Assessing the performance of morphologically based river typing in Scotland using a geomorphological and ecological approach

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STATEMENT OF ORIGINALITY

I hereby confirm that this is an original piece of work conducted independently by the undersigned and all work contained herein has not been submitted for any other degree. All research material has been duly acknowledged and cited.

Signature of candidate:

Victoria Susan Milner

Date: 31st May 2010

for my family and partner

ABSTRACT

Traditionally, the interactions between geomorphic character and aquatic biodiversity have been widely acknowledged, but poorly quantified. However, the coupling of these disciplines is currently rising up legislative and political agendas, such as the European Union Water Framework Directive (EU WFD). The Directive requires Member States to classify rivers into types based on their natural morphology and geomorphic processes, and to link the biota to river types existing under natural conditions. Typing now forms the basis for evaluating environmental sensitivity to river engineering and determining reference conditions for river restoration. The Scottish Environment Protection Agency (SEPA) has adapted the Montgomery and Buffington (1997) channel typology developed in the Pacific Northwest of the USA for use in Scotland. The modified typology identifies eleven distinct channel types (e.g. bedrock, plane-bed, wandering and meandering). In this study, 43 reference condition sites in the upper River Dee catchment in the Cairngorms, Scotland were chosen to determine the geomorphic validity of the proposed typology, and assess whether channel types support a distinct macroinvertebrate community. Agglomerative Hierarchical Cluster Analysis failed to clearly identify eleven channel types based on catchment controls or on physical habitat characteristics. Four clusters were observed based on catchment drivers and six on physical habitat. Boundaries appear to be fuzzy, relating to a collective number of interacting environmental variables, geological discontinuities, and the geographic complexity of a river system. Multivariate ordinations and Analysis of Similarity indicated that macroinvertebrate communities only differed significantly between bedrock and step-pool reaches. A redundancy analysis showed differences in macroinvertebrate abundances among channel types were related to hydraulic, catchment drivers, physical habitat and physico-chemical variables. The results of the study have important implications for the use of geomorphic typologies in predicting aquatic biota.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAS	Atomic Absorption Spectrometry
ANOSIM	ANalysis Of SIMilarity
ANOVA	ANalysis Of VAriance
Bank H	Bank Height
Bank W	Bankfull Width
BCDF	Bedrock Controlled Discontinuous Floodplain
BGS	British Geological Survey
BI	Braided Index
BW	Broken standing Waves
CA	Correspondence Analysis
CANOCO	CANOnical Community Ordination
CCA	Canonical Correspondence Analysis
CDT	Catchment Driver Typology
CF	Chaotic Flow
CH	Chute
CPOM	Coarse Particulate Organic Matter
CRESS	Centre for River EcoSystem Science
CSA	Cross sectional area
C Slope	Channel bed Slope
CW	Clunie Water
DCA	Detrended Correspondence Analysis
EA	Environment Agency
EC	European Commission
EDM	Electronic Distance Meter
FPOM	Fine Particulate Organic Matter
GIS	Geographical Information Systems
GS	Grain Size
HABSCORE	Habitat Score
HCA	Hierarchical Cluster Analysis
IndVal	Indicator Value
IQR	Inter-Quartile Range

LW	Lui Water
LWD	Large Woody Debris
MDA	Multiple Discriminant Analysis
MGB	Meandering Gravel Bed
MImAS	Morphological Impact Assessment System
MRPP	Multi-Response Permutation Procedure
NCC	Nature Conservancy Council
NERC	Natural Environment Research Council
NMMS	Non-Metric Multidimensional Scaling
NP	No Perceptible flow
NRA	National Rivers Authority
NRHP	National River Health Programme
OS	Ordnance Survey
PAST	PAlaeontological STatistics
PC	Principal Component
PCA	Principal Component Analysis
PHABSIM	Physical HABitat SIMulation
PHT	Physical Habitat Typology
POM	Particulate Organic Matter
Q	Discharge
QW	Quoich Water
RCC	River Continuum Concept
RCS	River Corridor Survey
RCTs	River Community Types
RD	River Dee
RDA	Redundancy Analysis
RHS	River Habitat Survey
RIVPACS	River InVertebrate Predication And Classification System
RP	Rippled flow
SEPA	Scottish Environment Protection Agency
SERCON	System for Evaluating Rivers for CONservation
SPSS	Statistical Package for the Social Sciences
SSSI	Sites of Special Scientific Interest
S-W	Shapiro-Wilk

TWINSPAN	Two-Way Indicator Species ANalysis
TSPI	Total Stream Power Index
UP	Upwelling
USPI	Unit Stream Power Index
UW	Unbroken standing Waves
Vel	Velocity
Water W	Water Width
WD	Water Depth
WDR	Width Depth Ratio
WFD	Water Framework Directive

1 Introduction

1.1 Rationale

A key goal of river science is to understand the structure and functioning of stream ecosystems. This goal requires an understanding of how the observation of environmental and ecological patterns relate to fluvial processes at various scales of space, time and organisational complexity. Patterns are an indication of the natural spatial and temporal heterogeneity within ecosystems (Levin, 1992). An appreciation of how ecosystems function relies on our ability to capture this heterogeneity across meaningful and interpretable scales (Underwood *et al.* 2000). However, a clear and widely accepted understanding of how natural ecosystems operate has eluded terrestrial and aquatic ecologists (Thorp *et al.* 2006), and fluvial geomorphologists are no exception. River ecosystems are dynamic, are energetically open and are characterised by a high degree of spatio-temporal variability (Ward, 1989; Thorp, 2009). An appreciation of the structure and function of ecosystems necessitates knowledge across four dimensions: longitudinal (upstream-downstream), lateral (main channel to the floodplain), vertical (surface and hyporheic zone), and temporal (microseconds through to geological and evolutionary time periods) (Ward, 1989). Spatiotemporal scales vary in importance to each of these four dimensions. An understanding of river ecosystems and their processes, structure, and function requires the development of tools and methodologies to capture patterns across relevant scales and dimensions (Thorp, 2009).

The linking of ecology to fluvial geomorphology, in particular via physical habitat characteristics, is a recent and on-going theme in river research and management (Vaughan *et al.* 2009). This trend has been partly driven by concerns that river systems are experiencing greater pressures from anthropogenic activities that specifically impact on hydromorphology. Negative impacts on river systems include reduction of floodplain areas (Maddock, 1999; Schmitt *et al.* 2007), habitat loss and degradation, fragmentation, erosion and sedimentation problems, increased algal blooms, and water resources allocation concerns (Brierley and Fryirs, 2005). In the future, river systems will have an additional pressure of responding to climate change (Willby *et al.* 2006; Durance and Ormerod, 2007; Clarke, 2009; Ormerod, 2009).

Vaughan *et al.* (2009) highlight how numerous terms have been used to describe the links and relationships between physical habitat and biological communities within rivers. Terms include ecogeomorphology (Parsons *et al.* 2003), ecohydrology or hydroecology (Wassen and Grootjans, 1996; Hannah *et al.* 2004; Zalewski, 2000), hydromorphology (European Commission, 2000) and ecohydromorphology (Thorp *et* al. 2006; Vaughhan *et al.* 2009). The combination of these terms in relation to key disciplines of fluvial geomorphology, hydrology and ecology can be viewed in Figure 1-1. This thesis will use these terms, and the disciplines covered in this thesis are highlighted in Figure 1-1.

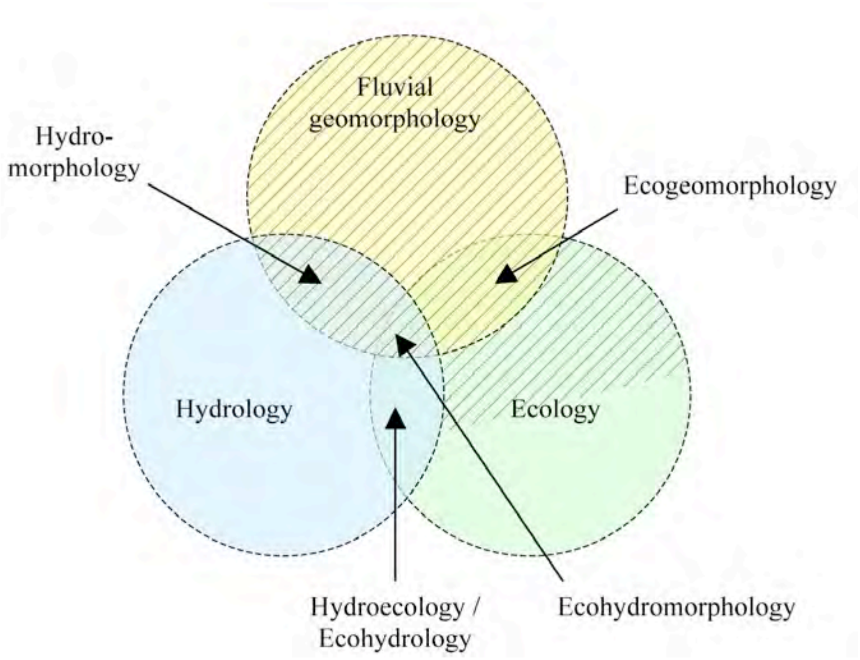


Figure 1-1: A conceptual Venn diagram showing the interconnections between different disciplines. Diagonal lines indicate the domain of this thesis.

A bibliographic survey of the ISI Web of Knowledge (http://apps.isiknowledge.com) Science Citation Index examined the use of several of these terms: ecohydrology, eco-hydrology, hydroecology and hydro-ecology. The survey searched for each term in the title, the topic of the article and the references in ISI-rated journals, books, reviews, and conference proceedings since 1991. The occurrence of use was: ecohydrology = 289, eco-hydrology = 54, hydroecology = 57, and hydro-ecology = 23 (Figure 1-2). Therefore, the term ecohydrology is more frequently used. The survey does not provide a comprehensive search of all ecohydrology/hydroecology studies, as many papers focussing on hydroecological or ecohydrological subject matter do no use the above terms. Hannah *et al.* (2004) hypothesise that the lack of use of the above terms may either indicate (i) a lack of knowledge of the new terminology, or (ii) a conscious decision to avoid contemporary jargon connected with a potentially passing scientific fashion. However, despite the limitations of the bibliographic studies, a clear pattern of authors using such interdisciplinary terms has noticeably increased since the early 1990s, and represents a shift in river research adopting a more multidisciplinary approach. The subject of this thesis is in accordance with this shift.

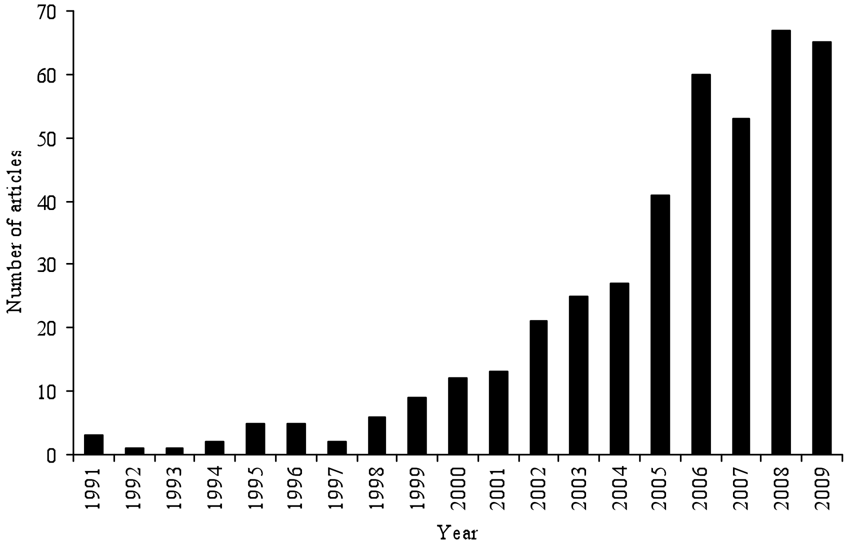
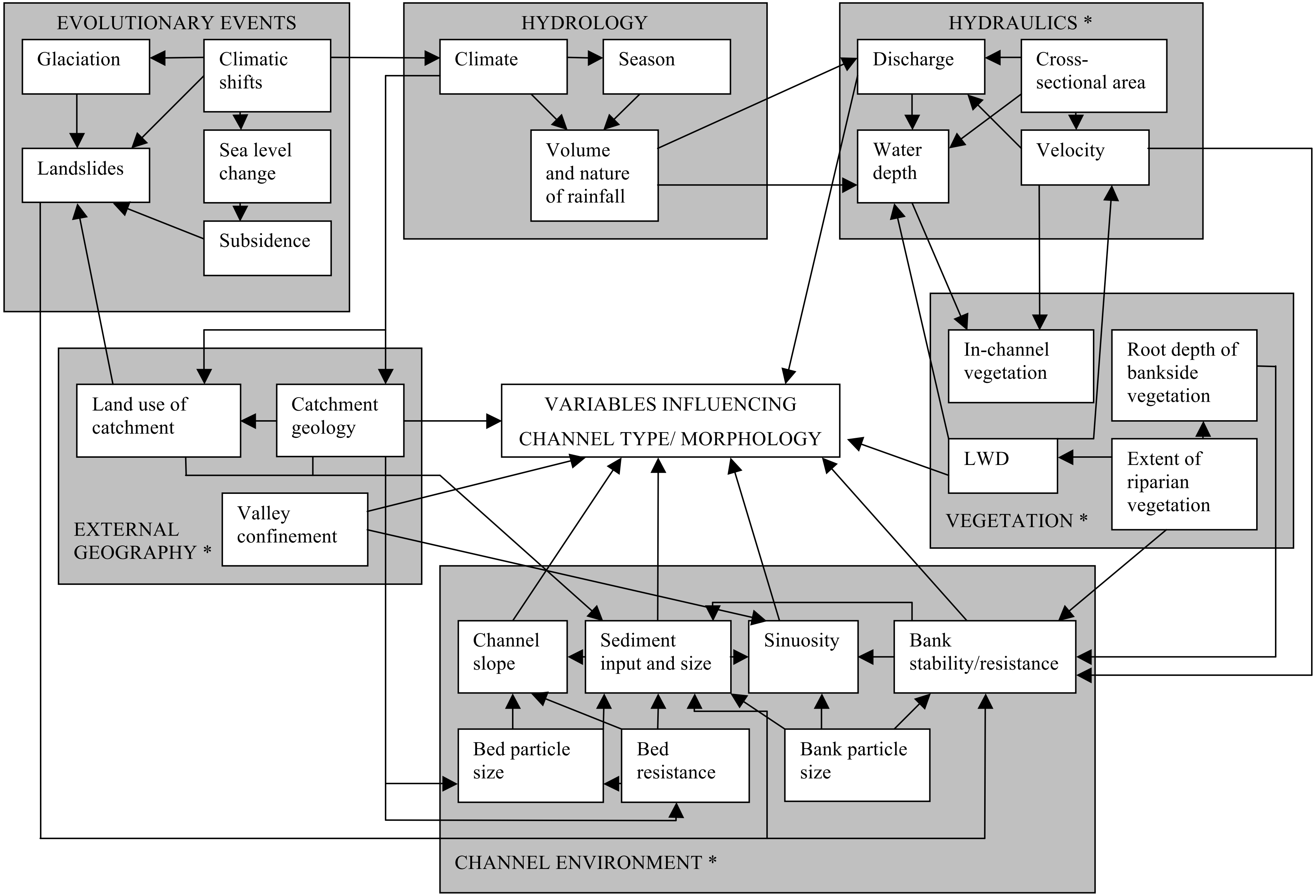
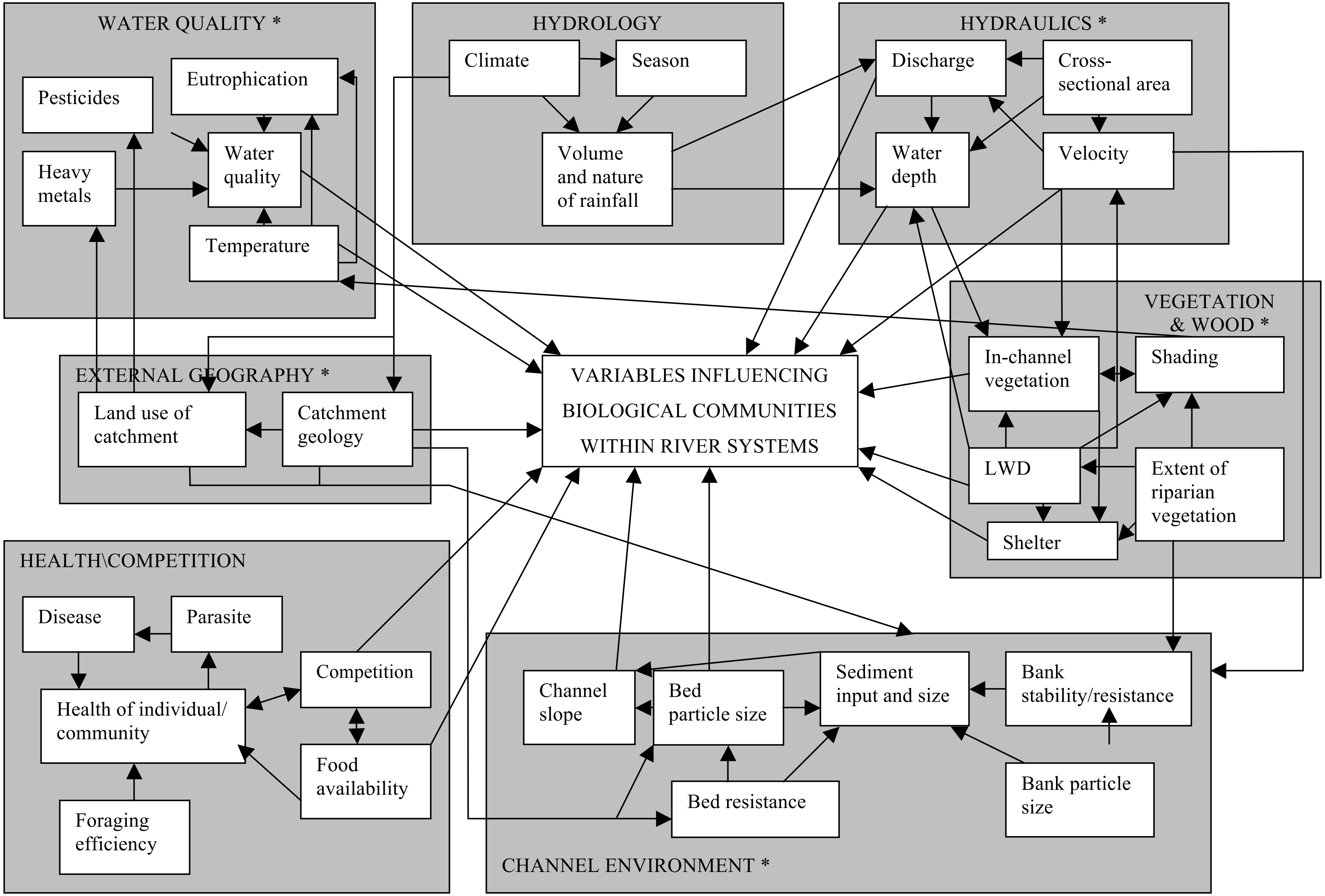


Figure 1-2: Number of articles using the terms ecohydrology, eco-hydrology, hydroecology and hydro-ecology since 1991.

Within the context of this thesis, the links between fluvial geomorphology, hydrology and ecology is shown in conceptual form in Figure 1-3.



a) Abiotic variables affecting channel morphology.



b) Abiotic and biotic variables influencing biological communities within river systems.

Figure 1-3: A conceptual model of the a) abiotic variables affecting channel morphology, and b) the abiotic and biotic variables influencing biological communities, used as framework within which this research was conducted. The thesis only focuses on a number of boxes, which are highlighted by an asterisk.

The links between fluvial geomorphology, hydrology and ecology, and the ecological importance of hydromorphology has been reinforced by the European Union's Water Framework Directive (EU WFD). The EU's WFD (formally known as 'Establishing a framework for the community action in the field of water policy 2000/60/EC') was implemented across the European Union on 22 December 2000 (European Commission, 2000). The legislation is partly a response to the recognition of the type and scale of harmful impacts to river systems (as mentioned above), combined with changes in environmental attitude and practice.

The Directive provides a framework to protect inland surface waters, transitional waters, coastal water, groundwaters and wetlands (Logan and Furse, 2002), and stipulates that Member States must achieve 'good ecological status' in these waters by 2015. Implicit within the Directive is an emphasis on Member States to develop efficient and effective surveillance and monitoring programmes to assess, police and sustain or improve these waters to good ecological status, with regard to fluvial geomorphology. The Scottish Environment Protection Agency (SEPA) and the Environment Agency (EA) have developed a risk based assessment tool termed the Morphological Impact Assessment System (MImAS) to predict the impacts from engineering activities on channel morphology. The tool will help to underpin restoration strategies and assist with biological classification. There is also the need to assess the biological significance and sensitivity of river typing differentiation and presence.

A geomorphic channel typology supports the MImAS tool. The channel typology is a modified version of the process-based typology developed by Montgomery and Buffington (1997) in the Pacific Northwest, USA (see Chapter 2, section 2.4.2 for a detailed description of the Montgomery and Buffington (1997) typology). Additional channel types have been added to include lowland environments, characteristic of the UK. The underlying principle of the typology is that channel types occur in areas with differing sets of geomorphological controls. The typology comprises eleven distinct channel types (Table 1-1), which have been reduced to six main channel types (A-F) based on geomorphic resistance and resilience to change (Table 1-2; Greig *et al*. 2006). The allocation of a reach to the correct parent channel type is critical to the accuracy of the tool, and in assessing the impact of engineering activities on the ecological status of rivers. Hence, testing of the channel typology (hereafter referred to as the SEPA typology) is needed to ensure the tool's success.

Channel type	Geomorphic Description
Bedrock channels	Most commonly found in upland areas, and are dominated by a bedrock substrate. Generally contain little, if any, bed sediment and have limited hydraulic connection with the riparian zone. Channel gradients tend to be high, resulting in a high transport capacity but limited sediment supply.
Cascades	Are restricted to upland areas with steep slopes and are characterised by disorganised bed material typically consisting of cobbles and boulders constrained by confining valley walls. The riparian zone is usually extremely small in extent. The large size of bed material, high levels of energy dissipation due to the bed roughness, dictate that the bed only becomes mobile in extreme floods (ca. >25 year return interval). Bedrock outcrops are common, and small pools may be present among the boulders.
Step-pool channels	Step-pool channels have a steep gradient and consist of large boulder clasts which form discrete sediment accumulations across the channel, forming a series of "steps" which are separated by intervening pools containing finer sediment. The stepped channel morphology results in zones of turbulence interspersed by more tranquil flows. High channel roughness and large bed material results in stable channels that respond only to very large flood events. The stream is generally confined by the valley sides.
Plane-bed channels	Generally moderate gradient streams with relatively featureless gravel/cobble beds, but include units ranging from glides, riffles and rapids. Sediment size and channel gradients are smaller than step-pool channels and deeper pool sections tend to be lacking. The river bed is generally armoured and, thus, mobilized in larger floods. Although channels are typically stable, they are more prone to channel change than any of the preceding channel types. Thus, with relatively more frequent bedload movement, they represent transitional channels between the more stable types listed above and the following more dynamic types of channel. Channels are generally straight and may be confined or unconfined by the valley sides.
Pool-riffle channels	Meandering and unconfined channels that are characterised by lateral oscillating sequences of bars, pools and riffles during low flow, resulting from oscillations in hydraulic conditions from convergent (erosive) to divergent (depositional) flow environments. The gradient of such channels is low-moderate and the width depth ratio high. The bed is predominantly gravel, with occasional patches of cobbles and sand. Accumulation of sediments in gravel bars indicates increasingly transport-limited conditions, though most large floods will produce some bedload movement on an annual basis, thus reducing the stability of the channel The banks are typically resistant to erosion, and lateral migration of the channel is limited, resulting in relatively narrow and intermittently deep channels.
Plane-riffle channels	Plane-riffle channels form an intermediate channel form between plane-bed and pool-riffle channels. They retain many of the attributes of pool-riffle channels, however, they generally have less defined pools, coarser (armoured) substrate and less extensive bar features.
Braided channels	Braided reaches are characterised by relatively high gradients (but ones that are less than upstream reaches) and/or abundant bedload. Sediment transport is usually limited under most conditions and the channel splits into a number of threads around instream bars. Poor bank strength renders them highly dynamic and channels will generally change even in relatively small flood events.
Wandering channel	These reaches exhibit characteristics of braided and meandering channels simultaneously, or if studies over a number of years, display a switching between divided and undivided channel types. Wandering channels may also be susceptible to channel avulsions during high flow events, where the channel switches to a historical planform. Wandering channels typically occur where a reduction of bed material size and channel slope is combined with a widening of the valley floor.
Low gradient actively meandering	Are unconfined low-gradient meandering channels with a bedload dominated by sand and fine gravel. Hence, the channel bed has marked fine sediment accumulations that are mobile in most flood events. These occur in higher order (i.e. typically lowland settings). The fine bed sediment erodible banks and unconfined settings means that such channels are dynamic and prone to change, they also often have extensive riparian zones and floodplains which are linked to the channel. Bars and pools may be present, and are associated with bends and crossing of the meander pattern.
Groundwater dominated channels	Groundwater-dominated rivers are low gradient channels, which are characterised by a stable flow regime; although limestone rivers with cave systems may display hydrological characteristics similar to freshet rivers. This stable regime is a product of the pervious catchment geology, and consequent reduction in overland flow that characterises groundwater-dominated streams. Bed movement is infrequent and sediments are predominantly transported in suspension. As bed disturbance is infrequent, deposited sediments may remain in the gravel for extended periods, promoting the accumulation of large quantities of fine sediment. Substrate generally comprises gravels, pebbles and sands, and glides and runs are the dominant flow types.
Low gradient passively meandering	These channels are typically found at lower extremities of the channel system. Generally they flow through resistant alluvium. They are typically 'fixed' in there planform geometry, which is sinuous. These channels are often incised and display low width depth ratios. The beds typically comprise fine sedimentary materials, although pockets of gravel can be present. These channels are typically deep and flows are dominated by glides, although runs may be associated with meander bends.

