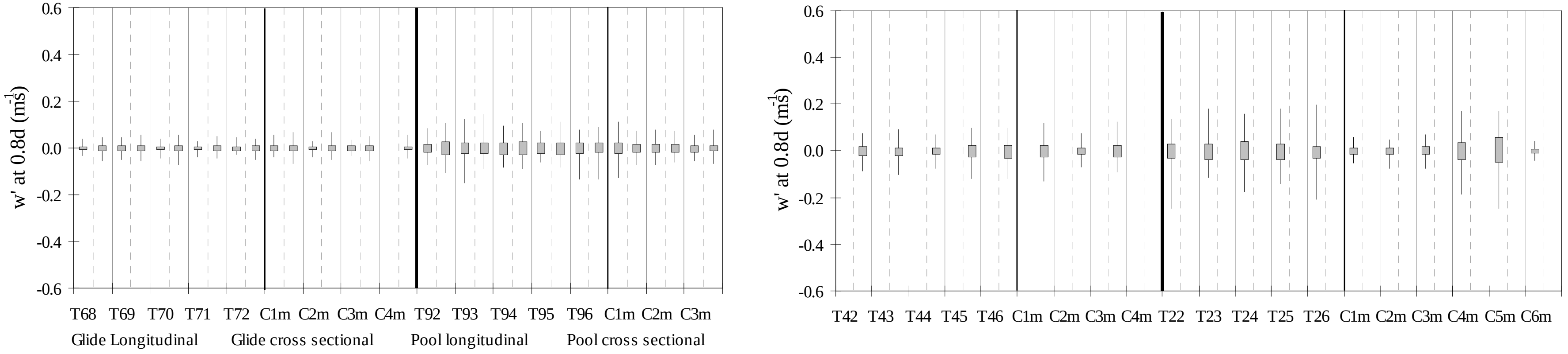


Figure 5.11 Boxplots for w' series showing median, interquartile range and absolute range of values within each series. Dotted grey gridlines separate low flow (left hand boxes) and intermediate flow (right hand boxes) for each sample location. At Napely Lodge Farm low flow samples are 0.6d on both plots.

variation, but the Napely Lodge Farm pool is consistently associated with larger ranges and interquartile ranges suggesting greater levels of turbulence intensity compared to the pool at Oakley Hall. The pool at Napely Lodge Farm also reveals some evidence of depth variation: samples close to the bed are generally associated with higher intensities compared to those close to the water surface, possibly reflecting flow intensification around microform roughness.

A further measure of intensity can be derived by calculating the root mean square (rms) values for the turbulent residuals, which provide an average measure of the intensity of fluctuations irrespective of sign. Figure 5.12a and b plot the rms values for streamwise and vertical velocity components. Overall, the relationship between the two rms components is approximately linear and positive, suggesting that vertical intensities increase linearly with streamwise intensities. Some variation in the nature of the relationship is noted with respect to different biotopes, however. Streamwise and vertical intensities are approximately equal within the glide, while vertical intensities are proportionately lower than streamwise intensities for the riffle and pool samples, suggesting that higher magnitude fluctuations in the streamwise dimension may suppress some vertical motion.

The average of the two rms values can be used to indicate the 'overall intensity' of fluctuations (Duncan *et al.*, 1970):

$$\text{'Overall intensity'} = \frac{1}{2}\left(\sqrt{\overline{u'^2}} + \sqrt{\overline{w'^2}}\right) \qquad \textbf{Equation 5.2}$$

The overall intensity values for the different biotopes are presented in Figure 5.12c. Overall intensity discriminates almost entirely between glide and pool biotopes at Oakley Hall at both flow stages, while at Napely Lodge Farm, the riffle and pool are associated with a large ‘overlap’ in values. The glide is characterised by very low intensities which increase at the higher flow stage and become more spatially homogeneous. Pools reveal the widest ranges of intensity values but show little variation in the absolute range of values with increasing stage (although this may be explored for the pool at Oakley Hall only).

Figure 5.13 explores the relationship between turbulence intensity and mean velocity which reveals some evidence of systematic behaviour (Clifford *et al.*, 1994). Evidence of a linear increase in intensity with mean streamwise or vertical velocity is strongest for both pool biotopes, suggesting that higher velocities enhance, rather than suppress the intensity of turbulence. However, R^2 values for linear regressions were generally below 0.5 and these are therefore not plotted. The most significant linear relationship ($R^2 = 0.72$) was noted for the streamwise component within the pool at Napely Lodge Farm, and relationships are generally stronger for the streamwise component compared to the vertical and for Napely Lodge Farm compared to Oakley Hall. This reflects the greater spatial heterogeneity and thus larger range of values associated with the pool at Napely Lodge Farm. At Oakley Hall, little variation is noted with increasing stage, although the relationship between intensity and mean streamwise velocity is slightly stronger, while the relationship with the vertical mean reveals increased scatter (Figure 5.13c and d).

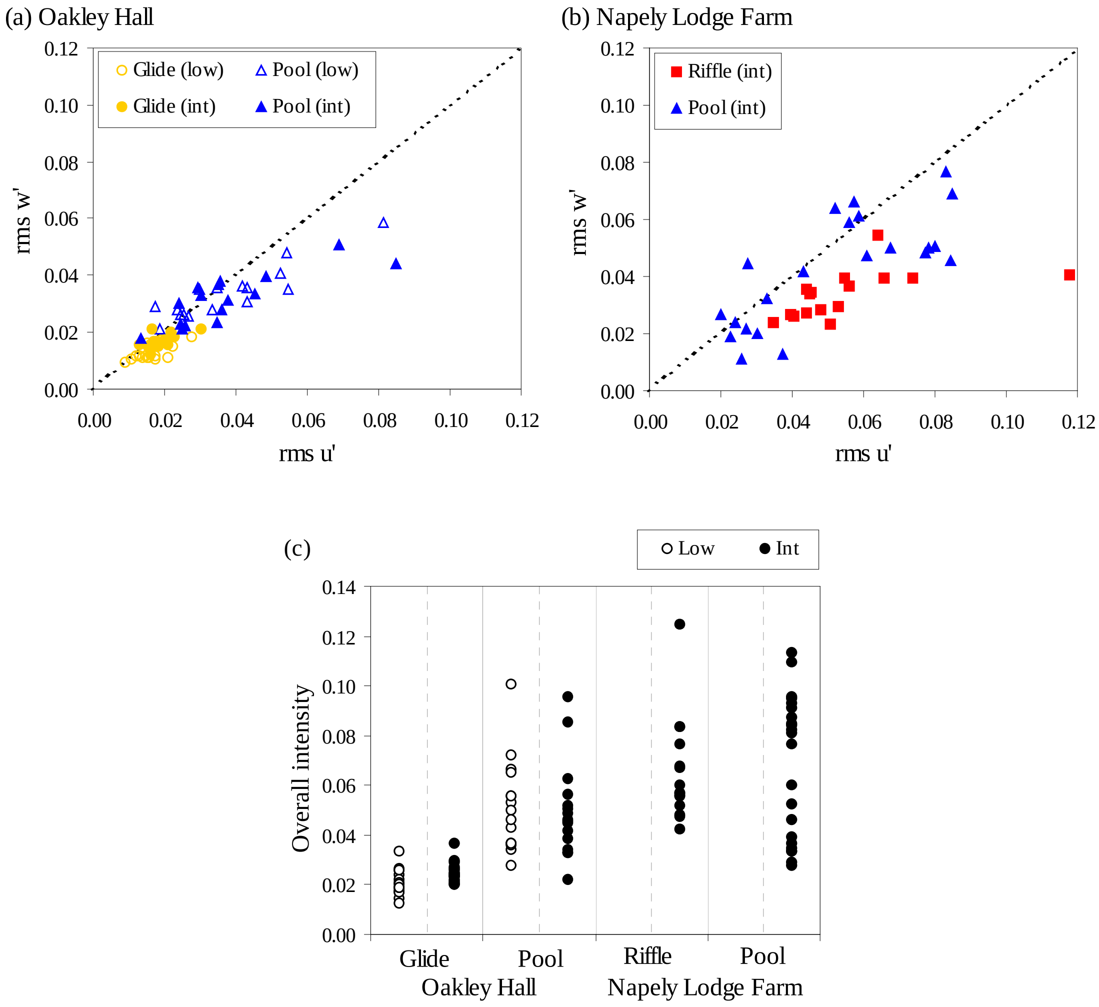


Figure 5.12 Comparison of the root mean square (rms) values for u' and w' for (a) Oakley Hall and (b) Napely Lodge Farm, and the range of overall turbulence intensity values for velocity series recorded within each biotope (c).

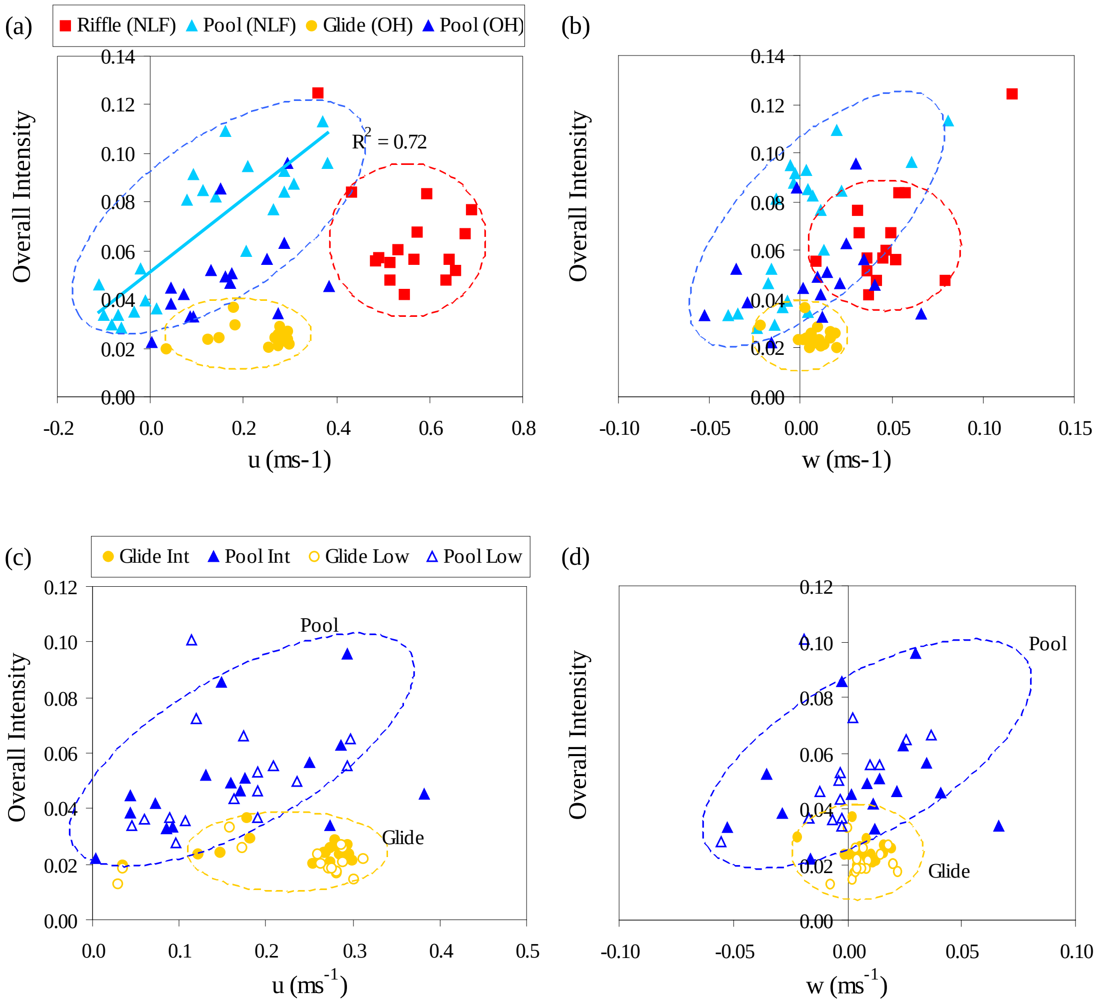
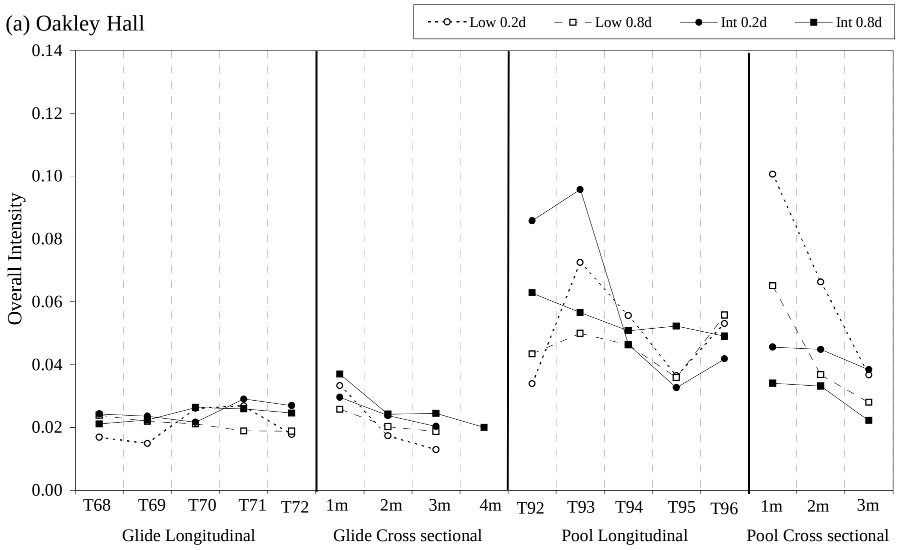


Figure 5.13 The relationships between mean velocities and overall turbulence intensity for all biotopes, at intermediate flow only for (a) Oakley Hall and (b) Napely Lodge Farm. (c) and (d) plot mean streamwise and vertical velocities respectively against turbulence intensity for Oakley Hall biotopes comparing low and intermediate flow stages (c and d). Linear regressions are plotted only where R^2 values exceed 0.5.

The spatial distribution of overall intensity is explored further in Figure 5.14. Once again, a continuum of increasing spatial heterogeneity is noted from glide, to riffle to pool biotopes, and the pool at Napely Lodge Farm is associated with the most pronounced spatial variation in values. Some localised increases in intensity may be attributed to the presence of particular flow obstructions, emphasising the influence of ‘microscale’ structures on flow organisation (Crowder and Diplas, 2000). For example, within the riffle (and particularly for samples close to the riverbed) increased intensities may correspond to the influence of flow obstructions such as pebble clusters. Within the pool at Oakley Hall, some of the strongest intensities are noted close to left bank, reflecting the intrusion of riparian tree roots into the flow. For the pool at Napely Lodge Farm, spatial variation appears more strongly related to the organisation of flow within the pool. The strongest intensities are associated with flow convergence at the pool head and in the proximity of the thalweg, while the large backwater zone is characterised by much lower intensities.

Within the pools, some variation in intensity is also noted with respect to relative depth. Within the pool at Oakley Hall, these variations are reveal a complex response to increasing flow stage: for samples close to the riverbed, intensities generally decrease with stage; but for samples close to the water surface, intensities increase with stage. For the pool at Napely Lodge Farm, variations in intensity with relative depth appear more spatially organised. Near-bed samples are consistently associated with higher intensities along the channel centreline and in proximity to the thalweg. In the backwater zone, however, intensities are higher at the water surface, perhaps reflecting the influence of rotational secondary circulations.


(a) Oakley Hall

(b) Napely Lodge Farm

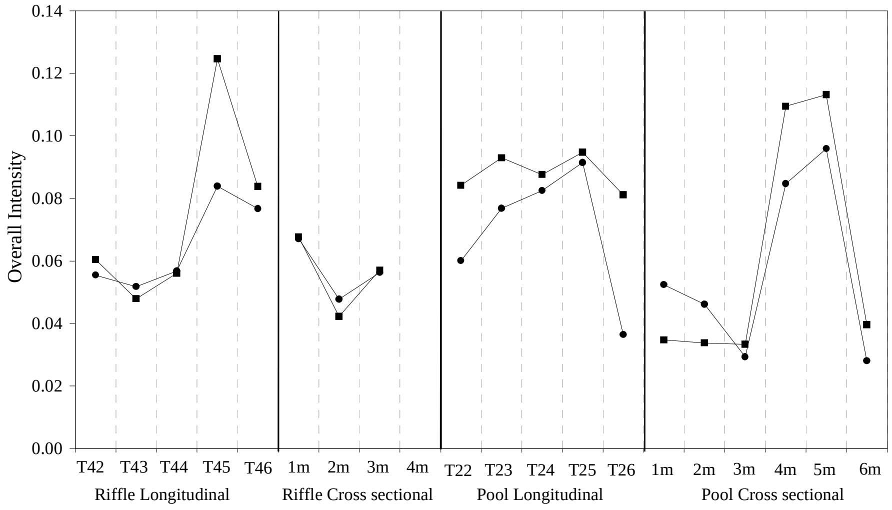


Figure 5.14 Overall intensity by sample location for (a) Oakley Hall and (b) Napely Lodge Farm. Longitudinal measurements were located 1 m apart upstream along the channel centreline and are denoted by a numeric transect code (which increases upstream). Cross sectional measurements refer to the distance from the left bank.

5.4.2 Turbulent event structure

Observations within a u'w' time series may be assigned to one of four turbulent ‘event’ types (bursts, sweeps, outward and inward interactions) depending on the relative signs of u' and w' (Figure 5.15). A threshold value of relative magnitude is often used in order to eliminate the influence of lower magnitude contributions that do not reflect discrete ‘events’. Event structure for the Tern data was computed using a threshold value of two standard deviations of u' following Gordon (1974) and Clifford and French (1992). The period, duration and contribution to the total stress of these events can provide further information on turbulent flow structure, but has to date been largely overlooked in biotope characterisation.

Table 5.1 presents data from selected laboratory and field studies of turbulent event structure within a variety of hydraulic environments in order to illustrate the range of features examined and values identified. The events are often intermittent in nature, but contribute significantly to the total stress. The largest contributions to the stress are generally associated with bursts (ejections of fluid away from the bed), followed by sweeps (compensatory inrushes; Lu and Wilmarth, 1973). Significantly lower magnitude contributions are generally associated with the ‘negative’ quadrants (outward and inward interactions).

Some variations in event characteristics have been associated with bed microforms and riffle-pool units. For instance, lower magnitude and vertically restricted bursts accompanied by infrequent low magnitude sweeps have been associated with sand ripples, in contrast to unrestricted higher magnitude bursts and frequent high magnitude sweeps found within dunes (Bennett and Best, 1996). Data presented by

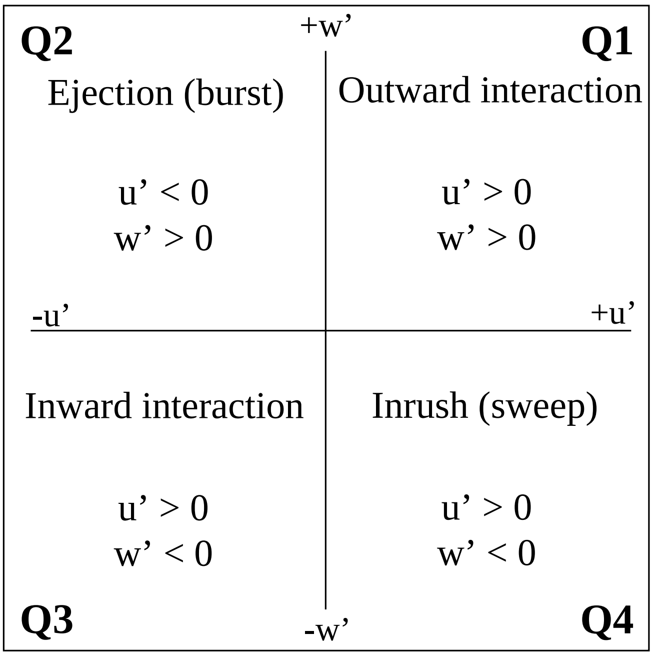


Figure 5.15 Turbulent event ‘quadrants’ identified from the joint distributional characteristics of u' and w'.

Author(s)	Study	Burst: Sweep ratio	Fractional stress contributions				Intermittency of stress contributions
			Bursts	Sweeps	Inward interactions	Outward interactions	
Grass (1971)	Laboratory - channel		~ 50 - 70%				
Lu and Wilmarth (1973)	Laboratory - wind tunnel	1.7	~ 77%	~ 55%	~ 32%	~ 32%	
Gordon (1974)	Field - Estuary		~ 68%	~ 60%	~ 15%	~ 15%	15% stress in 1% time 60% stress in 10% time
French and Clifford (1992)	Field – Saltmarsh channel						90% stress in 50% time 43% stress in 10% time
Clifford and French (1993b)	Field – Riffle in gravel-bed channel		~ 68%	~56%	~ 12%	~ 12%	
	Field – Pool in gravel-bed channel		~ 83%	~ 85%	~ 35%	~ 35%	
Lapointe (1996)	Field – Sand-bedded channel						6 – 70% stress in 0.5 – 4% time
Roy et al. (1996)	Field – gravel-bed river		~ 65 – 88%	~ 70 – 85%	~ 15 - 35%	~ 20 - -8%	

Table 5.1 Summary of burst-sweep data for selected publications from a range of hydraulic environments.

Clifford and French (1993b) for a small gravel-bed river identified higher magnitude contributions from all four quadrants for pool compared to riffle samples. Furthermore, stress contributions from bursts and sweeps were found to be approximately equal, in contrast to the asymmetry noted by Lu and Wilmarth (1973) for laboratory data.

The fractional contributions to the kinematic shear stress (-u'w') from each of the four event quadrants are presented in Figure 5.16. Overall, bursts are undetected in a higher proportion of series than sweeps, but show a larger proportion of very high magnitude contributions to the stress. Similarly, outward interactions are undetected in a higher proportion of series than inward interactions but are again associated with a very high proportion of high magnitude stress contributions. This highlights the intermittent, but high magnitude nature of these events. The ratio of bursts to sweeps shows a very broad range of values for all biotopes, falling both above and below the value of 1.7 identified by Lu and Wilmarth (1973) for laboratory data. However, this variation is likely to reflect the intermittency of the higher magnitude events which may exceed the 30 s sampling period used in this study (Gordon, 1974).

Figure 5.17 plots the fractional contribution of different events against the cumulative duration of the events for each series. The range of values are similar for all quadrants, and suggest that 20% of the series stress is accounted for by high magnitude events over a total duration of 1.5 s (5% of the 30 s series). While the levels of intermittency show some consistency with published works (Gordon, 1974; French and Clifford; 1992; Table 5.1), the absolute values of stress contributions for

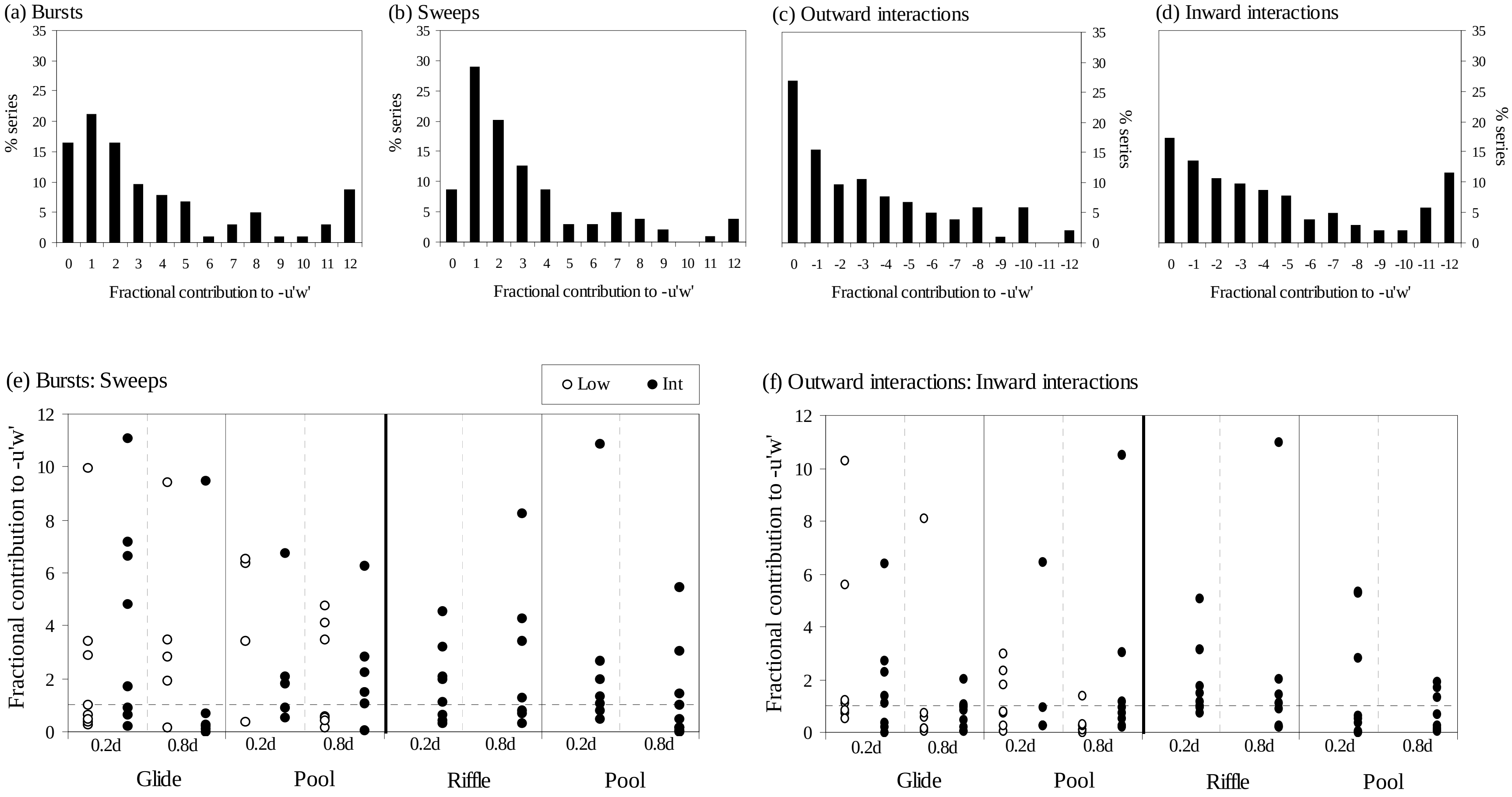


Figure 5.16 (a to d) Frequency histograms for the percentage of series associated with contributions of each event type to the series – u'w' for low and intermediate flow data combined, and the ratio of (e) bursts to sweeps and (f) outward to inward interactions.