Table 1-1: Geomorphic summary of channel types in the SEPA typology (modified from Greig *et al.* 2006).

Resistance/resilience classes	*Channel types*	*Terminology*
High resistance (bed and bank) Low resilience (bed and bank)	Bedrock, Cascade	A
High resistance (bank) medium resistance bed Low resilience (bank) low resilience bed	Step-Pool, Plane bed	B
Medium resistance (bed and banks) Low resilience (bed and banks)	Low gradient passive meandering	F
Low resistance (bed and bank) medium resilience (bed and bank)	Plane-riffle, Pool-riffle, Braided, Wandering	C
Medium resistance (bank) low resistance (bed) Low resilience (bed and banks)	Groundwater dominant (Chalk)	E
Low resistance (bed and bank) Low resilience (bed and bank)	Low gradient active meandering	D

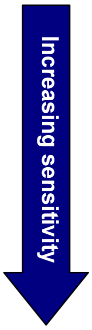


Table 1-2: Grouping of channel types based on resistance and resilience to change of channel boundary conditions (bed and bank) (reproduced from Greig *et al*. 2006).

The SEPA typology has received very limited field testing on three rivers in Scotland (Centre for River Ecosystem Science (CRESS), 2006). A study by CRESS (2006) used several physical variables: valley slope, sinuosity, valley width and geology to discriminate the channel types in the typology. However, the findings of the study found substantial overlap in the physical characteristics of the different channel types. Further work is therefore needed to identify if there are variables that can clearly discriminate channel types, and testing of the overall geomorphic validity of the typology is required. As stated earlier, there is a need to understand the biological relevance of geomorphic types present.

1.2 Thesis aims

The overarching aim of this thesis is to assess the performance of morphologically based river typing in Scotland using a geomorphological and ecological approach. Additionally, the work will assess whether the application of river typing within a scientific framework can improve our understanding of the links between fluvial geomorphology and aquatic biodiversity. This overarching aim is divided into four main sub-aims. Each sub-aim is associated with several hypotheses that are inherent within each result chapter. These four main sub-aims are listed below:

a) To determine the usefulness of catchment drivers to produce a functional, geomorphic typology.

b) To identify if physical habitat characteristics can generate a functional, geomorphic typology.

c) To determine whether geomorphic types harbour distinct invertebrate faunas, and to verify whether catchment drivers, physical habitat or physico-chemical variables are important determinants of community structure.

d) To assess variants in the professional judgement of geomorphologically based channel types.

1.3 Thesis Structure

The thesis consists of seven chapters, including this introductory chapter. Chapter 2 comprises a review of literature in this field, four results chapters address the main aims as stated above, and finally a conclusions chapter summarises the overall findings of the research project.

Chapter 2 begins with an introduction to the classification of river systems. The basis, objectives and theoretical principles underpinning river classifications are discussed. Major geomorphic and biotic classifications are reviewed. The links and interactions between fluvial geomorphology and biological communities are then examined, in relation to classification systems.

Chapters 3 to 6 present the results of this research. At the start of each chapter, the sampling design, equipment, methodological approach, and the datasets used are described, followed by a section on the data analysis employed. Chapters 3 to 5 explore the characterisation of river systems at a variety of spatial scales. In Chapter 3, catchment drivers derived from GIS and map based procedures are used to discriminate channel types. Chapter 4 examines the effectiveness of using physical habitat traits measured at the reach scale to classify channel types. Chapter 5 assesses the effectiveness of identifying channel types based on macroinvertebrate fauna. This chapter also examines whether channel types within geomorphic types based on catchment drivers and physical habitat characteristics have a distinct macroinvertebrate fauna. Finally, the chapter examines if catchment drivers, physical habitat characteristics or physico-chemical variables are the dominant influences on macroinvertebrate fauna. Chapter 6 investigates the perception of channel types across different disciplines, varying levels of involvement in river classification systems, and different geographic regions.

The final chapter, Chapter 7 examines and discusses the key findings. The overall success of classifying channels into types based on catchment drivers, physical habitat characteristics, and on macroinvertebrate fauna is discussed. The chapter also comments on the implications of the research to the scientific community, and also presents guidance and recommendations regarding channel typing to organisations charged with the management and protection of water courses, such as the Scottish Environment

Protection Agency (SEPA). The chapter finishes with final conclusions and recommendations relating to the aims and hypotheses of the research.

2 Geomorphic and biotic approaches to river classification

2.1 Introduction

This chapter reviews the scientific literature that supports the research presented in this thesis. The chapter starts with an introduction to classification: the basis, objectives and theoretical principles underpinning classifications. Major geomorphic and biotic classifications are reviewed. Links between fluvial geomorphology and biological communities are then assessed, in relation to classification systems. The literature review stresses the importance of adopting a multidisciplinary approach to study the typing of channel morphology and implications for biological communities. Finally, the chapter concludes by identifying priorities for further research on the subject of river typing.

2.2 Basis and application of classifications

2.2.1 What is classification?

Classification is a process of ordering objects or environmental variables into groups based on shared characteristics or traits (Newson *et al.* 1998). Classification allows objects or environmental variables to be listed and placed into different groups. If a group of objects or variables can be split into smaller subgroups; and these subgroups can be recognised from similar characteristics and behaviour patterns, then a series of characteristics can be attributed to the object. This procedure may permit prediction of the behaviour of a river under different conditions (Kondolf, 1995).

Newson *et al.* (1998) recognise that classification involves three different steps: taxonomy, typology and allocation (Figure 2-1). Taxonomy is an objective procedure consisting of ordering objects into classes based on their measured characteristics, whereas a typology is a subjective, judgemental process of identifying different classes (Newson *et al.* 1998). Taxonomists have referred to these two processes as *natural* and *special* classifications (Sneath and Snokal, 1973). The classification of animals into species is regarded as a natural classification. However, river classifications founded on typologies are more common, such as the River Continuum Concept (RCC) by Vannote *et al.* (1980) and the Montgomery and Buffington (1997, 1998) typology developed for mountain drainage basins in the Pacific Northwest, USA (see section 2.4.2 and Figure 2-7).

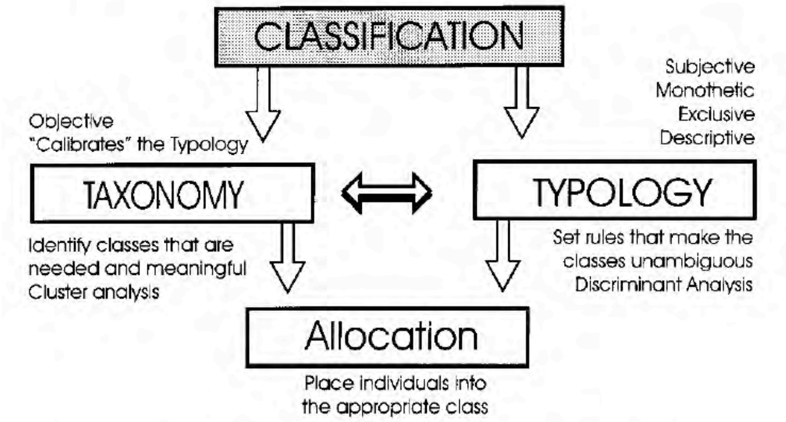


Figure 2-1: The properties and processes of classification (reproduced from Newson *et al.* 1998).

2.2.2 Objectives of classifications

A main goal of classification systems is to organise, simplify and understand the natural forms and processes within environmental systems (Juracek and Fitzpatrick, 2003). In the context of rivers, this information would aid river scientists to predict a river's behaviour from its appearance (Rosgen, 1994), and contribute to recommendations regarding channel maintenance, and conservation and restoration issues. Another primary objective of classification systems is to improve communication between disciplines by standardising terminology, and avoid using jargon such as alpha-numeric codes to define stream classes (Swanson, 1989; National Research Council, 1992).

Montgomery and Buffington (1997) believe a typology should be applicable on more than a regional scale, be adaptable to regional variability, and be based on channel morphologies that results from channel processes. In addition, typologies ought to encompass the whole channel network rather than focus on sections of channels harbouring desirable organisms or indicator species (Montgomery and Buffington, 1997), be low cost to implement (Naiman *et al.* 1992), and provide a reproducible framework of communication for river managers and professionals across disciplines (Rosgen, 1994).

2.3 Controlling factors on channel morphology and geomorphic thresholds in river systems

An underlying principle of geomorphic classification systems is that channel types are the product of varying combinations of geomorphological controls (Church, 2002). The premise of classification is that channel morphology is the dependent variable resulting from a combination of independent variables (Kellerhals *et al.* 1976; Kellerhals and Church, 1989; Thorne, 1997; Eaton *et al.* 2004). The main independent variables influencing channel morphology are the volume and timing of water from upstream, the volume, timing and character of sediment delivered to the channel, the nature of the materials through which the river flows, geological history, and the topography of the landscape (Church, 1992). Secondary variables influencing channel morphology are local climate, such as a prolonged freezing during winter (Kellerhals *et al*. 1976), and riparian land use (Church, 1992). A significant change in one or more of these independent variables may cause a series of channel adjustments, which may cause an adjustment in channel morphology (Rosgen, 1994). For example, a landslide or removal of riparian vegetation and subsequent bank erosion may considerably increase sediment input into a river system; the additional sediment and resultant deposition may cause a change in channel morphology at the site or downstream. River morphology is therefore, influenced by a range of interacting independent variables. The interactions between sediment supply and transport capacity throughout a stream network are particularly important in determining channel morphology. The amount of water supply at any given point in the stream network depends on drainage basin size, with a near linear increase in stream discharge with drainage area (Robert, 2003). As drainage area increases, bed material size usually systematically decreases, with changes in channel properties and a rise in sediment storage (Church, 1992; Robert, 2003; Figure 2-2). The reduction in channel gradient and particle size, increases in channel size and sediment storage, and a slow steady increase in average channel velocity signify the complex interactions between several independent variables on channel morphology (Church, 1992; Knighton, 1998).

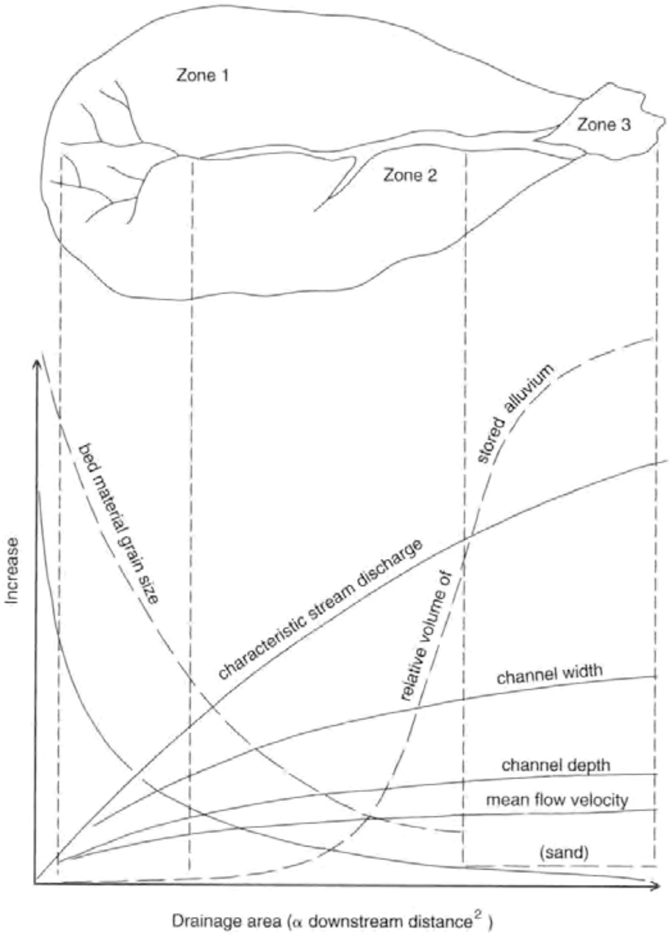


Figure 2-2: Schematic representation of the variation in channel properties through a drainage basin (based on a concept of Schumm, 1977; reproduced from Church, 1992).

The dominant variables affecting channel morphology can be expressed in a simplistic way by a qualitative relation by Lane (1955):

$$Q_s/Q \sim S/D$$

where Q_s is sediment transport, Q is streamflow (so Q_s/Q represents sediment concentration), S is channel gradient and D denotes sediment calibre. A rearrangement of the expression to:

$$Q_s \sim QS/D$$

indicates that sediment transport directly corresponds to stream power (represented by QS), and is inversely related to the calibre of the sediment (Church, 2002). This expression stresses that the capacity of a stream to transport its sediment load, and the competence of a stream to move particles of different sizes creates distinctive conditions (Church, 2002). The size of particles will affect the ability of a stream to transport its load, and this depends upon what material enters the stream system. The interaction of these variables creates individual channel morphologies by transporting, sorting and storing sediment in different ways (Figure 2-3). The physical processes associated with a stream's transport capacity relative to sediment supply create different thresholds in channels.

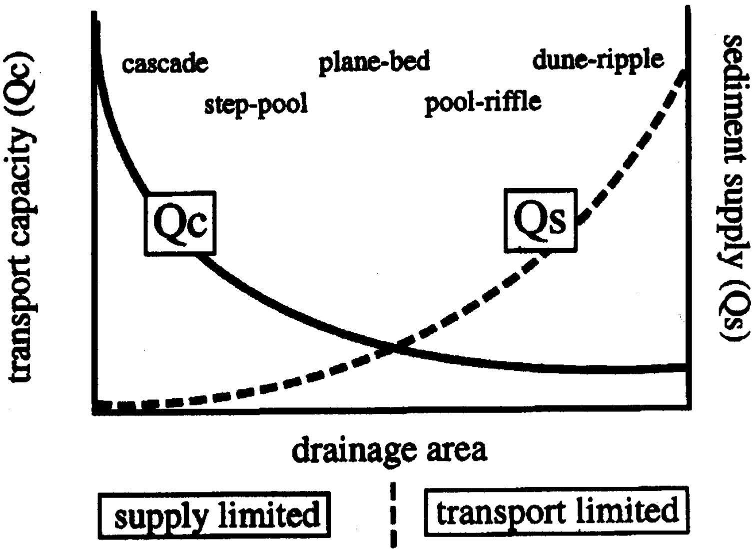


Figure 2-3: Schematic representation of the transport capacities relative to sediment supply conditions for different channel types (reproduced from Montgomery and Buffington, 1997).

Church (2002) argues that these thresholds or boundaries between channel types can be identified if the sediment size distribution of the bed and bank material, the forces generated by the combination of channel slope, discharge regime, and flow resistance of the channel are known. Thresholds imply a sharp break between channel types (e.g. between meandering, straight and braided, Leopold and Wolman, 1957), but this transition may be gradual in the field. Additionally, thresholds may change position in a channel as a result of differing trends of sedimentation prompted by tectonics, climate change or human activity (Church, 2002). The sensitivity and behaviour of a channel is an important process response trait of these channel types, but is rarely included within river classifications.

Traditionally, most classification systems have distinct boundaries identifying channel types or rules for placing objects into classes. For example, a channel type or object is definitely a member or not a member of a channel type or class. In this classical view, no members are more representative of a channel type or class than are its other members (Goodwin, 1998). However, this classical view in regard to river classifications does not represent all situations in aquatic systems. Zadeh (1965) suggested the use of fuzzy set theory as a new branch of mathematics to help analyse complex biological systems. Fuzzy set theory offers a more flexible approach where a membership function can be implemented to relate the degree of membership, μA, of a particular value to a set. A value of μA can range from 0 to 1, with 0 denoting non-membership and 1 indicating definite membership (Openshaw, 1996). Openshaw (1996) advocated the advantages of fuzzy modelling over the classical view of science from Klir and Yuan (1995) as:

- Offering a method of portraying irreducible observation and measurement in uncertainties in whatever form they appear.
- Providing better resources for managing complexity. Fuzzy models increase their superiority with greater complexity in the system.

- Displaying more expressive power, and being able to manage a greater range of problems and having the ability of dealing in mathematical terms with problems that need the use of natural language.
- Possessing an aptitude of capturing human commonsense and reasoning, so that this cognition and intuition can be included rather than excluded from computer programmes.

Fuzzy modelling has been used in river restoration projects by being incorporated into an ecohabitat suitability model similar to PHABSIM (Physical HABitat SIMulation; Schneider and Jorde, 2003). The model was created using fuzzy logic as an alternative to traditional habitat suitability curves (Schneider and Jorde, 2003). The researchers believed that fuzzy modelling yields better results compared to the traditional habitat suitability curve-based models. The approach has also been applied to assess the habitat suitability requirements for many macroinvertebrate (Van Broekhoven *et al*., 2006) and fish species (Wang and Xia, 2008).

2.4 A review of geomorphic classification systems

A large number of classifications and typologies have been developed in fluvial geomorphology since the late 20th Century (Figure 2-4 and Table 2-1). The numerous approaches to classifications and typologies reflect the wide range of disciplines, the large number and variety of variables used, different objectives for which the systems were designed, and the challenge of simplifying complex, diverse, natural systems (Kondolf, 1995). This review aims to provide a broad overview of prominent classifications and typologies (recent summaries of classification efforts are given in Goodwin, 1998 and Kondolf *et al.* 2003).

Early classification systems used philosophical notions derived from evolutionary theory to classify rivers. The geographic cycle of Davis (1899) classifies landscapes and rivers according to the relative stage of adjustment in an evolutionary cycle of youthful, mature and old. Subsequent classification systems have been founded on the identification of channel pattern by trained geomorphologists (Kondolf, 1995), and recent classifications and typologies are often process based that incorporate combinations of sediment transport and discharge regimes, and also slope and valley characteristics, bed material or mobility, and position within the channel network.

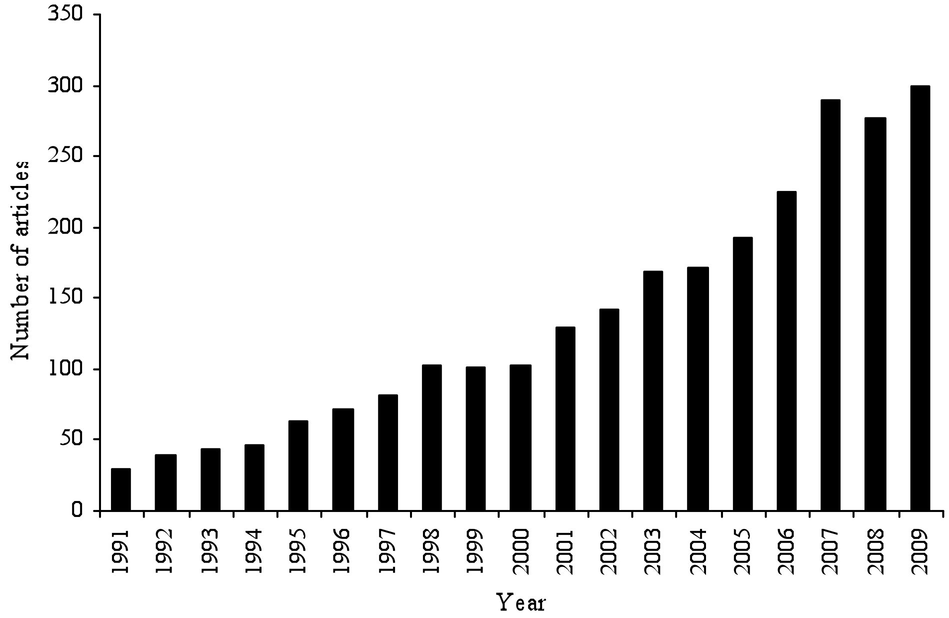


Figure 2-4: Number of articles using the terms river classification and river typology since 1991.

	Geographical unit (geology, climate)	Valley or valley bottom morphology	Channel pattern, sinuosity	Channel morphology	Channel dimensions	Gradient	Stream power	Substrate size	Sediment load (type and/or intensity)	Transport capacity to sediment supply	Morphodynamic units	Morphodynamic adjustments	Instream features	Bankside features	Stream order/ Network position	Altitude	Landuse	Number of variables used
Leopold and Wolman (1957)			●															1
Rust (1978)			●															1
Lotspeich (1980)	●																	1
Cloots and Maire (1980)	●	●	●	●														4
Ferguson (1981)			●				●											2
Maire and Wilms (1984)		●	●	●		●		●				●						6
Brussock *et al*. (1985)	●																	1
Frissel *et al*. (1986)	●	●	●	●		●		●	●		●	●						9
Cupp (1989a,b)		●	●															2
Otto (1991)		●	●			●												3
Nanson and Croke (1992)		●	●	●			●	●	●			●						7
National Rivers Authority (1992)					●								●	●			●	4
Corbonnois and Zumstein (1994)	●	●				●												3
Downs (1994, 1995)	●					●						●						3
Rosgen (1994, 1996)		●	●	●		●		●										5
Petit (1995)			●				●											2
Nanson and Knighton (1996)	●	●	●	●		●	●	●	●			●						9
Bethemont *et al*. (1996)	●			●		●	●	●										5
Bernot *et al*. (1996)	●	●	●	●		●	●	●										7
Montgomery and Buffington (1997)				●			●		●									3
Newson (1997)	●			●	●	●					●					●		6
Boon *et al*. (1997, 1998)	●			●	●	●					●					●		6
Alabyan and Chalov (1998)		●	●	●														3
Brierley and Fryirs (2000)		●	●	●		●		●					●					6
Snelder and Biggs (2002, 2005)	●	●				●	●								●		●	6
Schmitt *et al*. (2007)		●	●		●	●	●	●				●	●		●	●		10
Ferréol *et al*. (2008)	●				●										●	●		4
Orr *et al*. (2008)		●					●								●			3

Table 2-1: Range of variables used in geomorphic classification systems and typologies (modified and updated from Kondolf *et al.* 2003).

2.4.1 Process-based classifications

Leopold and Wolman (1957) developed a classification characterising broad differences in channel patterns and processes. The classification distinguished straight, meandering and braided channel patterns based on relationships between slope and discharge. This pattern based approach was later expanded to include anastomosing channels (Smith and Smith, 1980; Knighton and Nanson, 1993; Makaske, 2001), and also anabranching channels (Nanson and Knighton, 1996). Lane (1957) used quantitative slope-discharge relationships to define braided, intermediate and meandering channels. A classification based on channel stability (stable, eroding or depositing) and on the dominance of sediment transport (mixed load, suspended load or bedload) was developed by Schumm (1963) for alluvial channels.

In Canada, Kellerhals *et al.* (1972, 1976), Galay *et al.* (1973) and Mollard (1973) have proposed descriptive classification systems for describing a wide range of stream morphologies. The Kellerhals *et al.* (1972, 1976) classification uses a combination of channel patterns, channel islands, bars, and degree of lateral activity to define a variety of channel types (Figure 2-5). Kellerhals and Church (1989) believe classifying rivers based on the appearance of the channel and the floodplain is justified, as these characteristics reflect presently active processes that govern channel morphology. The combined work of these Canadian studies provides excellent description and interpretation of fluvial features, and offers one of the most detailed and comprehensive lists of channel and valley features (Rosgen, 1994).

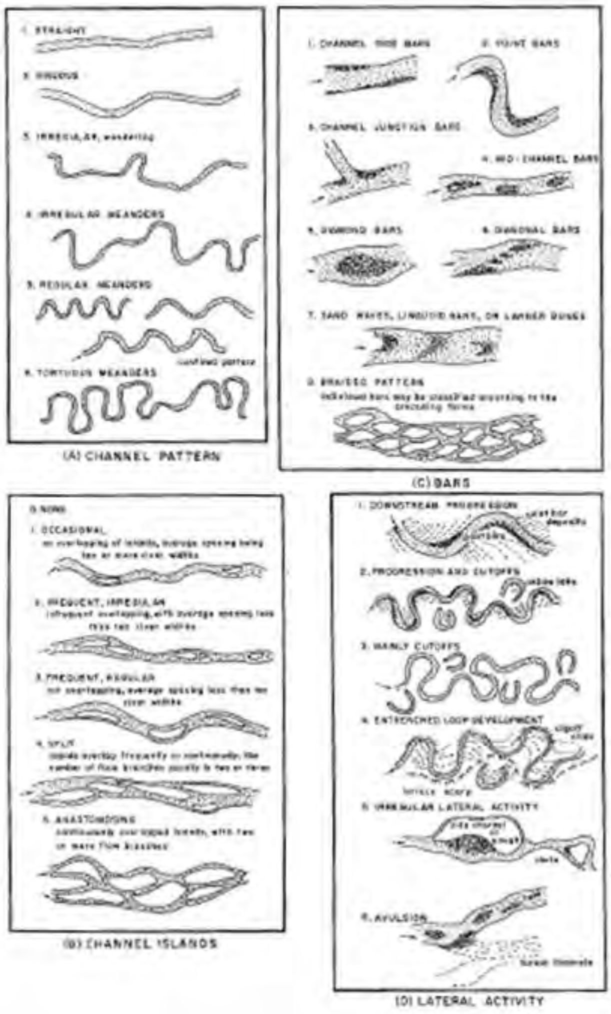


Figure 2-5: Classification of planform features of river channels (reproduced from Kellerhals *et al*. 1976, and modified by Kellerhals and Church, 1989).

Other classifiers have used scale to identify river systems. Church (1992) presented a channel classification using channel size and sediment size. The classification is based on the ratio of flow depth (*d*) to a grain size index (*D*), typically the median size of the bed material (Church, 1992). The classification defines three types of alluvial channel based on the ratio of *d/D*. Small channels are identified as having a *d/D* <1, where the relative roughness is large and a single clast can comprise major elements of channel form (Plate 2-1a). The morphology of the bed frequently consists of a series of steps, pools and cascades. Intermediate channels possess a *d/D* between 1 and 10 (the depth can potentially be 10 times larger than the bed material size) (Church, 1992). Intermediate channels tend to occur on channel gradients between 0.1 and 1 per cent, and contain repeating pool-riffle sequences (Plate 2-1b). The final category, large channels possess a *d/D* ratio of >10 (Plate 2-1c). This type of river is commonly meandering or braiding, with the pattern dependent on the interactions of sediment supply (calibre and volume), discharge, channel gradient and bank stability (Church, 1992; Knighton, 1998).

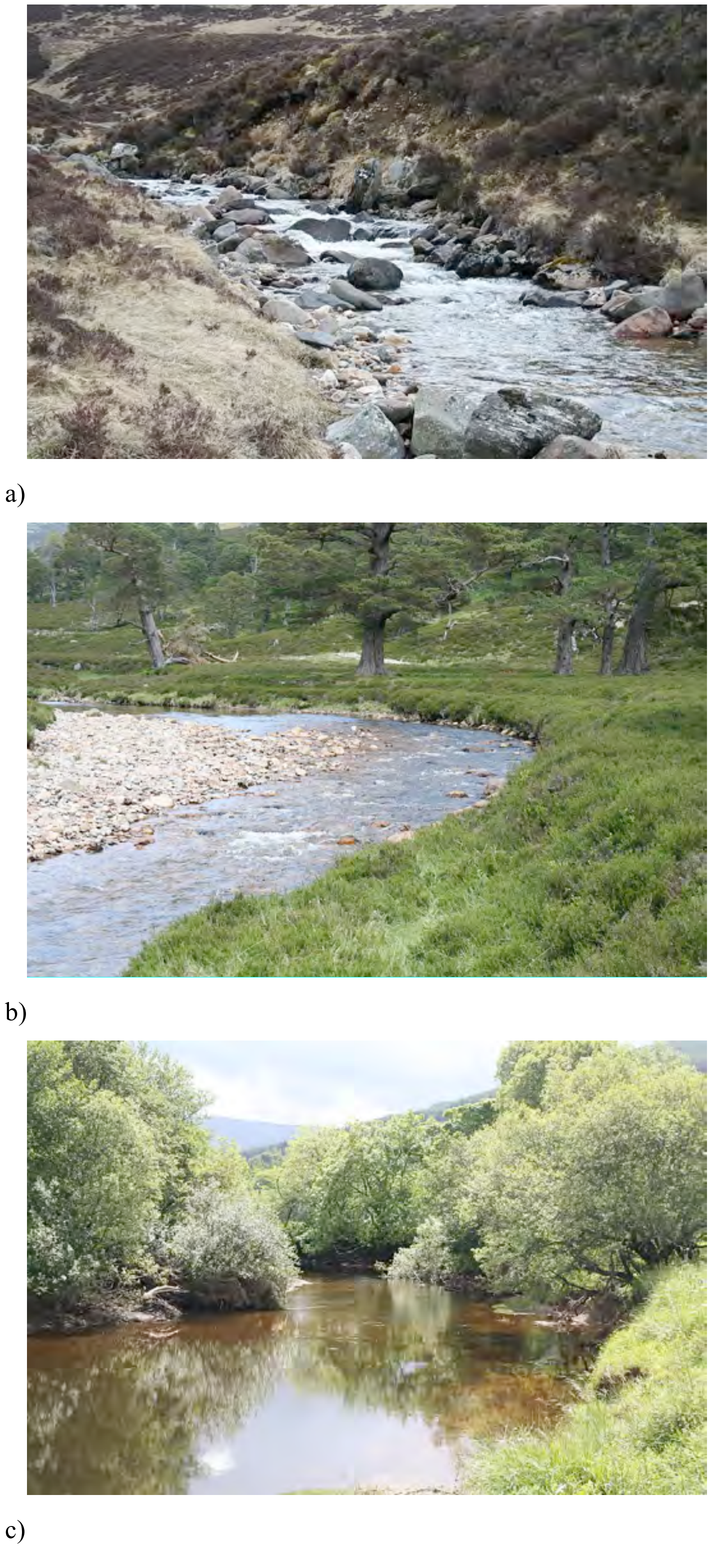


Plate 2-1: Examples of alluvial channel types in Church's (1992) classification in a Scottish context: a) The Allt a'Ghlinne Bhig - a small channel (d/D <1), b) The Derry Burn - an intermediate channel (1 < d/D <10), and c) The River Balvag - a large channel (d/D >10).

2.4.2 Hierarchical-based classifications

Classification systems incorporating a hierarchical framework that link large regional scales (catchments) to small microhabitat scales are becoming increasingly common (Naiman *et al*. 1992). The approach addresses different variables affecting channel morphology over a range of spatial and temporal scales (Frissell *et al*. 1986; Van Niekerk *et al*. 1995). Hierarchical classifications consist of interlocking spatial units whereby the variability of each smaller hierarchical unit is restricted by that of the higher hierarchical level (Kondolf *et al.* 2003). The first hierarchical level often identifies streams within a given physiographic region with similar lithology, precipitation and vegetation properties (e.g. the R.Dee). Subsequent hierarchical levels are constrained by that of the higher hierarchical level (Kondolf *et al.* 2003), and allow further subdivision of stream classes based on progressively smaller features.

An early hierarchical classification was proposed by Warren (1979). The classification comprised 11 levels ranging from a regional scale (>10km²) to a microhabitat scale (<1m²) based on climate, substrate, water chemistry, biota, and culture. Although the classification was not robust, the principles supporting the classification provided a valuable contribution to stream classification theory through the development of a theoretical structure for a complex hierarchical system (Naiman *et al.* 1992). The classification emphasised the significance of assessing the potential of a stream rather than its existing condition. Assessing potential conditions for stream systems helps determine natural changes from anthropogenic disturbances (Naiman, *et al.* 1992). Frissell *et al.* (1986) extended Warren's classification by including spatially nested levels of resolution, such as the watershed, valley segment, reach, pool/riffle, and microhabitat (Figure 2-6). At each level in the hierarchy, systems develop at a specified spatial-temporal scale (Frissell *et al.* 1986). The stream classification was specifically developed for use on second and third order channels in forested mountain environments (Van Niekerk *et al.* 1995). However, this development represented an important advancement by incorporating both source and processes of development, and form and pattern within each hierarchical level (Naiman, 1998).

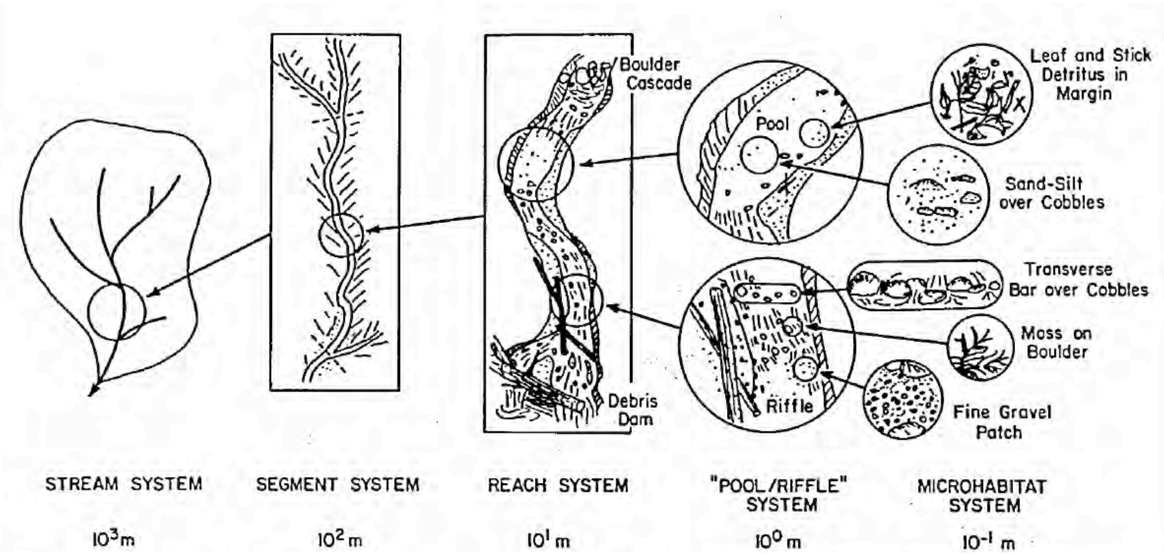


Figure 2-6: The hierarchical organisation of a stream system and its habitat subsystems (reproduced from Frissell *et al.* 1986).

A well known hierarchical model is the Montgomery and Buffington (1997, 1998) process-based, channel typology developed for use in mountain drainage basins in the Pacific Northwest of the USA. The typology addresses morphological response to the relative ratio of sediment supply to transport capacity (Figure 2-7). The typology identifies three dominant channel substrates: bedrock, alluvium and colluvium. Bedrock reaches are generally confined by valley sides and typically possess high transport capacities to sediment supply (Montgomery and Buffington, 1997). Reaches are dominated by steep slopes, and little alluvial material is stored on the valley bed and rock is the common substrate. In comparison, alluvial reaches are characterised by an array of morphologies and roughness configurations that occur on a variety of slopes, confinement settings with little, no or a well established floodplain. Five alluvial channel morphologies are identified: cascade, step-pool, plane-bed, pool-riffle, and dune ripple. Colluvial reaches constitute the final channel reach. Colluvial reaches are small headwater streams that typically flow over a colluvial valley fill substrate, and show small and periodic fluvial transport. Shallow and ephemeral flows in headwater environments have limited ability to mobilise sediment, so material from adjacent valley slopes is deposited to form significant colluvial valley fills (Montgomery and Buffington, 1997). In summary, each channel type has a characteristic channel-bed morphology. A detailed synopsis of channel features associated with each channel type is outlined in Table 2-2.

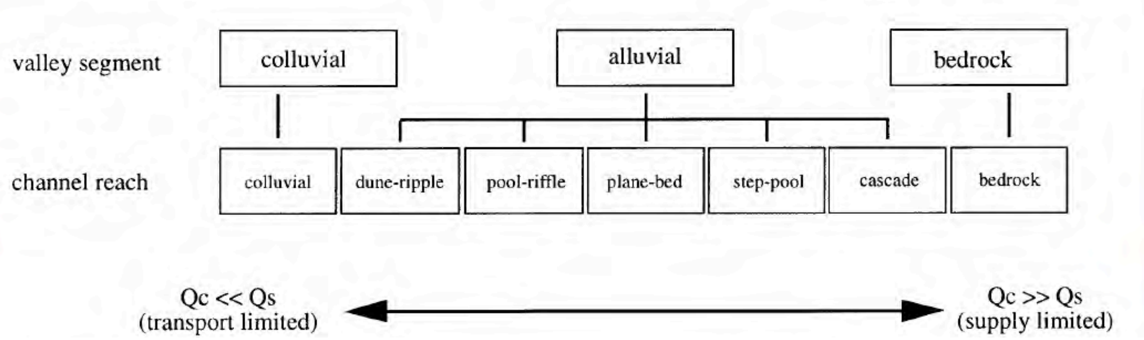


Figure 2-7: Channel types of Montgomery and Buffington shown as a function of transport capacity to relative sediment supply (reproduced from Montgomery and Buffington, 1997).

	Channel type						
	Dune ripple	Pool-riffle	Plane-bed	Step-pool	Cascade	Bedrock	Colluvial
Typical bed material	Sand	Gravel	Gravel-cobble	Cobble-boulder	Boulder	Rock	Variable
Bedform pattern	Multilayered	Laterally oscillatory	Featureless	Vertically oscillatory	Grains, banks	Irregular	Variable
Dominant roughness elements	Sinuosity, bedforms (dunes, ripples, bars) grains, banks	Bedforms (bars, pools), grains, sinuosity, banks	Grains, banks	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains
Dominant sediment sources	Fluvial, bank failure	Fluvial, bank failure, debris flows	Fluvial, bank failure, debris flows	Fluvial, bank failure, debris flows	Fluvial, bank failure, debris flows	Fluvial, bank failure, debris flows	Hillslope, debris flows
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical pool spacing (channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable	Unknown

Table 2-2: Key features of each channel reach type (modified from Montgomery and Buffington, 1997).

The concepts of process domains and litho-topographic units underpinning this typology allow for classification at much larger spatial scales than simply channel reaches (Montgomery, 1999). Process domains contain similar geomorphological processes, and thus comparable sediment transport dynamics and disturbance regimes (Kondolf *et al.* 2003). Channels within a process domain ought to have similar disturbance histories, and different process domains occur in a longitudinal sequence downslope (Figure 2-8). The theory of litho-topographic units is that areas should be identified with similar lithology and topography, and within which channels should harbour similar characteristics (Kondolf *et al.* 2003).

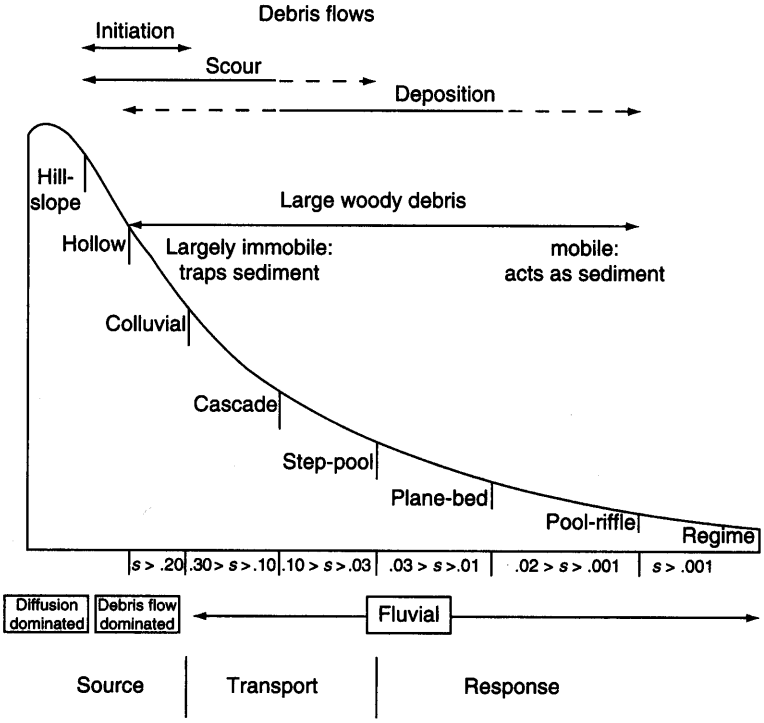
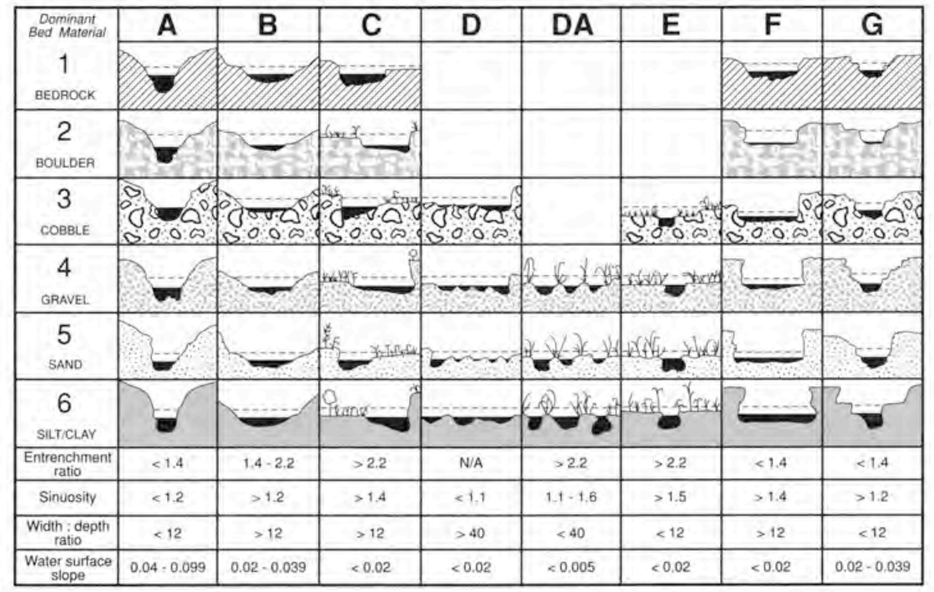


Figure 2-8: Process domains of Montgomery and Buffington (1997) arranged along a longitudinal gradient (reproduced from Montgomery and Buffington, 1997).

2.4.3 *Classifications used for management purposes*

Many classifications have been developed for management purposes in the UK (Newson *et al.* 1998), France (Schmitt *et al.* 2007), the United States (Rosgen, 1994, 1996), New Zealand (Snelder and Biggs, 2002), and Australia (Brierley and Fryirs, 2005). A well known hierarchical classification system that has gained wide implementation in the United States is the Rosgen (1985, 1994, 1996) classification system based on a morphological arrangement of stream characteristics (Figure 2-9). Rosgen's (1984) initial classification system identified 25 stream types. Later iterations of the classification extended the stream types to 94 as of 1996 (Rosgen, 1996). Stream types are defined based on four levels of progressive specificity. Level 1 identifies stream types based on entrenchment, gradient, width/depth ratios and sinuosity into seven major stream categories along the river continuum, from steep cascading channels (A), to riffles dominated with rapids (B), to low gradient pool-riffle streams (C) and braided channels (D), to low gradient pool-riffle types (E and F), and streams occupying gullies (G) (Rosgen, 1994). Within these seven main stream categories, specific sub-groups are defined by Level 2 based on the dominant bed material, from bedrock to silt and clay. The use of an alpha-numeric code, such as 'A1, A2, B1, B2' allows more sub-groups to be accommodated compared to a descriptive classification, but the alpha-numeric code system lacks a clear explicit description, such as a 'low gradient active meandering' channel (Brice, 1982). Level 3 further subdivides stream types according to the current stability, potential and function of the channel. The final subdivision, Level 4 defines the predicted stream conditions through streamflow, sediment load and further geomorphological appraisal.

The Rosgen classification (Rosgen, 1996) has been widely employed by ecologists and managers in federal, state and local government agencies in the USA as a tool to assess the physical characteristics of stream reaches and to guide restoration and rehabilitation plans (Juracek and Fitzpatrick, 2003). However, there is concern regarding the use of the Rosgen classification for assessing channel stability and predicting fluvial process and channel form (Miller and Ritter, 1996; Doyle and Harbor, 2000). Critics cite its dependence on ill-defined empirical relationships, the oversight of current equilibrium state conditions, a failure to acknowledge that a given disturbance may cause a range of geomorphic outcomes and its lack of a process-based framework (Miller and Ritter, 1996). The unwillingness of organisations outside of North America to implement the Rosgen classification implies the tool may not have universal applicability as a predictive tool for river restoration.



	A	B	C	D	DA	E	F	G
Entrenchment ratio	< 1.4	1.4 - 2.2	> 2.2	N/A	> 2.2	> 2.2	< 1.4	< 1.4
Sinuosity	< 1.2	> 1.2	> 1.4	< 1.1	1.1 - 1.6	> 1.5	> 1.4	> 1.2
Width : depth ratio	< 12	> 12	> 12	> 40	< 40	< 12	> 12	< 12
Water surface slope	0.04 - 0.099	0.02 - 0.039	< 0.02	< 0.02	< 0.005	< 0.02	< 0.02	0.02 - 0.039

Figure 2-9: Morphological stream types inherent within the Rosgen (1994) classification (reproduced from Rosgen, 1994).

In the UK, the River Habitat Survey (RHS) was developed by the Environment Agency (EA) in 1994 as a method to assess the character and habitat quality of rivers based on their physical structure (Raven *et al.* 1997, 1998b). The technique consists of four parts (i) a standard field survey method, (ii) a large computer database for entering and comparing results from surveys, (iii) a methodology for determining habitat quality, and (iv) a system for recording the extent of artificial channel modification (Raven *et al.* 1998a). Data is collected at 10 equidistant ‘spot-checks’ along a 500m length of stream or river channel (Wilkinson *et al.* 1998). Data is gathered from a combination of maps and stream gauging records (e.g. altitude, slope, geology, distance from source and mean annual flow) and field surveys (e.g. width, depth, geomorphological units and also artificial modifications such as weirs, dams, fords, bank reinforcement, and channel deepening). An important output of the RHS is the generation of a semi-natural river typology based on a subset of minimally impacted reference sites. The typology allows sites to be compared to “reference” conditions in the context of the same river type (Environment Agency, 2002). The typology is based on the principle that many key attributes at each site in the baseline survey are correlated to map-based variables, such as altitude, slope, distance to source, and height of source (Jeffers, 1998). A principal component analysis (PCA) was performed on the map-based variables relating to a surveyed site to reduce the large number of variables used to two principal components (Kondolf *et al.* 2003). The first principal component denoted an increasing gradient of altitude and slope, whereas the second principal component related to discharge and symbolised a possible “energy” gradient (Jeffers, 1998). The PCA biplot (Figure 2-10) was split into arbitrary lines across a continuum to delineate eight river types: montane, upland, lowland and coastal sites with either high or low potential energy. The four map-based variables or the scores of the two principal components enables prediction of some major habitat features (Jeffers, 1998). In the future, revisions to include more geomorphological data to aid river restoration should improve the tool further.