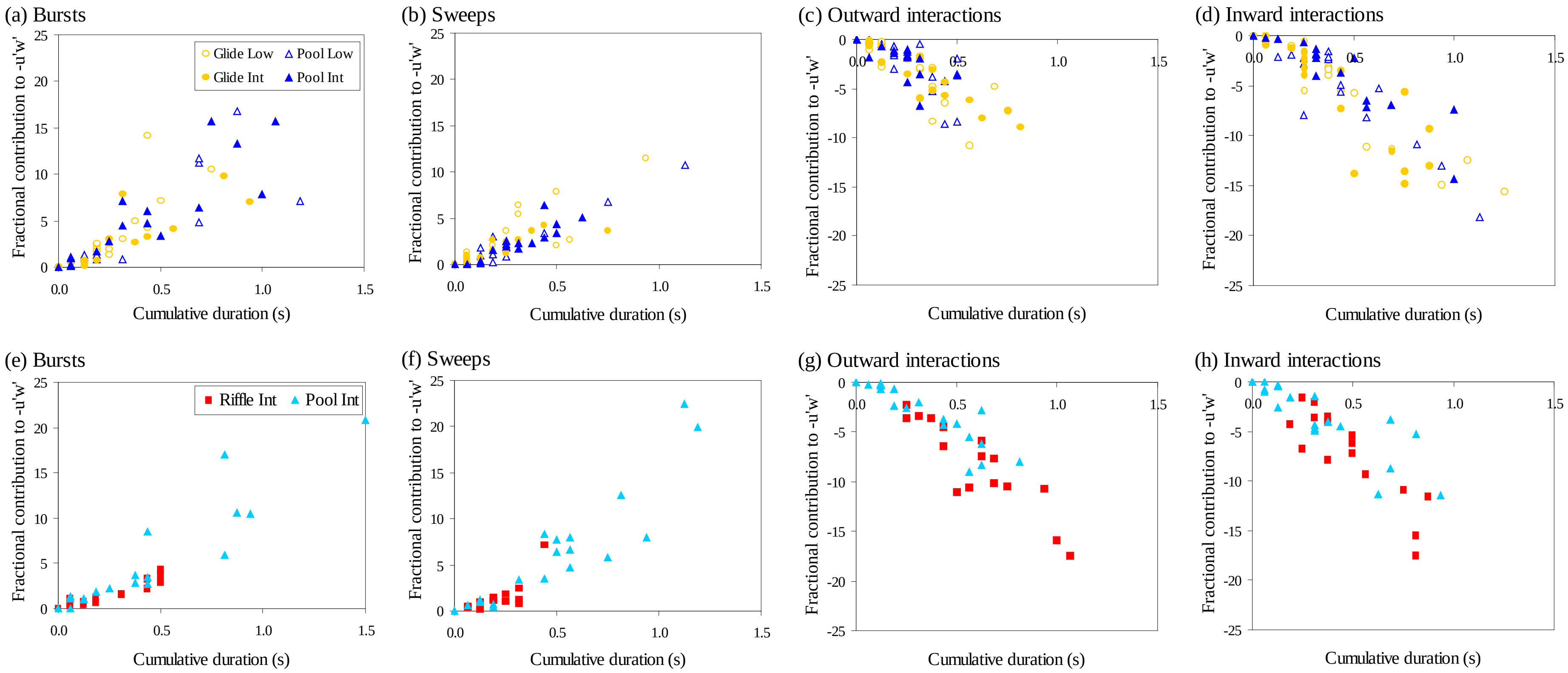


Figure 5.17 Cumulative fractional stress contribution and duration of each of the four turbulent event types for Oakley Hall (a to d) and Napely Lodge Farm (e to h). Each point represents the cumulative stress/ duration of a particular event type within a time series.

bursts and sweeps are lower than reported laboratory and field values, perhaps again reflecting the influence of the sampling period.

As with other measures, however, some indications of between biotope variations are present, suggesting a potential for further investigation perhaps using longer duration series. In particular, two broad clusters of series can be identified for each plot in Figure 5.17 corresponding to: (i) low magnitude, short cumulative duration events; and (ii) events associated with longer cumulative duration and increased scatter in magnitude. For bursts and sweeps, the higher-magnitude, longer-duration events are predominantly associated with pool series. For outward and inward interactions the higher magnitude, longer duration events are principally associated with riffle and glide samples. This is particularly apparent for Napely Lodge Farm, since higher-magnitude, longer-duration bursts and sweeps are not observed within the riffle. This may reflect greater intermittency of burst and sweep events within the riffle (which are therefore not captured by the sampling interval), but may also be associated with greater boundary layer roughness, implying that turbulence generation may be more strongly controlled by vortex shedding from pebble clasts and clusters. The existence of such flow structures is explored in the follow section.

5.4.3 Characteristic flow structures

Alternative means of exploring the presence of coherent flow structures within the boundary layer are concerned with the identification of ‘characteristic’ or ‘dominant’ eddies from velocity series. This may proceed by analysis in the ‘time domain’ through autoregressive modelling, and in the ‘frequency domain’ using spectral density analysis. The following sections present the results of analysis using these two complementary approaches performed on data from the River Tern.

i) Autoregressive modelling

In the same way that correlation coefficients may be obtained from the standardised covariance of two independent variables, so the autocorrelation coefficient may be derived from the covariance of two observations of the same variable in a time series separated by a time lag (k). Autocorrelation coefficients for successive values of k may be visually inspected using a correlogram or 'sample autocorrelation function' (ACF.). The ACF may be used to identify whether the fluctuations in a time series are random, characterised by short term fluctuation, or alternate on either side of the mean (Chatfield, 2004). ACFs plotted for turbulent time series in small sand- and gravel-bedded rivers have revealed oscillations characteristic of a damped sine wave which has been interpreted to represent a second-order 'pseudo-periodic' autoregressive process (Robert *et al.*, 1993). Such characteristics indicate that a tendency to periodic behaviour exists in the series, but that this is disturbed by 'shocks' from a random component which create a constantly changing phase and period (Box and Jenkins, 1976).

The modelling of stationary physical processes using autoregressive (AR), moving average (MA) or mixed (ARMA) time series models allows these characteristics to be expressed statistically. AR models are essentially linear regressions where the velocity value is regressed against previous values in the time series rather than a separate variable. They are generally described as 'stochastic', meaning that different sets of observations generated by such a model over the same time period would reveal different characteristics but obey the same probabilistic laws (Harvey, 1981).

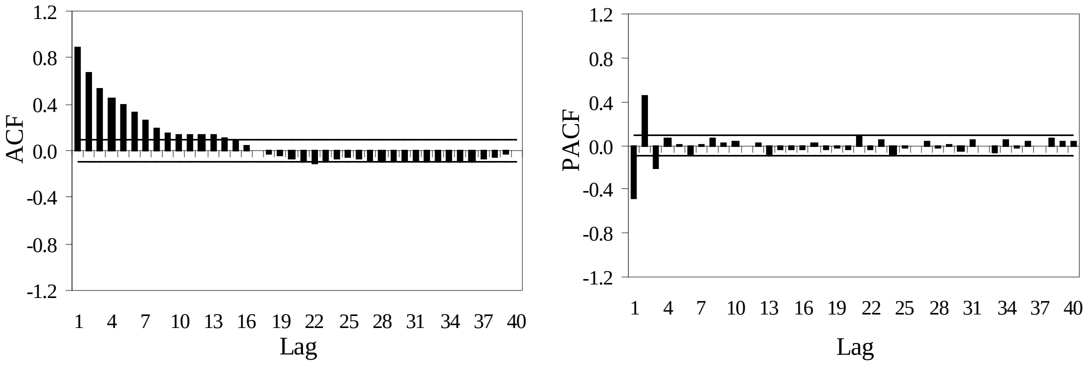
MA models linearly regress observations against the random shocks of previous observations, thus incorporating past deviations from the series mean into predictions of the ‘current’ value. In both AR and MA modelling, the specified model order represents the number of time periods in the past used to predict the current value in the time series.

AR models are appropriate to situations where it can be assumed that values in a time series depend linearly on immediate past values plus a random error term (Chatfield, 2004). Second-order autoregressive, or AR(2) models are a popular choice in geophysical applications since they may be directly associated with specific pseudo-cyclic physical phenomena such as riffle-pool sequences (Richards, 1976) and turbulent flow structures (Clifford, 1996a). Provided that model parameters meet certain inequality requirements, the average frequency of the deterministic component may be interpreted as the characteristic vortex shedding frequency (Clifford *et al.*, 1992b), although the minimum detectable wavelength is limited by the velocity sensor head diameter (Lane *et al.*, 1993). More complex processes may require mixed models (ARMA) which require fewer model parameters but have less obvious physical interpretations.

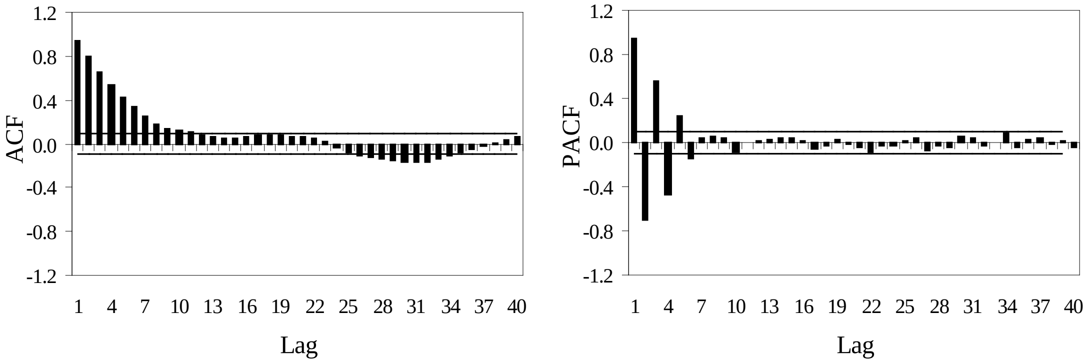
The autocorrelation function (ACF) and partial autocorrelation function (PACF) are generally used as indicators for the order and type of model appropriate for a particular time series (Chatfield, 2004). As a general rule, an autoregressive process of order p is characterised by an autocorrelation function which decays exponentially, and a partial autocorrelation function which cuts off after lag p. For an MA(p) process, the ACF cuts off after lag p, and the PACF decays exponentially. Both the ACF and PACF of a mixed ARMA process are generally characterised by a mixture of damped exponentials and sine waves.

ACFs and PACFs were plotted for each velocity series in SPSS 14.0. ACFs were generally characterised by a slow decay, with some oscillation either side of zero, whereas the PACFs were characterised by a ‘cut-off’ after around the first two to four lags (Figure 5.18). The cutting off of the PACF suggests an autoregressive process, although the number of parameters suggested by the PACF varied between series. The most appropriate choice of model was therefore somewhat unclear from the inspection of ACFs and PACFs and so three types of model were tested for each series in order to evaluate goodness of fit.

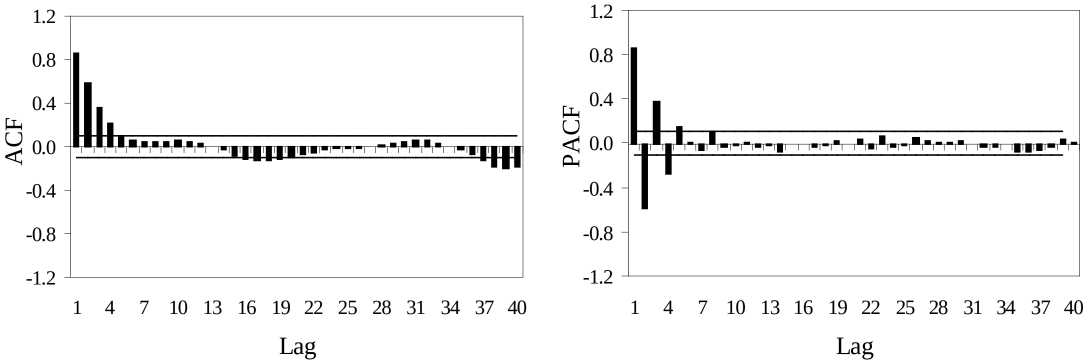
For reasons of parsimony the number of parameters was restricted to two (Box and Jenkins, 1976). Second order AR and MA models, and the mixed model ‘ARIMA (1,0,1)’, were therefore fitted to each series and assessed for goodness of fit using the calculated R^2 value. MA(2) models and ARIMA(1,0,1) models were generally associated with higher R^2 values overall and therefore provide a better fit. However, the AR(2) model was chosen for further analysis for several reasons. Firstly, R^2 values associated with series modelled with AR(2) models are considered acceptable in the context of contemporary field studies (Clifford *et al.*, 1992b; Robert *et al.*, 1993): no series were associated with an R^2 value below 0.5, and for 77% of all series, the R^2 value generated by AR(2) models exceeds 0.8. Furthermore the improvements in model fit generated by fitting an MA or ARIMA model were relatively small.


(a) Glide (OH)

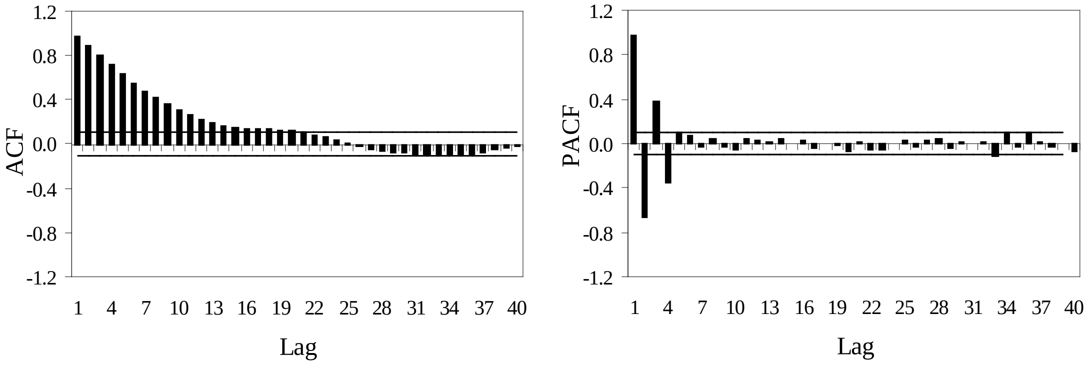
(b) Glide (OH)


(c) Pool (OH)

(d) Pool (OH)


(e) Riffle (NLF)

(f) Riffle (NLF)


(g) Pool (NLF)

(h) Pool (NLF)

Figure 5.18 Example autocorrelation functions (ACFs) and partial autocorrelation functions (PACFs) for each physical biotope. Horizontal lines indicate significance level.

Secondly, AR(2) models are associated with direct physical interpretations, while moving average and mixed models present difficulties for interpretation. Thirdly, while the cut-off of PACFs at lags greater than 2 suggests greater ‘complexity’ than is accounted for by AR(2) models, this complexity is explored in greater detail using spectral density analysis in Section 5.4.4, allowing AR(2) models to be used as a first step in the analysis of coherent flow structures.

The fitting of an AR(2) model to a time series assumes that the series is characterised by a second-order autoregressive process of the form:

$$y_t = \varnothing_1 y_{t-1} + \varnothing_2 y_{t-2} + \epsilon_t$$ ***Equation 5.3***

This states that the present value of the series (y_t) is a function the two preceding values (y_{t-1} and y_{t-2}) multiplied by constants (model parameters $\varnothing_1$ and $\varnothing_2$) plus an error term (ϵ_t). The process may be decomposed into a stochastic and a deterministic component (Harvey, 1981) and, provided that the process is stationary, the deterministic component may be used to provide information on the characteristics of ‘average’ flow structures (Clifford and French, 1993a). The two model parameters must satisfy certain conditions for the deterministic component to represent a stationary process:

(a) $\varnothing_1 + \varnothing_2 < 1$

(b) $-\varnothing_1 + \varnothing_2 < 1$

(c) $\varnothing_2 > -1$ **Equation 5.4**

The parameter values satisfy the conditions for stationarity for all series. However, an additional condition must be satisfied for the deterministic component to be considered pseudo-periodic (Richards, 1979):

$$Ø_1^2 + 4Ø_2 < 0 \qquad \textbf{Equation 5.5}$$

The condition for pseudo-periodicity is satisfied by 82% of series (Table 5.2). Interestingly, some variation in the proportion of series associated with pseudo-periodic behaviour is noted between biotopes. For instance, pool samples are associated with a higher proportion of non-pseudo-periodic series compared to both riffle and glide samples for each site respectively. Again, this suggests a more complex flow structure in pools, reflecting interactions between burst-sweep structures and vortices shed from irregularly-sized woody debris, grain roughness elements and larger bedform-related flow structures associated with morphological transitions. Furthermore, the deeper water and slower velocities within pools may promote interaction and coalescence of flow structures of varying size.

The model parameter values associated with each modelled series are presented in Figure 5.19. The relationship between the two parameters is necessarily negative, but again, some variation between biotopes is evident. Generally, pool samples are associated with higher $Ø_1$ values compared to glide and riffle samples. This reflects the fact that observations at one lag distance exert a stronger influence on the current value in the series. This again emphasises the complex nature of the flow environment within pools by suggesting weaker correlations between observations located further apart in time (and space) compared to glide and pool biotopes.

Series	Site	Physical biotope	Low flow			Intermediate flow		
			No. series	No. pseudo-periodic series	No. non pseudo-periodic series	No. series	No. pseudo-periodic series	No. non pseudo-periodic series
u'	Oakley Hall	Glide	16	11	5	18	13	5
		Pool	16	15	1	16	14	2
	Napely Lodge Farm	Riffle	9	9	0	16	16	0
		Pool	22	14	8	22	12	10
w'	Oakley Hall	Glide	16	16	0	18	18	0
		Pool	16	13	3	16	14	2
	Napely Lodge Farm	Riffle	0	N/A	N/A	16	16	0
		Pool	0	N/A	N/A	22	15	7

Table 5.2 Satisfaction of the condition for pseudo-periodicity by site, biotope and flow stage for each velocity component.

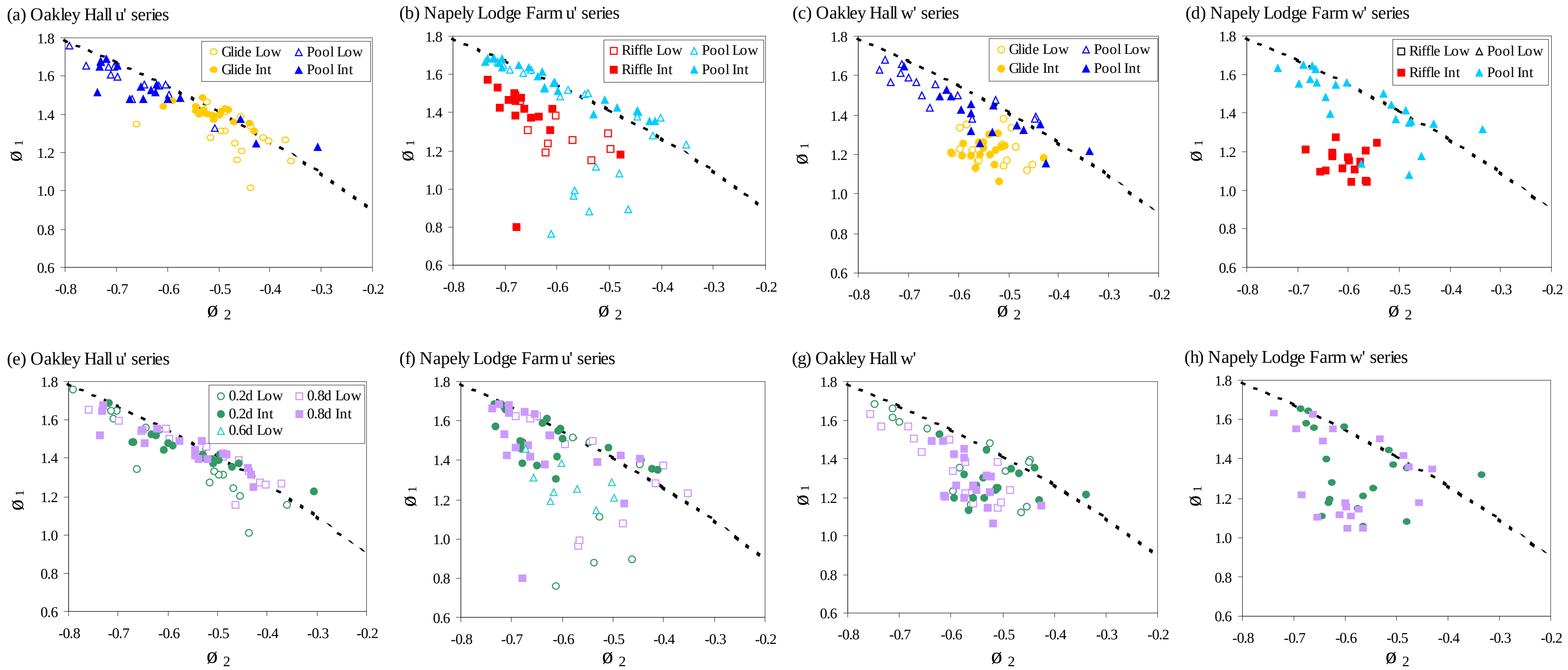


Figure 5.19 AR(2) model parameter values for each series by biotope and flow stage (a to d) and relative depth and flow stage (e to h) for each site and for each of the two velocity components. The dotted line represents the threshold for pseudo-periodicity.

Significantly, variations in the model parameter values between biotopes are more significant than variation associated with the relative depth of the measurement.

ii) Flow structure size and origin

For series satisfying the pseudo-periodicity inequality, the average frequency of the deterministic periodic component derived from the AR(2) process may be used to calculate the average frequency of the dominant flow structure (Clifford *et al.*, 1992b):

$$\mathrm{Cos}\,2\pi f = Ø_1\left(\sqrt[2]{-Ø_2}\right)^{-1} \qquad \textbf{Equation 5.6}$$

The inverse of the frequency, f, is the period, (P) or time taken for the passage of the flow structure past the sensor, measured in seconds. This assumes G. I. Taylor's substitution, that the sequence of events at a fixed point represents the movement of an unchanging pattern of turbulence past that point (Reynolds, 1974), and provides only an 'average' indication of eddy size. Furthermore, dependency of the model on the previous two observations in a series means that higher frequency flow structures are likely to be modelled better than lower frequency oscillations.