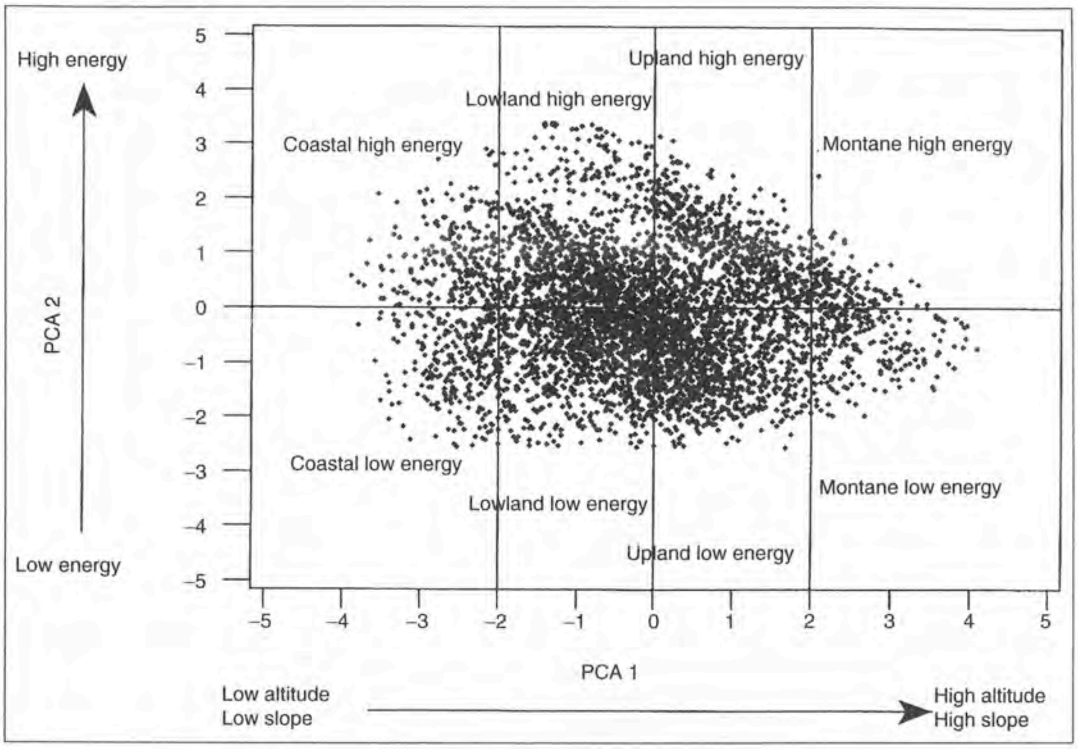


Figure 2-10: Principal Component Analysis conducted on 4569 English and Welsh sites described by their altitude, slope, distance from source and altitude of the source, depicting the semi-natural river typology of the RHS approach (reproduced from the Environment Agency, 2002).

The RHS has had extensive coverage in the UK. However, a limitation of the typology is the exclusion of a process-based approach. No process-response relationships are available, and hence, the typology has no ability to predict the future character and response of river systems. The RHS typology also does not incorporate a hierarchical framework. Therefore, processes operating at finer scales (other than the catchment scale) cannot be incorporated into the system. Furthermore, there has been no testing of the ecological relevance of the RHS typology, and links to meso-habitat features have not been established.

The River Styles framework (of Brierley and Fryirs, 2000) has been applied in many coastal catchments of New South Wales, Australia. The geomorphic approach has been used to classify channel types, evaluate the physical condition of rivers, and prioritise restoration activities (Chessman *et al.* 2006). River Styles are sections of river defined by a set of characteristics that include a degree of valley confinement, a specific channel planform and a range of geomorphic features and bed materials (Brierley and Fryirs, 2005). The River Styles approach consists of four stages (Figure 2-11). The first stage classifies all river reaches in a drainage basin based on valley confinement, channel planform, geomorphic features and prevailing bed materials. Geomorphic features comprise channel morphologies such as bedrock steps, depositional features including point bars and physical biotopes, riffles and cascades. Bed materials include a range of substrates from bedrock, boulders and cobbles to sand and silt. The second stage comprises a comparison of the geomorphic condition of a reach to a 'natural' reference condition for the relevant style (Fryirs, 2003). In stage three, the condition of a reach is assessed and positioned on a trajectory of either progressive deterioration or recovery. Where relevant the possibility for recovery is appraised. The amalgamation of these stages provides a platform for prioritising reaches for restoration, and to aid the design of structural activities where required to aid the latter (Chessman *et al.* 2006). This process constitutes the last stage of the approach. The procedure of the River Styles Framework is outlined in Figure 2-12.

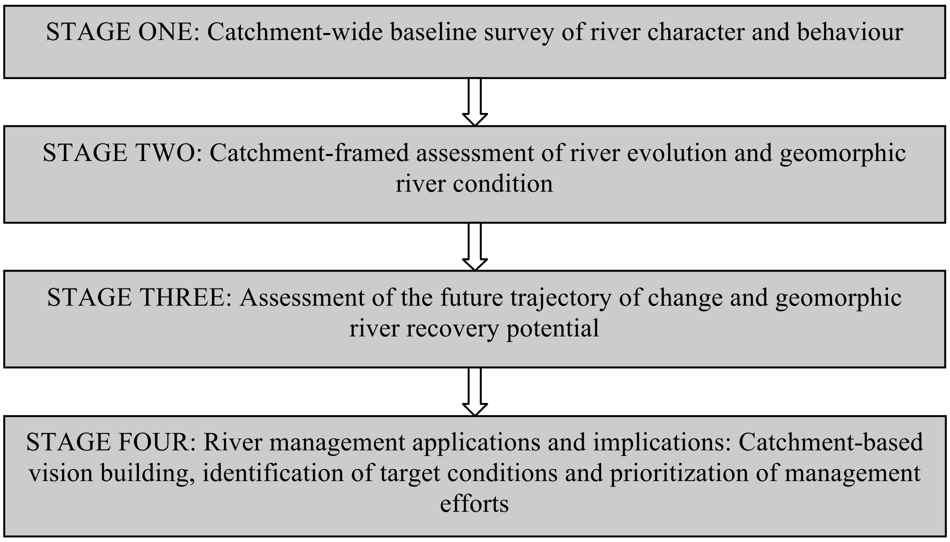


Figure 2-11: Stage of the River Styles Framework (reproduced from Brierley and Fryirs, 2005).

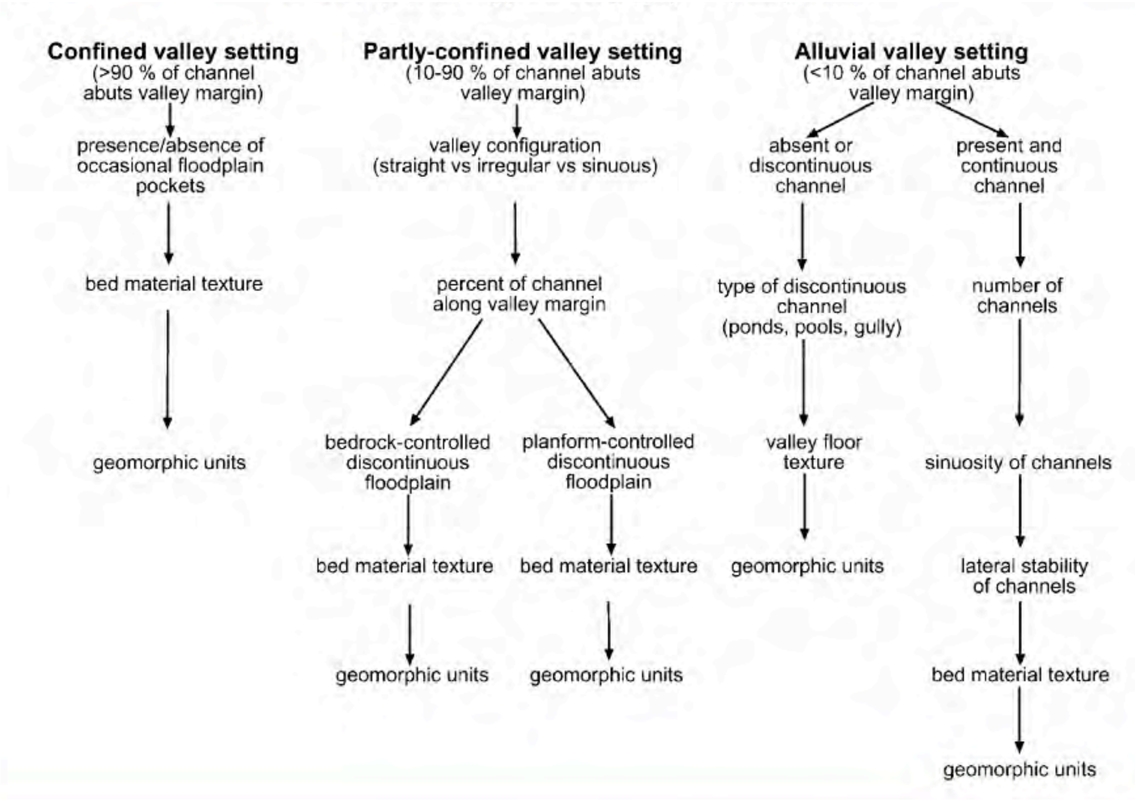


Figure 2-12: Procedure used to identify River Style (reproduced from Brierley and Fryirs, 2002).

The River Styles Framework was partly developed to address specific characteristics of the Australian landscape, such as the presence of bedrock outcrops, ancient alluvial deposits, variable relief, erratic downstream patterns and limited sediment availability, and to incorporate the effects of post colonisation anthropogenic pressures on the landscape. The typology would be unlikely to have generic application to UK river systems due in part to landscape differences and disturbance histories between the tow countries. The River Styles Framework is also likely to be very intensive for application from an operational perspective. For example, the interpretation of landscape features necessitates a high level of geomorphic experience, which is unlikely to be available. A lack of geomorphic input (i.e. understanding of how a river system operates within a valley setting) would devalue the typology and lead to erroneous errors. Implementation of the River Styles Framework also requires aerial photography and intensive field reconnaissance. In addition, there has also been limited testing of the ecological relevance of the River Styles Framework, and the approach assumes meso-habitat units are relevant to biota.

The EU WFD has resulted in a surge of typologies being developed for management purposes. Implicit within the Directive is a requirement for Member States to characterise rivers by developing a typology of river reference status (i.e. with minimal modification by human activities) (Schmitt *et al.* 2007), based on ecoregions (the zoogeographical regions of Europe according to Illies, 1978), and physical characteristics, such as altitude, size, geographical location and geology. Illies (1978) developed a directory of freshwater fauna covering the distribution and ecology of 14,457 species within Europe. The fauna distribution was classified in 25 regions, based on the major geographic and geo-political regions such as the Alps, Great Britain, and Italy (Figure 2-13 and Table 2-3). WFD guidelines have incorporated this ecoregion map of Illies (1978) into their recommendations to Member States for developing a typology. Within ecoregions, Member States can either opt for using either a fixed typology 'System A' or by adopting an alternative characterization 'System B' typology. The 'System A' typology is based upon catchment area (small 10-100km², medium 100-1000 km², large 1000-10,000 km² and very large >10,000km²), catchment geology (calcareous, siliceous and organic), and altitude (lowland <200m, mid-altitude 200-800m, and high altitude >800m; European Commission, 2000). An underlying assumption of the WFD typology is that biological communities are broadly similar at reference sites and within stream types, and thus form a type-specific biological target (Sandin and Verdonschot, 2006). Any deviation from these type-specific biological reference conditions indicates degradation in aquatic biota. Therefore, the typology is a method to record the spatial variability among watercourses.

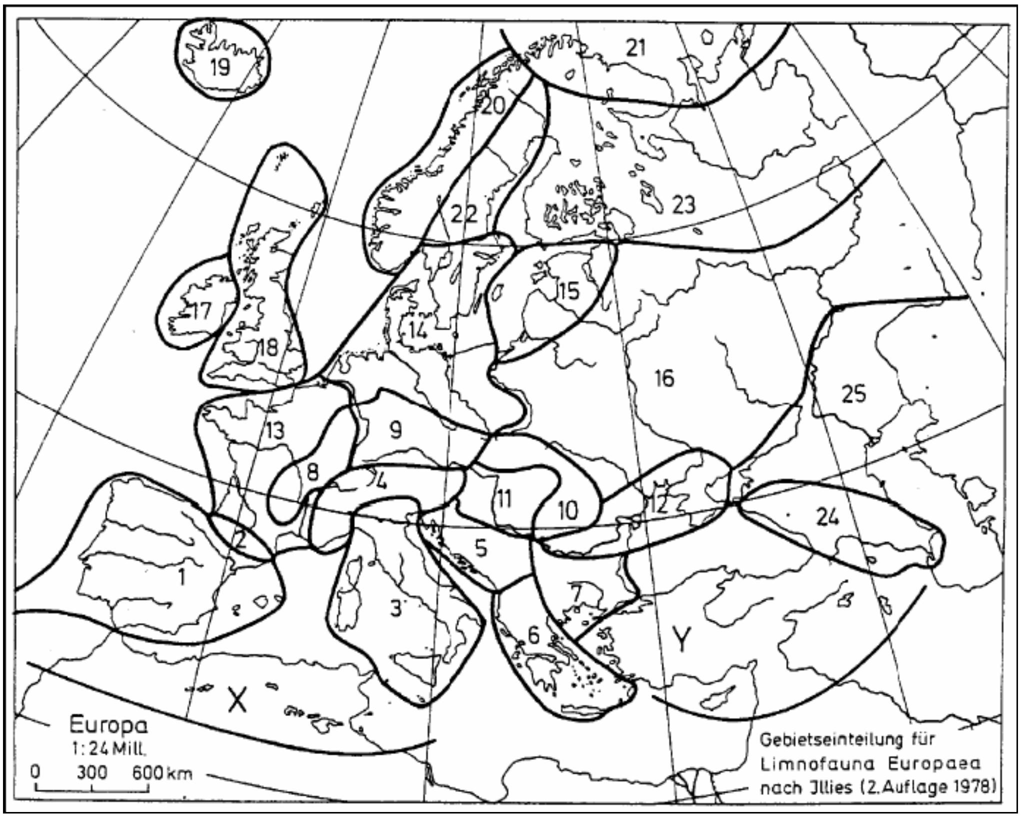


Figure 2-13: Map of ecoregions in Europe (reproduced from Illies, 1978).

	Ecoregions
1	Iberic-Macaronesian region
2	Pyrenees
3	Italy, Corsica and Malta
4	Alps
5	Dinaric western Balkan
6	Hellenic western Balkan
7	Eastern Balkan
8	Western highlands
9	Central highlands
10	The Carpathians
11	Hungarian lowlands
12	Pontic province
13	Western plains
14	Central plains
15	Baltic province
16	Eastern plains
17	Ireland and Northern Ireland
18	Great Britain
19	Iceland
20	Borealic uplands
21	Tundra
22	Fenno-Scandian shield
23	Taiga
24	The Caucasus
25	Caspic depression

Table 2-3: Ecoregions in Europe, relating to map in Figure 2.12 (reproduced from Illies, 1978).

An alternative approach for Member States is to type rivers using ‘System B’, which is similar to System A in incorporating ecoregions and five compulsory variables of latitude, longitude, catchment size, catchment geology and altitude, but has a further fifteen optional variables, such as distance from river source, mean water width, mean water depth, mean water slope and river discharge (flow) category (European Commission, 2000). Collectively, Member States can potentially produce a wide range of river typologies. Furthermore, an extensive range of stream types could be defined within a typology for each ecoregion. For example, using ‘System A’, each ecoregion has a maximum of four size classes, x 3 altitude classes, x 3 geology classes, which gives a total of 36 stream types. For a country such as the Czech

Republic comprising four (Illies) ecoregions, the maximum number of streams and river types is 144, though in reality not all these types will exist. The requirement of the WFD for Member States to develop a typology has resulted in a variety of different typologies across Europe. Table 2-4 shows a selected number of WFD typologies developed by a range of Member States.

Country	System A or B	Ecoregion	Variables	Stream types
Scotland (UK)	A	18	Ecoregion, area, altitude & geology.	15
England and Wales (UK)	A	18	Ecoregion, area, altitude & geology.	21
Northern Ireland (UK)	A	17	Ecoregion, area, altitude & geology.	12
Ireland	B	17	Ecoregion, area, altitude, geology/hardness & slope	12
Romania	B	10, 11, 12, 16	Ecoregion, area, altitude, geology, lithological river bed structure, yearly mean flow, yearly minimum monthly flow, channel slope, annual mean precipitation & annual mean temperature	32 types & 43 sub-types
Bulgaria	A	7, 12	Ecoregion, area, altitude & geology.	38
Hungary	B	9, 10, 11	Ecoregion, area, altitude, slope, geology, sub-ecoregions & river bed material	19
Serbia and Montenegro	B	5,10, 11, 12, 7	Ecoregion, area, altitude, geology & substrate characteristics	17 types, 3 Danube types & 8 sub-types
Latvia	B	15, 16	Ecoregions, area, altitude, geology, stream velocity, depth, summer temperature & structure of bed.	22
Norway	B	20, 21, 22, 14	Ecoregion, climatic region, geology, size, slope & substrate	26
Germany	B	4, 8, 9 & 14	Ecoregion, area, altitude, geology, sub-ecoregions (more differentiated geology, valley form, & slope) & dominant substratum	24
Austria	B	4, 5, 9, 11, (3 & 10*)	Ecoregion, area, altitude, geology, geomorphology, climate, watersheds, discharge regime type, vertical vegetation zones, vegetation types & biota	15 (Bioregions)

* Ecoregions present in country, but occupy a very small percentage of the land area.

Table 2-4: River typologies developed by Member States as requested by the EU WFD.

2.5 A summary of biotic classification systems

Linking biological communities to the physical characteristics of a catchment has practical implications for determining the conservation potential of river systems (Naiman *et al.* 1992). Many biotic classifications have either been based on patterns of species distribution, community structure or biotic functions. Biological communities respond to changing ecological conditions over a range of spatial-temporal scales, and thus, can be a sensitive indicator of environmental vitality or integrity (Naiman *et al.* 1992). Biotic classification systems and methods have been based on fish (Huet, 1954; Pennack, 1971), macroinvertebrate assemblages (Cummins, 1974; Wright *et al.* 1984), riparian vegetation patterns (Harris, 1988) and aquatic macrophytes (Holmes, 1989; Dodkins, 2002; Table 2-5). Biotic classification systems are based on the underlying premise that there is a predictable relationship between stream biota and the geomorphic and hydrological controlling variables (Thomson *et al.* 2001, 2004).

	Variable								
Classification/method	Geology, altitude, slope	Flow features	Water chemistry	Channel dimensions	Substrate types	In-stream features	Bankside features	Land use	Biota
RIVPACS (Wright *et al.* 1984, 1998)	●		●	●	●	●			Invertebrates
HABSCORE (Milner *et al.* 1993, 1998)	●	●		●	●	●			Fish
Fisheries Classification Scheme (Mainstone *et al.* 1994)	●			●					Fish
RHS (Raven *et al.,* 1997, 1998)	●	●		●	●	●	●	●	Macrophytes
River Plant Communities Classification (Holmes *et al*. 1998)	●	●		●	●	●			Macrophytes
SERCON (Boon *et al*. 1997, 1998)	●	●	●	●	●	●	●	●	Invertebrates, fish & macrophytes

Table 2-5: Summary of UK based biotic classifications and methods. Abbreviations are RIVPACS = River Invertebrates Prediction and Classification System, HABSCORE = Habitat Score, and SERCON = System for Evaluating Rivers for Conservation (reproduced and modified from Ravel *et al*. 1998c).

2.5.1 Vertebrate classifications

Many biotic stream classifications have been based on fish, partly due to biological and political motivations. Hawkes (1975) believes that fish are a good indicator of the ecological conditions of river systems as they are presumed to be near the top of the aquatic food chain. Furthermore, many fish species are endangered and/or have an important economic or recreational value. For example in Scotland, the Atlantic salmon *(Salmo salar)* contributes between £50-100 million per annum to the Scottish economy from recreational fisheries (Scottish Office, 1997). Therefore, the need to identify, classify and manage their habitat is paramount. Fishery biologists have an additional task of determining fish community associations, their ecological requirements, and developing methods to sustain their numbers given the increasing fragmentation and deterioration of habitats (Schiemer *et al*. 1991).

Many fishery ecologists have divided a river system longitudinally into classes based on the common fish species present (Table 2-6). The classes of dominant fish species correspond to the stream ordering system developed by Horton (1945) and Strahler (1957). In the early 1980s, studies by Platts (1979), Barila *et al.* (1981) and Cushing *et al*. (1983) indicated relationships between stream order, fish species and ecologically significant variables, such as channel gradient, channel width and depth, and bed sediment characteristics (Mosley, 1987). However, in the last 20-30 years, this longitudinal variation in river character and ecology has been increasingly viewed as a continuum compared to a series of distinctive zones or channel types (Mosley 1987).

Strahler order	Illies and Botosaneanu 1963		Ricker 1934	Huet 1954		Carpenter 1928	Pennack 1971	Nevins 1969
0	Zone 1	Source			Highland brooks	Head stream		
1	Zone 2	Rill and rivulet	Spring creek				Dace trickle	
2	Zone 3	Small stream, fed by 2 & rills	Swift trout stream	Trout zone		Trout zone	Trout feeder	Mountain or torrent phase
3	Zone 4	Brook of stream, fed by 2 & small streams	Slow trout stream				Trout stream	
4-6	Zone 5	Montane or piedmont river		Grayling zone	Lowland course	Minnow reach	Bass or pickerel stream	Shingle phase
6-8	Zone 6	Middle course of a river	Warm river	Barbel zone		Upper reach	Catfish or carp stream	
>7	Zone 7	Lower plains course		Bream zone		Lower reach		Silt phase
						Brackish estuary	Tidal stream	Tidal phase

Table 2-6: Vertebrate classifications based on longitudinal river zones (modified from Mosley, 1987).

2.5.2 Invertebrate classifications

Classification systems based on benthic invertebrate community structure can be useful to indicate organic pollution, detect acid stress, habitat loss and overall stream degradation (Hering *et al.* 2004). As macroinvertebrates demonstrate diverse life-history strategies, they are good indicators of both short and long-term change, and local and large-scale disturbances (Minshall, 1988). However, as in all biotic classification systems, an appreciation of potentially confounding factors such as zoogeography, dispersal limitation, disturbance regimes, biotic interactions, and productivity, which change species-habitat relationships, should at least be acknowledged, if not incorporated into the model.

A well renowned method of describing invertebrate, macrophyte and fish communities longitudinally along a river or a stream is the River Continuum Concept (RCC) of Vannote *et al.* (1980). The approach places invertebrates into ecologically meaningful trophic guilds, and explains changes in the functional roles of assemblages through the river network (Cummins, 1974). The RCC portrays how the structure and function of invertebrate assemblages in streams changes from the headwaters to the mouth of a river due to longitudinal gradients in externally and internally derived energy inputs (Figure 2-14). Invertebrate communities are assigned to three main groups: headwaters (orders 1-3), medium-sized streams (orders 4-6), and large rivers (orders >6). Headwater streams are strongly influenced by riparian vegetation, which contributes large inputs of allochthonous nutrients, and also restricts autotrophic production by shading. As the stream size increases downstream, allochthonous inputs decrease and the autochthonous processing of nutrients transported from upstream becomes more important. The transported nutrients are the main food sources for all subsequent living processes. The allochthonous material degrades from coarse particulate organic matter (CPOM) in typically low order streams to progressively finer particulate organic matter (FPOM) with increasing distance downstream. The composition of aquatic communities mirrors these changes in both the nutrient substrates and the physical characteristics of the river system. Invertebrate communities alter from predominantly shredders in low-order headwater streams to primarily grazers in medium-sized streams, to collector dominated communities in the higher order streams. Fish communities experience a similar shift from dominance by invertebrate predators in headwater environments to grazer-dominated communities in medium-sized streams to iliophagous dominance in the potamon. Finally, macrophytes change from being submerged in high order streams through periphyton to phytoplanktonic communities within the main channel.

The RCC has proved very popular among stream ecologists. However, while the theoretical continuum may be applied successfully to a main channel, the presence of tributary junctions disturb the pattern (Bruns *et al.* 1984). A joining tributary often will disrupt the hydrological and sedimentary pattern of the main channel, and can therefore, account for abrupt transitions apparent at the confluence of two large watercourses. Furthermore, the continuum may be disturbed or possibly reversed by geomorphological irregularities in the typical shape of the river profile (Welcomme, 1985).

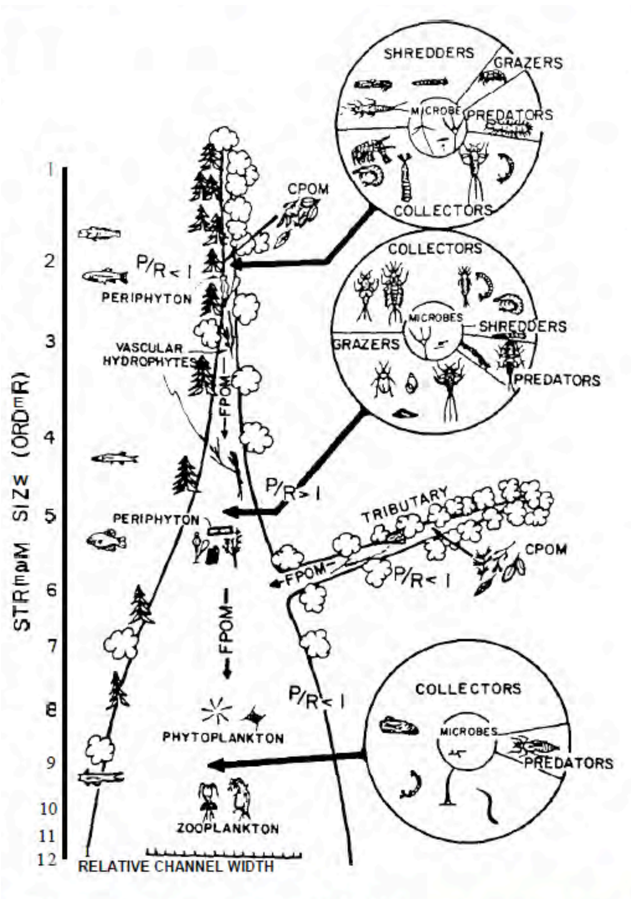


Figure 2-14: Conceptual relationship between stream size and the progressive shift in structural and functional attributes of lotic communities (reproduced from Vannote *et al.* 1980).

In the UK in 1977, a research project started that resulted in the development of RIVPACS (River InVertebrate Prediction And Classification System; Wright *et al.* 1998). The initial objectives were (i) to develop a biological classification of macroinvertebrate communities of unpolluted running waters in Great Britain, and (ii) to determine if the type of macroinvertebrate assemblages expected at a specific site could be predicted using physical and chemical attributes (Wright *et al.* 1998). The initial version of RIVPACS was based on the selection of 268 good quality reference sites along the length of 41 river systems in Great Britain (Wright *et al.* 1984, 1998). Two-way Indicator Species Analysis (TWINSPAN) was subsequently used to classify the macroinvertebrate data into 16 groups; Multiple Discriminant Analysis (MDA) was then used to link these 16 biological groups to 30 environmental variables for each site (Wright et al. 1984). The success of RIVPACS can be partly measured by its adoption in other countries. In Australia, Smith *et al.* (1999) developed AusRivAS (the Australian River Assessment Scheme) to assess the ecological condition of Australian rivers as required by the country's National River Health Programme (NRHP). This version of RIVPACS has been modified again for use in Portuguese streams to develop regional and national predictive models (Feio *et al.* 2009).

2.5.3 Plant classifications

Classification systems based on riparian vegetation patterns (Harris, 1988; Swanson *et al.* 1998) and aquatic macrophytes (Holmes, 1983, 1998) have also been developed. Classification systems based on the former have high conservation potential as riparian forests are active boundaries at the transition between terrestrial and aquatic systems, and are thus sensitive indicators of environmental change (Naiman *et al.* 1988, 1989; Naiman and Décamps, 1990). Riparian forests also influence the physical and biological characteristics of river systems through shading and stabilising the channel, and acting as a buffer to floods (Swanson *et al.* 1982; Naiman and Décamps, 1990).

In the late 1980s, Harris (1988) grouped riparian vegetation into six geomorphic valley types, based on species composition in the Sierra Nevada Mountains of California, USA. The classification included emerging concepts from landscape ecology and hierarchical theory, such as addressing appropriate scales for the classification of ecological and management purposes, and investigating the influence of catchment controls on smaller-scale patterns (Naiman *et al.* 1992). The six riparian vegetation units varied in sensitivity to management, and are useful for resource inventory, ecological study and prediction of human-induced pressure (Harris, 1988). The processes determining the observed patterns in the riparian vegetation unit could not be deduced. However, the classification still made significant progress in trying to link different landscape processes to biotic resources, and attempted to predict the sensitivity of stream segments to disturbance (Naiman, 1998).

Between 1978 and 1982, the Nature Conservancy Council (NCC) commissioned extensive river surveys throughout England, Scotland and Wales to form the basis for a national river classification based on macrophytes (Holmes *et al.* 1998). The aim of the project was to produce a classification that could be used as a framework to select different types of rivers for statutory protection as Sites of Special Scientific Interest (SSSIs: Boon, 1992). Holmes *et al.* (1998) highlight that from the outset, it was clear that additional work was necessary to assess the temporal stability of plant communities, and this has led to several revisions of the macrophyte classification. The initial macrophyte classification consisted of 1055 sites surveyed on more than 200 rivers by a single surveyor (Holmes, 1983). The resulting classification was hierarchical in nature, and at the highest level consists of four broad groups (A-D), which indicate an environmental gradient from lowland, eutrophic rivers to effectively upland, torrential and oligotrophic (Holmes *et al.* 1998). These four main groups are split into 10 River Community Types (RCTs) with further division into 38 sub-types. In later revisions, an additional 459 sites were added to the existing 1055 sites, and analysed using TWINSPAN (Holmes *et al.* 1998). Holmes *et al.* (1998) report that many sites retained their allocation to a RCT, whereas other sites were reassigned to a RCT. The addition of new sites and the reallocation procedure improved the overall classification and helped eliminate some anomalies in the original system (Holmes *et al.* 1998). The classification has reinforced the view that aquatic macrophytes offer a useful tool to classify rivers, and indicates that most communities are relatively stable over time in the absence of natural stress or human disturbance (Holmes *et al.* 1998). Willby *et al.* (2009) subsequently linked the biological classifications of Holmes *et al.* (1998) to site specific environmental data, and produced a 16 type environmental classification based on alkalinity, slope and geology that best summarised the variation in macrophyte based types across the UK.

This review has summarised a variety of biotic classification based on fish, invertebrates, riparian forests and macrophytes. Biotic classifications are undoubtedly useful to assess the conservation potential of a river. However, these classifications require intensive efforts to measure and monitor community characteristics, particularly for invertebrates (Naiman *et al.* 1992; Naiman, 1998). Biotic classifications need to be coupled to physical habitat of channels and large scale variables of a catchment to make links between processes and land use change. This information would be highly useful to restore physical habitat, and to better understand the requirements of stream biota.

2.6 Linking fluvial geomorphology to biological communities

Traditionally, the interactions between geomorphic character and biological communities have been widely recognised, but poorly quantified (Orr *et al.* 2008). Despite numerous attempts to classify aquatic systems using both physical and biological variables (see reviews above), successfully combining these two different disciplines into one, process-based typology that incorporates a range of spatial and temporal scales has proved elusive (Thomson *et al.* 2004). A typology successfully incorporating both disciplines would greatly help in monitoring and prioritising conservation and restoration efforts (Frissell *et al.* 1986; Newson *et al.* 1998; Bain *et al.* 1999). A process-based typology that effectively combines physical and biological components of aquatic systems would improve both conservation and restoration measures through more easily interpretable comparisons of sites, and advance understanding of functional processes within water courses (Thomson *et al.* 2004).

As the structure and dynamics of physical habitats constituting riverine environments are perceived as the template on which biological organisms evolve and communities are organised (Townsend and Hildrew, 1994), geomorphic classification systems offer a logical basis to generate a classification that is both physically and ecologically meaningful (Frissell *et al.* 1986; Naiman *et al.* 1992; Newson and Newson, 2000). Hierarchical models that include habitat features at a certain spatio-temporal scale are positioned within the context of larger-scale and longer-term factors, that restrict their behaviour, have received much attention (Frissell *et al.* 1986; Hawkins *et al.* 1993, Newbury and Gaboury, 1993). However, the ecological relevance of hierarchical, process based classification systems has rarely been tested (Thomson *et al*. 2004).

Thomson *et al.* (2004) hypothesise that for any geomorphic classification or typology to be useful in ecological applications, it is must be ecologically meaningful. At the very least, the relationships between geomorphic character, functional habitats (*sensu* Harper *et al.* 1992) and biological assemblages must be understood. Ideally, each channel type or class within a geomorphic classification would harbour a distinctive biological assemblage, showing similar ecological functioning and dynamics

(Thomson *et al*. 2004). While this scenario is unlikely across a wide variety of geomorphic features and scales; hierarchical geomorphic classifications may provide a tool to link ecological patterns and physical process across a wide range of multiple, spatial scales (Thomson *et al*. 2004). Excluding the work of Chessman *et al*. (2006) and Thomson *et al*. (2004) on the River Styles Framework in Australia, there have been few studies investigating the links between geomorphic classifications and stream biota at the reach scale.

Channel types within geomorphic classifications are composed of differing combinations of geomorphic units (e.g. pools, runs, riffles, cascades, and floodplains). For example, bedrock steps and plunge pools are typical of step-pool reaches, whereas pools, riffles and glides dominate pool-riffle morphologies. Many studies have indicated that different geomorphic units support relatively distinct biological communities, especially for macroinvertebrates (e.g. Brown and Brussock, 1991; Braaten and Berry, 1997). As many channel types consist of different sets of geomorphic units, it is logical to expect that channel types ought to have distinct habitat and biota at least within the climatic and biographical limits at the reach scale (Thomson *et al.* 2001). This principle underpins the River Styles framework of Brierley and Fryirs (2000).

In hierarchical geomorphic classification systems and typologies, such as the Montgomery and Buffington (1997, 1998) typology and the River Styles framework, the local physical structure of geomorphic units within each channel type or River Style is affected by hydrological and geomorphological processes at a higher level, such as valley confinement, topographic setting, discharge regime, and geology.

Therefore, geomorphic units of a specific channel type are likely to be physically, and thus, biologically more similar within rather than between channel types (Thomson *et al*. 2004). Furthermore, geomorphic units should in theory should be physically more similar within reaches of similar morphology compared to reaches of different morphology if reach-scale morphology directly affects physical processes at the geomorphic unit and smaller scales (Thomson *et al*. 2004). If geomorphic units are physically and biologically more similar within channel types, then a classification or typology will offer a useful basis for ecological management.

2.7 Summary

Rivers are dynamic, complex ecosystems (Ward, 1989; Thorp, 2009). The wide range of river processes has resulted in a variety of river sizes, channel forms and characteristics. This variability in form and processes has created challenges for classification as tension exists between generalisation and capturing the particular local characteristics of a river system (Kondolf *et al*. 2003). Unsurprisingly, efforts to classify rivers have resulted in the proliferation of geomorphic and biotic classifications and typologies serving different purposes. Despite the number of attempts to classify rivers using both physical and biological variables (see reviews above), few studies have successfully integrated the two disciplines into a process-based typology nested within a range of spatio-temporal scales (Thomson *et al.* 2004).

2.8 Thesis in context of the literature

This literature review has highlighted the need for a multidisciplinary approach to study the dynamic interactions and controlling variables on channel morphology and biological communities. No published studies have been undertaken in Scotland to explore whether applied river typing can improve our understanding of fluvial geomorphology and aquatic biodiversity. This thesis will address the use of geomorphic typologies to characterise river systems, and explore which variables best stratify channel types. Additionally, the study will also examine and test the geomorphic validity of the SEPA typology, and explore the links between fluvial geomorphology and invertebrate fauna. Specifically, it assesses whether channel types in the SEPA typology support distinct macroinvertebrate communities. This thesis aspires to contribute to the growing evidence base that links fluvial geomorphology and aquatic biodiversity, and intends to support WFD implementation in Scotland.

3 Geomorphological typing of Scottish rivers using catchment drivers

3.1 Introduction

The previous chapter (Chapter 2) reviewed the history and application of typologies, and identified how, traditionally, variables used to classify channel types and river systems have been obtained from observations and/or measurements in the field. A Geographical Information Systems (GIS) has the ability to provide data as a continuum across a wide geographical area to type river systems, and may offer an attractive alternative or complimentary approach to the use of field-derived data. This chapter examines the effectiveness of catchment drivers, derived from map and GIS procedures, to discriminate channel types in the SEPA typology. The chapter also explores whether multivariate techniques using catchment drivers can produce a functional typology.

3.2 Rationale

Numerous studies have used catchment drivers obtained from GIS to classify channel types and river systems (e.g. Jeffers, 1998; Snelder *et al.* 1999; Snelder and Biggs, 2002; Sear, 2006). The EU WFD requires Member States to develop a geomorphic typology based on ecoregions, geographical location, and physical characteristics, such as altitude, size, and geology (see Chapter 2, section 2.4.3). This need will encourage increasing use of GIS as a tool to classify river systems. The classification of river systems remotely using GIS would significantly reduce the amount of time required by surveyors in the field. Furthermore, a larger geographical area could be typed more quickly using GIS rather than solely relying on field surveys, and using GIS would eliminate any subjectivity present among field surveyors, and hence improve the accuracy and consistency of typing river systems.

3.3 Aims and hypotheses

The key aims of this chapter are to establish whether catchment drivers can reliably distinguish channel types in the SEPA typology, and examine whether multivariate methods can produce a functional typology. A subsidiary aim is to also investigate the downstream spatial pattern of channel types. The research hypotheses related to the key aims are:

e) The downstream distribution of channel types typically changes from step-pool, plane-bed, plane-riffle, pool-riffle, active meandering to passive meandering reaches.

f) Catchment drivers can be used as predictors to identify channel types in the SEPA typology.

g) Multivariate techniques can statistically separate channel types in the SEPA typology using catchment drivers.

3.4 Methods

3.4.1 Study reaches and sites

Sixty-seven study reaches were selected on seven river systems in Scotland (Figure 3-1). The majority of the study reaches (43) were located in the upper River Dee (39) and adjacent Allt a'Ghlinne Bhig (4) catchments (Figure 3-2). The upper River Dee and Allt a'Ghlinne Bhig was chosen as the main study area as a field reconnaissance survey revealed the catchments contained a variety of channel types. The location of study sites were chosen to reflect the changes in channel morphology occurring downstream. For instance, a study site was selected on the main stem of the River Dee, and a second study site was chosen when a change in channel type occurred in a downstream direction. River Dee 1 is a bedrock channel type for example, and River Dee 2 is a plane-bed channel type (see Appendix A). Study sites were continued to be selected using this rationale. The methodology ensured that a mixture of channel types was surveyed, which reflected changes in the controlling factors affecting channel morphology (see Chapter 2, section 2.3).

The upper River Dee and Allt a'Ghlinne Bhig was also chosen to reduce the efforts of potentially confounding factors that are known to effect aquatic biodiversity (discussed in Chapter 5). For example, flow regime, land use, water temperature and water quality is known to influence macroinvertebrates (Chessman *et al.* 2006). In an effort to reduce these potentially confounding factors, the majority of geomorphic surveys and all macroinvertebrate surveys were conducted in one area - the upper River Dee and adjacent Allt a'Ghlinne Bhig catchment.

Although the River Dee and Allt a'Ghlinne Bhig catchments possess a medley of channel types; not all channel types in Scotland are present within this area. Therefore, specific river systems were selected to ensure all channel types were represented and surveyed. For example, the River Feshie was selected due in part to its distinct braided character, and the Endrick Water was chosen as it contains a distinctive meandering pattern (see Figure 3-1 for locations of river systems). The remaining study sites on the other river systems were included to ensure an equal number of channel types present in Scotland were represented.

The River Dee rises in the Cairngorm Mountains at an altitude of 1250m, and initially flows south from the Pools of Dee through Glen Dee before draining eastward to enter the North Sea at Aberdeen. The main stem of the Dee is 140km in length and drains a catchment with an area of approximately 2200km^2 (Langan *et al.* 1997). The catchment is principally upland in character with 60% of the area lying above an altitude of 300m (Wade *et al.* 1999). All the study reaches are located in the upper River Dee catchment, north of Braemar (Figure 3-2), and have altitudes ranging from 325m to 650m, with a catchment area of approximately 320km^2. Mean annual precipitation in the upper catchment is over 1500mm (Soulsby *et al.* 1997). Snow accumulations in winter can be considerable on the main mountain plateaux, and snowmelt can markedly affect the annual hydrological regime (Goody, 1988). The geology of the catchment is mostly granite and quartzose-mica-schist, with minor outcrops of limestone, graphitic schist and slate, and epidente, hornblende schist. Thirteen other study reaches were located in the adjacent Allt a'Ghlinne Bhig (4) catchment, and nearby Allt Dubhaig (6) and the River Feshie (3) catchment, which are very similar in character to the upper Dee, but have much smaller catchment areas

(27.5km², 15km², and 230km² respectively). Both the Allt Dubhaig and the River Feshie drain westwards off the Cairngorm plateau into the River Spey. Eleven other study reaches were located mostly on lower gradient lowland rivers situated further afield; namely the rivers Glass (2), Balvag (4), Endrick (3) and Teith (2) (with catchment areas of 573km², 176km², 240km², and 575km² respectively). Four study reaches were situated in the headwaters of the Allan Water (catchment area of 210km² respectively), a tributary of the River Forth. These rivers similarly drain hard rock geologies in the uplands, but in the lowlands, the valley floors are alluvial in character. Precipitation in these catchments varies between 1000-1500mm.

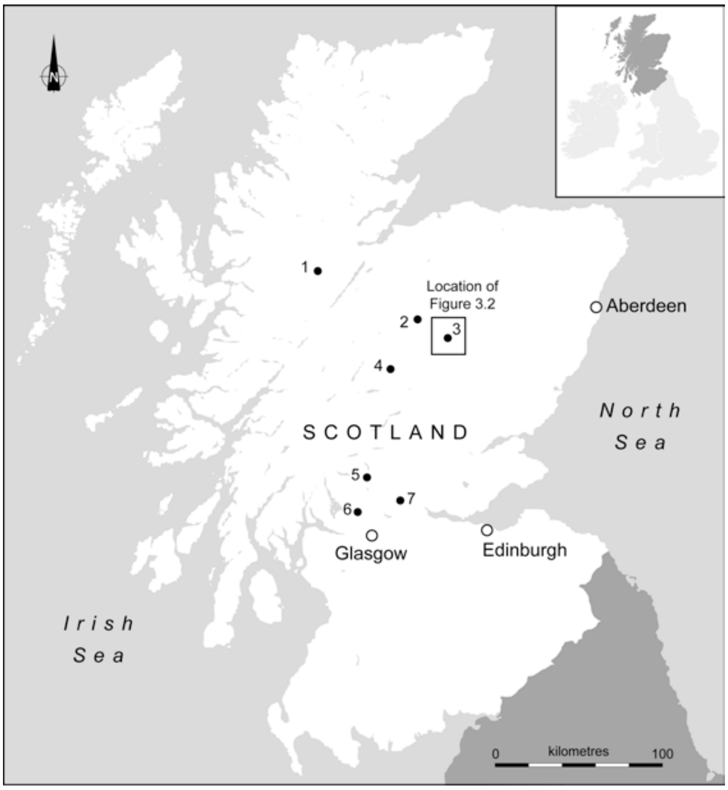


Figure 3-1: Location of seven river systems used in the study (points). River systems are 1 = R. Glass, 2 = R. Feshie, 3 = R. Dee, 4 = Allt Dubhaig, 5 = R. Balvag, 6 = Endrick Water, and 7 = R. Teith.

3.4.2 Geomorphic classification and assessment

The classification of study reaches into channel types was initially determined by reference to the SEPA typology (Chapter 1, Table 1-1) and the averaged expert opinion of three fluvial geomorphologists: Dr Richard Jeffries, SEPA, Professor David Gilvear, the University of Stirling and myself. All three fluvial geomorphologists have been involved with testing and applying the SEPA typology to the Scottish fluvial environment, and are familiar with the river systems used. River reaches throughout each of the catchments of interest that were greater than third order were classified into one of nine possible channel types (e.g. step-pool, plane-bed, wandering reach. See Chapter 1, Table 1-1 for channel types). Figure 3-2 shows the classification of reaches into the SEPA channel types, in the upper River Dee and adjacent Allt a'Ghlinne Bhig catchments. A detailed topographic setting of the study reaches can be viewed in Appendix A. All study reaches were in "near natural" condition with very few or no channel modifications. Two digital photographs recorded the character of each study reach (Appendix B).

Study reach locations (see Appendix C for GPS co-ordinates) were entered into Arc View (version 9.1), a GIS software package, and a range of map-based variables were derived (e.g. catchment area, valley slope, sinuosity). Table 3-1 indicates the method and how each of the catchment driver variables was defined. The British Geological Survey OS map of the UK was used to ascertain bedrock (1:250,000) and superficial geology (1:50,000) for each study reach. To compare geological properties between different channel types, solid geology categories were reduced into three classes: sandstone, metamorphic and igneous rocks. The classes were selected as potentially having differing susceptibilities to fluvial erosion. Similarly, superficial geology was categorised into alluvial, river terrace, fluvio-glacial deposits and till for the same reason. The simplified geological classes were used to reduce the wide range of lithological characteristics present in the UK (Harvey *et al*. 2008a). Harvey *et al.* (2008a) also used the approach of simplifying geological classes in a study that characterised river reaches by rock type. This overall dataset is described as the “catchment driver” dataset.

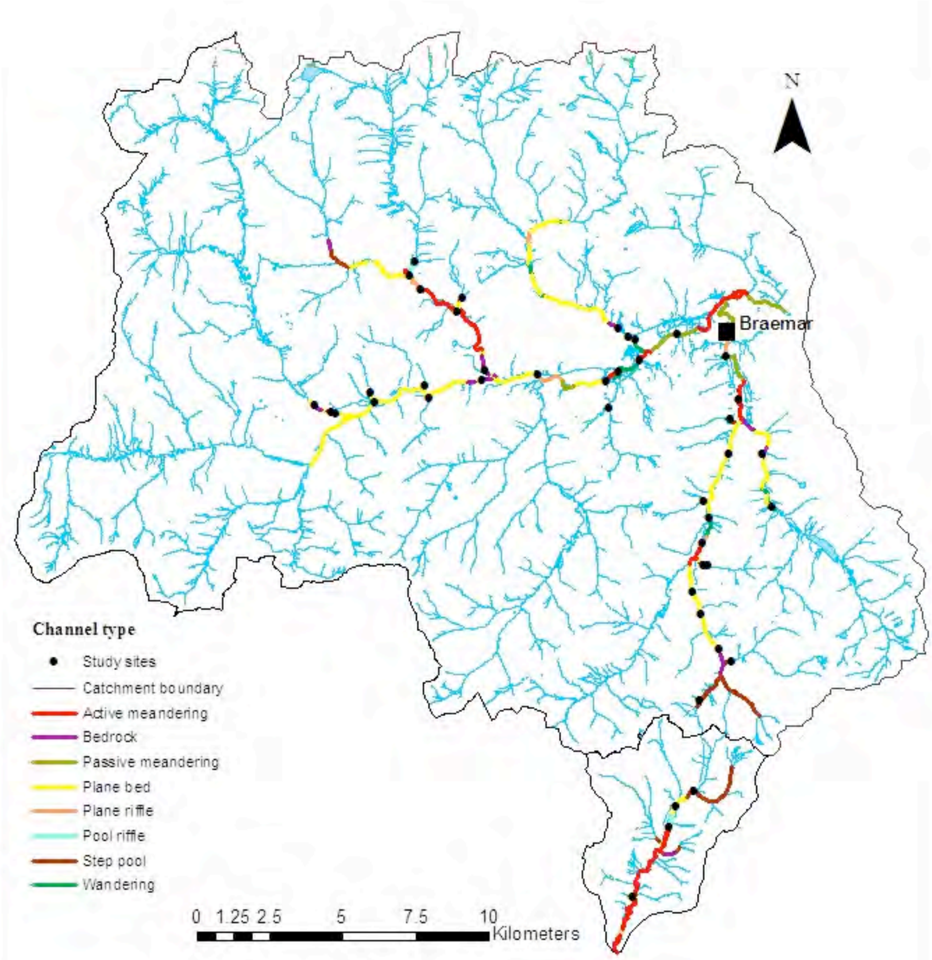


Figure 3-2: Map of the upper River Dee and Allt a’Ghlinne Bhig catchments illustrating the distribution of SEPA channel types and study reaches based on an OS 1:25,000 map.