The coefficient of variation for each series may be used as a check that the size of eddies is relatively constant through time, and therefore the 'average' statistics provide a satisfactory representation. Coefficients of variation for u' series are plotted according to sample location, flow stage and relative depth in Figure 5.20. Values generally fall below or close to 0.1 for glide and riffle samples suggesting minimal variation in eddy shape (Clifford, 1997). However, values are higher for both pools, suggesting that average eddy statistics derived from AR(2) models may be subject to

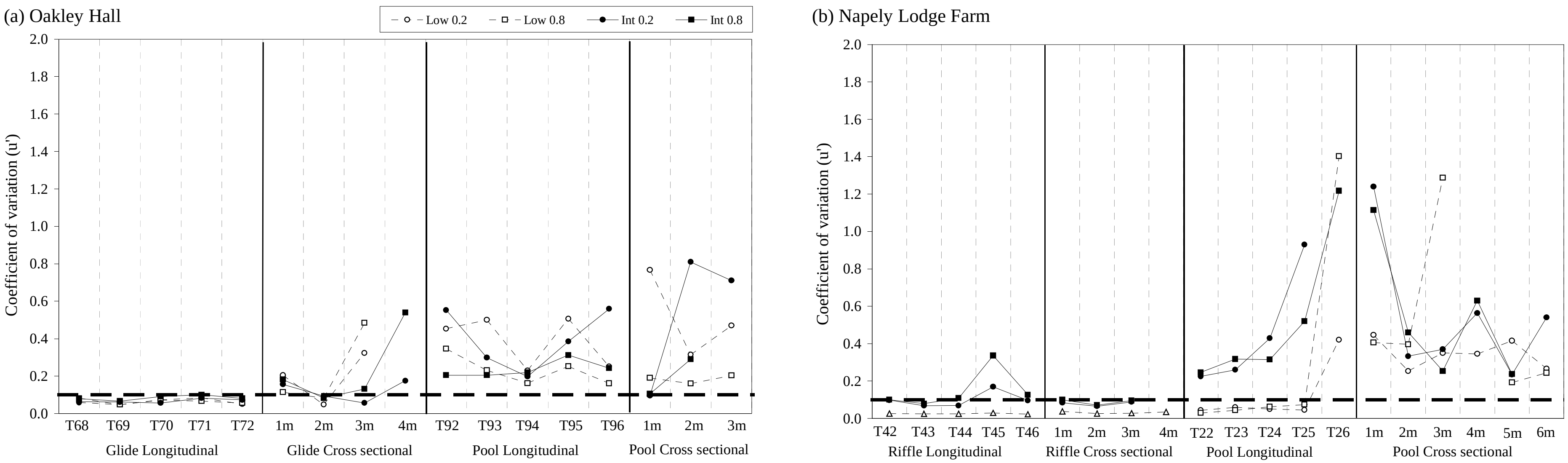


Figure 5.20 The coefficient of variation for u' series. The threshold value of 0.1, used to indicate consistent eddy size and shape, is indicated by a dotted line. Four large outliers (ranging up to 20.29), all associated with pool samples, are removed in order to improve visual display. Longitudinal measurements were located 1 m apart upstream along the channel centreline and are denoted by a numeric transect code (which increases upstream). Cross sectional measurements refer to the distance from the left bank.

higher levels of error. These samples are retained in the analysis, but ‘average’ values may be less representative of the flow structures recorded.

Figure 5.21 presents the dominant period derived from AR(2) models for each series according to physical biotope and flow stage. All series are characterised by a periodic component with an average period of between 1 s and 2 s duration, however, some variation between biotopes is noted. Riffle and glide biotopes are associated with similar ranges of values, which contract to a more restricted range of values with increasing discharge. The pools, however, reveal contrasting patterns. At Oakley Hall, the pool is characterised by a very restricted range of values at the lower flow stage, which plot ‘within’ the range identified for the glide. At the higher flow stage, a large amount of overlap with the glide is still noted, but the pool reveals a slight increase in the range of dominant periods detected. In contrast, the pool at Napely Lodge Farm is characterised by a much larger range of values at the low flow which contracts to a very tight range of values close to 1 s duration at the higher flow stage. This partly relates to a lower sample number, since more of the intermediate flow series within the pool failed to meet the condition for pseudo-periodicity.

Assuming that Taylor’s substitution applies, the average period derived from AR(2) models can multiplied by the mean velocity to provide a spatial measure of eddy length (L) (Clifford and French, 1993a):

$$L = uP$$ **Equation 5.7**

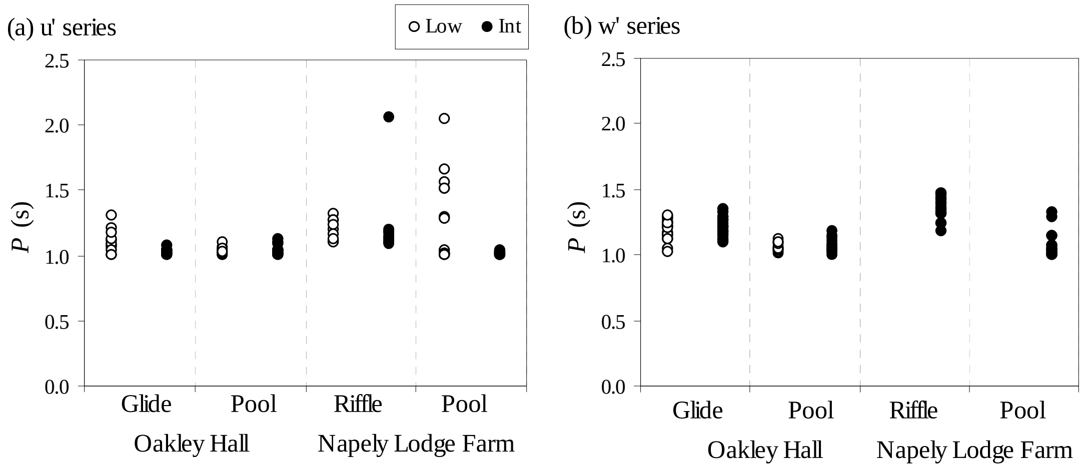


Figure 5.21 Dominant period (*P*) derived from pseudo-periodic AR(2) models for each biotope and flow stage for u' and w' series.

Figure 5.22 plots the eddy length scales derived from each series by biotope and flow stage. At Oakley Hall, glide and pool biotopes show similar ranges of length scales at both flow stages, suggesting a dominance of structures smaller than 0.4 m in length. In contrast, riffle and pool biotopes at Napely Lodge Farm are clearly differentiated by eddy lengths. The riffle is characterised by a larger range of larger eddy sizes (up to 1.05 m) compared to the pool at both flow stages, although the absolute range of values is reduced at the intermediate flow stage. Additionally, eddy lengths within the riffle are associated with a narrower range of values compared to the pool, particularly at low flow, suggesting greater spatial homogeneity in flow structure. Once again, these variations between biotopes appear more significant than any variation associated with the relative depth of the measurement.

Spatial variations in eddy length within each biotope are explored in further detail in Figure 5.23. Once again the glide demonstrates strong homogeneity spatially, with depth and with increasing flow stage. The riffle is also associated with relatively strong spatial homogeneity, but shows systematic variation in flow structure size with relative depth and discharge. At the intermediate flow stage, flow structures reveal an overall reduction in size. Furthermore eddy sizes associated with samples close to the water surface are consistently larger compared to those near the bed, possibly reflecting the evolution and coalescence of structures with distance from the boundary. Greater spatial heterogeneity is noted within the pools, but this appears relatively unsystematic. There is some tendency for larger flow structures towards the pool tail, perhaps reflecting the interaction and coalescence of structure of varying size generated by the morphological transition and vortex shedding from smaller roughness elements.

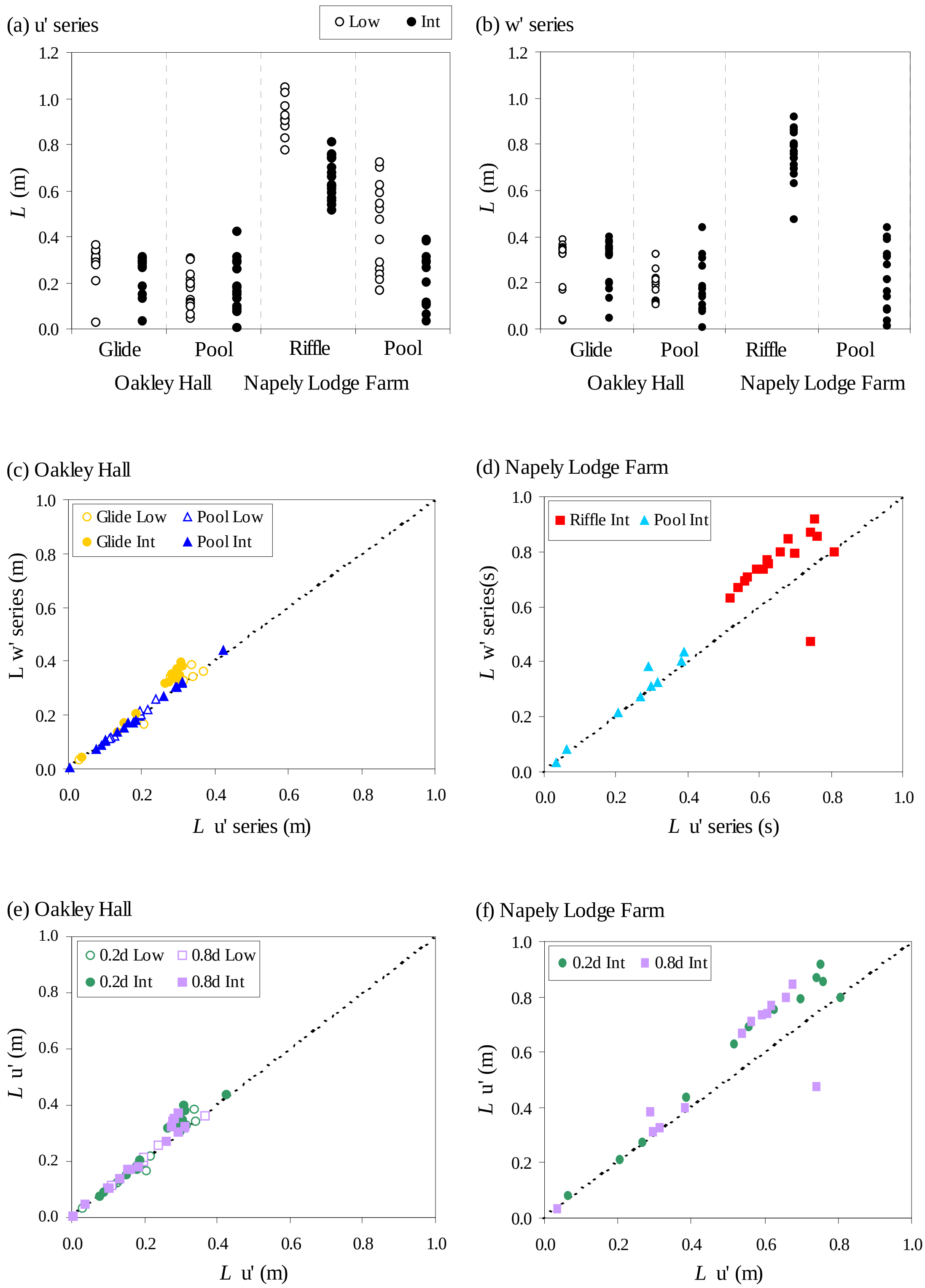
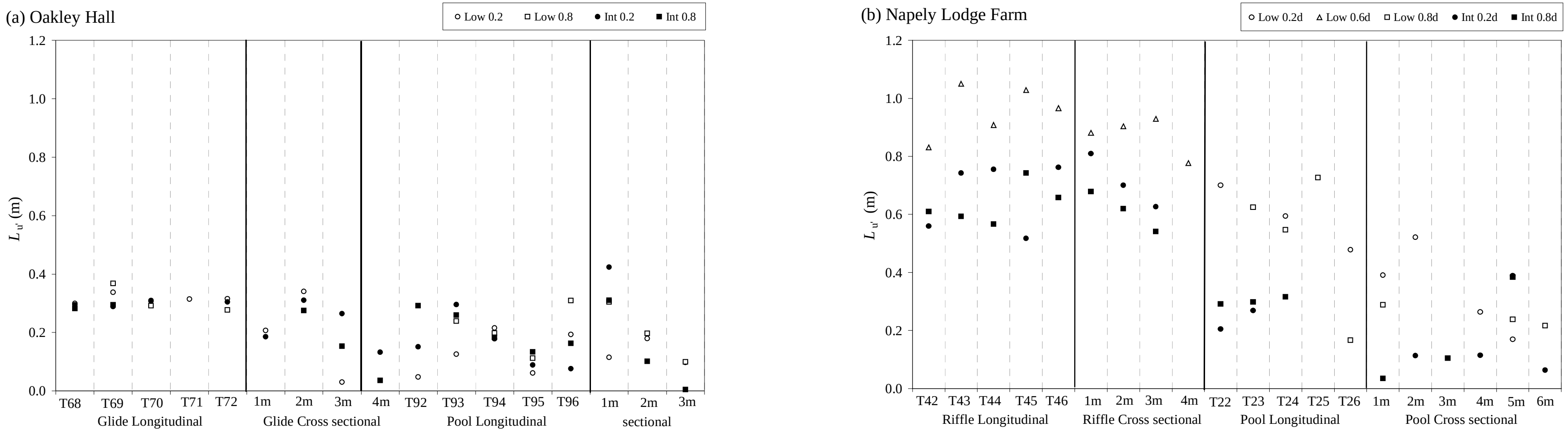


Figure 6.22 Dominant eddy length scale (*L*) derived from pseudo-periodic AR(2) models for each biotope and flow stage for u' and w' series for (a) Oakley Hall and (b) Napely Lodge Farm, and comparison of values derived from u' and w' series according to biotope (c and d) and relative depth (e and f).



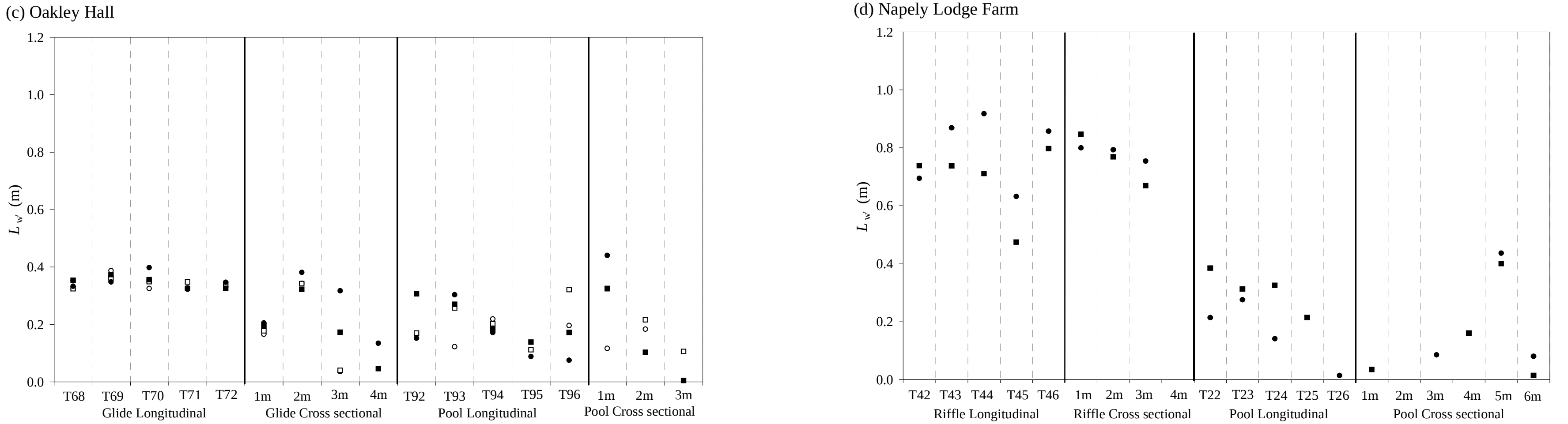


Figure 5.23 Dominant eddy length scale (*L*) derived from pseudo-period AR(2) models applied to u' series for (a) Oakley Hall and (b) Napely Lodge Farm by sample location, and applied to w' series (c and d). Longitudinal measurements were located 1 m apart upstream along the centreline and are denoted by a numeric transect code (which increases upstream). Cross sectional measurements refer to distance from left bank.

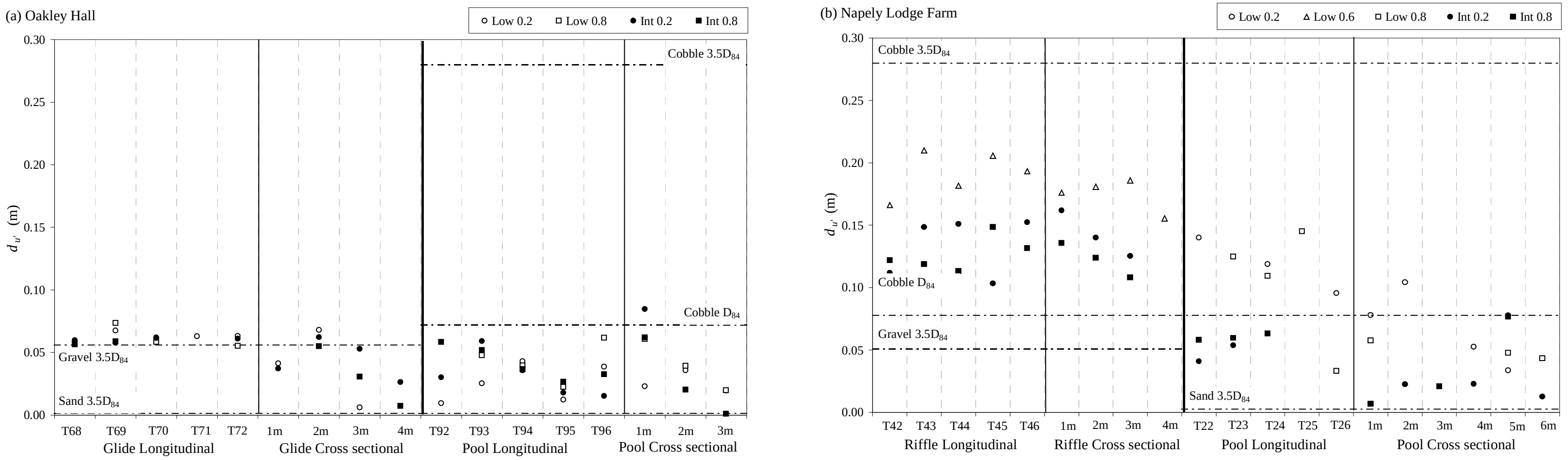
By following the methodology of Clifford *et al.* (1992b), the eddy length may be converted into an estimate of the diameter (*d*) of the body responsible for shedding the dominant vortices. This requires rearrangement of the equation for Strouhal number (S), which represents a dimensionless frequency of vortex shedding, assuming an approximate value of S = 0.2:

$$\text{(a)}\ S = \frac{fd}{u} \qquad \text{(b)}\ d = \frac{0.2u}{f} \qquad \textbf{Equation 5.8}$$

Calculated values of *d* may then be compared to the calibre of substrate(s) characteristic of each physical biotope as identified in Chapter 4. Commonly, percentiles derived from cumulative mass curves (e.g. D_{50}, D_{84}, D_{90}) are used as descriptors of grain size distributions (Bridge, 2003). However, in natural gravel bed rivers, the grain size is frequently scaled up ($3.5D_{84}$) in order to provide an estimation of roughness length which reflects small-scale form resistance such as microtopographic bedforms (Clifford *et al.*, 1992b). Figure 5.24 plots the values of *d* by sample location with respect to the grain size characteristics (D_{84}) and effective roughness length ($3.5D_{84}$) within each respective physical biotope. For sand and gravel samples, only the $3.5D_{84}$ is plotted, since D_{84} values are several orders of magnitude smaller than the dominant eddy length and are unlikely to represent the bodies responsible for vortex shedding.

Within the glide at Oakley Hall, average eddy sizes suggest shedding structures of approximately 0.05 to 0.07 m for most sample locations. This suggests close correspondence with the $3.5D_{84}$ for gravely shoals within the glide, possibly reflecting

(a) Oakley Hall (b) Napely Lodge Farm



(c) Oakley Hall (d) Napely Lodge Farm

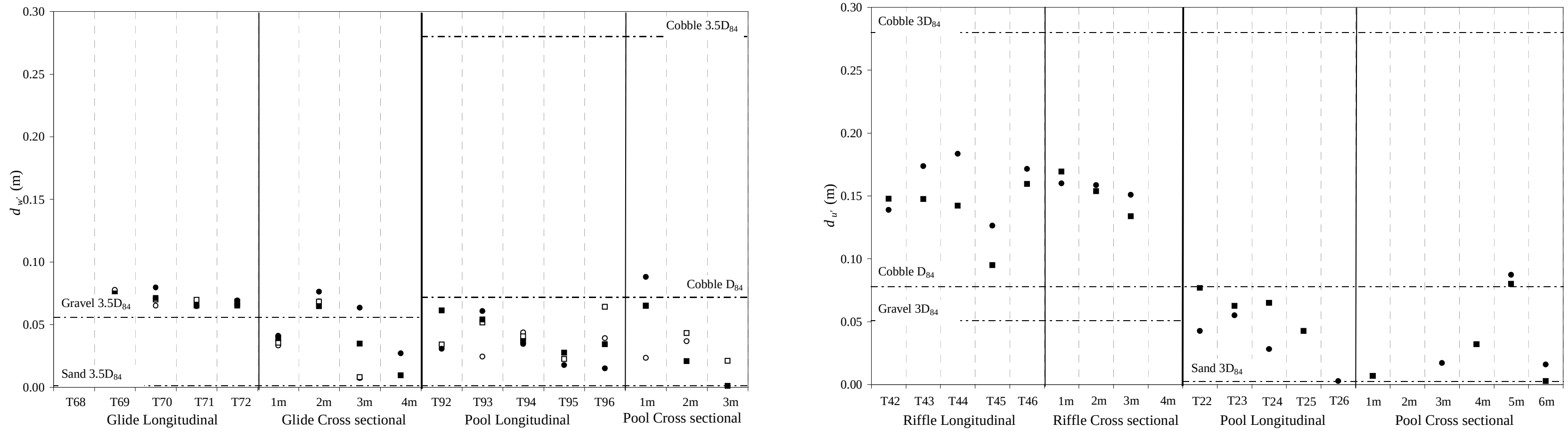


Table 5.24 Estimated diameter (*d*) of vortex-shedding body derived from modelled u' and w' series by sample location with respect to the $D_{84}$and 3D_{84} for substrates found within each respective biotope. Longitudinal measurements were located 1 m apart upstream along the centreline and are denoted by a numeric transect code (which increases upstream). Cross sectional measurements refer to distance from the left bank.

the influence of microtopography on vortex generation. Spanwise sand ridges observed within sandy areas of glides constitute an additional microtopographic roughness element which may also be responsible for the observed structures. Most values of *d* within the glide are much larger than the $3.5D_{84}$ for sand, perhaps due to growth and evolution of eddies with distance from the bed. Within the riffle, estimates of shedding body size are much larger, suggesting the presence of flow obstructions between 0.1 m and 0.2 m in diameter. Values of *d* are larger than the $3.5D_{84}$ for gravel and the D_{84} for cobbles, but smaller than the $3.5D_{84}$ for cobbles. This may reflect the influence of small clusters of pebbles, or the evolution of eddies shed from larger individual pebble particles with distance from the boundary.

Within the pools, the estimated size of shedding structures varies between 0.001 m and 0.18 m, reflecting the complexity of bed material composition which included sand, cobbles and woody debris. Furthermore, as suggested previously, evolution and coalescence of eddies may be more prominent in pools as a result of the deeper water, which may partially explain the large scatter in values for *d*. For many of the series, values for *d* fall close to the D_{84} for cobbles, suggesting shedding from individual particles. However, shedding is also likely to related to the accumulations of irregularly sized woody debris which may also help to explain some of the variation in values.

This analysis illustrates the direct effects of microscale flow obstructions on the organisation of flow structures within the water column. Eddies shed from both smaller elements associated with individual particles, and larger microform roughness elements associated with cluster bedforms and organic debris interact to create a complex flow environment in the outer flow zone. This further emphasises the importance of substrate composition in determining physical habitat characteristics, not simply within the benthic zone but throughout the water column.

5.4.4 Spectral signatures

i) Spectral density

When analysed in the 'frequency domain', the variance of a time series may be represented as a summation of many sinusoidal functions of varying frequencies. The contributions of each of these to the total series variance may be isolated by Fourier analysis (Rayner, 1971) and smoothed using weighted moving averages or 'windows' of varying sizes to produce a 'spectral density estimate' (Davis, 2002). Spectral density techniques are commonly applied in a range of fluvial research contexts from macroscale investigations of morphological structure within large rivers (Carling and Orr, 2000) to microscale investigations of turbulence and sediment suspension (Lapointe, 1996).

The spectral density function represents the Fourier transform of the ACF, and has the added advantage of providing information on the *range* of eddy scales in addition to the dominant or 'characteristic' flow structures. The detectable range of frequencies is determined by both the series length and the sampling interval (Davis, 2002). The lowest detectable frequency is determined by the number of observations (n) in the series since information cannot be obtained for signals with a period greater than $(n-1)/2$. The highest detectable ('Nyquist') frequency, is restricted to wavelengths of twice the sampling interval. Since the spectral density estimate must account for all of the variance within the series, the variance contributed by frequencies higher than the Nyquist frequency must be distributed among the lower bands, a problem known as ‘aliasing’ (Davis, 2002). Aliasing was not considered to represent a significant problem in this analysis since the sampling interval was small enough to account for turbulent frequencies identified in previous work (Kirkbride, 1993; Clifford and French, 1993b).

Spectral density analysis was performed in SPSS 14.0 on the turbulent residuals u' and w' in order to eliminate contributions to the variance from the series mean, and spectral estimates were smoothed using the Tukey-Hanning filter with a window of 5 lag widths. Series with missing data were excluded from the spectral analysis for purposes of comparability, since the number of observations in a given series determines the detectable range of frequencies, as described above. This permitted the computation of spectral density estimates for 112 out of a total of 135 series.

ii) Flow structure ranges

The morphology of the spectrum can provide an indication of whether periodic variations are the dominant feature of the series, or whether a wide range of frequencies are responsible for the observed variation (Rayner, 1971). Frequency spectra may be converted to a spatial analogue, the wavenumber spectra, in order to aid interpretation of the scale of flow structure structures associated with varying contributions to the series variance (Clifford and French, 1993a; Clifford and French, 1993b) using the conversions:

$$\text{(a)}\quad E(K)=\frac{U}{2\pi}S\left(f_n\right) \qquad\qquad \text{(b)}\quad K=2\pi f_n/U \qquad\qquad \textbf{Equation 5.9}$$

Where $S(f_n)$ represents the frequency spectrum at frequency f_n and the wavenumber (K) is measured in radians per metre.

Wavenumber spectra for all complete series were computed and examined visually (see Appendix B). A simple indication of the overall series variance can be identified from the magnitudes of $E(K)$ which reveals some variation between biotopes. Glide and riffle biotopes are associated with lower variances (generally around 10^{-3}) compared to the pools (10^{-2}). For the glide, variance is reduced at the intermediate flow stage, while the riffle is associated with similar magnitudes of variance between flow stages but shows some cross sectional variation at low flow.

The maximum wavenumber identified for each series is plotted in Figure 5.25, providing an indication of the scale of the *smallest* flow structures contributing to the variance. Again, some differentiation between biotopes is observed. Wavenumber maxima for riffle samples are low, reflecting the dominance of larger flow structures associated with cluster bedforms identified in Section 5.4.3. Maxima are comparatively higher for the glide, corresponding to the smaller flow structures observed in Section 5.4.3, and reveal significant variation for the pool biotopes reflecting the strong spatial heterogeneity of flow structure size which is once again more pronounced for the pool at Napely Lodge Farm.

Visual examination of the morphology of wavenumber spectra can provide further detail on flow organisation. Wavenumber spectra for all series are provided in Appendix B, but Figure 5.26 presents example spectra for each physical biotope at

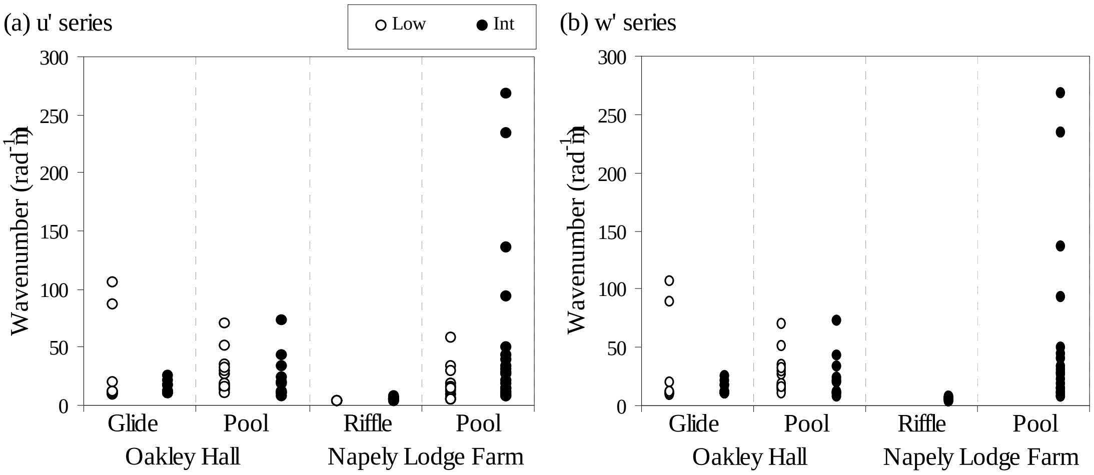
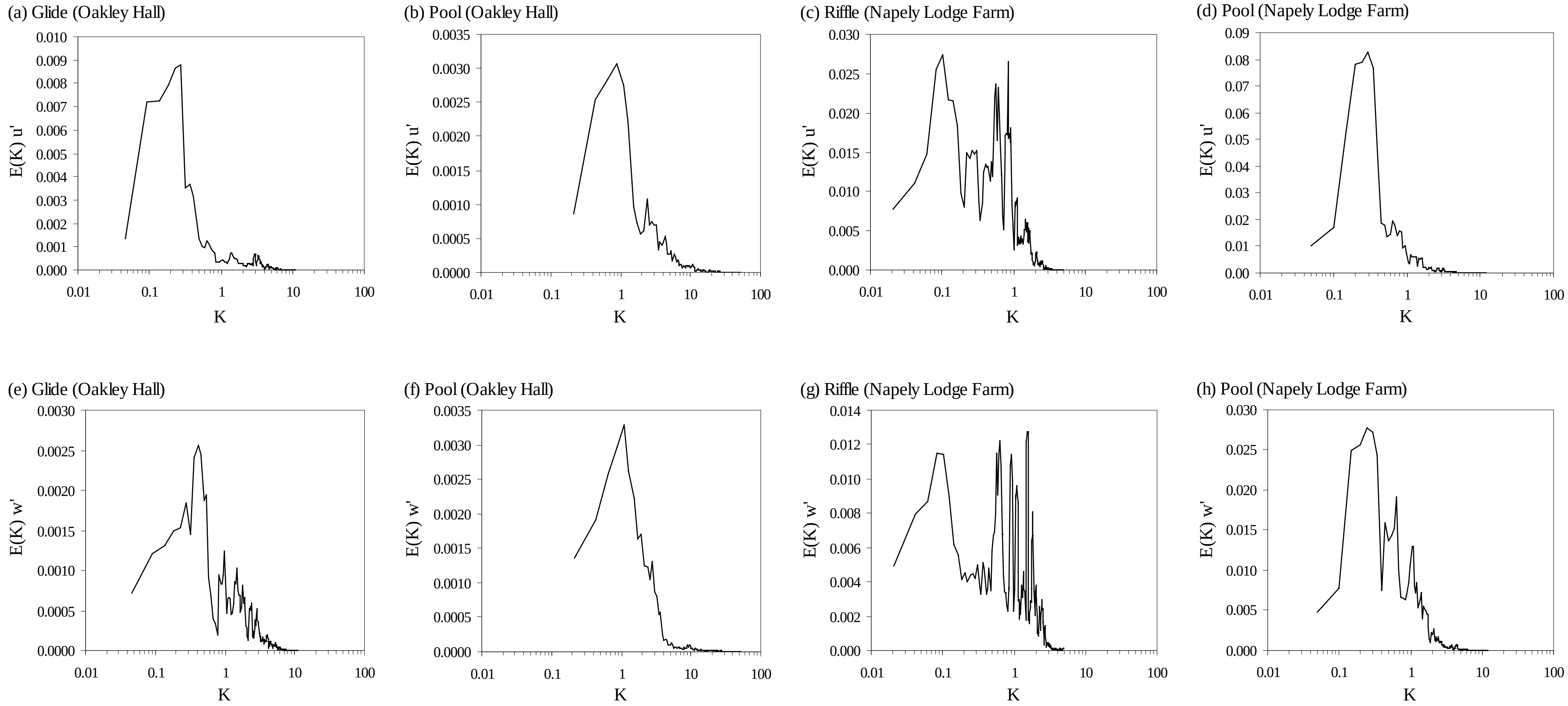


Figure 5.25 Maximum wavenumber values for u' and w' series by biotope and flow stage derived from wavenumber spectra. Two large outliers exceeding 700 rad m^{-1} associated with pool samples are excluded to improve visual display.

each site at low flow in order to illustrate the broad characteristics. The morphology of wavenumber spectra demonstrate strong spatial homogeneity for glide and riffle samples, consistent with other measures explored in previous sections and generally variations between biotopes appear more significant than variations with relative depth of the measurement. This is generally maintained across flow stages for both biotopes, although for some riffle samples spectral peaks reveal a shift to the right at the higher flow stage suggesting a reduction in the average size of flow structures consistent with AR(2) models in Section 5.4.3 and the observations of Clifford (1996a). The morphology of wavenumber spectra are relatively similar for samples within the pool at Oakley Hall, but at Napely Lodge Farm the pool is characterised by pronounced spatial variation in spectra morphology at low flow, which is then reduced at the higher flow stage.

However, two features of the morphology of wavenumber spectra are of particular interest: (i) truncation of the spectral density function at low or high wavenumbers; and (ii) the occurrence and character of spectral peaks. Truncation of spectral plots at high wavenumbers suggests that the sampling interval is too large to capture the highest frequency fluctuations. Truncation at low wavenumbers suggests that larger flow structures with periods greater than the sample length contribute in some way to the series variance. Truncation at high wavenumbers was absent from the Tern data set, in contrast to published data for lower frequency sampling at 2 Hz and 10 Hz (Clifford and French, 1993b), suggesting that the 16 Hz sampling interval was sufficient to capture the smallest flow structures. Truncation at low wavenumbers was observed within all biotopes, but this was most obvious for the pools, suggesting significant variance is associated with larger flow structures with periods greater


(a) Glide (Oakley Hall)

(b) Pool (Oakley Hall)

(c) Riffle (Napely Lodge Farm)

(d) Pool (Napely Lodge Farm)

(e) Glide (Oakley Hall)

(f) Pool (Oakley Hall)

(g) Riffle (Napely Lodge Farm)

(h) Pool (Napely Lodge Farm)

Figure 5.26 Sample wavenumber spectra for each of the four biotopes at low flow. (a) to (d) present spectra for u' series and (e) to (f) spectra for w' series.

than 30 s which was not completely removed by detrending procedures. Some contrasts between pools are noted regarding levels of truncation across discharges, however. For the pool at Oakley Hall, truncation at low wavenumbers becomes more frequent at the higher flow stage, suggesting a stronger influence of larger scale structures, perhaps associated with secondary circulations. In contrast, truncation is reduced at the higher discharge for the pool at Napely Lodge Farm, suggesting that larger flow structures are less prominent, possibly reflecting the intensification of flow identified in Chapter 4.

The occurrence and character of spectral peaks within the spectrum can provide an indication of the complexity of the flow organisation. A peak in the frequency spectrum is interpreted to suggest that a certain oscillation in the sequence accounts for a large amount of the total series variation. In the case of turbulent velocity time series, this is often interpreted to represent a prominent eddy structure (Venditti and Bauer, 2005). In contrast, a ‘spiky’ profile indicates contributions from a wider range of wavenumbers. Singular spectral peaks are less apparent for riffle spectra compared to glide and pool samples. Instead, riffles demonstrate peaks at relatively low wavenumbers (representing larger flow structures) and a subsequent ‘spikey’ decay towards higher wavenumbers, suggesting that a variety of smaller flow structures contribute significantly to the variance. This may reflect the variety of clast sizes associated with the pebble-gravel substrate creating a range of eddy shapes and sizes.

Spectral peaks are more obvious for the glide spectra, suggesting a simpler flow structure characterised by vortices with similar dimensions. This is consistent with the flume-like nature of the glide which is associated with strong homogeneity of substrate composition and a simple bed topography. Some spectra for both pools are also characterised by a prominent spectral peak. For the pool at Oakley Hall, this is generally associated with higher wavenumbers for near-bed samples, supporting the idea of evolution and growth of flow structures over depth. Near-bed samples also reveal a higher incidence of secondary peaks at higher wavenumbers perhaps suggesting a more complex flow structure associated with vortices of varying size shed near the boundary which coalesce over depth creating a simpler flow structure near the water surface. More complex, 'spikier' profiles are associated with both faster-flowing pool head and mid-pool locations, and within the backwater zone towards the left bank. Spectral peaks reveal a shift to higher wavenumbers at the intermediate flow stage suggesting a reduction in the average size of flow structures as identified for the riffle.

iii) Average flow structure size

Assuming Taylor's hypothesis applies, an estimate of the characteristic length scale associated with the highest contribution to the series variance can be obtained by multiplying the period (the inverse of the frequency) associated with the peak spectral density by the mean streamwise velocity (Best, 1993; Clifford and French, 1993a). Figure 5.27 plots these derived length scales for each physical biotope and compares these to length scales derived from AR(2) models. Length scales were plotted for all series and therefore reveal significant variation since some series (principally associated with the riffle) did not demonstrate a pronounced spectral peak. This creates significant overlap between biotope categories in contrast to the observations in section 5.4.3. Eddy lengths derived from spectral peaks are generally much larger than those derived from AR(2) models (often over 1 m in length), and this

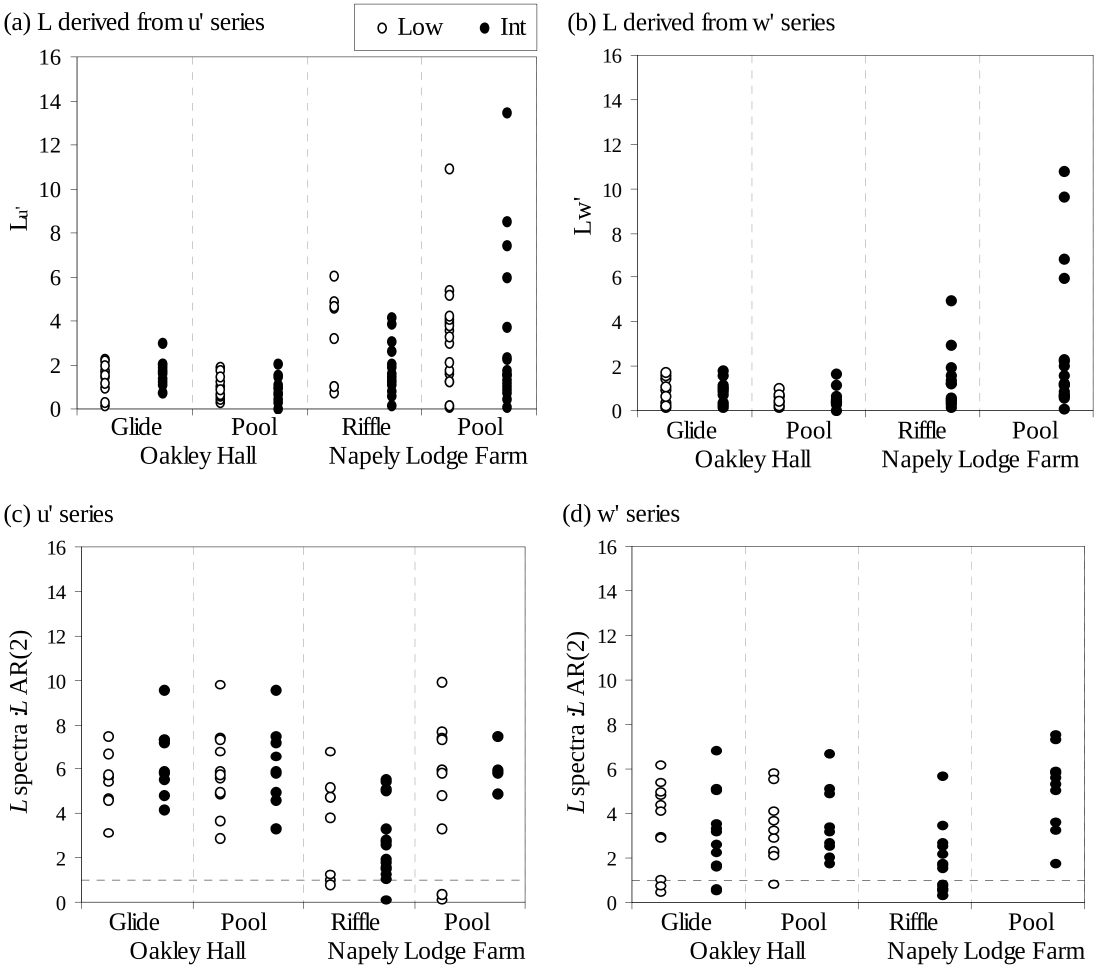


Figure 5.27 Eddy lengths derived from velocity spectra for (a) u' series and (b) w' series, and the ratio of length scales derived from spectra to those derived from AR(2) models for u' and w' series (c and d).

is more pronounced for u' series compared to w'. This is a consequence of using the spectral peak to represent the average eddy size, which ignores the influence of smaller turbulent fluctuations associated with the ‘spiky’ decaying limb of spectra.

Overall, however, results presented in this section support the idea of a continuum of increasing hydraulic complexity from glide, to riffle to run biotopes in terms of flow structure characteristics and levels of spatio-temporal variation.

5.5 PHYSICAL BIOTOPES AND SEDIMENT TRANSPORT

So far, biotope characterisation studies have attempted only relatively simple explorations of sedimentology in the form of dominant substrate characteristics. The following sections present the methodology and results of a set of experiments which attempt to identify variations in sediment transport mechanisms within and between physical biotopes, since such characteristics are likely to have a direct influence on biota through the distribution of sediments, nutrients and pollutants within the channel.

5.5.1 Sampling design

Within the same physical biotopes sampled for velocity characteristics (see Plate 5.1), suspended sediment experiments were conducted during a stable low flow period in June 2005 and on the falling limb of a flood event in July 2005 (See Chapter 2 Section 2.3.5 for discharges and exceedences). Two ‘arrays’ of three Partech IR40C infra red turbidity probes were deployed to monitor turbidity levels for the duration of artificially created sediment ‘pulses’. On each array, probes were positioned at 0.2, 0.6 and 0.8 of the water depth from the surface and arrays were spaced 2 m apart longitudinally along the channel centreline (Figure 5.28). Sediment pulses comprising fine silts collected from channel margins (See Chapter 2, Section 2.3.4 for grain size distributions) were released upstream of the first array at 0.2, 0.6 and 0.8 of the water depth. Shallow depths within the riffle biotope limited the experiment to a single release and detection depth at 0.6.

The Partech IR40C probes measure the extent to which light passing through the water is reduced as a result of water turbidity by relating the attenuation of an incident optical beam to the mass of material in transport (Clifford *et al.*, 1995). Probes were connected to a Campbell Scientific CR10X datalogger logging at a frequency of 11 Hz for one minute prior to sediment release, thus providing an indication of the ‘ambient’ turbidity levels, and for three minutes following each release to ensure that enough time was allowed for the pulse to pass both probes. A velocity time series was taken beside the upstream probe array in order to provide an indication of the mean flow velocity.

5.5.2 Calibration and data cleaning

Partech IR40C turbidity probes were calibrated for offsets and in order to check for a linear response to increasing sediment load. Individual probe offsets were determined by laboratory calibrations in clear water (Figure 5.29a). However, field readings taken prior to the release of sediment pulses generally fall below the clear-water calibration levels, reflecting the sensitivity of probes to variations in ambient light. In order to improve visualisation of time plots, and since actual sediment concentrations are not relevant to the experiment, the ‘ambient’ turbidity value was subtracted from turbidity

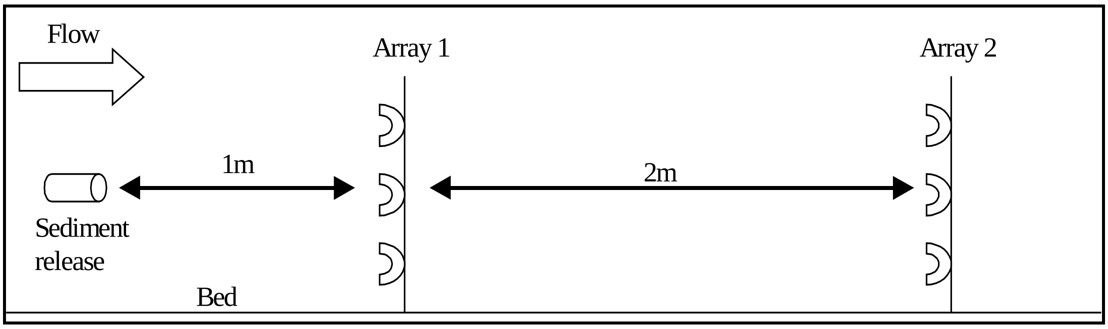


Figure 5.28 Sampling design for the microscale sediment transport experiments.

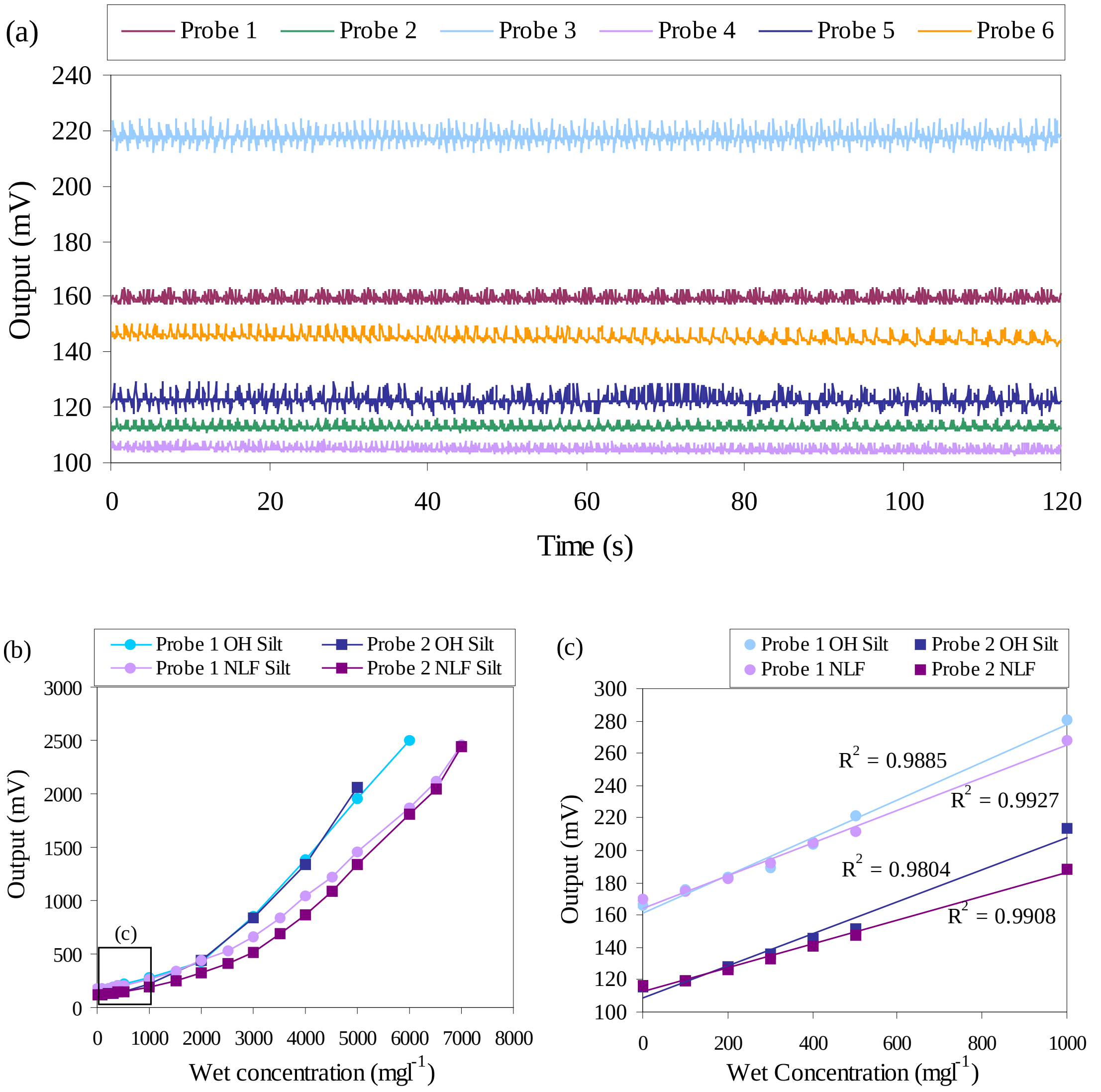


Figure 5.29 (a) Clear-water offset values for IR40C turbidity probes used in microscale sediment experiments. (b) laboratory calibration curves for field sediments collected from each field site. (c) Linear trends fitted to the probe output range identified for field deployments.

series in order to simultaneously remove the offset and account for ambient light conditions.

Although the absolute sediment concentrations are not required, probe response to increasing sediment load must be linear in order to provide an accurate indication of variations in sediment concentrations. A calibration curve was obtained by incrementally adding small samples of well-mixed sediment of known weight to a known volume of water. Curves reveal a characteristic sigmoid trend (Clifford *et al.*, 2995; Figure 5.29b). However, the field ranges observed for the turbidity monitoring experiments are relatively narrow and fall within the lower part of the curve, meaning that the relationship between sediment concentration and probe output is approximately linear (Figure 5.29c), and therefore probe output provides an accurate proportional representation of changing sediment concentrations.

Partech IR40C probes are frequently associated with a high frequency switching transient when used in conjunction with data loggers (Clifford *et al.*, 1995). Since this represents an electrical effect it was ignored, and analysis focused on the overall characteristics of detected pulses. Time plots for sediment release experiments were produced by comparing probes located at the same relative depth on upstream (A1) and downstream (A2) probe arrays (a total of 53 plots). Unfortunately a logging error meant that traces for the June release at 0.8 of the depth within the glide were lost. In all cases, sediment pulses were advected past both probes within 60s of the time of release, and therefore the remaining parts of the series were discarded.