Method	Variable	Code	Description
Map derived	Catchment area	C Area	The upstream catchment area between the start of the study reach to the catchment divide (km²) based on an OS 1:25,000 map.
GIS derived	Altitude of reach	Alt	Altitude of reach (metres a.s.l.).
	Distance from source	Dist Sou	The distance from a study reach to a river's source (km). River source is defined as the most distant point from the river's mouth, based on an OS 1:25,000 map.
	Stream power	S Power	Upstream catchment area multiplied by valley slope (km²/m) based on an OS 1:25,000 map.
	Solid geology	Sol Geol	Solid geology category as assigned by the British Geological Survey OS 1:250,000 map.
	Stream order	S Order	Strahler stream order based on an OS 1:25,000 map.
	Superficial geology	Sup Geol	Superficial geology category as assigned by the British Geological Survey OS 1:50,000 map.
	Sinuosity	Sinu	A measure of the river's planform (m). The length of the channel from the start to the end of the study reach, divided by the straight line distance between the upstream and downstream ends, measured on an OS 1:25,000 map.
	Valley slope	V Slope	Valley slope was defined as the change in channel length between the upstream and downstream contour line, based on an OS 1:25,000 map (m/km).
	Valley width	V Width	The width of the valley divided by the channel width (m). Width of the valley was defined as the distance between the first contour line located on either side of the reach, measured on an OS 1:25,000 map (m/m).

Table 3-1: Description of catchment driver variables from map and GIS based methods.

3.4.3 Data analysis

Ten catchment driver variables were selected for statistical analysis (Table 3-1). The physical processes within rivers, and hence their morphology, are governed by topographic gradient, the volume and time distribution of water supplied from upstream, the volume, time distribution and character of sediment delivered to the channel, and the type of material through which the river flows (Church, 1992). The catchment driver variables chosen for statistical analysis relate to these four factors controlling physical processes and the resulting channel morphology. Solid geology and superficial geology control sediment delivery to a river via erosion rates. The amount of erosion and input of material from the river banks is controlled in part by channel sinuosity. Similarly, valley width and solid geology dictate the ability for a channel to migrate across a floodplain, subsequently affecting the amount of sediment entering a river system. Valley slope directly controls the volume and time distribution of water and sediment transported to a river system. Altitude does not directly influence channel morphology. However, the variable was chosen as a surrogate for temperature due to its potential influence on macroinvertebrates (discussed in Chapter 5). Furthermore, altitude indirectly changes the type of vegetation along a river bank, which influences bank stability. Therefore, altitude may indirectly act as a catchment driving variable on channel morphology.

Prior to data analysis, the Shapiro-Wilk's (S-W) statistical test was used to check the frequency distributions of the catchment drivers for normality. Variables were transformed using log- or sqrt-transformations. Despite the different transformation methods that were used to approach the normal distribution, few catchment driver variables exhibited a normal distribution. In the cases where the applied transformation produced even more skew than the original data, the untransformed data was used. As a general rule, the majority of environmental data do not follow a normal distribution (Scott and Clarke, 2000, Reimann *et al*. 2005), which is the product of a combination of interacting non-linear dynamics, feedbacks and thresholds resulting in outliers within environmental systems (Peh *et al*. 2008).

Data analysis consisted of several contrasting multivariate statistical techniques. Firstly, agglomerative Hierarchical Cluster Analysis (HCA) was performed to group the study reaches based on their catchment drivers. Secondly, Principal Components Analysis (PCA) was used to validate the variation between study reaches in terms of their likely catchment drivers. The two techniques are complementary as HCA provides a good fit if natural data clusters are present, whereas PCA offers an overview of the phonetic structure (similarities and differences) of the data set (Rohlf, 1970; Harvey *et al.* 2008b).

An agglomerative Hierarchical Cluster Analysis (HCA) was conducted to validate the 'similarity' of channel types in terms of their predictor variables. HCA is commonly used in both geomorphological and ecological applications and offers an objective approach to identify groups with similar attributes without the need for an arbitrarily defined number of clusters (Harvey *et al*. 2008b). Schmitt *et al.* (2007) used HCA to develop a quantitative morphodynamic typology of rivers on the French Upper Rhine basin. Wright *et al.* (1984) and Holmes *et al*. (1999) used TWINSPAN, an alternative method of cluster analysis to classify river reaches in the UK into groups based on their macroinvertebrate or macrophyte composition respectively. In the statistical analyses, all HCAs throughout the thesis use the minimum variance (Ward's method) clustering procedure (based on joining two groups for which the increase in overall cluster variance is least), and use an Euclidean correlation measure. The output of the HCA is an agglomeration schedule detailing the stages of the clustering process, and a dendrogram (Harvey *et al*. 2008b).

Principal Components Analysis (PCA) was carried out to identify which catchment drivers obtained from GIS, dominated any clusters generated from the agglomerative HCA. Jeffers (1998) also employed PCA using RHS data, to generate an ordination of survey sites based on four map-based variables that allowed prediction of several habitat features. Data used to calculate the catchment driver variables were standardised prior to PCA, which was based on a correlation cross-products matrix. In PCA, linear combinations of the original variables are created that express the maximum amount of variability in the original dataset (Scott and Clarke, 2000). The principal component (PC) scores classified according to the cluster group were tested for normality and all have a normal distribution. The first principal component axis (or new variable) accounts for the maximum amount of data variability possible in a single variable, and successive PCs axes explain as much as possible of the residual variance (Scott and Clarke, 2000). The justification for using PCA is that since the first few components explain the majority of the data variability, they should also characterise the most important information in the data. By synthesising multiple variables into a small number of PCs, the number of variables to be investigated is decreased (Scott and Clarke, 2000). Table 3.2 displays a synopsis of all statistical techniques presented in this chapter.

Factor of interest	Type of statistical technique	Input dataset	Typology used to group channel types
Identify SEPA channel types based on catchment driver characteristics	Boxplots	Catchment-driver data	SEPA
Determine any significant differences between channel types	One-way ANOVA and Kruskal-Wallis tests	Catchment-driver data	SEPA
Identify uncorrelated catchment driver variables	HCA	Catchment-driver data	N/A
Identify any catchment driver groups	HCA	Catchment-driver data	SEPA
Identify percentage of data variability described by the catchment driver variables	PCA	Catchment-driver data	SEPA
Determine any significant differences between channel types	ANOVA	PC1 and PC2 axis scores	Catchment-driver

Table 3-2: Summary of all statistical methods used in this chapter.

The methodology followed in this study, including fieldwork, map work and statistical analysis procedures is highlighted in Figure 3-3. Exploratory data analysis and HCA were conducted in Minitab (version 15.1) and SPSS (Statistical Package for the Social Sciences; version 16.0). PCA was performed in the Canoco software package (version 4.5, ter Braak and Šmilauer, 1998), and Kruskal-Wallis tests were conducted in the PAST (PAlaeontological STatistics) software package (version 1.94b, Hammer *et al.* 2001).

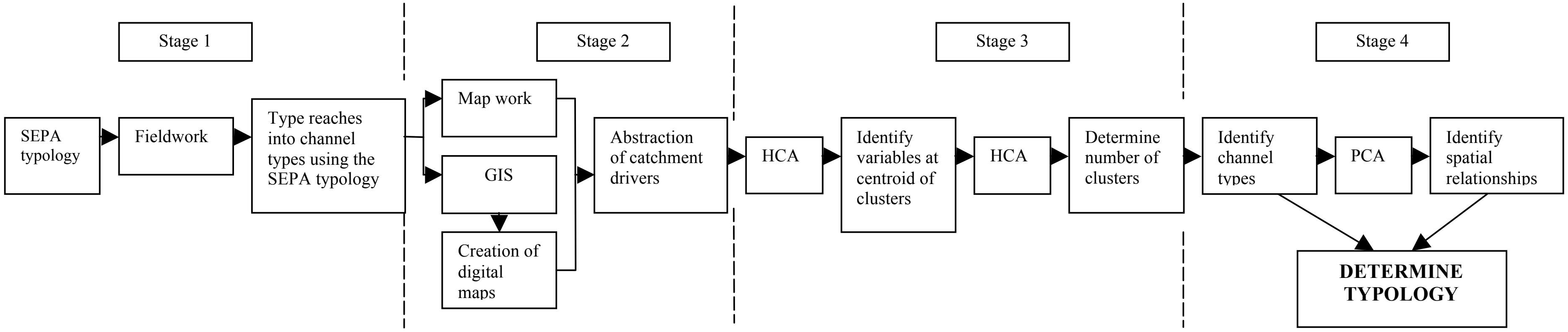


Figure 3-3: Methodology followed during study.

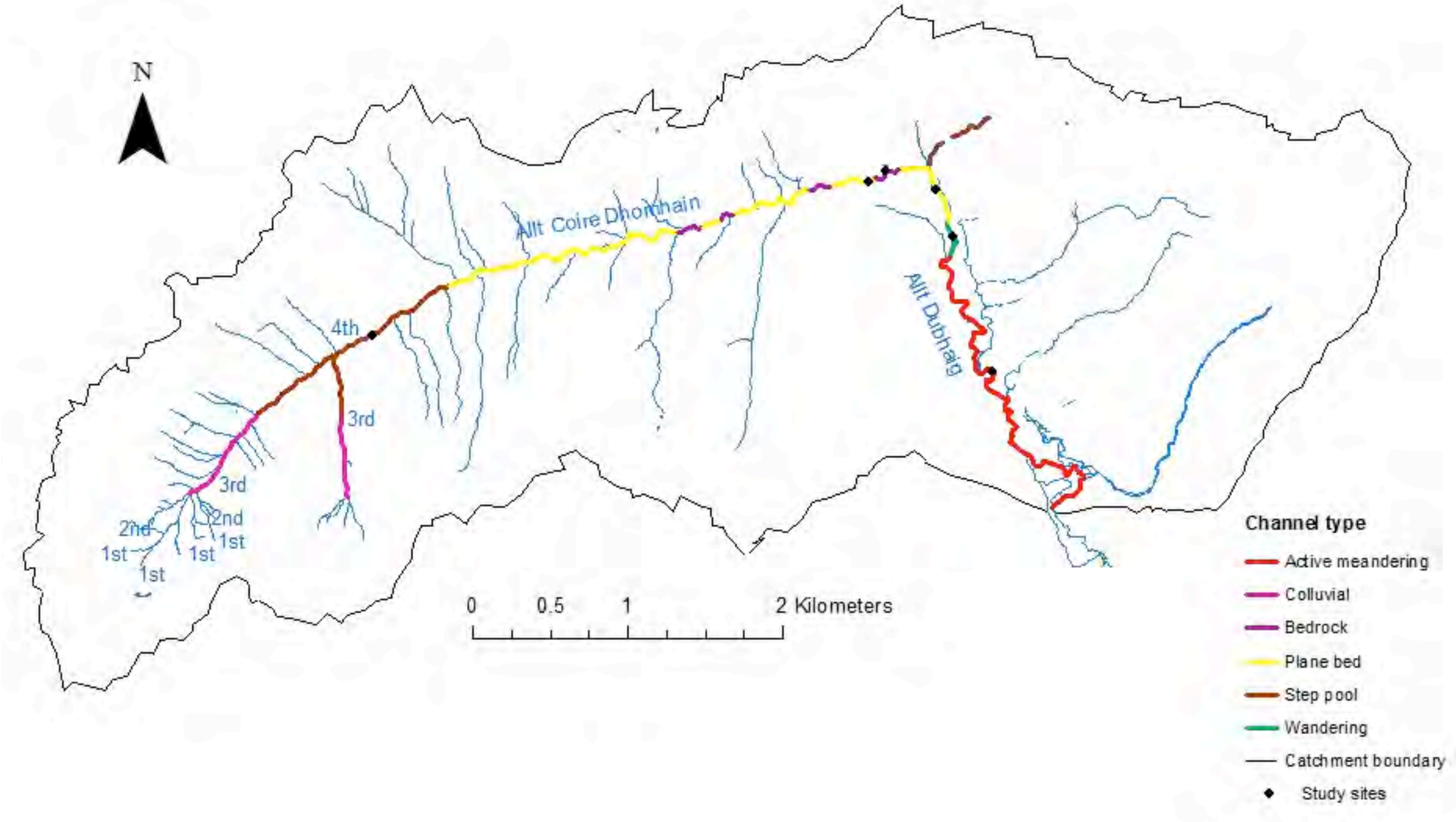
3.5 Results

3.5.1 The downstream distribution of channel types typically changes from step-pool, plane-bed, pool-riffle, active meandering to passive meandering.

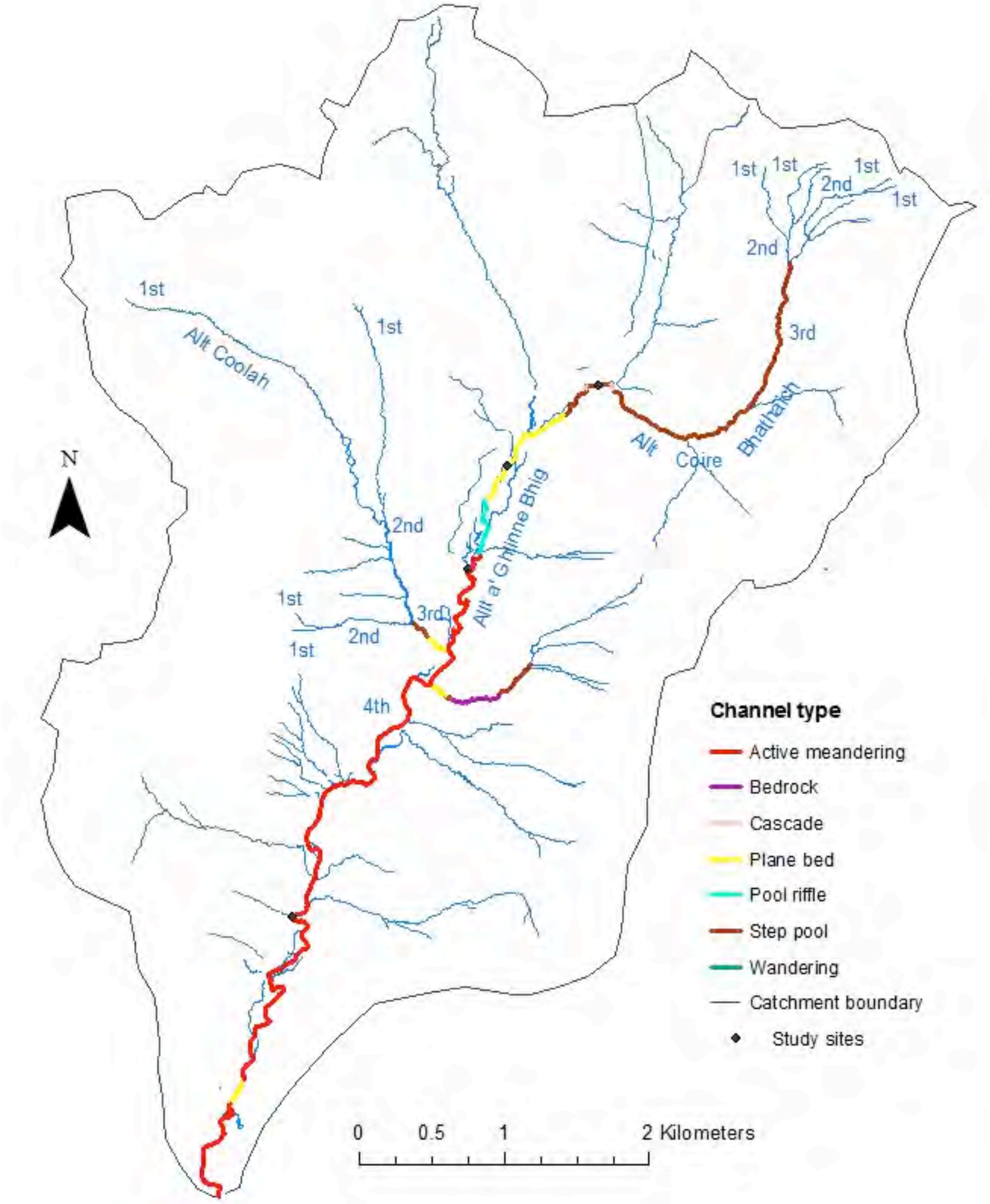
The frequency of channel types classified according to the SEPA typology is shown in Table 3-3. Of the eleven channel types in the SEPA typology, nine types were identified in the fieldwork procedure. An initial aim of the fieldwork procedure was to survey an equal number of representative different channel types. However, this aim proved unachievable as there were low numbers of braided and pool-riffle reaches in the catchments of interest. The number of study reaches surveyed is however, considered to be representative of the abundances of channel types in the Scottish upland landscape. The dominant types are typical of upland hard rock geologies and generally occur in a downstream sequence of step-pool, plane-bed, and plane-riffle, through to meandering types. A similar sequence of channel types was also found in the Pacific north-west of the USA (Montgomery and Buffington, 1997, 1998). The downstream progression of channel types for the Allt Dubhaig and Allt a'Ghlinne Bhig is given as an example (Figure 3-4). The longitudinal characteristics of both streams are shown in Figure 3-5 and 3-6.

SEPA channel type	Channel code	Frequency
Active meandering	A	11
Bedrock	B	6
Braided	D	3
Passive meandering	M	8
Plane-bed	P	14
Plane-riffle	R	5
Pool-riffle	O	2
Step-pool	S	14
Wandering	W	4
Total		67

Table 3-3: Frequency of study reaches per channel type in the SEPA typology.

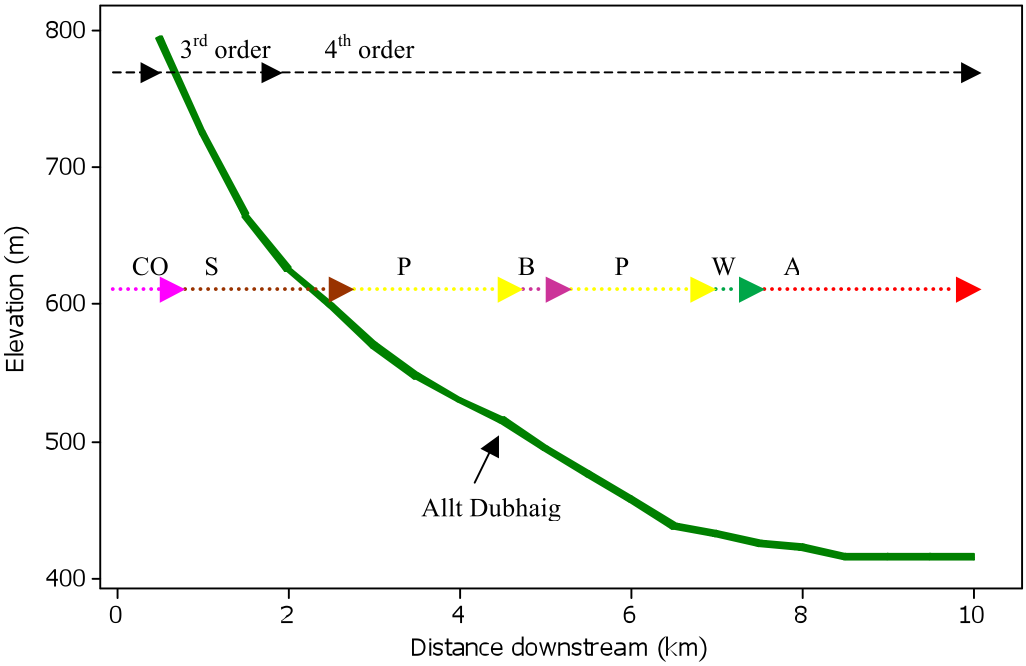


a) Allt Dubhaig

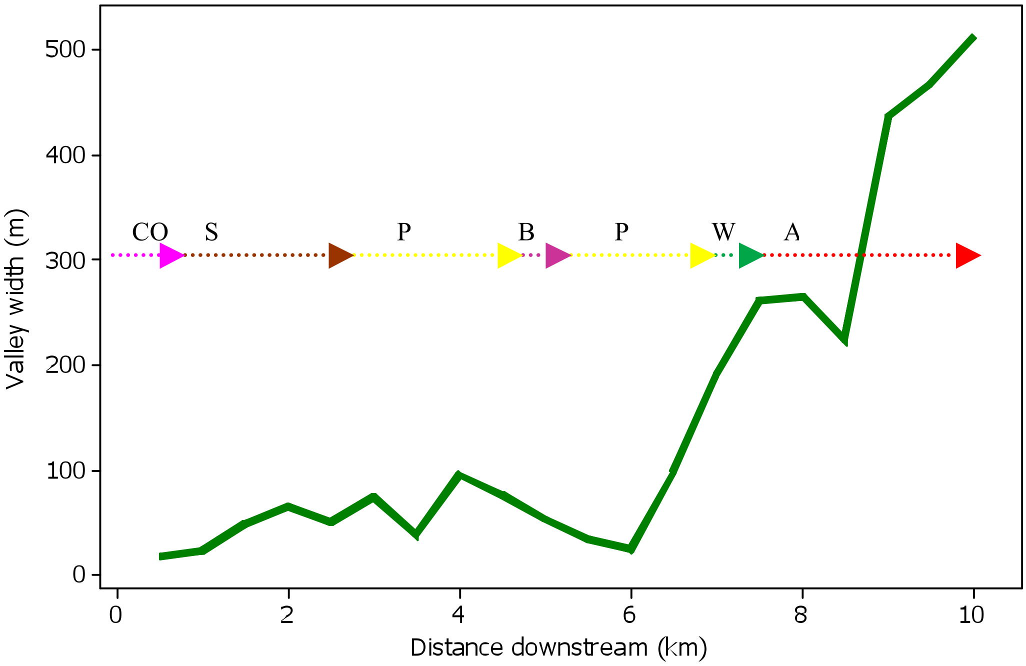


b) Allt a'Ghlinne Bhig

Figure 3-4: The downstream changes in the spatial arrangement of channel types in the a) Allt Dubhaig and the b) Allt a'Ghlinne Bhig catchments.

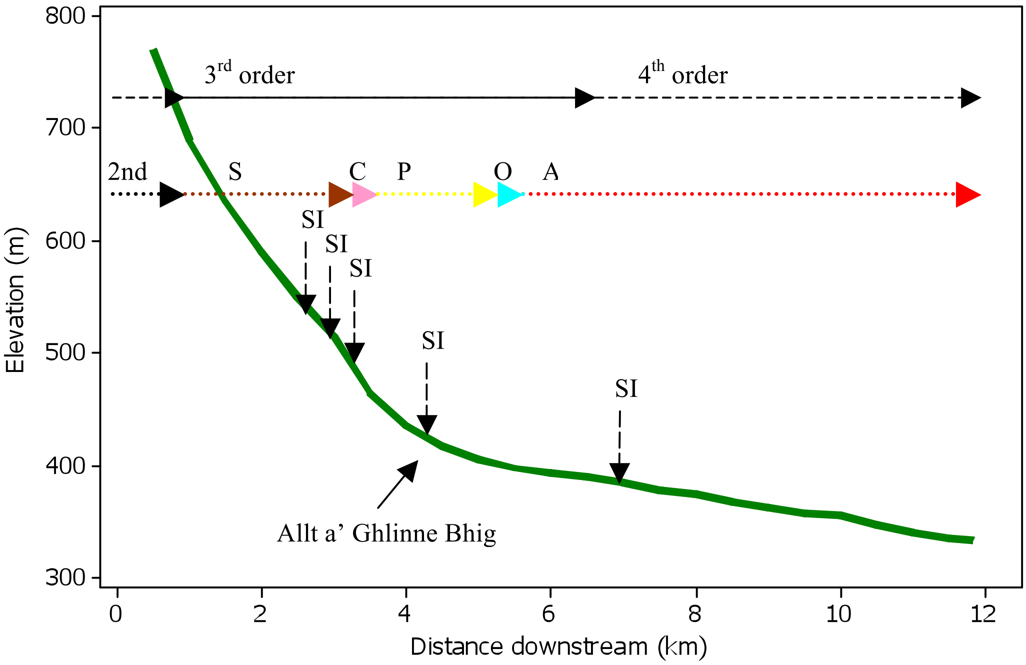


a) Stream profile

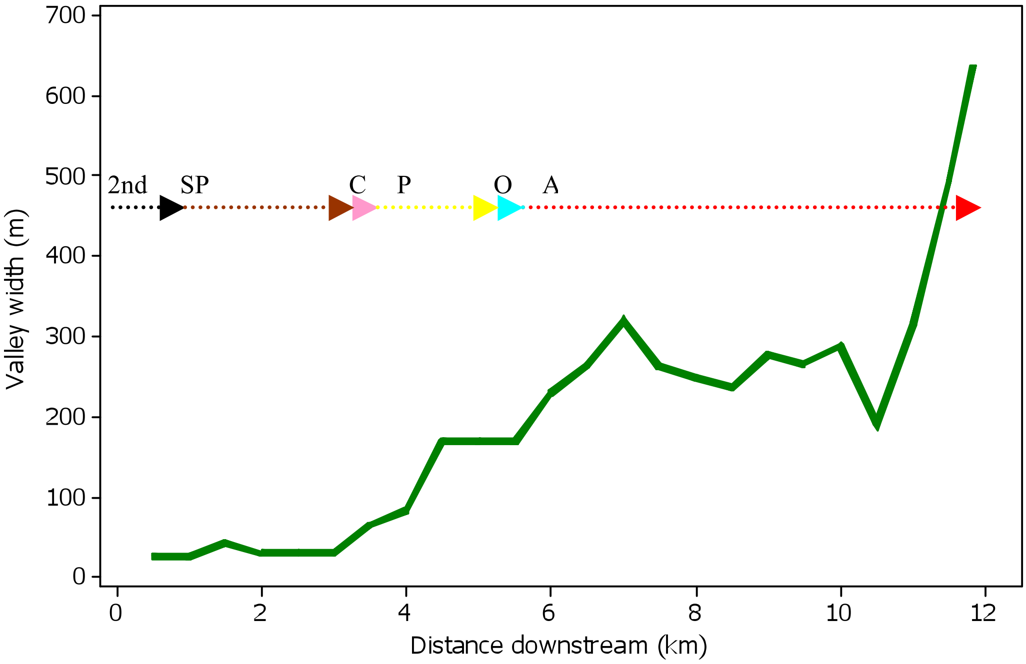


b) Downstream changes in valley width (m)

Figure 3-5: Longitudinal characteristics and channel type changes in the Allt Dubhaig. Channel codes are shown in Table 3-3, and CO = Colluvial.



a) Stream profile



b) Downstream changes in valley width (m)

Figure 3-6: Longitudinal characteristics and channel type changes in the Allt a'Ghlinne Bhig. Channel codes are shown in Table 3-2, and C = Cascade and SI= Significant sediment input.

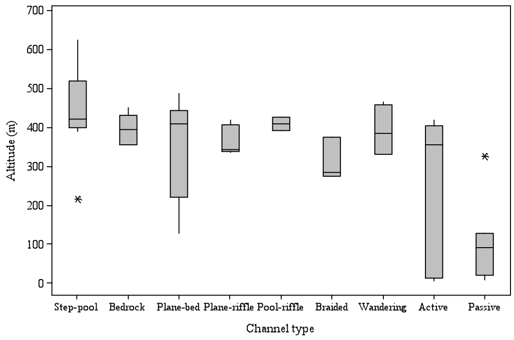
3.5.2 *Catchment drivers can be used as predictors to identify channel types in the SEPA typology.*

Table 3-4 shows a summary of the descriptive statistics for the catchment driver dataset. Data for altitude, distance from source, upstream catchment area, stream power, sinuosity, stream order, solid and superficial geology, valley slope, and valley width are presented as boxplots for channel types in the SEPA typology (Figure 3-7). The distributions of channel types clearly overlap with few channel types possessing a discrete distribution based on any catchment driver variable, although some patterns are apparent. An overall trend of increasing median values is present, from step-pool through to passive meandering reaches based on catchment area, distance from source, stream power, and valley width characteristics. Step-pool channels have a distinctly smaller catchment area, lower distance from source, smaller stream order, and lower stream power distribution, and passive meandering reaches have a distinct median value based on catchment area variations.

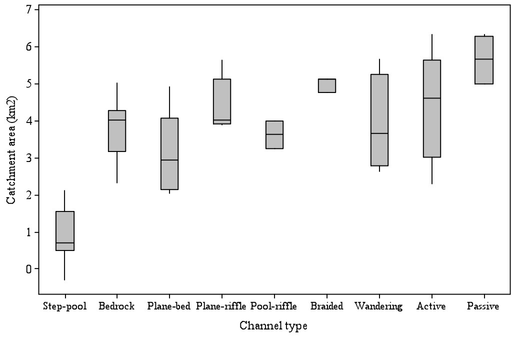
Catchment driver variable	Min	Max	Med	Mean	SD	Skew	S-W (P)
Altitude of reach	6	650	394	343.3	151.7	-0.81	<0.005
Catchment area	0.8	560.5	49.3	103	143.4	1.95	0.052*
Distance from source	0.88	58.27	11.57	14.51	12.88	1.4	0.088*
Solid geology	1	3	2	1.97	0.43	-0.19	<0.005
Sinuosity	1.01	2.22	1.10	1.19	0.26	2.57	<0.005
Stream order	1	6	5	4.55	1.2	-0.81	<0.005
Stream power	0.89	79.23	13.95	18.09	18.33	1.81	0.398*
Superficial geology	1	4	1	1.90	1.33	0.92	<0.005
Valley width	3.33	92.36	23.61	27.77	19.35	0.9	0.055*
Valley slope	0.04	19.57	1.13	2.86	3.94	2.25	0.015

Table 3-4: Summary of descriptive statistics. Variables exhibiting a normal distribution, indicated by a S-W $P > 0.05$ are marked with an asterisk.

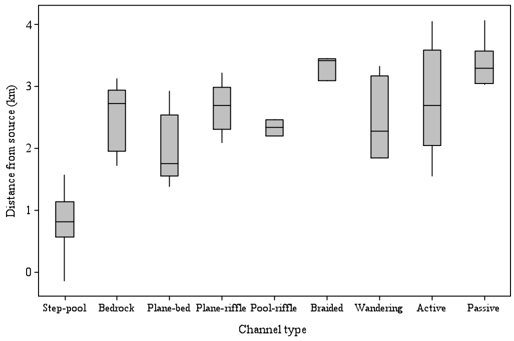
Variations in altitude are related to channel types, with an overall trend of decreasing medians from step-pool through to passive meandering reaches. Reaches with altitudes exceeding 422m are likely to have a step-pool morphology, whereas reaches with an altitude below 91.6m are likely to be passive meandering reaches with a pool-riffle morphology. Variations in valley slope are strongly related to channel types, with an obvious trend of decreasing medians from step-pool reaches through to passive meandering reaches. Differences in sinuosity between channel types are relatively small. Active meandering reaches have the greatest range in sinuosity and the highest median values occur among the alluvial channel types. Median values generally increase among the alluvial channels from step-pool to actively meandering channels, with the exception of passive meandering reaches. Superficial geology clearly distinguishes step-pool and bedrock channels (Figure 3-7h), but poorly discriminates between the other types. Till and glacio-fluvial materials govern the geology of both step-pool and bedrock channels, in contrast to alluvium, and alluvial and river terrace deposits dominating alluvial types. Similarly, solid geology is also a poor discriminator as step-pool, bedrock, braided and wandering reaches are all characterised by metamorphic rocks. Plane-bed, plane-riffle, and pool-riffle reaches occur on both igneous and metamorphic lithologies, whereas active and passive meandering reaches are underlain by metamorphic and sedimentary geologies. Overall, channel types cannot be defined based on a single catchment driver, apart from step-pool reaches.



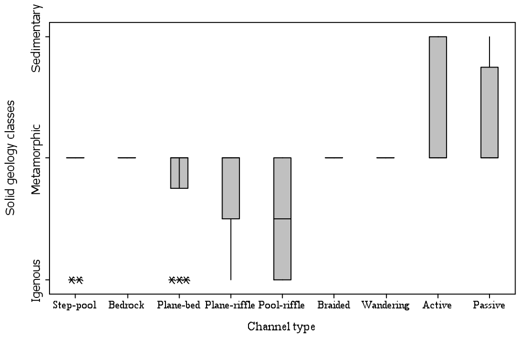
a) Altitude



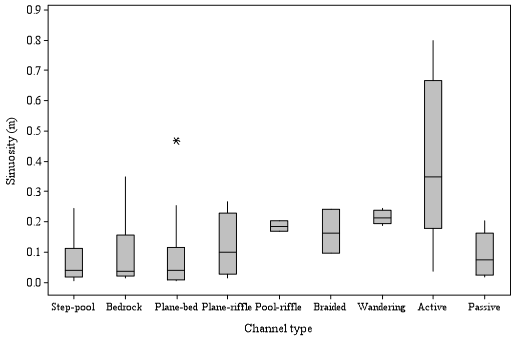
b) Catchment area†



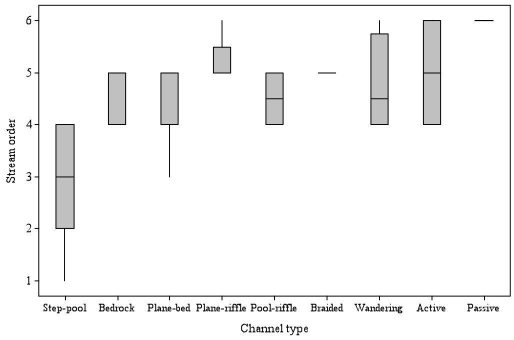
c) Distance from source†



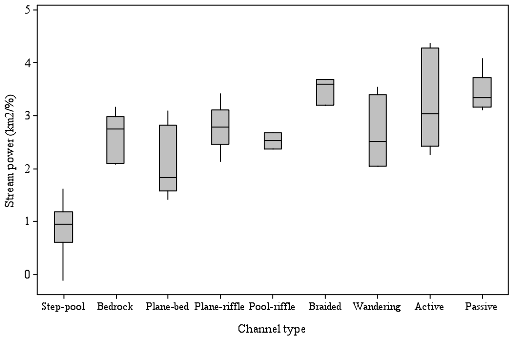
d) Solid geology



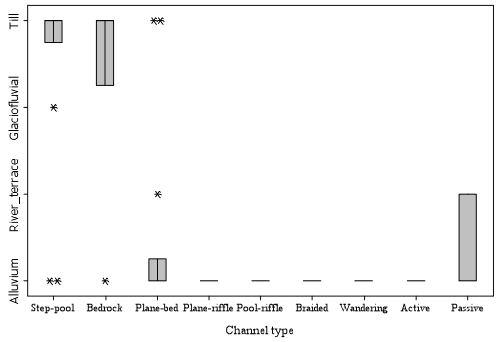
e) Sinuosity†



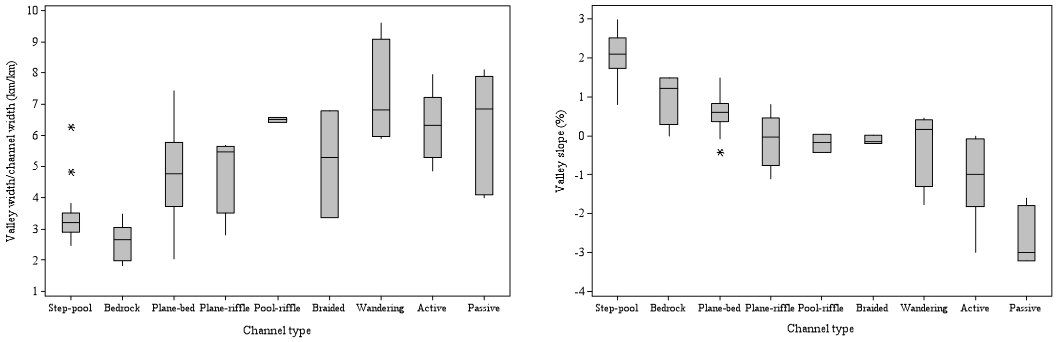
f) Stream order



g) Stream power†



h) Superficial geology



i) Valley width† j) Valley slope†

Figure 3-7: Boxplots for catchment driver variables (a-j) measured for 67 study reaches surveyed in the study. Boxes represent the first and third quartiles, vertical lines signify upper and lower tenths, asterisks indicate outliers, and † indicates data has been transformed.

One-way Analysis of Variance (ANOVA, conducted on parametric data) and Kruskal-Wallis tests (performed on non-parametric data) indicated some significant differences between channel types for most catchment driver variables, apart from solid geology (Tables 3-5 and 3-6). For example, step-pool channels were statistically different from bedrock, plane-bed, plane-riffle, braided, wandering, active meandering and passive meandering at the 0.001 significance level (Table 3-5). Channel types were most clearly distinguished by their channel bed slope, superficial geology and stream order characteristics. The results indicate that some catchment driver variables are more successful than others at discriminating specific channel types. Each catchment driver variable discriminated step-pool reaches. Step-pool reaches were mostly separated by having significantly smaller catchment areas, being close to the river source, being underlain by till geologies and occupying steep slopes. Sinuosity proved successful at identifying active meandering reaches from the other channel types. Passive meandering reaches were noticeably different occurring on gentle slopes. Bedrock channels are notably distinguished from all other channel types, excluding step-pool reaches based on superficial geological characteristics. Valley width also separated bedrock reaches from wandering, active meandering and passive meandering reaches, with the former channel type possessing a very limited floodplain.

Variable	*P*-value	Channel type	Post-hoc test group
Catchment area	<0.001	Step-pool	Bedrock Plane-bed Plane-riffle Braided Wandering Active Passive
		Plane-bed	Passive
Distance from source	<0.001	Step-pool	Bedrock Plane-bed Braided Active Passive
	<0.01	Step-pool	Plane-riffle Wandering
	<0.001	Plane-bed	Passive
Stream power	<0.001	Step-pool	Bedrock Plane-bed Plane-riffle Braided Wandering Active Passive
	<0.01	Plane-bed	Passive
Valley width	<0.01	Step-pool	Wandering Active Passive
	<0.001	Bedrock	Wandering Active
	<0.01	Bedrock	Passive

Table 3-5: Results from a one-way ANOVA conducted on catchment driver variables, showing P-values, and channel types identified from the post-hoc procedure.

Variable	*P*-value	Channel type	Post-hoc test group
Altitude	<0.05	Step-pool	Braided Plane-riffle
	<0.01	Step-pool	Active
	<0.001	Step-pool	Passive
	<0.001	Passive	Plane-bed
	<0.01	Passive	Bedrock Plane-riffle Wandering
	<0.05	Passive	Pool-riffle
Stream order	<0.001	Step-pool	Bedrock Plane-bed Plane-riffle Active Passive
	<0.01	Step-pool	Braided
	<0.05	Step-pool	Wandering
	<0.01	Bedrock	Passive
	<0.001	Plane-bed	Passive
	<0.05	Plane-riffle	Passive
		Braided	Passive
Superficial geology	<0.001	Step-pool	Active Plane-riffle
	<0.05	Step-pool	Braided Wandering
	<0.01	Step-pool	Passive Plane-bed
	<0.01	Bedrock	Active
	<0.05	Bedrock	Plane-bed Plane-riffle Passive Wandering
Sinuosity	<0.001	Active	Step-pool Passive
	<0.05	Active	Bedrock Plane-bed
	<0.05	Wandering	Plane-bed Passive
	<0.01	Wandering	Step-pool
Valley slope	<0.001	Step-pool	Plane-bed Plane-riffle Active Passive
	<0.01	Step-pool	Bedrock Wandering
	<0.05	Step-pool	Pool-riffle
	<0.05	Bedrock	Plane-riffle
	<0.001	Bedrock	Active
	<0.01	Bedrock	Passive
	<0.001	Plane-bed	Active
	<0.05	Plane-bed	Braided
	<0.05	Passive	Wandering Plane-riffle
	<0.01	Passive	Braided
	<0.001	Passive	Plane-bed Active

Table 3-6: Results from Kruskal-Wallis performed on catchment drivers, showing P-values, and channel types identified from the post-hoc procedure.

3.5.3 Multivariate techniques can statistically separate channel types in the SEPA typology using catchment drivers.

An agglomerative HCA was initially performed on the catchment driver dataset. The outputs of a HCA are an agglomeration schedule (Table 3-7) and a dendrogram (Figure 3-8). The agglomeration schedule shows the steps taken during the clustering process, starting with the linking of variables with the highest similarity. Linkages form an initial level of clustering in the dendrogram, which identifies three clusters (Figure 3-8), each comprising three to four variables. The number of clusters in the dendrogram (the cluster solution) is determined by a large difference in distance level between each step in the agglomeration schedule. A good cluster solution is before a large difference in distance level. A large difference between distance levels occurs between step seven and eight, which corresponds to a three cluster solution. The variables at the centroid of each cluster (valley slope, valley width, and catchment area) were entered into a subsequent HCA, to identify if the study reaches clustered into the channel types in the SEPA typology. The centroid variables were chosen to reduce the co-linearity between variables.

Step	Number of clusters	Distance level	Difference between distance level
1	9	0.01	
2	8	0.05	0.03
3	7	0.12	0.07
4	6	0.33	0.21
5	5	0.57	0.24
6	4	0.68	0.11
7	3	0.74	0.06
8	2	1.33	0.59
9	1	4.86	3.53

Table 3-7: Agglomeration schedule generated in HCA using catchment driver variables.

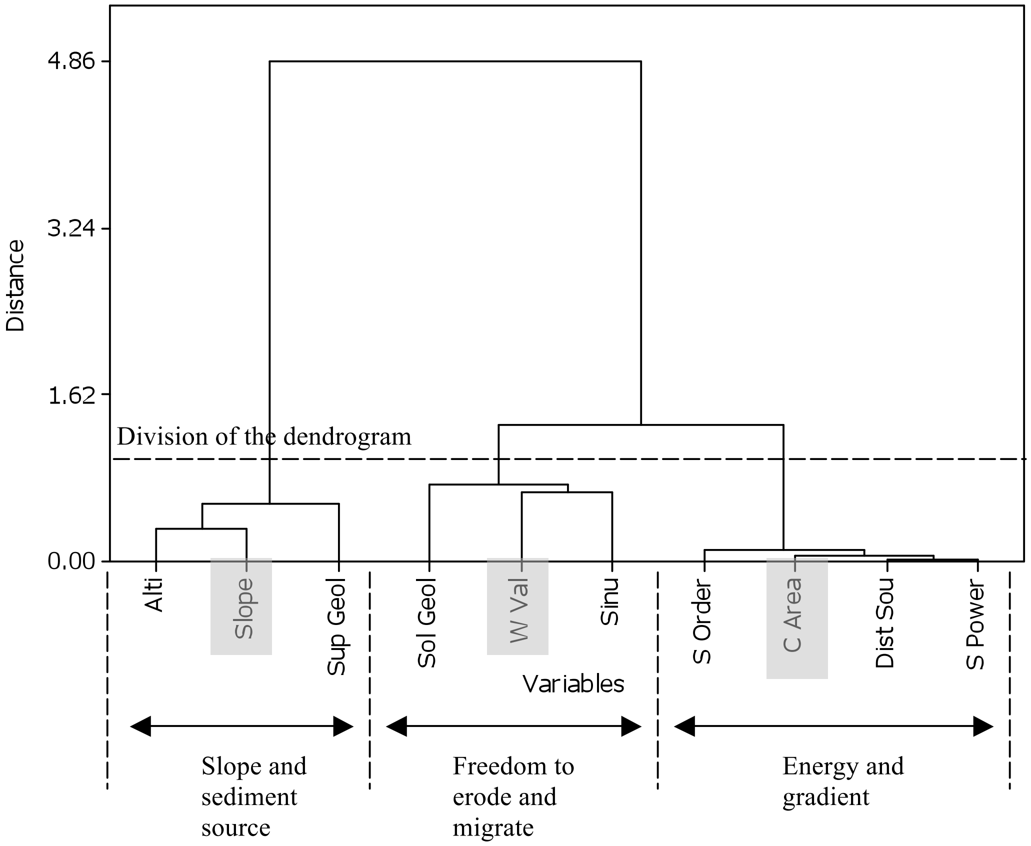


Figure 3-8: Dendrogram of the catchment driver variables produced in HCA. Catchment driver codes are shown in Table 3.1. Variables highlighted in grey tone denote centroid variables that are used in subsequent analyses.

The output of a second HCA (clustering of the study reaches) is displayed in the agglomeration schedule in Table 3-8, and the dendrogram in Figure 3-9. The agglomeration schedule shows a large difference in distance level between steps 63 and 64, implying the division of a four cluster solution. Each cluster consists of 14 to 19 study reaches.

Step	Number of clusters	Distance level	Difference between distance level
1	66	0.01	
2	65	0.02	0.02
3	64	0.08	0.06
4	63	0.09	0.01
5	62	0.09	0.00
6	61	0.14	0.05
7	60	0.18	0.04
8	59	0.20	0.02
9	58	0.20	0.01
10	57	0.21	0.01
↓	↓	↓	↓
58	9	2.602	0.41
59	8	2.89	0.29
60	7	3.99	1.09
61	6	6.51	2.53
62	5	7.01	0.50
63	4	7.79	0.78
64	3	14.90	7.11
65	2	25.63	10.73
66	1	36.19	10.56

Table 3-8: Agglomeration schedule for HCA of the 67 study reaches.

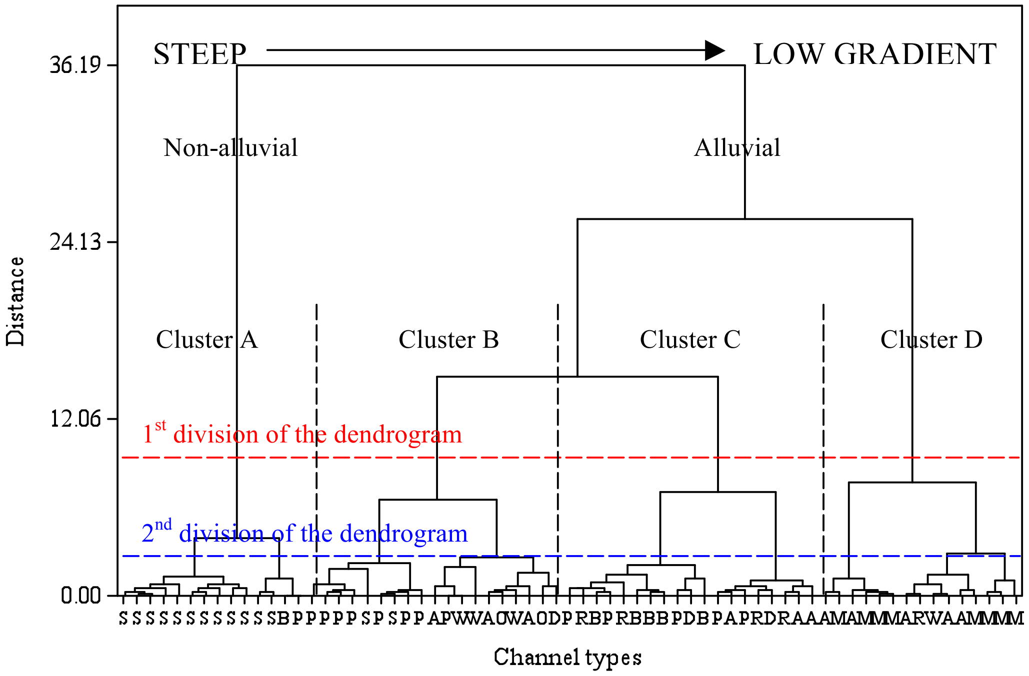


Figure 3-9: Dendrogram of the 67 study reaches using valley slope, upstream catchment area and valley width. Channel codes are shown in Table 3.2.