In order to objectively delimit sediment pulses within each trace, the ambient turbidity was used as a threshold above which observations can be considered part of the introduced sediment pulse. However, this resulted in the inclusion of small infrequent fluctuations in turbidity, possibly related to intermittent sediment suspension events (Lapointe, 1996), as discrete pulses. The threshold was therefore increased to one and a half times the ambient range, to provide a stricter means of pulse delimitation. Pulses associated with only one or two observations above this threshold were disregarded, since it is possible that these reflect natural turbidity fluctuations associated with turbulent mixing.

5.5.3 Sediment pulse characteristics

Fine sediment ‘pulses’ of limited duration are a common cause of disturbance in river systems. Large-scale pulses may originate from the natural mobilisation of channel and floodplain sediments or runoff from agricultural land or construction sites during storm events (Watanabe *et al.*, 2005). Such events may have important implications for instream biota particularly where toxic contaminants are adsorbed to minerogenic particles (Hose *et al.*, 2002). Smaller-scale interactions between turbulent mixing processes and suspended material under more stable hydrological conditions are also of great significance for aquatic organisms, for instance regarding the distribution of food and nutrients within the channel (McNair *et al.*, 1997).

A sediment pulse originating from a single source will be distributed longitudinally, vertically and transversely according to a combination of advective, diffusive and dispersive mixing processes. Advection refers to the process by which velocity currents move the sediment cloud in a downstream direction away from the release location. ‘Pure’ advection moves the pulse downstream as a coherent body without change in concentration, but a second process, known as ‘turbulent diffusion’ causes the pulse to spread out vertically within the water column and transversely towards the banks (Rutherford, 1994). Turbulent eddies break up the sediment plume, increasing concentration gradients and accelerating the molecular diffusion process which transfers sediment from areas of high concentration to areas of low concentration (Allen, 1985), ultimately altering the size, shape and concentration of the sediment cloud. Since most river channels are characterised by widths many times greater than the water depth, complete diffusion is generally achieved more rapidly in the vertical dimension throughout the water column, than transverse diffusion across the channel (Rutherford, 1994). An additional process, ‘dispersion’ may result in the movement of the sediment cloud bodily either towards the banks (transverse dispersion), or vertically within the water column (vertical dispersion).

In order to analyse the transmission of suspended sediment within different biotopes, the sediment plume detected by each turbidity probe was considered as a discrete event in the manner of a flood pulse hydrograph (Figure 5.30). Table 5.3 provides the mean velocity conditions at the first probe array within each biotope. For each pulse detected at each probe for the various sediment releases, the advection time, time to peak, time to recession and total duration of the pulse was calculated, along with the peak turbidity value. Figure 5.31 plots these statistics for the various releases within different physical biotopes. Overall, pulses generally reach the first array between 5s and 25s following the release, and the second array between 10s and 30s after the release. The duration of pulses varied between less than 1s to over 30s and generally

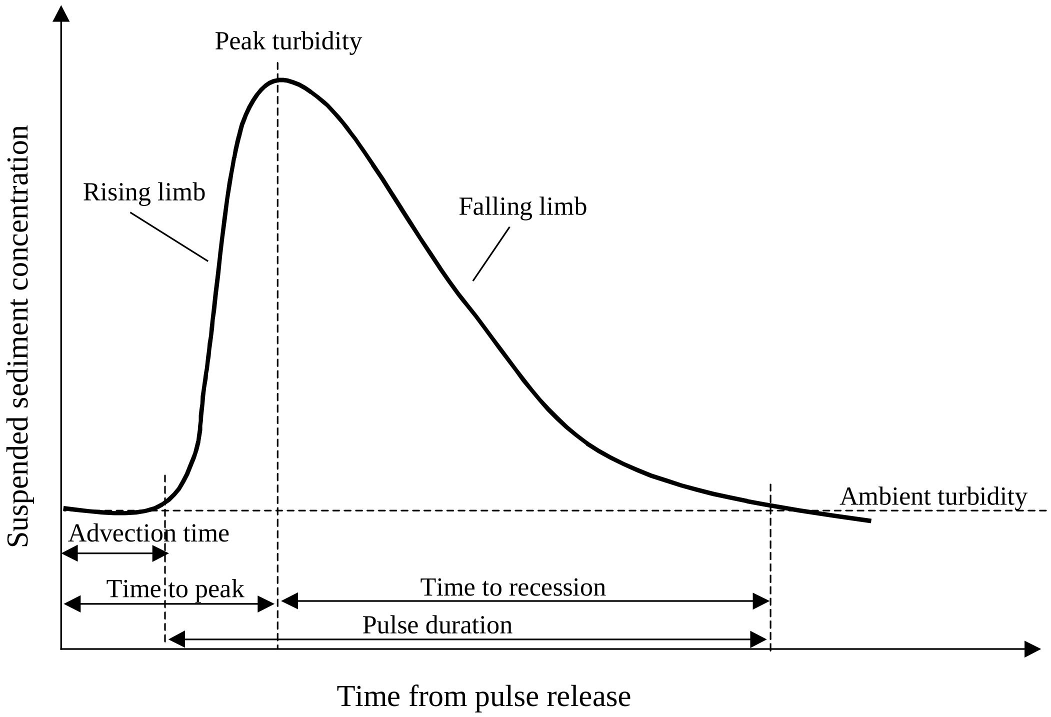


Figure 5.30 Flood hydrograph theory applied to sediment pulses, modified from Bridge (2003: Figure 1.3, p. 8)

Site	Date	Physical biotope	U (ms^{-1})	W (ms^{-1})
Oakley Hall	June	Glide	0.30	-0.14
		Pool	0.82	-0.16
	July	Glide	0.33	-0.30
		Pool	0.20	-0.34
Napely Lodge Farm	June	Riffle	0.80	0.08
		Pool	0.62	3.14
	July	Riffle	0.46	-0.31
		Pool	0.07	-0.34

Table 5.3 Mean velocity measured at array 1 during sediment releases for each physical biotope.

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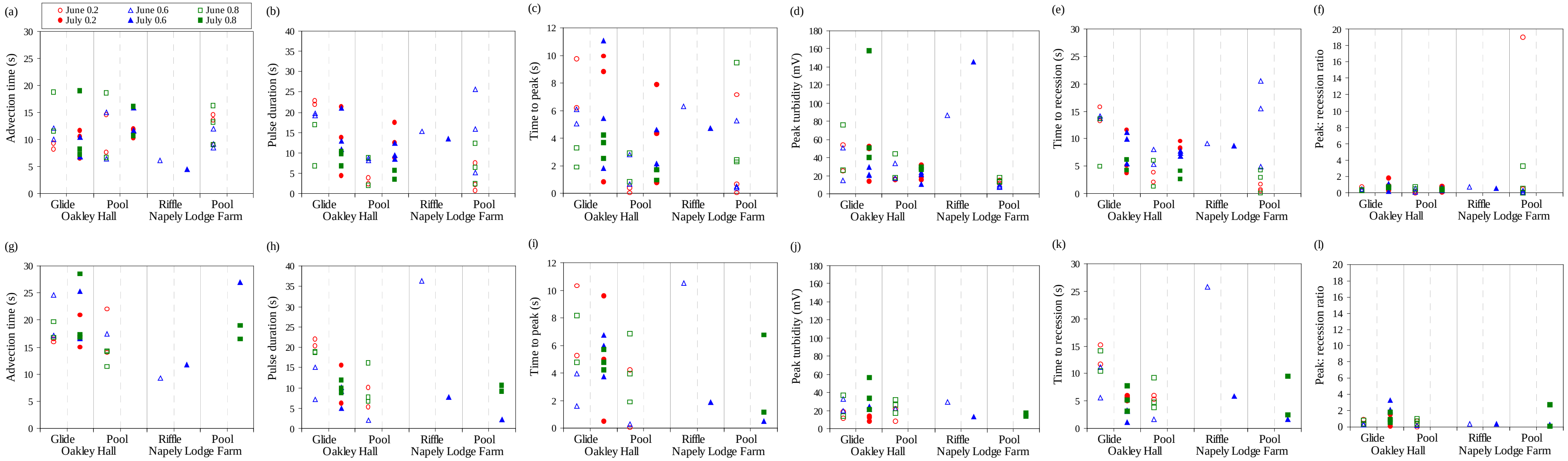


Figure 5.31 Sediment pulse statistics for array 1 (a to f) and array 2 (g to l) by the relative depth of detecting probes.

the rising limb of the sediment concentration was shorter than the falling limb as noted for ‘advection zones’ proximal to the release location (Rutherford, 1994).

Sediment pulse statistics also show some variation between physical biotopes. At Oakley Hall, the glide is generally associated with a wider range of pulse statistics, suggesting that the characteristics of the detected pulse are dependent on the height of the release in the water column and the position of the detecting probe, possibly reflecting a structured, logarithmic velocity profile. Pulses advected within the riffle are advected downstream rapidly, reflecting the high flow velocities (Table 5.3), but are relatively long in duration, possibly reflecting longitudinal elongation of the pulse as a result of velocity shear within the water column (Rutherford, 1994). The data sets for both pools are relatively fragmentary since a number of pulses were not detected by probes.

Table 5.4 lists the probes associated with the most rapid advection, longest duration and highest maximum turbidity value on each array for each sediment release. Some variation in the response of pulses to variations in the depth of release and the position of probes is observed. For the glide, pulses are generally advected most rapidly and are of longer duration within the upper part of the water column, irrespective of the location of the release. This suggests that vertical diffusion is achieved close to the pulse source and therefore traces reflect the logarithmic structure of the velocity profile. This is less clear for the July experiment, however, perhaps reflecting a change in the organisation of the velocity profile with the passage of the flood event. The turbidity maximum migrates towards the bed with distance from the release,

				Longest pulse duration		Most rapid advection		Maximum turbidity	
Site	**Date**	**Biotope**	**Release depth**	**A1**	**A2**	**A1**	**A2**	**A1**	**A2**
Oakley Hall	June	Glide	0.2	0.2	0.2	0.2	0.2	0.8	0.6
			0.6	0.2	0.2	0.2	0.2	0.8	0.5
			0.8	N/A	N/A	N/A	N/A	N/A	N/A
		Pool	0.2	Not detected	0.2	Not detected	0.2	Not detected	0.2 & 0.6
			0.6	0.6	0.8	0.2	0.6	0.6	0.8
			0.8	0.8	0.8	0.6	0.8	0.8	0.8
	July	Glide	0.2	0.2	0.2	0.6	0.2	0.2	0.6 & 0.8
			0.6	0.2	0.6	0.2	0.2 & 0.6	0.2	0.8
			0.8	0.6	0.8	0.6	0.2	0.8	0.8
		Pool	0.2	0.2	Not detected	0.2	Not detected	0.2	Not detected
			0.6	0.2	Not detected	0.6	Not detected	0.8	Not detected
			0.8	0.2	Not detected	0.8	Not detected	0.8	Not detected
Napely Lodge Farm	June	Pool	0.2	0.6	Not detected	0.6	Not detected	0.2	Not detected
			0.6	0.6	Not detected	0.2 & 0.8	Not detected	0.8	Not detected
			0.8	0.8	Not detected	0.6	Not detected	0.8	Not detected
	July	Pool	0.2	Not detected	0.8	Not detected	0.8	Not detected	0.8
			0.6	Not detected	0.8	Not detected	0.8	Not detected	0.6
			0.8	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected

Table 5.4 Relative depth of probes associated with the longest pulse duration, most rapid advection and maximum turbidity value at each array for each sediment release. Riffle is excluded since shallow depths permitted only one probe at each array.

reflecting the tendency for pulse migration towards regions of lower diffusivity (Rutherford, 1994).

Pulse statistics may also be expressed as a ratio (array 1: array 2) in order to assess the change over distance from release for probes positioned at the same relative depth on arrays 1 and 2. Figure 5.32 plots the ratios for different pulses statistics for each physical biotope for the various sediment releases. Analysis is limited principally to the glide, since pool samples frequently failed to detect the pulse on both arrays, and only two pulses were conducted within the riffle for each experiment due to low water depths. However, some broad trends are observed. Overall, pulses are detected first at array 1 which was positioned closer to the release location, with the exception of one pool sample which may reflect the influence of rotational flow circulations. The glide reveals a tendency for longer duration pulses at array 2 during the July experiment, perhaps reflecting the effects of vertical velocity shear. The peak turbidity is generally higher for array 1 probes, reflecting the diffusion and settling-out of particles over distance from the release. Some instances of higher peak turbidities at the second array suggest an increase in sediment concentrations close to the bed as particles migrate vertically towards the boundary.

For the pool at Oakley Hall, probes located within the upper water column fail to detect all pulses during the June experiments, suggesting rapid dispersion of pulses transversely or vertically within the water column following release. In contrast, all probes detect each sediment pulse for the July experiments, again suggesting a re-

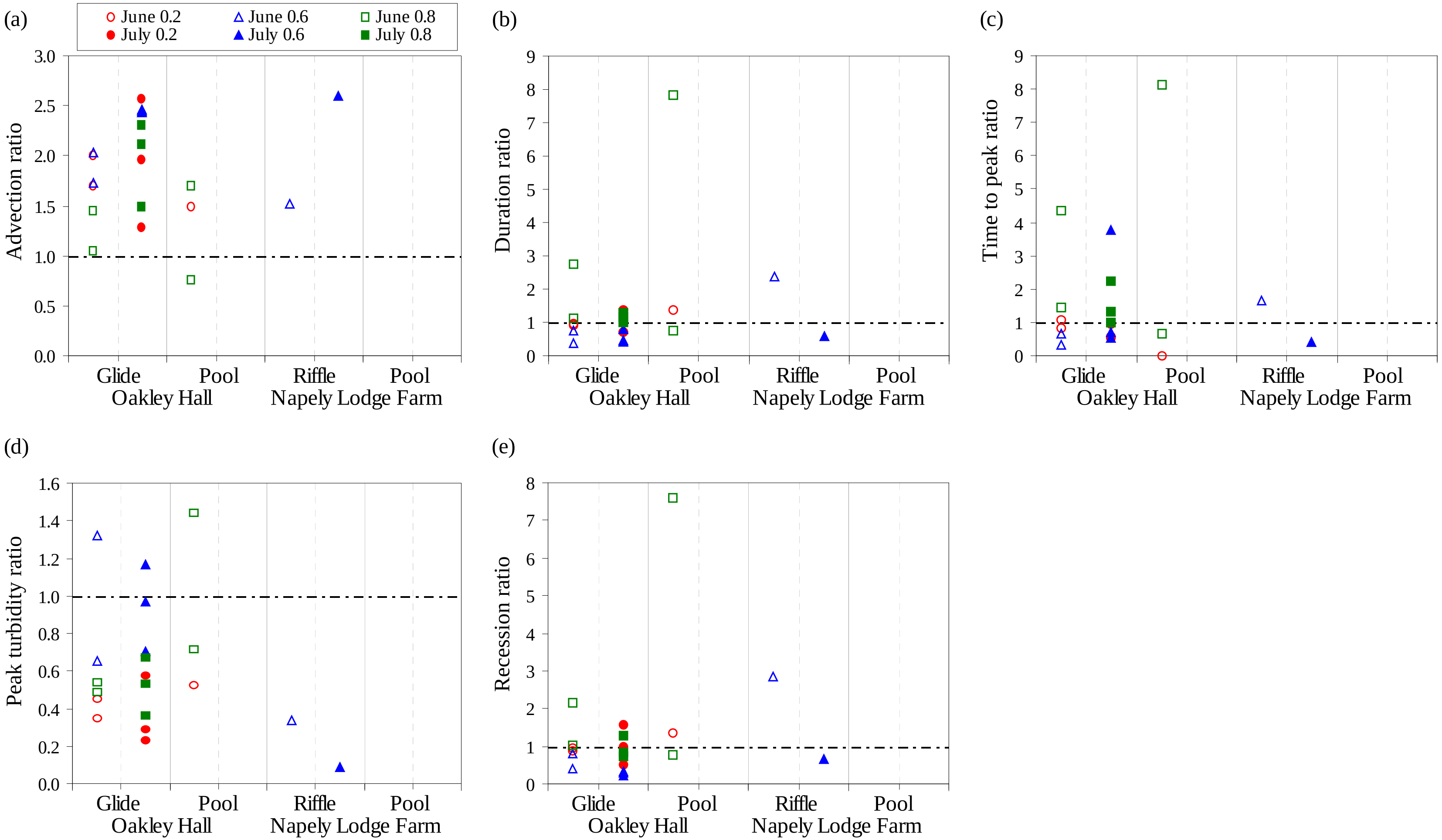


Figure 5.32 Ratio of array 1 to array 2 for pulse statistics by relative depth of detecting probe.

organisation of velocities within the water column and longitudinally during the flood event. This is further emphasised by variations in the location of the longest duration pulses: for the June experiments these occur close to the bed, but in July they occur close to the water surface.

5.5.4 Identification of mixing processes

Perhaps the most significant information to be derived from the experiments, however, relates to the interpretation of the dominant mixing processes operating within different biotopes. A systematic process was devised in an attempt to determine the mixing process responsible for the observed detection or otherwise of sediment pulses at various relative depths within the physical biotopes.

Within all biotopes (and for both sets of experiments), pulses are detected at array 2 suggesting that the complete settling-out of particles, or diffusion to ambient levels between the release location and second array is unlikely. Detection of sediment pulses within pairs of probes located at the same relative depth on each array was therefore considered within the context of surrounding probes in order to determine whether the distribution of the sediment pulse within the channel was controlled by longitudinal advection, transverse dispersion or vertical dispersion. Figure 5.33 represents the systematic process used to identify the dominant mixing mechanisms and indicates which physical biotopes were associated with each of type of process.

Sketches of the dominant mixing processes attributed to various pulse detection scenarios are provided in Figure 5.34, and Figure 5.35 plots the mixing characteristics of different biotopes quantitatively, according to the frequency of processes attributed

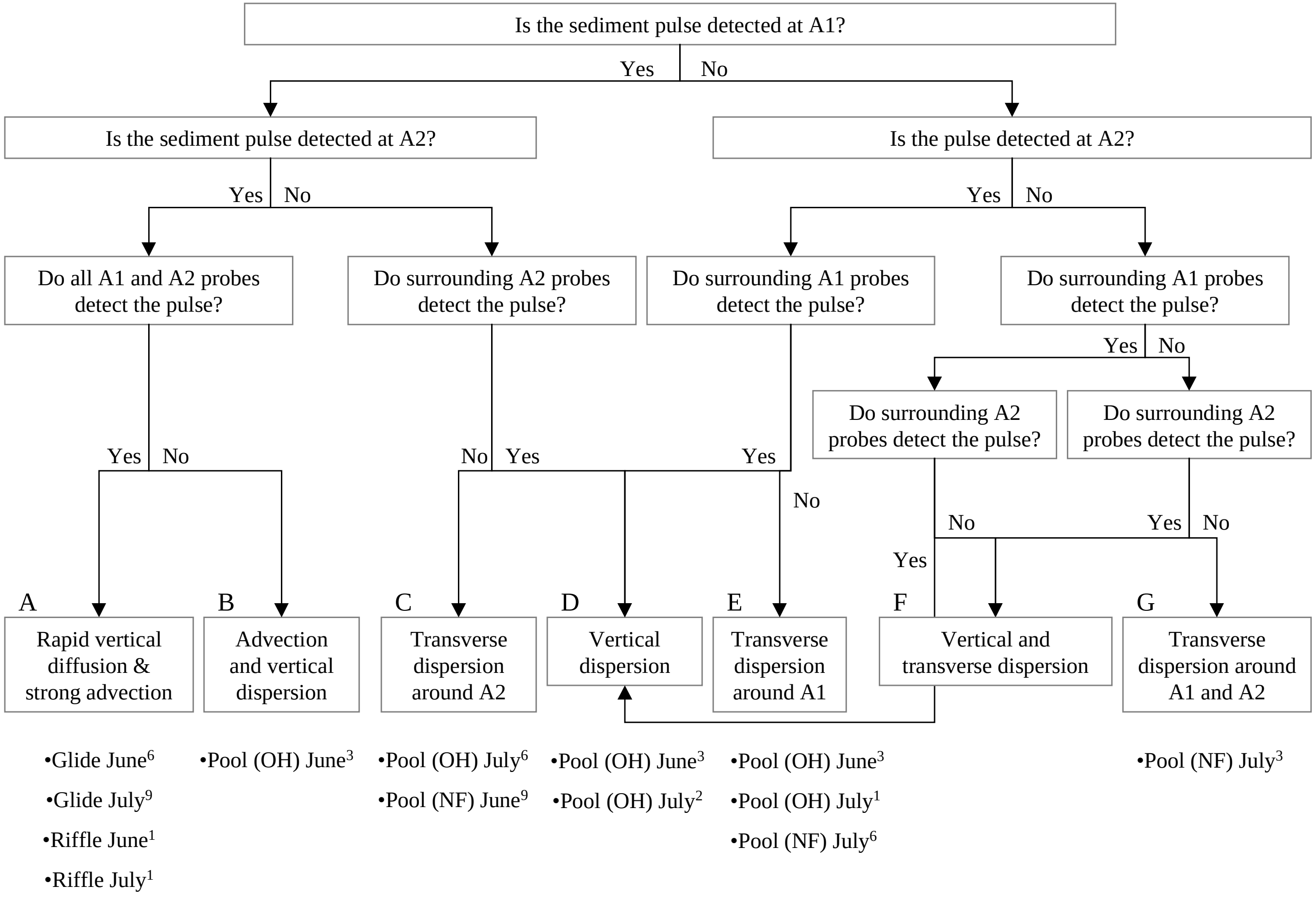
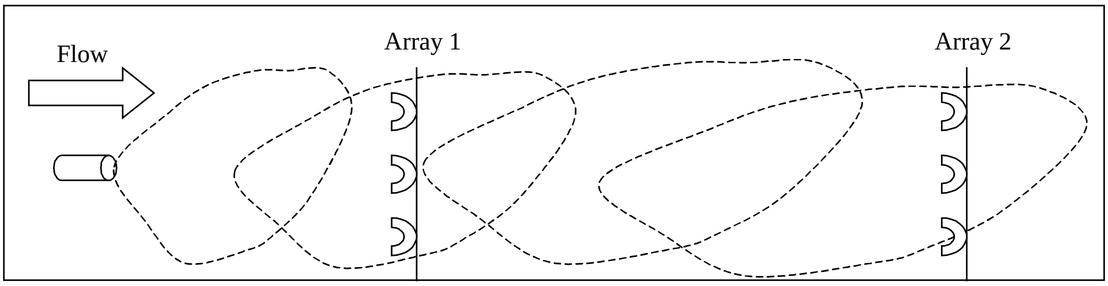
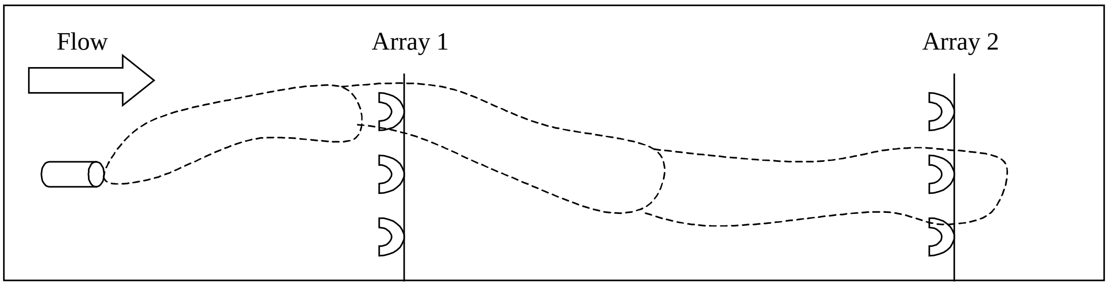


Figure 5.33 Systematic process used to identify the various mixing processes responsible for the observed sediment transfer signal. Superscript values denote the number of probe pairs allocated to each mixing process for each biotope and experiment date.

(a) Vertical diffusion and advection (cross sectional view)



(b) Vertical dispersion (cross sectional view)



(c) Transverse dispersion (aerial view)

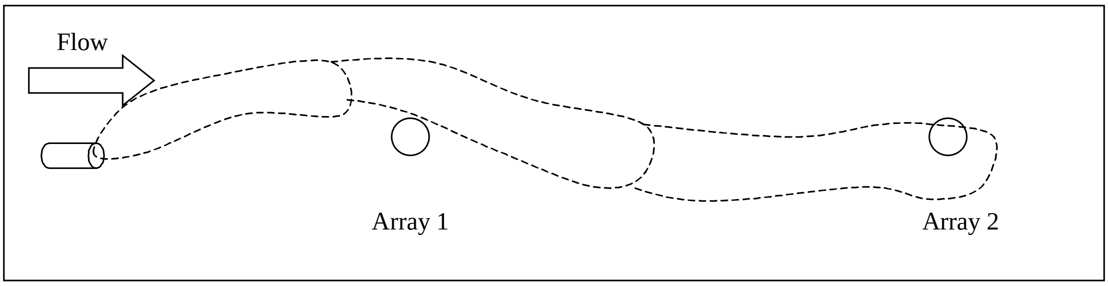


Figure 5.34 Sketches to illustrate the principal sediment mixing processes identified from suspended sediment experiments: (a) rapid vertical diffusion and downstream advection, (b) vertical dispersion by upwelling or downwelling currents and (c) transverse dispersion laterally towards either bank.

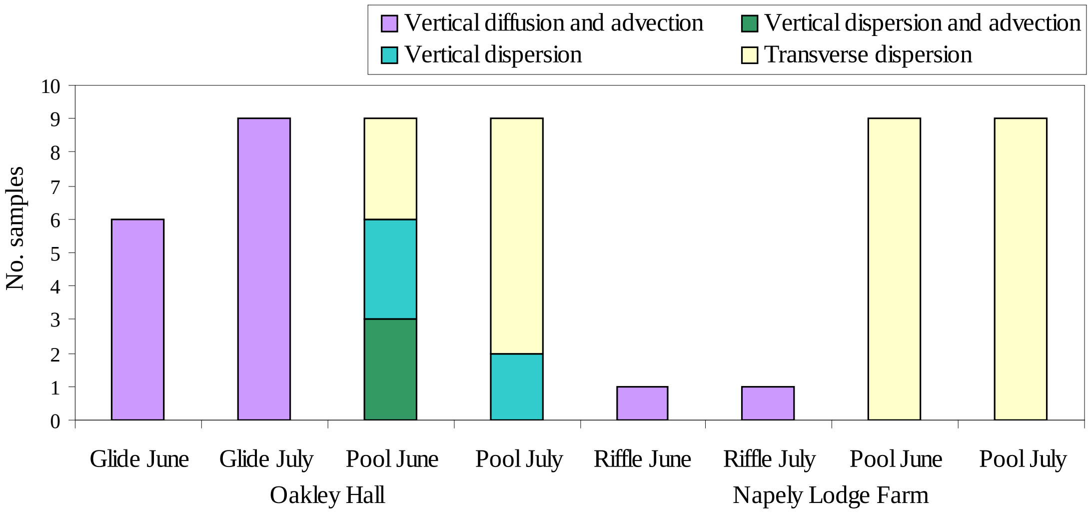


Figure 5.35 The number of sediment pulse experiments (at various release depths) attributed to each of the four main mixing processes for each physical biotope and experiment date.

to different sediment releases. Sediment pulses are detected by all probes within glide and riffle biotopes, irrespective of the depth of the sediment release. This suggests that the downstream advection of sediment by flow velocity is strong enough to overcome (at least in part) depositional and diffusive processes over short distances (Figure 5.34a). Vertical diffusion of the pulse appears to occur rapidly over the 1 m distance between the release and array 1 since all probes on array 1 detect the pulse irrespective of the release depth (although this can only be assessed for the glide). In contrast, there are several instances where probes fail to detect sediment pulses released within the pools. Discounting deposition, this suggests the bodily movement of the pulse by dispersion either vertically within the water column (Figure 5.34b), or laterally towards either bank (Figure 5.34c). Where the pulse is detected at different probe depths on each array, dispersion was considered to occur in the vertical dimension, associated with upwelling or downwelling currents. Where all probes on one or both of the arrays failed to detect the pulse, dispersion was considered to occur transversely by deflection of the sediment plume by meander currents or secondary circulations.

The pool at Oakley Hall is characterised by a combination of vertical and transverse dispersion, depending on the depth of the sediment release and the hydrological context of the experiment. Transverse dispersion becomes more prominent for the July experiment, however, suggesting a re-organisation of flow and possible intensification of the thalweg on the waning limb of the flood event which deflects the plume away from the channel centreline. In contrast, the pool at Napely Lodge Farm is consistently associated with transverse dispersion for both experiments, although the nature of this varies. For the June experiment, all sediment releases were deflected around the second probe array, which reflects the routing of sediment away from the mid-pool zone by the thalweg. The July experiment, however, is associated with a combination of dispersion around the first array only, and dispersion around both arrays, reflecting the complex flow environment involving rotational secondary circulations.

This section supports the idea of a relatively homogeneous physical structure of the glide biotope, and to a lesser extent the riffle, associated with a structured logarithmic velocity profile which competently advects an introduced sediment pulse downstream and demonstrates predictable mixing behaviours. In contrast, pools are very complex hydraulic environments which is of great significance for the routing of particulate matter, which appears dependent on the depth of the source, and the organisation of velocities within the channel associated with the wider hydrological regime.

5.6 DISCUSSION AND CONCLUSIONS

This chapter employs a range of statistical approaches to analyse a variety of hydraulic parameters at the microscale within selected physical biotopes. Overall, hydraulic parameters suggest that between-biotope variation is more significant than variation with relative depth within individual biotopes. Table 5.5 and Table 5.6 present the results of Mann-Whitney tests performed in order to test this observation for statistical significance (homogeneity of variance was too high for a parametric test). Variation between biotopes does appear more significant than variation within biotopes, since differences between relative depth groups (0.2 and 0.8) fail to show statistical significance for all parameters. However, the discriminatory ‘success’ of different parameters depends upon the combination of physical biotopes studied, similar to

		Mann-Whitney significance level (P) for physical biotope groups				
Site	**Flow stage**	**u**	**w**	**Intensity**	**-u'w'**	**Eddylength**
Oakley Hall	Low	**0.026**	**0.017**	**<0.001**	1.000	**0.002**
	Intermediate	**0.022**	0.506	**<0.001**	0.313	0.185
Napely Lodge Farm	Intermediate	**<0.001**	**<0.001**	0.781	**<0.001**	**<0.001**

Table 5.5 Results of the Mann-Whitney tests performed on biotope groups at each site for different variables. Emboldened values highlight groups which are statistically different at the 0.05 significance level ($P < 0.05$).

		Mann-Whitney significance level (P) for relative depth groups				
Site	**Flow stage**	**u**	**w**	**Intensity**	**-u'w'**	**Eddylength**
Oakley Hall	Low	0.402	0.780	0.724	0.809	0.551
	Intermediate	0.433	0.946	0.786	0.079	0.239
Napely Lodge Farm	Intermediate	0.817	0.583	0.488	0.172	0.701

Table 5.6 Results of the Mann-Whitney tests performed on relative depth groups at each site for different variables.

observations by Jowett (1993). Turbulence intensity, for instance, clearly distinguishes pool and glide biotopes at Oakley Hall, while average eddy size provides better discrimination between pool and riffle biotopes at Napely Lodge Farm (Table 5.6).

Higher-order flow properties generally provide greater differentiation between biotopes compared to simpler series-averaged velocity and stress properties. Three hypotheses for the principal causes of observed flow structure are identified: (i) burst-sweep turbulence generation; (ii) vortices shed from individual clasts and bed microforms and (iii) larger structures associated with flow obstructions such as tree roots and larger scale form roughness. These interact to produce different hydrodynamic environments within each of the riffle, glide and pool biotopes. The glide is associated with the 'simplest' flow structure, possibly reflecting a dominance of burst-sweep structures (since it is strongly homogeneous and flume-like), while the riffle shows comparatively greater complexity reflecting the influence of vortex shedding from microform roughness (since it is associated with the highest relative roughness over the largest discharge range). The pools represent the most hydraulically complex environments, characterised by a combination of burst-sweep structures and vortices shed from both smaller grain roughness elements and larger form roughness structures and flow obstructions which interact and coalesce over depth.

However, the range of hydraulic measures studied in the chapter suggest that physical biotopes demonstrate different levels of 'within-biotope' hydraulic variation. When considered in terms of spatial variation (longitudinally and cross sectionally), variation with depth through the water column, and temporal variations in response to increasing discharge, glide, riffle and pool biotopes are clearly segregated in conceptualised 3-dimensional space (Figure 5.36). The glide provides a relatively uniform environment, associated with strong spatial homogeneity and little variation in hydraulic parameters with discharge. Riffle hydraulics demonstrate relatively strong spatial homogeneity, but vary systematically with distance from the boundary and with increasing discharge. In contrast, both pools exhibit strong spatial heterogeneity in various physical parameters compared to respective glide and riffle units, unsystematic variations with relative depth and a highly complex hydraulic response to increasing stage. Furthermore, the two pools demonstrate different levels of internal variation. Generally, the more pronounced morphological character of the pool at Napely Lodge Farm gives rise to greater hydraulic heterogeneity, emphasising the importance of interactions between channel morphology and hydraulics highlighted in Chapter 4.

These findings suggest that the internal hydraulic complexity of different biotopes constitutes an additional physical biotope ‘characteristic’ which may provide greater transferability of concepts between reaches compared to the mean values or ranges of hydraulic parameters identified for specific biotopes. Furthermore, the research suggests that certain biotopes, such as pools, introduce a more complex mosaic of physical habitat to the channel than others, such as glides. Since physical habitat heterogeneity is often considered closely related to biotic diversity this has implications for habitat assessments and rehabilitation design and appraisal projects.

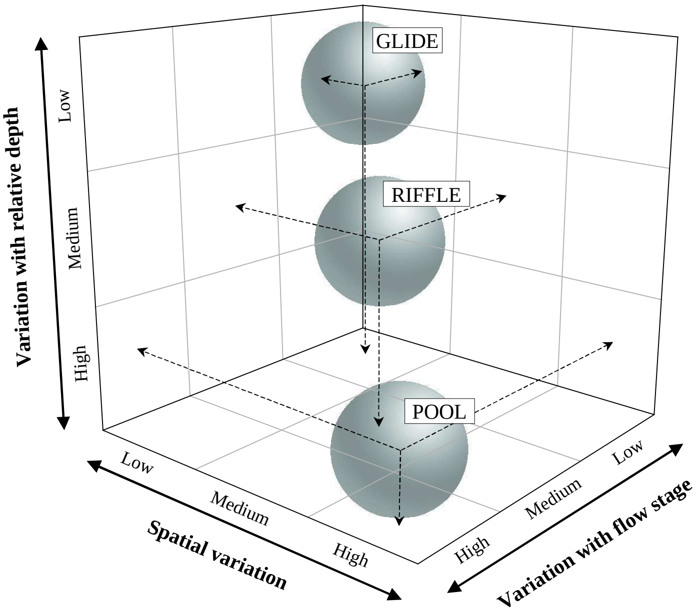


Figure 5.36 Conceptual classification of physical biotopes according to levels of internal variation in hydraulics spatially, with depth and with flow stage.

These variations in physical habitat complexity are also manifest in the distribution of particulate matter within different physical biotopes. Although sediment transport experiments present here are preliminary and restricted in scope, the results suggest that the hydraulic homogeneity associated with the glide biotope, and to a lesser extent the riffle, is manifest in a more organised and competent longitudinal transfer of sediments downstream. In contrast the spatio-temporal heterogeneity of hydraulics within pools creates a complex mixing environment whereby the routes taken by particulate matter are strongly dependent on the location of the source and the wider hydrological context. Depending on these factors, sediments, nutrients and pollutants may be rapidly advected downstream or reside for long periods in marginal zones. These observations suggest implications for the dispersal of sediments, nutrients and pollutants within different physical biotopes. Further field deployments would help to clarify observed patterns and identify processes operating within the full range of physical biotopes associated with UK rivers.

The microscale hydrodynamics of physical biotopes described above may have particular significance for the portability of the biotope concept. Physical habitat at the ‘mesoscale’ is often considered highly dependent upon wider characteristics of the catchment or sub-catchment (Frissell *et al.*, 1986; Wadeson and Rowntree, 1994; Cohen *et al.*, 1998). However, hydraulic variation at the microscale, which will be determined principally by the presence of roughness elements and flow obstructions, may offer greater transferability across different sites and additionally has the most direct influence on the survival of individual organisms.

CHAPTER 6 CONCLUSIONS

The research presented in previous chapters adopts an integrated approach to the exploration of stream habitat organisation at the reach scale. The research design encompasses a range of spatial scales and scientific methods in an attempt to both disclose broad relationships and allow inferences with regard to causal processes. Ultimately, the research provides an opportunity to assess the 'robustness' of the physical biotope concept as a means of classifying instream habitat at the mesoscale, and to evaluate the potential of the approach in habitat inventory, appraisal and rehabilitation schemes. The following sections summarise the principal conclusions with respect to each of the main research objectives detailed in Chapter 1:

1. *Examine the correlations between physical biotopes and functional habitats*
2. *Evaluate output data derived from rapid field survey techniques*
3. *Investigate the existence and integrity of physical biotopes at the reach scale*
4. *Assess the robustness of physical biotopes with varying flow stage*
5. *Explore higher resolution 'within-biotope' hydraulic characteristics*

Recommendations for further research are made in Section 6.2.

6.1 SUMMARY AND CONCLUSIONS

6.1.1 Correlations between physical biotopes and functional habitats

The examination of correlations between physical biotopes and functional habitats represents the first research objective identified in Chapter 1 (Table 1.1). Physical biotopes provide a means of simplifying the complex morphological, hydraulic and ecological structure of river channels at the sub-reach scale. However, while these features have been associated with some distinctions in hydraulics (Jowett, 1993; Wadeson, 1994; Padmore, 1997a) and are conveniently identified in the field by rapid visual assessments (Environment Agency, 2003), these traits alone do not demonstrate ecological significance (Maddock, 1999). The concept of biologically functional habitats, developed by stream ecologists, offers a means of exploring the ecological validity of physical biotopes. However, previous attempts to link the two phenomena have been associated with limited success for several reasons.

Biotope identification through visual observation of surface flow character is associated with significant error, and a single physical biotope may support a variety of flow types over a particular discharge range. For this reason, the use of Froude number as a descriptor of physical biotopes is necessarily associated with significant 'overlap' between biotope categories due to the range of flow environments associated with an individual biotope. Moreover, because the Froude number is a ratio measure, very different velocity and depth combinations may be associated with the same Froude number, obscuring hydraulic variation within and between physical biotopes.

Chapter 3 presents the results of the extensive interrogation of a comprehensive national data set of habitat features that provides some ecological validation of the physical biotope concept. Correlations between surface flow types and functional habitats are identified at a relatively broad level, and an ecological 'classification' of flow types is derived. At the national level, functional habitats reveal broad 'preferences' for *assemblages* of flow types that are indicative of different reach-scale morphologies (step-pool, riffle-pool and glide-pool). These reach-scale morphologies and their respective flow type assemblages are organised along an energy gradient from high to low altitude and slope conditions in conjunction with distance from the river source, creating a hierarchical habitat structure which comprises channel morphology, flow types, substrate and vegetation types.

This flow type classification (see Figure 3.14 and 3.17 in Chapter 3) is derived from data from over 4 000 river reaches across the UK, traversing a range of geological settings and catchment contexts and providing a national picture of flow biotope and functional habitat distributions. Considering, therefore, that the data span a wide range of fluvial environments across geological boundaries and at various altitudes and slopes, the associations identified between functional habitats and flow types show impressive strength. Some of the variability observed is likely to result from the influence of extraneous factors such as light, water chemistry and biological interactions which may also influence the distribution of certain functional habitats, as well as the complex system of feedbacks that exists between aquatic plants and channel hydraulics.

6.1.2 Rapid reconnaissance methods and the representation of habitat features

The second research objective identified in Chapter 1 refers to the evaluation of output data derived from rapid field assessments of habitat features. In the context of international environmental policy, the UK must satisfy requirements for river habitat inventory, assessment, rehabilitation and appraisal at a national scale. The physical biotope approach offers a practical focus for management at each of these stages by allowing rapid assessments of habitat features in the field (Raven *et al.*, 1997). Furthermore, the approach provides: (i) simultaneous assessment of water, sediment and biotic aspects of habitat quality (Borja *et al.*, 2004); (ii) an indication of physical, and hence biological diversity (Padmore, 1998); and (iii) a suitable focus for enhancement, rehabilitation or construction of habitat features (Kemp *et al.*, 2000). Such surveys may be particularly important within the final monitoring and appraisal stages of management projects (Harper *et al.*, 1998a; Harper *et al.*, 1998b) which are often associated with a dearth of financial support despite the vital role of monitoring and appraisal in improving the success of rehabilitation schemes.

Results presented in this thesis derived from RHS and field study demonstrate that the spatial resolution of survey schemes has a significant effect on the output data derived from rapid field assessments of habitat features, with different habitat features affected in different ways. Certain flow types, such as no perceptible flow and upwelling, for instance, occur principally as secondary or marginal phenomena and are therefore under-represented by transect-level survey schemes. However, slow flowing 'marginal' zones are objectively identified as a hydraulic cluster by multivariate analysis, emphasising their physical coherence as a distinct habitat 'patch'. Such areas are known to provide ecologically important flow refugia for invertebrates and fish, suggesting that they should be accounted for in habitat assessments. In contrast, other flow types frequently occupy the majority of the channel width but are over-estimated by transect-level observations to the detriment of marginal zones. Furthermore, the level of cross sectional variation in both surface flow character and quantified hydraulic characteristics varies between physical biotopes, so that certain biotopes are associated with higher levels of internal heterogeneity both spatially (across the channel width) and temporally (with increasing stage).

Similar issues apply to the recording of functional habitats, particularly the organic categories. Detailed analyses at field sites identified that vegetative functional habitats are associated with different spatial distributions. Specifically, certain habitats appear more ‘patchy’, while others are restricted to linear distributions associated with the channel margins. These marginal functional habitats are therefore more likely to be under-represented by coarser resolution ‘transect’ scale surveys. Within the RHS database, this problem is particularly clear with respect to ‘trailing vegetation’, which is necessarily restricted to channel margins and therefore accounts for a low percentage of cover across the channel width. Additionally, variation in the magnitude of seasonal change in habitat cover between categories suggests that the seasonal timing of surveys will have a greater influence on certain habitats.

However, information losses resulting from coarser survey resolutions may be an acceptable price to pay in return for fast, cost-effective cataloguing of features on such a scale as used in RHS, particularly since rare or unique natural features are accounted for and levels of human intervention are explicitly recorded. In such instances, fine detail on physical structure may be overlooked in favour of extending the geographic coverage of observations to allow evaluation of the quality status of water resources at a national level. Furthermore, the focus of coarser survey schemes on only the more prominent or extensively occurring features does appear to strengthen relationships across various river types and environmental contexts, providing a broad overview which may be explored in more detail by finer scale surveys at selected sites.

The RHS database thus represents an extensive national resource that can be used to complement more detailed, intensive field investigations of form and process relationships. The classification derived in Chapter 3 suggests the idea of correlations between habitat features at relatively broad scales, relating to *assemblages* of features positioned along a continuum. Such relationships or classifications derived from extensive data sets from a wide range of different sites can be used to form a general basis for habitat assessment and rehabilitation.

6.1.3 The physical integrity and hydrodynamics of physical biotopes at the sub-reach scale

The third and fourth research objectives outlined in Chapter 1 relate to the exploration of the integrity of physical biotopes at the reach scale in the context of varying discharge. The coherence and 'patchiness' of physical biotopes at the sub-reach scale appears to be strongly dependent upon the amplitude of reach-scale morphological variations, emphasising the strong relationships between channel morphology and hydraulics. However, significant deviations from the 'characteristic' flow types used to identify physical biotopes in the field were identified at the study sites, and these deviations were more pronounced for certain biotopes. Pools, for instance, demonstrate high cross sectional variability in surface flow characteristics and underlying hydraulics, while glides are more consistently associated with the 'characteristic' smooth boundary turbulent flow and exhibit lower levels of 'within-biotope' variability.

Furthermore, while increases in stage have been associated with a 'drowning-out' of morphological controls on channel hydraulics and consequent homogenisation of the flow field, data for Napely Lodge Farm suggest that a flow 'intensification' occurs at the intermediate discharge which increases cross sectional variability in certain parts of the channel. This may be related to the complex physical structure which comprises a sinuous channel with a series of bends, bank irregularities, and flow obstructions such as tree roots. Some of these features may become more significant at higher discharges as they become incorporated into the wetted width, and may increase variation in the form of jet and wake effects.

Hydraulic parameters fail to discriminate clearly between physical biotopes, but instead are associated with broad ranges that overlap but form a continuum of ‘slower’ or more ‘tranquil’ environments to ‘faster’ or ‘rougher’ biotopes and associated flow types. Biotopes and flow types are, however, generally restricted to a relatively narrow range of *either* velocities or water depths. ‘Slower’ categories are associated with a wide range of water depths, but are restricted to a narrow range of velocities, while ‘faster’ biotopes and flow types are associated with a wide range of velocities but a narrow range of water depths. Physical biotopes are therefore associated with broad *assemblages* of habitat variables that reveal some overlap but provide a general description of the local physical environment. This corresponds with ideas presented in Chapter 3, which suggest correlations at relatively broad levels. Thus, in order to be ‘portable’ between sites, physical biotopes may be considered as ‘relative’ units of habitat positioned along a continuum (Jowett, 1993), and whose detailed physical structure will vary according to reach-scale variables such as gradient and planform.

6.1.4 ‘Within-biotope’ variation and microscale hydraulics

Results presented in Chapter 5 simultaneously address the fourth and fifth research objectives outlined in Chapter 1 by focusing on higher resolution hydrodynamics ‘within’ physical biotopes at different flow stages. The analysis of high frequency velocity characteristics and localised transfer of suspended sediment within selected physical biotopes indicates that more detailed hydraulic parameters may provide better discrimination between physical biotopes compared to more conventional mean velocity and depth values. These characteristics are also of ecological importance since channel hydraulics at microscales have a direct influence on the survival of individual organisms (Biggs *et al.*, 2005). Despite these considerations, more detailed hydraulic parameters have so far been largely overlooked in biotope studies.

Overall, ‘simpler’ series-averaged measures such as mean velocity and kinematic shear stress appear less powerful at discriminating between biotopes compared to more complex, ‘higher-order’ flow properties such as turbulence intensity, event structure and eddy size. However, the discriminatory ‘success’ of different hydraulic parameters depends upon the combination of physical biotopes studied. For example, pool and glide biotopes at Oakley Hall are clearly distinguished by turbulence intensity, while the average eddy size provides greater discrimination between pool and riffle biotopes at Napely Lodge Farm.

While some overlap in the ranges of parameters is noted between biotopes, when considered in combination the higher-order flow properties describe three different hydrodynamic environments. This is again consistent with ideas in Chapter 3 and Chapter 4 of correlations at broader levels relating to ‘assemblages’ of variables that provide a general description of habitat. The riffle provides an environment where flow structure is dominated by the shedding of vortices from pebble clusters, and where the nature of local hydraulics appears dependent upon flow stage. In contrast, the glide represents a homogeneous flume-like environment associated with a simpler flow structure that varies little across flow stages. The pools represent the most hydrodynamically complex environments as a result of interactions between burst-sweep structures; vortices shed from microform roughness; and flow structures produced by larger scale flow obstructions and form roughness and demonstrate a complex response to increasing flow stage.

Overall variations in hydraulics *between* biotopes appear more significant than variation *within* biotopes. However, variations in the levels of ‘internal’ heterogeneity between different physical biotopes emphasise the variations in internal complexity identified in Chapter 4. Three scales of variation can be identified from the analysis: spatial variation in streamwise and cross-stream dimensions; temporal variation associated with discharge; and variation with distance from the riverbed. When these characteristics are conceptualised as variables in three-dimensional space, riffle, pool and glide are clearly partitioned on the grounds of internal complexity. Pools are the most heterogeneous biotopes, characterised by high-levels of variation in all three dimensions. Riffle hydraulics vary relatively systematically with stage and depth through the water column but demonstrate high spatial homogeneity. The glide represents a strongly spatially homogeneous, transitional environment associated with very low levels of internal hydraulic variation. Again, the influence of bedform amplitude on biotope characteristics is apparent at these microscales, since the more topographically prominent pool at Napely Lodge Farm demonstrates much higher levels of variation than the more subtle feature at Oakley Hall.

The hydrodynamic characteristics and variations in internal ‘complexity’ identified for different physical biotopes constitute additional biotope characteristics that provide greater detail than more conventional temporally- or spatially-averaged measures. Significantly, these characteristics may represent the most ‘successful’ scale of transferability between sites for two reasons. Firstly, because microscale hydrodynamics are principally dependent on highly localised conditions such as grain form roughness elements, and secondly because the same physical biotopes may demonstrate similar levels of variability across different sites, irrespective of the ‘absolute’ ranges of hydraulic variables.

The research presented in this thesis adopts a multi-scale, multi-parameter approach to the characterisation of aquatic habitat. The results reveal broad classifications of habitat features into ‘assemblages’ that reveal some ‘overlap’ but describe fundamentally different hydrodynamic environments. The physical biotope, therefore, appears to offer an appropriate level of simplification of the complex structure of aquatic habitat for the purposes of habitat assessment, appraisal and rehabilitation.

6.2 RECOMMENDATIONS FOR FURTHER RESEARCH

The research presented in this thesis highlights several areas that would benefit from further study. These can be considered in the context of: (i) ‘macroscale’ research associated with studies across rivers of varying ‘type’ at the national level; (ii) ‘mesoscale’ research associated with the identification and characterisation of biotopes within a river reach; and (iii) ‘microscale’ studies of hydraulics within individual biotopes.

6.2.1 Research at the macroscale

At the macroscale, the functional habitat concept requires further field-testing within different river types and management contexts in order to test the integrity of biological relationships throughout the UK. Similarly, further testing of the flow type classification developed in Chapter 3, possibly using subsets of the RHS data set, will test the robustness of the classification for different river types and potentially identify some of the factors responsible for the observed scatter.

6.2.2 Research at the mesoscale

At the mesoscale, objective multivariate methods of physical habitat characterisation appear to provide a more productive and informative approach compared with the more subjective focus on visually identified features. This suggests that future investigations of biotope hydraulics should take the form of detailed, objective explorations of the physical structure of a reach, in line with more recent work (Clifford *et al.*, 2002a; Clifford *et al.*, 2002b; Emery *et al.*, 2003). This type of approach provides an opportunity to objectively identify areas of the channel with similar hydraulic behaviour from comprehensive field data sets.

The field research presented in Chapter 4 suggests that the relationships between surface flow conditions and underlying hydraulics is complex and stage-dependent. This requires further field research focused at various relative depths through the water profile, and at varying flow stages in order to assess the reliability of inferences on hydraulic behaviour from surface flow characteristics. The influence of vegetation growth on these relationships through disruption of velocity profiles may also be examined by measuring hydraulic parameters within and around vegetation stands and along riverbanks over a range of discharges.

Aquatic biota require different types of habitat for different lifestages; for different activities such as feeding, resting and shelter (Mosely, 1982); and for the provision of habitat for prey (Aadland, 1993). It is likely, therefore, that the *combinations* of physical biotopes present in a river reach or segment will have a significant influence on biological organisation. Future research may expand on initial explorations of biotope 'patchiness' and 'diversity' (Padmore, 1998) to identify a means of classifying the heterogeneity or 'complexity' of habitat, which is known to correlate strongly with habitat quality and biodiversity (Gorman and Karr, 1978; Gubala, 1996; Beisel *et al.*, 2000). The variations in the internal complexity of different biotopes identified in this thesis suggest that indices of heterogeneity may be developed which may involve weighting of different biotopes and assemblages according to the complexity of habitat they provide.

6.2.3 Research at the microscale

At the microscale, analysis of turbulent properties and sediment transfer routes reveals some variation between biotopes. Further studies are required both to identify whether the characteristics observed for the study sites are representative of similar rivers, and in order to explore the microscale ecohydraulics of the full range of physical biotopes identified for UK rivers. The sediment transport component of the microscale research presented in Chapter 5 represents the first attempt of its kind at identifying variations in the transport pathways within different physical biotopes. Further information on the mixing processes operating in physical biotopes may be gained by using more intensive deployments of turbidity probes and velocimeters within the biotopes. Additionally, the characteristics of large-scale sediment pulses associated with flood events may be examined by longer term monitoring of sediment transport.

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APPENDICES

APPENDIX A: Cluster centre characteristics for Chapter 4 K-means cluster analyses.

	Cluster centre characteristics		
Cluster	**U (ms^{-1})**	**Depth (m)**	**Substrate**
Margins	0.04	0.23	Silt
Mid-pool	0.12	0.74	Pebble
Pool margins	0.06	0.61	Silt
Glide	0.19	0.29	Sand
Run	0.18	0.24	Pebble
Riffle	0.19	0.28	Gravel

Cluster centre characteristics for Oakley Hall low flow clusters based on streamwise velocity, depth and substrate.

	Cluster centre characteristics		
Cluster	**U (ms^{-1})**	**Depth (m)**	**Substrate**
Margins	0.05	0.26	Silt
Mid-pool	0.13	0.87	Pebble
Pool margins	0.20	0.58	Sand
Glide	0.20	0.27	Sand
Run	0.24	0.35	Pebble
Riffle	0.23	0.38	Gravel

Cluster centre characteristics for Oakley Hall intermediate flow clusters based on streamwise velocity, depth and substrate.

	Cluster centre characteristics		
Cluster	**U (ms^{-1})**	**Depth (m)**	**Substrate**
Margins	0.01	0.23	Silt
Pool	0.02	0.73	Silt
Glide	0.18	0.28	Sand
Run	0.16	0.37	Pebble
Riffle margins	0.19	0.20	Gravel
Riffle centre	0.39	0.17	Gravel

Cluster centre characteristics for Napely Lodge Farm low flow clusters based on streamwise velocity, depth and substrate.

	Cluster centre characteristics		
Cluster	**U (ms^{-1})**	**Depth (m)**	**Substrate**
Margins	0.01	0.24	Silt
Mid-pool	0.17	0.46	Pebble
Pool margins	0.10	0.57	Sand
Glide	0.12	0.23	Sand
Riffle (gravel)	0.33	0.25	Gravel
Riffle (pebble)	0.17	0.46	Pebble

Cluster centre characteristics for Napely Lodge Farm intermediate flow clusters based on streamwise velocity, depth and substrate.

	Cluster centre characteristics				
Cluster	**U (ms^{-1})**	**V (m^{s-1})**	**W (m^{s-1})**	**Depth (m)**	**Substrate**
Margins	0.04	0.0066	0.0036	0.30	Silt
Pool	0.12	-0.0923	-0.0353	0.74	Pebble
Glide	0.20	0.0029	-0.0153	0.32	Sand
Glide (gravel)	0.13	0.0005	-0.0045	0.60	Gravel
Run	0.19	0.0021	-0.0169	0.26	Pebble
Riffle	0.23	0.0146	-0.0211	0.25	Gravel

Cluster centre characteristics for Oakley Hall low flow clusters based on streamwise, cross-stream and vertical velocity, depth and substrate.

	Cluster centre characteristics				
Cluster	**U (ms^{-1})**	**V (m^{s-1})**	**W (m^{s-1})**	**Depth (m)**	**Substrate**
Margins	0.05	0.0006	0.0041	0.28	Silt
Mid-pool	0.13	-0.0648	-0.0405	0.87	Pebble
Pool margins	0.21	-0.0213	-0.0142	0.57	Sand
Glide	0.20	0.0008	-0.0216	0.27	Sand
Run	0.24	-0.0070	-0.0274	0.35	Pebble
Riffle	0.23	-0.0386	-0.0120	0.38	Gravel

Cluster centre characteristics for Oakley Hall intermediate flow clusters based on streamwise, cross-stream and vertical velocity, depth and substrate.

	Cluster centre characteristics				
Cluster	**U (ms^{-1})**	**V (m^{s-1})**	**W (m^{s-1})**	**Depth (m)**	**Substrate**
Margins	0.01	0.0050	0.0008	0.32	Silt
Mid-pool	0.04	0.0240	-0.0111	0.56	Pebble
Pool margins	0.15	-0.0089	-0.0036	0.48	Sand
Glide	0.19	-0.0055	-0.0105	0.20	Sand
Riffle (gravel)	0.31	-0.0022	-0.0179	0.20	Gravel
Riffle (pebble)	0.26	0.0286	-0.0248	0.27	Pebble

Cluster centre characteristics for Napely Lodge Farm low flow clusters based on streamwise, cross-stream and vertical velocity, depth and substrate.

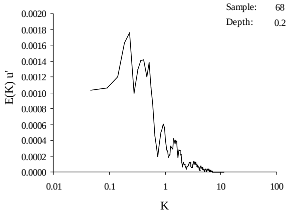
	Cluster centre characteristics				
Cluster	**U (ms^{-1})**	**V (m^{s-1})**	**W (m^{s-1})**	**Depth (m)**	**Substrate**
Margins	0.01	-0.0108	-0.0081	0.25	Silt
Pool	0.10	0.0194	-0.0047	0.57	Sand
Glide	0.13	0.0001	0.0023	0.24	Sand
Run	0.33	0.0014	-0.0333	0.36	Pebble
Riffle margins	0.18	0.0038	-0.0248	0.33	Gravel
Riffle centre	0.39	-0.0018	-0.0414	0.23	Gravel

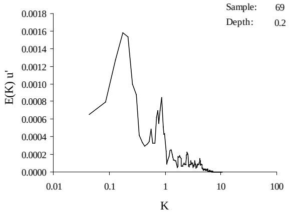
Cluster centre characteristics for Napely Lodge Farm intermediate flow clusters based on streamwise, cross-stream and vertical velocity, depth and substrate.

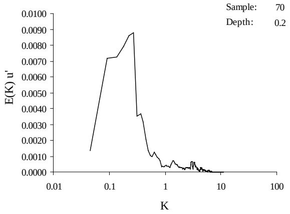
APPENDIX B: Wavenumber spectra for velocity time series

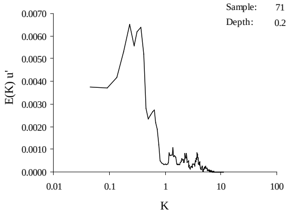
Site: Oakley Hall   Flow stage: Low   Biotope: Glide   Velocity component: u’

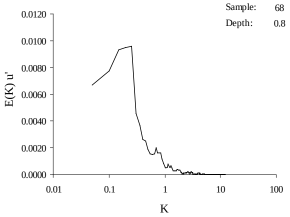
Longitudinal transect

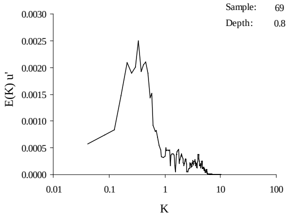


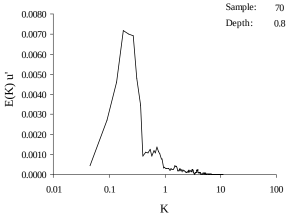




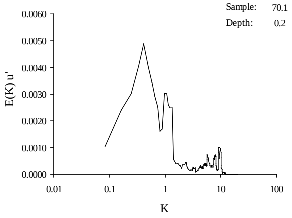


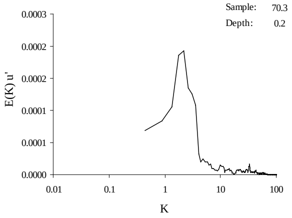


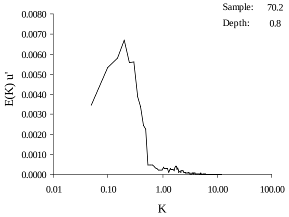


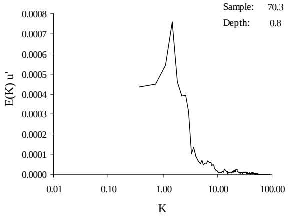


Cross sectional transect



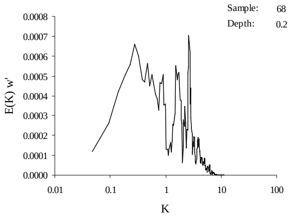


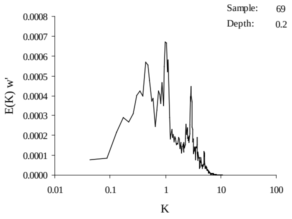


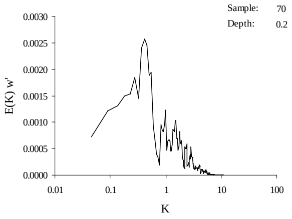


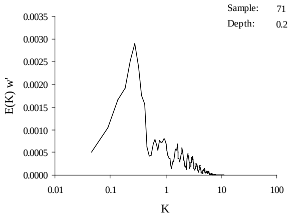
Site: Oakley Hall Flow stage: Low Biotope: Glide Velocity component: w’

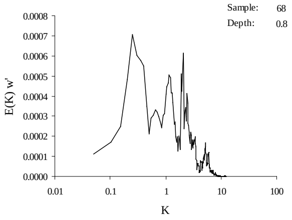
Longitudinal transect

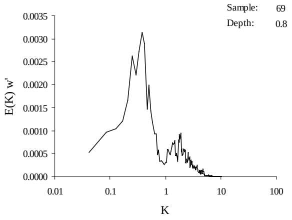


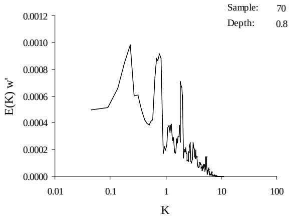




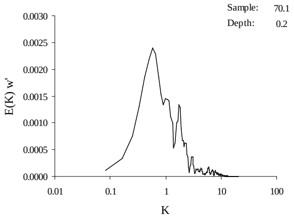


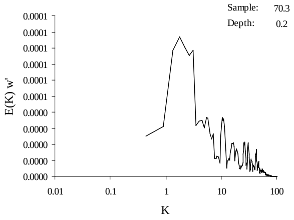


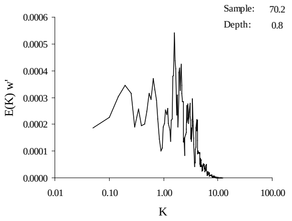


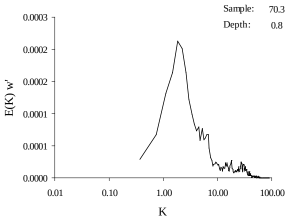


Cross sectional transect



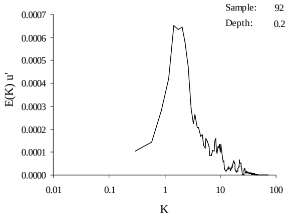


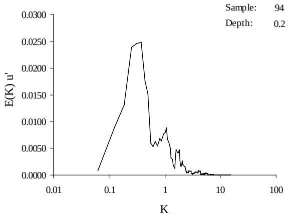


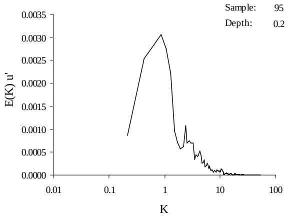


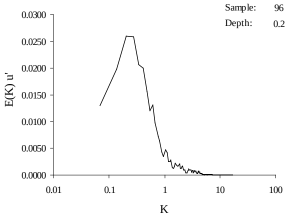
Site: Oakley Hall Flow stage: Low Biotope: Pool Velocity component: u’

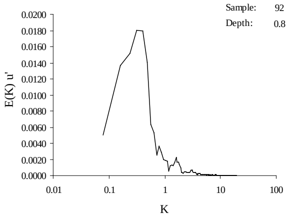
Longitudinal transect

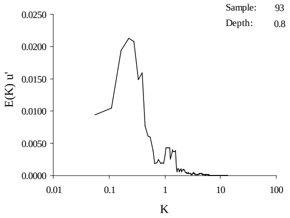


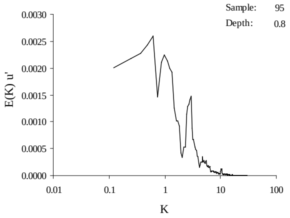


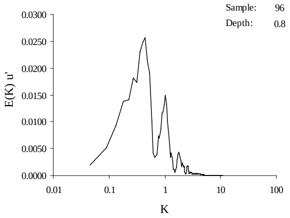




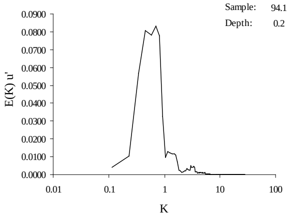


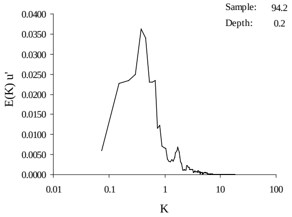


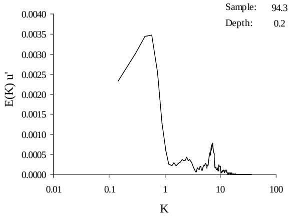


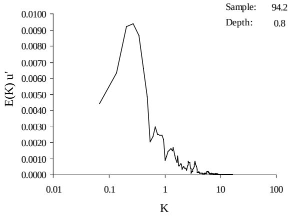


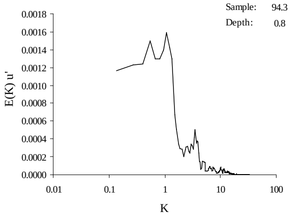
Cross sectional transect





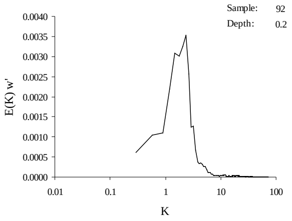


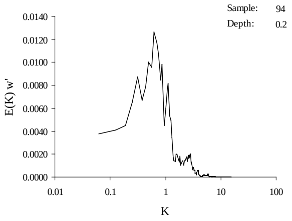


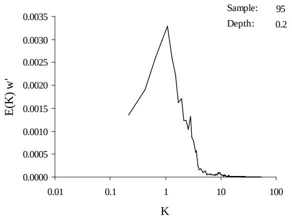


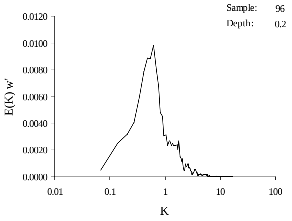
Site: Oakley Hall Flow stage: Low Biotope: Pool Velocity component: w’

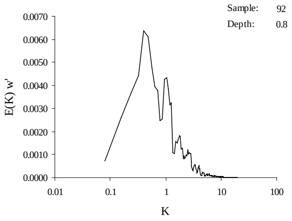
Longitudinal transect

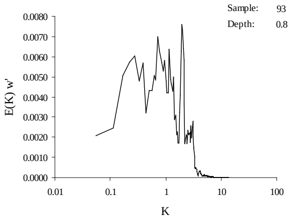


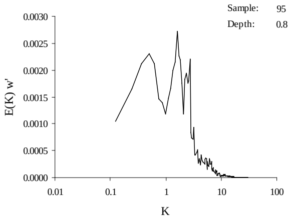


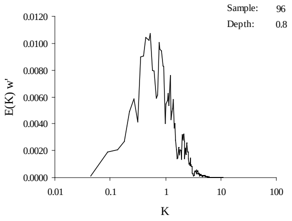




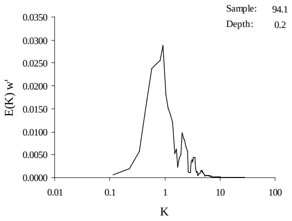


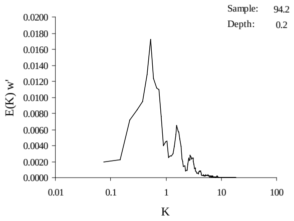


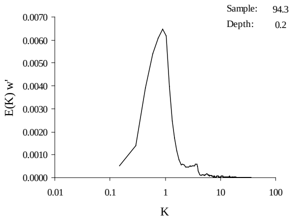


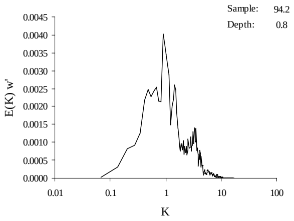


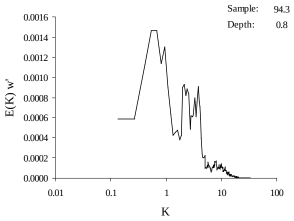
Cross sectional transect





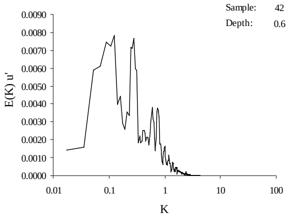


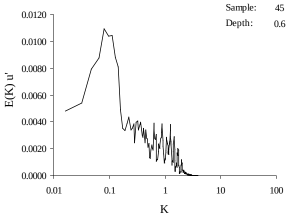


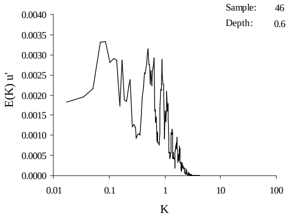


Site: Napely Lodge Farm Flow stage: Low Biotope: Riffle Velocity component: u’

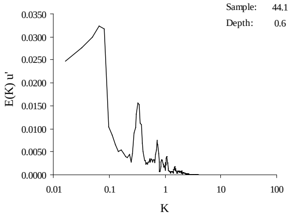
Longitudinal transect

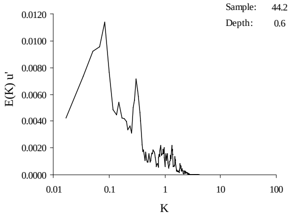


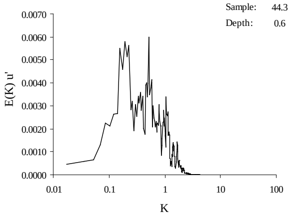


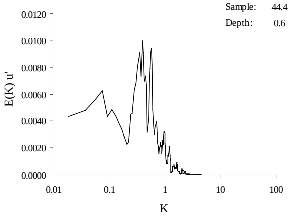


Cross sectional transect



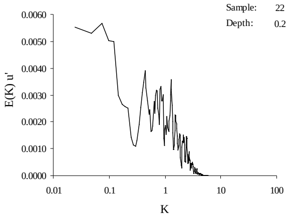


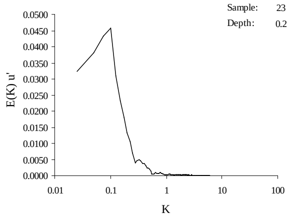


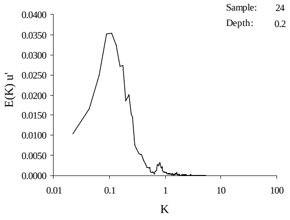


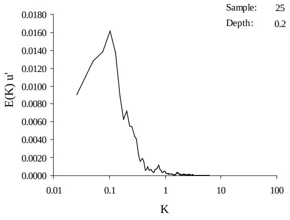
Site: Napely Lodge Farm Flow stage: Low Biotope: Pool Velocity component: u’

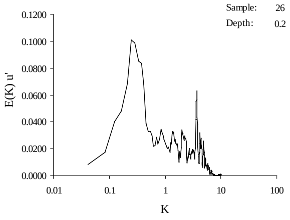
Longitudinal transect

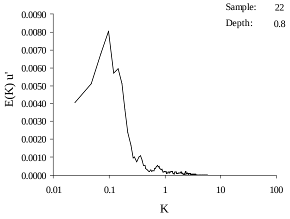


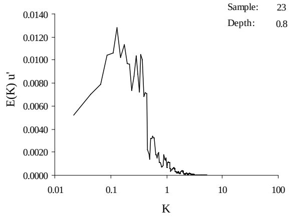


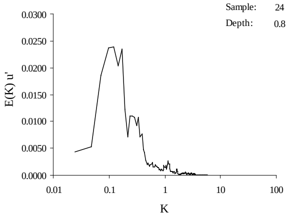


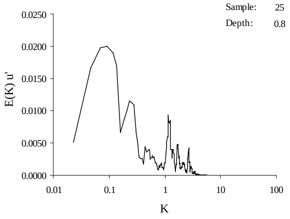


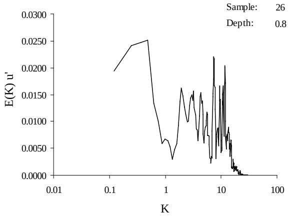




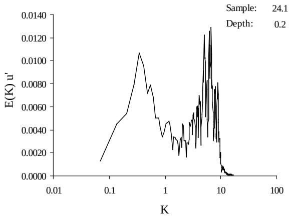


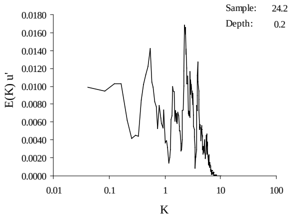


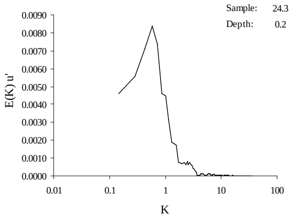


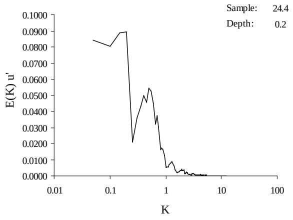


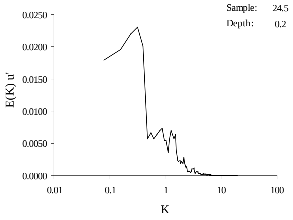
Cross sectional transect

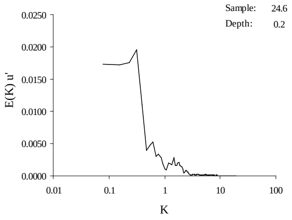


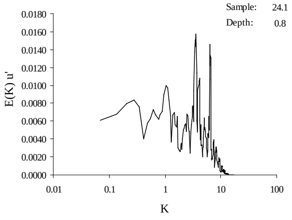


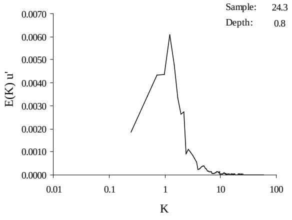


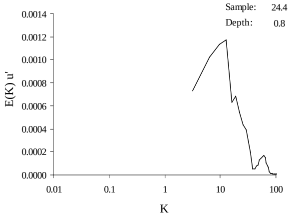


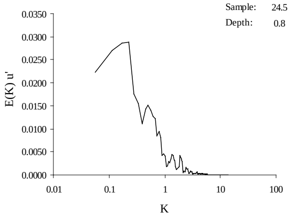


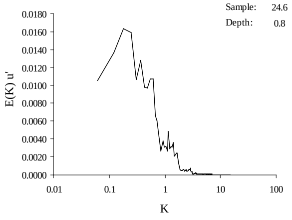






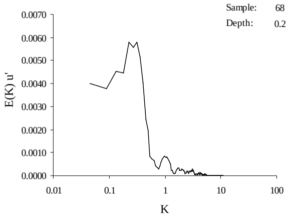


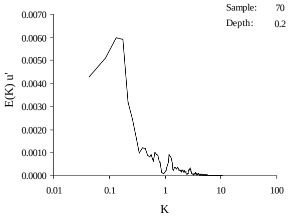


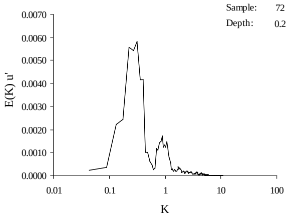


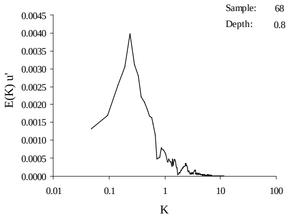
Site: Oakley Hall Flow stage: Intermediate Biotope: Glide Velocity component: u’

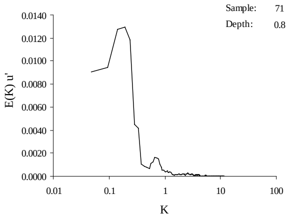
Longitudinal transect

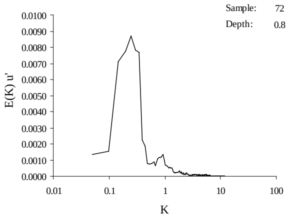




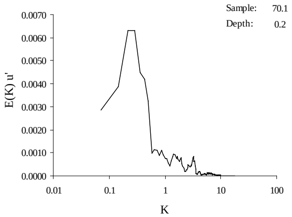


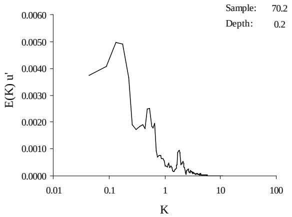


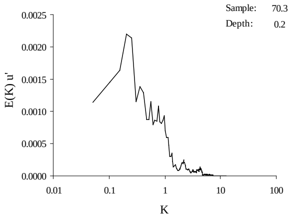


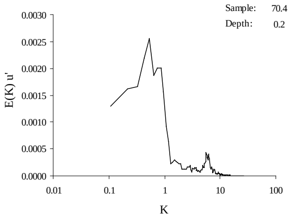


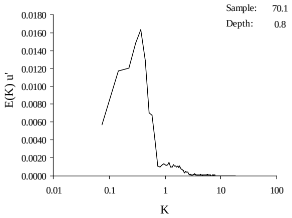
Cross sectional transect

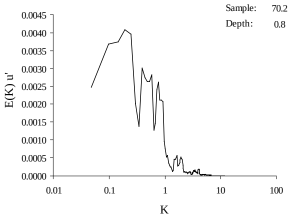


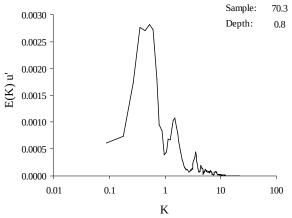






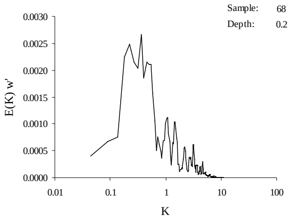


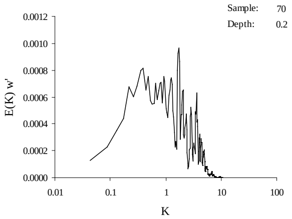


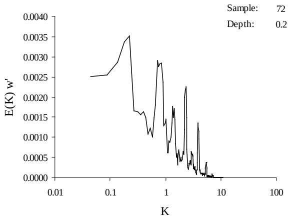


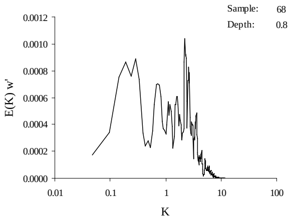
Site: Oakley Hall Flow stage: Intermediate Biotope: Glide Velocity component: w’

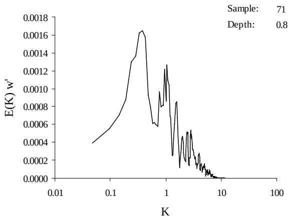
Longitudinal transect

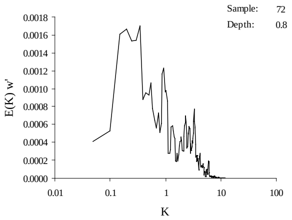




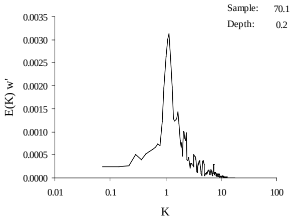


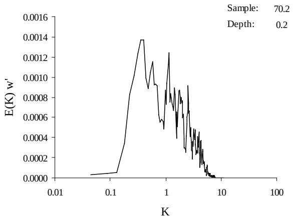


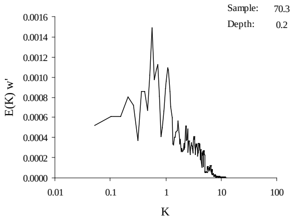


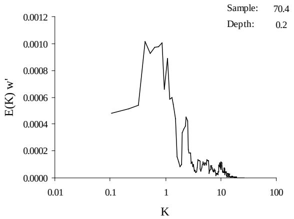


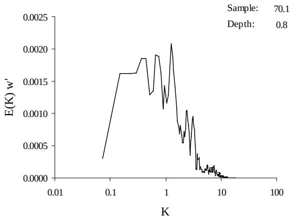
Cross sectional transect

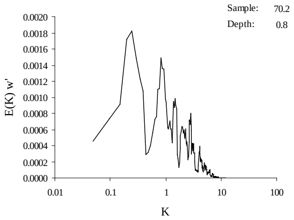


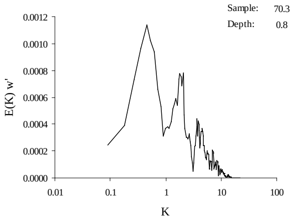






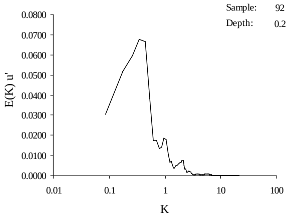


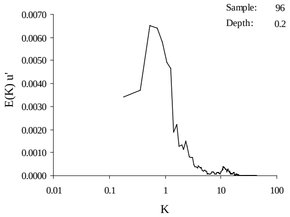


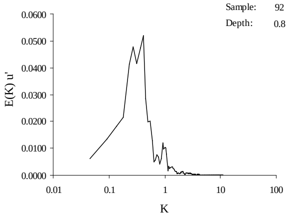


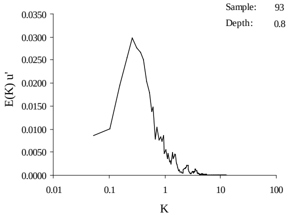
Site: Oakley Hall Flow stage: Intermediate Biotope: Pool Velocity component: u’

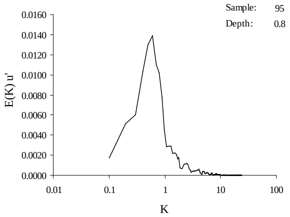
Longitudinal transect

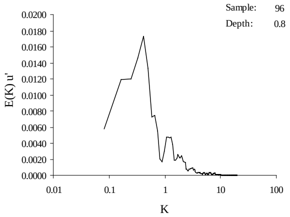




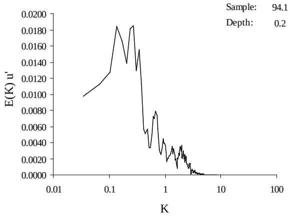


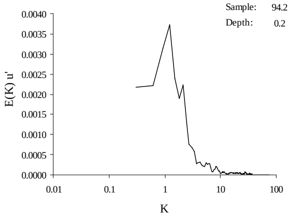


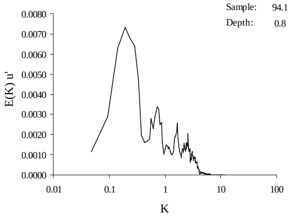


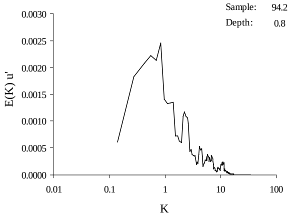


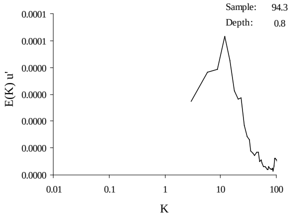
Cross sectional transect





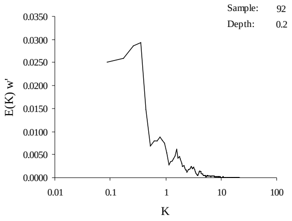


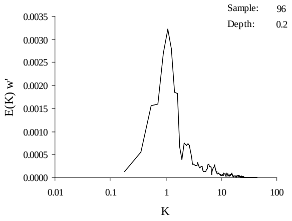


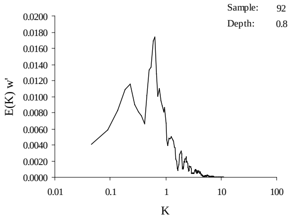


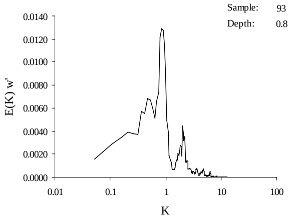
Site: Oakley Hall Flow stage: Intermediate Biotope: Pool Velocity component: w’

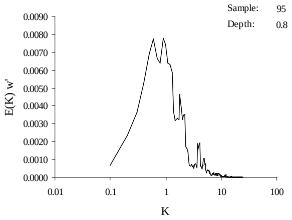
Longitudinal transect

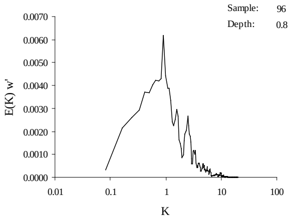




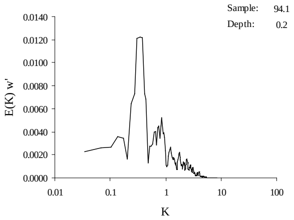


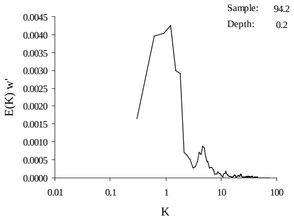


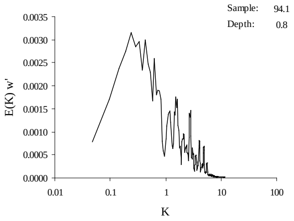


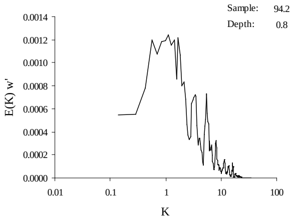


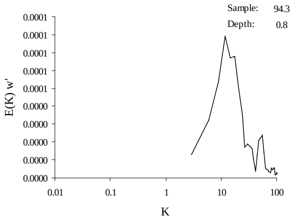
Cross sectional transect





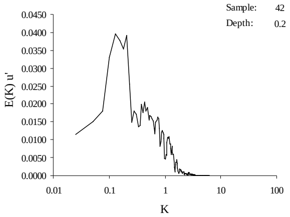


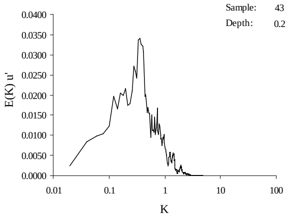


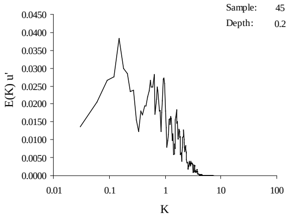


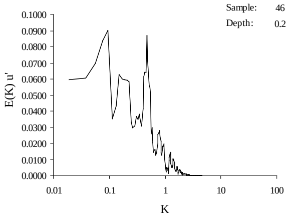
Site: Napely Lodge Farm Flow stage: Intermediate Biotope: Riffle Velocity component: u’

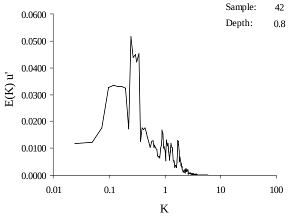
Longitudinal transect

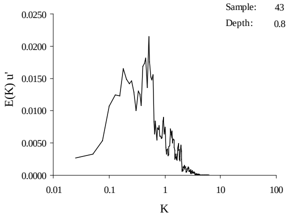


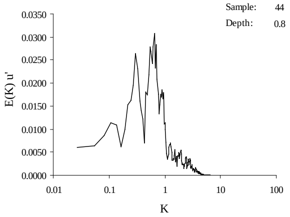


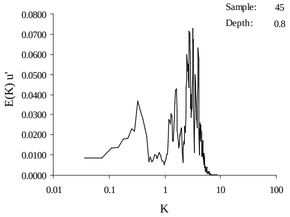




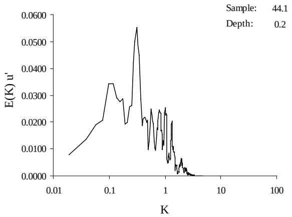


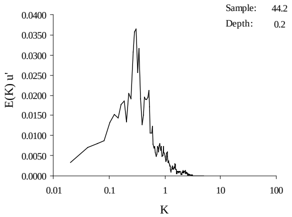


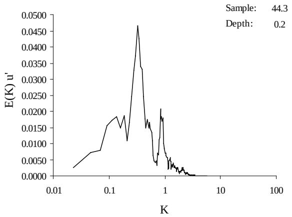


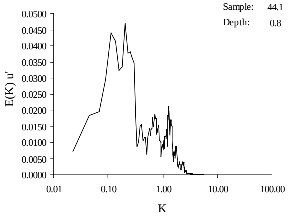


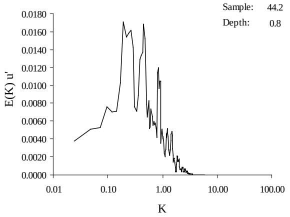
Cross sectional transect

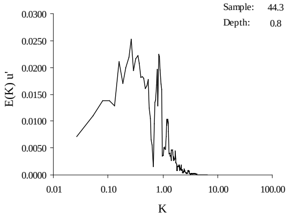






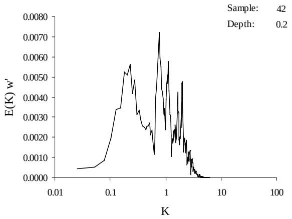


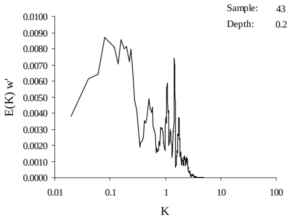


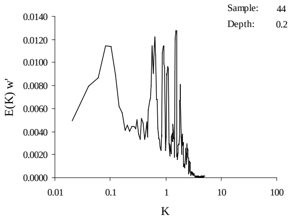


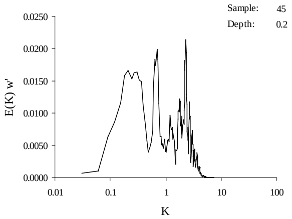
Site: Napely Lodge Farm Flow stage: Intermediate Biotope: Riffle Velocity component: w’

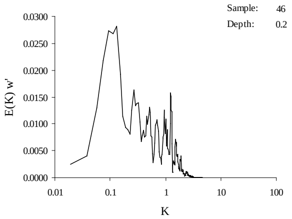
Longitudinal transect

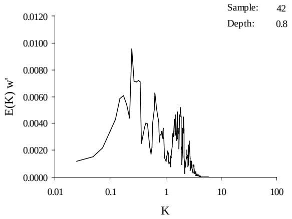


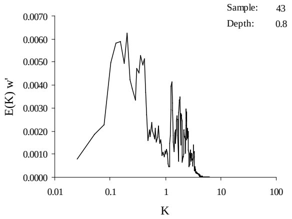


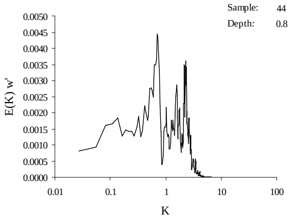


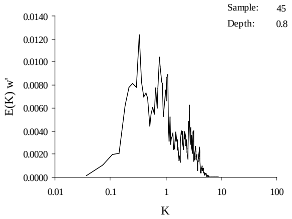




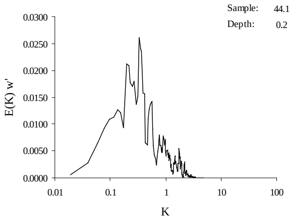


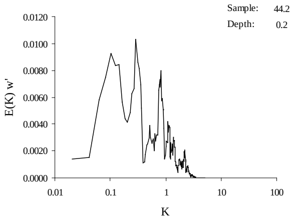


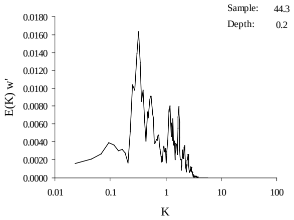


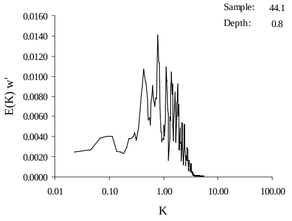


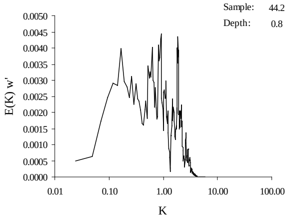
Cross sectional transect

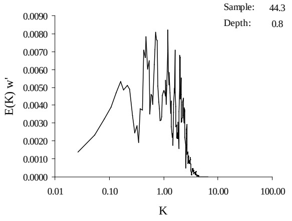






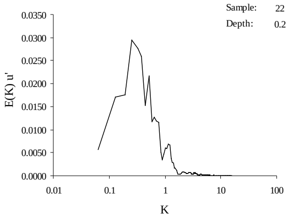


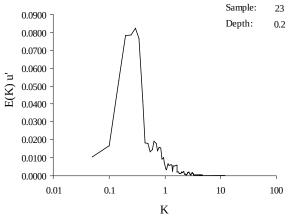


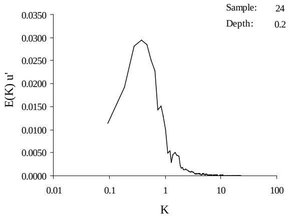


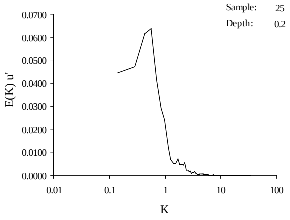
Site: Napely Lodge Farm Flow stage: Intermediate Biotope: Pool Velocity component: u’

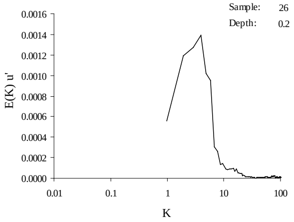
Longitudinal transect

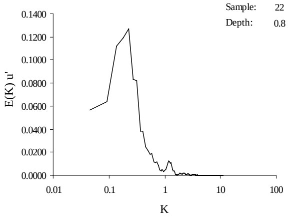


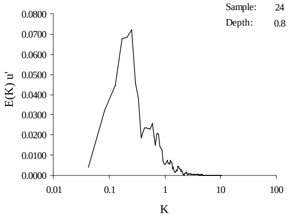


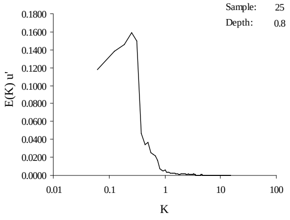


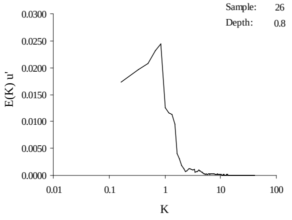




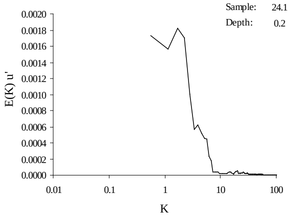


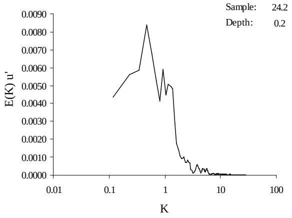


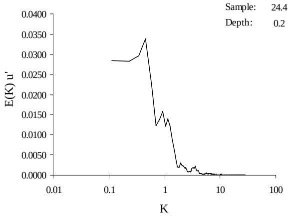


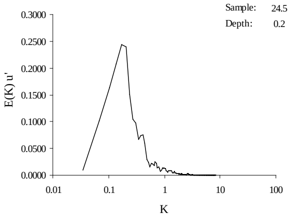


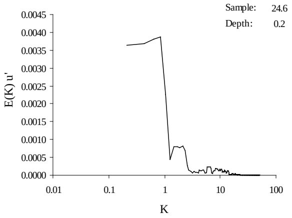
Cross sectional transect

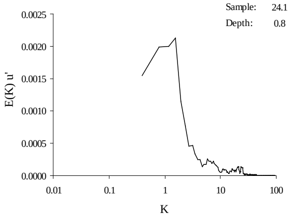


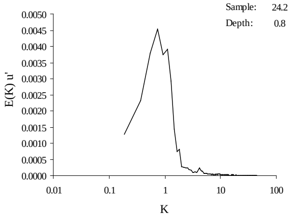


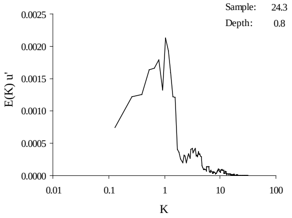


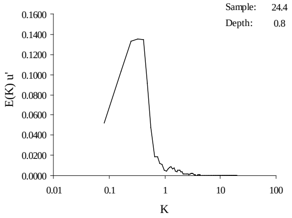


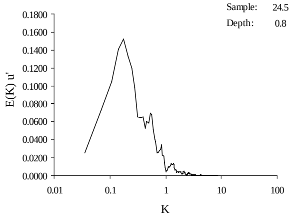


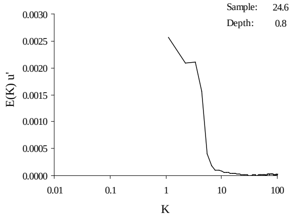






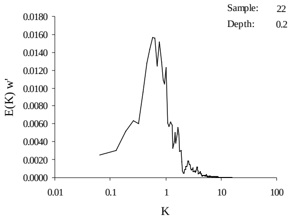


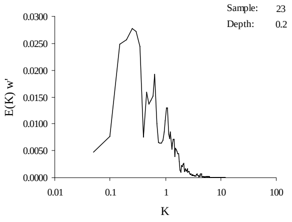


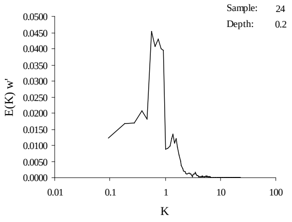


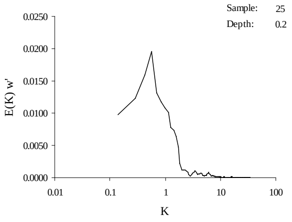
Site: Napely Lodge Farm Flow stage: Intermediate Biotope: Pool Velocity component: w’

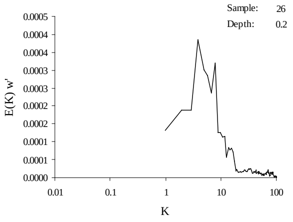
Longitudinal transect

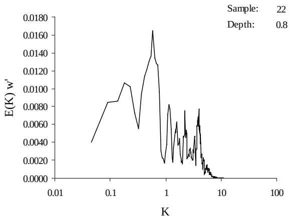


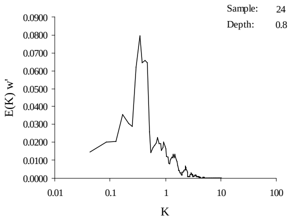


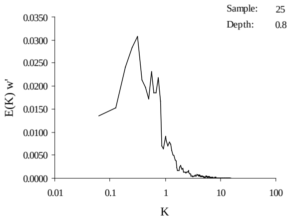


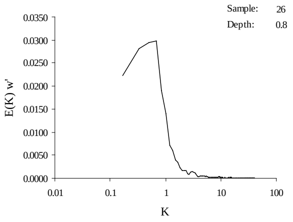












Cross sectional transect