The first cluster in Figure 3-9, “Cluster A” consists predominantly of step-pool reaches. A combination of six different SEPA channel types constitutes the second cluster, “Cluster B”; the majority are plane-bed reaches with two active meandering reaches, one braided reach, two pool-riffle reaches, two step-pool reaches and three wandering reaches are also present (Table 3-9). The third cluster, “Cluster C” also contains a heterogeneous mixture of channel types, including active meandering, bedrock, braided, plane bed, and plane-riffle reaches. Passive meandering reaches govern the last cluster, “Cluster D” with three other types also present. The combination of channel types forming each cluster are summarised in Table 3-9.

	Cluster			
SEPA channel type	A	B	C	D
Active meandering		3	3	5
Bedrock	1		**5**	
Braided		1	2	
Passive meandering				**8**
Plane-bed	1	**8**	**5**	
Plane-riffle			4	1
Pool-riffle		2		
Step-pool	**12**	2		
Wandering		3		1
Total	14	19	19	15

Table 3-9: Number of SEPA channel types identified in each cluster of the dendrogram in Figure 3-9. Numbers in bold indicate the most common recurring channel type in each cluster.

The most commonly occurring channel type in each cluster was used to classify the cluster as a whole. Hence, the four clusters formed in the HCA are interpreted as typically representing step-pool, plane-bed, bedrock/plane-bed, and passive meandering channels. Step-pool reaches clearly dominate Cluster A, and plane-bed reaches govern Cluster B. However, both bedrock and plane-bed reaches are the prevailing channel type in Cluster C, with many other channel types also been present.

As a consequence of this co-occurrence of many diverse channel types, the Cluster was renamed as a semi-constrained channel in an attempt to reflect the broad characteristics of the channel types present. Passive meandering channels are the most frequently occurring channel type in Cluster D, but the cluster also contains five active meandering reaches. To better portray the characteristics of the majority of reaches, Cluster D will simply be known as a 'meandering' channel type. These broad channel type groupings generated by the HCA: step-pool, plane-bed, semi-constrained, and meandering, will now be referred to as the 'Catchment Driver Typology'.

The HCA generated four clusters. However, closer inspection of the dendrogram in Figure 3-9 reveals sub-clusters within the four main clusters. Also, further inspection of the agglomeration schedule (in Table 3-8) supports the presence of sub-clusters, and reveals a marked increase in distance levels between steps 59 and 60, and also between steps 60 and 61. These imposed cut-offs would indicate the presence of seven and eight clusters respectively. The increase in distance level is greatest between step 60 and 61 (2.53) compared to steps 59 and 60 (1.09), so the analysis will focus on the 8 cluster division. Each of the four main clusters is split into two sub-clusters. Similar to the above procedure, the most frequently occurring channel type was used to classify the sub-cluster as a whole. However, as one channel type appeared dominant in more than one sub-cluster, additional terminologies were used indicating transitional channel types (Table 3-10). Based on this rationale, the eight sub-clusters have been designated as: step-pool, stepped-bed (transitional between step-pool and plane-bed reaches), plane-bed, an upland gravel, meandering bed (transitional between wandering and active meandering channels), bedrock, glide-pool (transitional between plane-bed and active meandering), active meandering, and passive meandering. Similar to the four main clusters, the majority of sub-clusters comprise a heterogeneous mix of channel types, which implies variability within the clusters based on catchment drivers, and suggests the presence of fuzzy boundaries. Alternatively, the mixture of channel types within one cluster maybe due to misclassification of the reach, or imply that there are too many channel types in the SEPA typology, and merging of channel types may thus be appropriate. The second division in the dendrogram (in Figure 3-9) was rejected, in favour of the initial cut-off, as it resulted in high variability in group size and had little relationship to the SEPA channel types. However, both Table 3-9 and 3-10 demonstrate that one channel type may occur across several catchment driver clusters, and as a result, is not unique to a particular combination of variables. One catchment driver cluster will therefore, generally contain several different SEPA channel types.

	Sub-cluster							
SEPA channel type	A1	A2	B1	B2	C1	C2	D1	D2
Active meandering				**3**		**3**	2	3
Bedrock		1			**5**			
Braided				1	1	1		
Passive meandering							**4**	**4**
Plane-bed		1	**7**	1	3	2		
Plane-riffle					2	2		1
Pool-riffle				2				
Step-pool	**10**	**2**	2					
Wandering				**3**				1
Total	10	4	9	10	11	8	6	9

Table 3-10: Number of SEPA channel types identified in each of the eight sub-clusters in the dendrogram in Figure 3-9. Numbers in bold indicate the most common recurring channel type/s in each cluster.

Principal Components Analysis (PCA) was performed on the three variables derived from the dendrogram in Figure 3-8. The PCA bi-plot for axes one and two is shown in

Figure 3-10. The points symbolise the study reaches, which are grouped according to channel types in the Catchment Driver typology. All of the polygon distributions of the channel types are separate, which indicates the agglomerative HCA (Table 3-10) has generated a typology containing channel types with distinct catchment driver characteristics. Table 3-11 shows the eigenvalues and percentage of variance accounted for by the three principal components (PCs) from the ordination. The vast majority of the variation in the PCA ordination is summarised by the first two PCs. As the first two PCs cumulatively account for a very high percentage of the data variability, addition analysis therefore, will focus on these first two components.

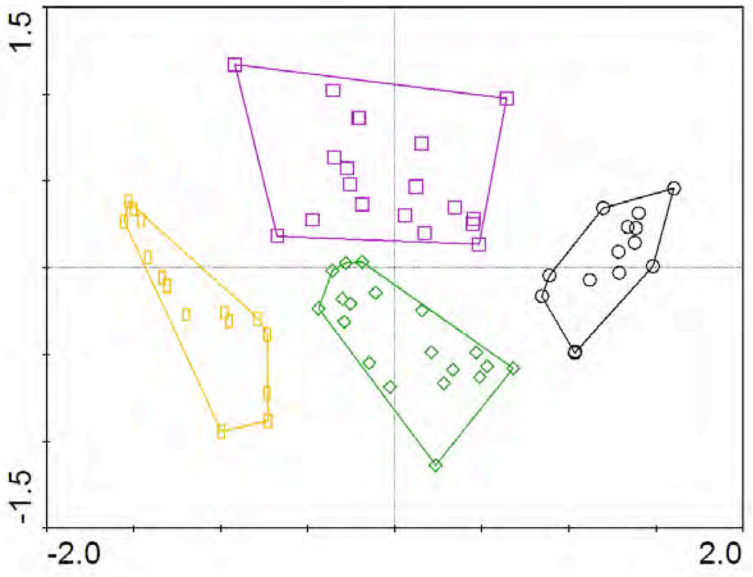


Figure 3-10: Distribution of samples based on several catchment drivers in PCA space. Channel types are ○ step-pool, □ plane-bed, ◊ semi-constrained, and ▮ meandering.

Axes	1	2	3
Eigenvalues	0.727	0.239	0.034
Percentage variance	72.7	23.9	3.4
Cumulative percentage variance	72.7	96.6	100

Table 3-11: Eigenvalues, percentage and cumulative variance for catchment drivers used in PCA.

Figure 3-11 displays the positioning of catchment drivers in PCA space. The arrows signify increasing values of catchment drivers radiating out from the centre of the bi-plot to the arrowhead. Hence, study reaches near the origin of the arrows possess low values of catchment drivers, whereas study reaches located near the arrowhead possess high values of that catchment driver. For examples, step-pool samples are clustered along the positive axis of PC1 (Figure 3-10). Their position in the bi-plot indicates the reaches occur on steep slopes with small catchment areas, in confined settings. In contrast, meandering reaches are located on the left hand side of the PCA bi-plot (Figure 3-10). The reaches occur on gentle gradients, have a wide floodplain, and have a large catchment area.

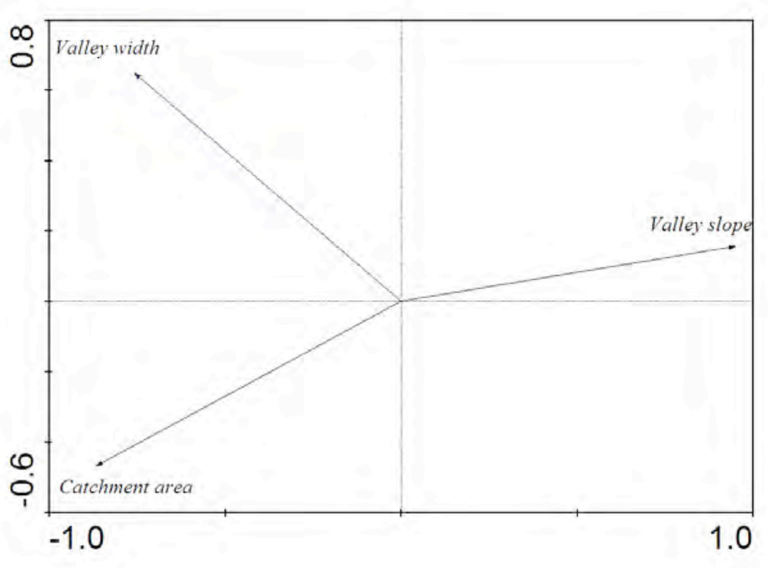


Figure 3-11: Distribution of catchment drivers in PCA space.

Table 3-12 presents the results of the post-hoc comparisons performed in a one-way ANOVA, conducted on the axis scores of PC1 and PC2. Channel types were derived from the clusters generated in the dendrogram in Figure 3-9. The results from the PC1 axis scores indicate that all pair-wise comparisons of channel types are statistically significant at the 0.001 significance level, apart from plane-bed and semi-constrained reaches. The results from the PC2 axis scores reveal that step-pool reaches are statistically different from plane-bed, and semi-constrained reaches. Also, plane-bed reaches are significantly different from semi-constrained and meandering reaches.

PC	*P*-value	Channel type	Post-hoc test group
PC1	<0.001	Step-pool	Plane-bed Semi-constrained Meandering
		Meandering	Plane-bed Semi-constrained
PC2	<0.01	Step-pool	Plane-bed
	<0.05	Step-pool	Semi-constrained
	<0.001	Plane-bed	Semi-constrained Meandering

Table 3-12: Results from a one-way ANOVA conducted on PC1 and PC2 axis scores, showing P-values, and the groupings generated in the Catchment Driver typology.

In summary, the analysis indicates that an agglomerative HCA failed to separate the study reaches into the SEPA channel types. Instead of a cluster clearly representing one channel type, each of the four clusters comprised a heterogeneous mixture of channel types. The four clusters were re-named as step-pool, plane-bed, semi-constrained, and meandering channels, and are known collectively as the ‘Catchment Driver Typology’. This typology could be generated remotely for a large number of river reaches using GIS-derived variables.

3.6 Discussion

The statistical analysis in this chapter presented a top-down approach to typing study reaches based on catchment driver variables derived through map work and GIS software. This approach builds on the existing work of characterising river systems based on landscape variables (Jeffers, 1998; Snelder and Biggs, 2000; Brierley and Fryirs, 2000, 2005; Orr *et al*. 2008), and ordination techniques (Schmitt *et al*. 2007; Harvey *et al*. 2008b). Jeffers (1998) used PCA to define a broad classification of river sites into montane, upland, lowland and coastal sites, and into sites with either high or low potential energy based on altitude, slope, distance from source and height of source derived from GIS software. Harvey *et al.* (2008b) used HCA and PCA to develop an ecologically meaningful classification using flow biotopes to define reach scale morphology. This study builds on the above studies and applies these techniques to the Scottish fluvial landscape. Overall, the study has found that using catchment driver variables and multivariate statistics cannot discriminate channel types in the SEPA typology.

3.6.1 The downstream distribution of channel types typically changes from step-pool, plane-bed, plane-riffle, pool-riffle, active meandering to passive meandering reaches.

The general downstream progression of channel types in the Allt Dubhaig and Allt a'Ghlinne Bhig catchments occur in a sequence of step-pool, plane-bed, and plane-riffle, through to meandering types in accordance with channel types in the Pacific north-west of the USA (see Chapter, Figure 2-8; Montgomery and Buffington, 1997, 1998). These initial results suggest that channel types have some predictable geographical positioning in the landscape. Bedrock reaches occur sporadically in the catchment due to local controls of steep gradients and hard geologies. The general pattern of channel morphology in the Allt Dubhaig and Allt a'Ghlinne Bhig catchments was found to be typical of other upland catchments in the study, and also in Scotland. Many catchments will share this broad downstream sequence of channel types (step-pool, plane-bed, plane-riffle and meandering reaches), but few catchments will have the exact sequence or possess all possible channel types due to the complex interactions of environmental variables, geological discontinuities, and the geographic complexity of a river system. Montgomery and Buffington (1997) highlight that the specific sequence of channel types varies in each catchment depending on local factors governing channel slope, discharge, sediment supply, bedrock lithology and disturbance history. The general downstream progression of the channel morphologies in the Allt Dubhaig and Allt a'Ghlinne Bhig catchments are accompanied by an inevitable reduction in channel bed slope and an increase in valley width (Figures 3-5 and 3-6).

3.6.2 *Catchment drivers can be used as predictors to identify channel types in the SEPA typology.*

The distribution of channel types based on the catchment drivers exhibited much overlap (Figure 3-7). Variations in catchment area, distance from source, sinuosity, stream order, stream power and valley width are linked to channel types, with an overall trend of increasing median values from step-pool reaches, through to passive meandering, and to passive meandering reaches. The differences in solid geology and superficial geology are relatively small, supported by the results from the ANOVA post-hoc tests. A trend of decreasing median values is present for altitude and valley slope. None of the catchment drivers separated channel types, apart from step-pool reaches. Step-pool reaches have a unique median and quartile range based on catchment area, distance from source, stream order, stream power and valley slope characteristics. Montgomery and Buffington (1997) also found that step-pool channels, and cascade channels could be distinguished based on slope values, but the distribution of alluvial channels: forced pool-riffle, pool-riffle and plane-bed channels overlapped.

The overlapping distribution of channel types based on catchment drivers reveals that reaches cannot be defined based on an individual variable, and therefore, the hypothesis that catchment drivers can be used as predictors to identify the SEPA channel types has to be rejected. Thus, a multivariate approach combining the best discriminating variables is needed. This may differ from simple hierarchical typologies that split groups of sites sequentially into an increasing number of types.

3.6.3 Multivariate techniques can statistically separate the channel types in the SEPA typology using catchment drivers.

The dendrogram generated by the agglomerative HCA (in Figure 3-9) identified four clusters. Each cluster comprises three to six SEPA channel types. The results of the HCA reveal that only two (step-pool and plane-bed) of the nine channel types classified in the field can be identified based on catchment driver variables. Thus, the SEPA channel types could not be separated based on a HCA, and the above hypothesis has to be rejected. The most commonly occurring channel type/s in each Clusters A and B was used to classify the cluster as a whole. However, as a mixture of channel types comprise Cluster C, a broad general label of 'semi-constrained' was chosen. Cluster D was named as a meandering channel type to mirror the characteristics of both active and passive meandering channels forming the cluster. Hence, the four clusters generated by HCA were interpreted as representing step-pool, plane-bed, semi-constrained, and meandering reaches.

The output of the agglomerative HCA combined with the PCA ordination indicates step-pool reaches in Cluster A typically occur in mountainous areas; reaches in Clusters B and C occur in upland areas, and meandering gravel-bed reaches in Cluster D are found in lowland environments. The reaches appear to be on a continuum from headwater to lowland settings. This is a similar pattern to the results obtained by Jeffers (1998) who characterised river habitats and predicted habitat features using ordination techniques. The study found that division of the plane of projection of a PCA ordination using four map-derived variables (altitude, slope, distance to source and height of source) generated eight zones, implying a broad classification of sites into montane, upland, lowland and coastal sites, and into sites with either high or low potential energy (Figure 3-12; Jeffers, 1998; Environment Agency, 2002). Sites designated as montane possess a PC1 value greater than or equal to 2.0, while those with a PC1 value less than 2.0 or greater than or equal to zero are denoted as upland. Likewise, sites with a PC1 value of less than zero but greater or equal to -2.0 are lowland, and sites possessing a PC1 value less than -2.0 are in coastal locations. The value of PC2 being greater or less than zero was also used to classify sites as having a high or low potential energy (Figure 3-12). Following a similar methodology to Jeffers (1998), lines have been drawn arbitrarily on the dendrogram generated by the HCA (in Figure 3-9), to show the positioning of channel types in the landscape (Figure 3-13). The lines were drawn arbitrarily at a PC1 value of 0.75 and at -0.75.

The value of PC1 axes in the biplot (Figure 3-13) range from -2.0 to 2.0, and the value of PC2 have a value from -1.5 to 1.5. The range of axis scores in the present study has a smaller value in comparison to the PC scores in the biplot generated by Jeffers (1998). The present study was conducted mainly in upland environments in Scotland, with some lowland reaches surveyed. However, the sites used by Jeffers (1998) were located across England and Wales, and thus, cover a much larger geographical distribution and range of conditions. The study recommends that any further work be conducted on a greater number of sites in lowland and coastal settings to obtain a more representative number of environments.

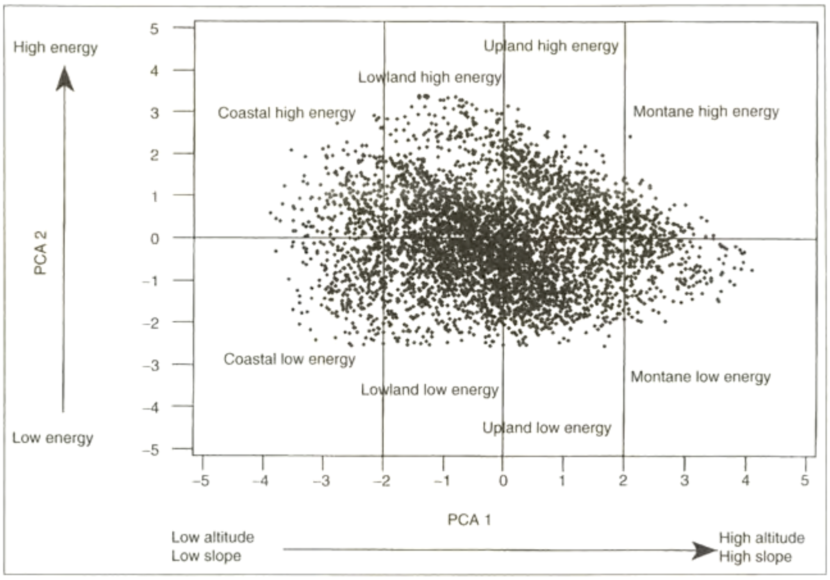


Figure 3-12: Principal Component Analysis conducted on 4569 English and Welsh sites classified by their altitude, slope, distance from source, and height of source (reproduced from the Environment Agency, 2002).

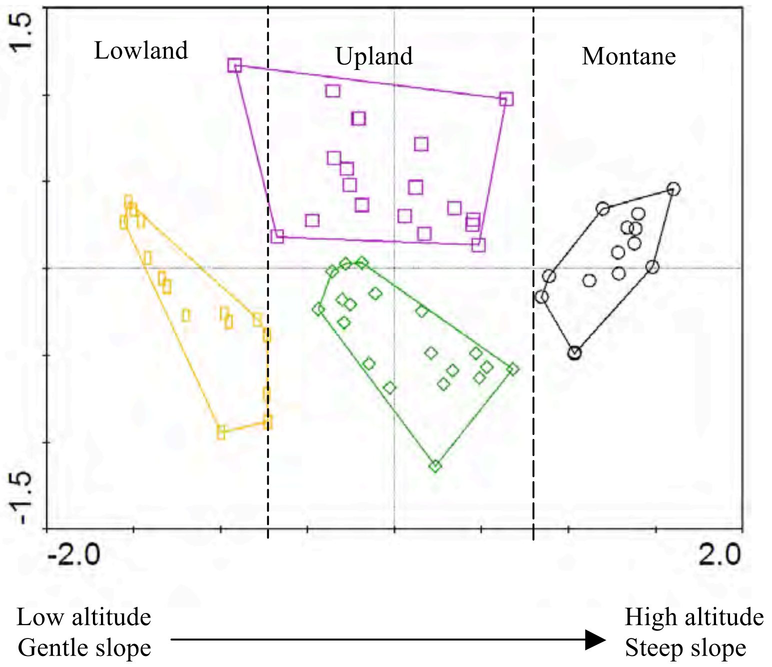


Figure 3-13: PCA ordination showing the position of channel types in a downstream continuum. Channel types are ○ step-pool, □ plane-bed, ◊ semi-constrained, and ▮ meandering.

The channel types identified in the dendrogram (in Figure 3-9) and PCA ordination are only likely to be useful for management purposes if they can be used to predict physical habitat characteristics of the sites, such as substrate, flow types, and channel and bank features (Jeffers, 1998) or relate to processes. The four broad channel types (step-pool, plane-bed, semi-constrained and meandering channels) generated in the first division of the agglomerative HCA presumably reflect the changing relative ratio of transport capacity to sediment supply through a catchment. Step-pool reaches (Cluster A) reflect supply-limited transport conditions, whereas plane-bed reaches are the most common channel type in Cluster B, and are typically viewed as transitional between supply- and transport-limited morphologies (Montgomery and Buffington, 1997, 1998). Plane-riffle reaches (in Cluster C) share traits of both plane-bed, and pool-riffle morphologies, and have a mixture of supply- and transport-limited conditions, although the presence of depositional features suggests they are a transport-limited environment. However, bedrock reaches (in Cluster C) lack a contiguous alluvial bed and have high transport capacities relative to sediment supply (Gilbert, 1914; Montgomery and Buffington, 1997, 1998). Active and passive meandering reaches are both prevalent in Cluster D. The presence of gravel bars in these meandering reaches implies they are transport-limited. The transport-limited characteristics of both plane-riffle and meandering reaches contrast with the more supply-limited characteristics of step-pool reaches, and the transitional character of plane-bed reaches. However, the results show that several channel types occur in each cluster, particularly in the semi-constrained group; therefore, the overall dominant processes of transport capacity to sediment supply will not be applicable to every reach in the cluster. As well as relating to processes, the reaches in the four groups need to relate to physical habitat characteristics, and to be ecologically relevant. This will be explored in Chapter 4 and 5.

In summary, three catchment drivers of valley slope, catchment area and valley width have emerged as key axes on the study reach groupings. These three catchment drivers are able to type reaches at a crude level used in the study, and have generated the following groupings of step-pool, plane-bed, semi-constrained, and meandering reaches. The groupings tend to be spatially positioned along a downstream continuum. Classifications based on these three variables may start to break down when up-scaling to larger catchments. For example, it may be advantageous to trial the methodology on a large catchment, such as the River Tay or the River Spey (catchment areas 4690km^2 and 3008km^2 respectively). The study advocates validation of the proposed methodology at larger catchment scales to identify if the results extend beyond the limits of the environmental settings, and the scale at which they were conducted.

3.7 General discussions and conclusions

3.7.1 Methodological approach

The methodology employed in this study has implications for classifying rivers in other geographical settings. The approach is relatively similar to the methods of Schmitt *et al.* (2007). The approach adopted in this study comprises four stages (as outlined in Figure 3-3). In the first stage, sites within a sub-catchment were typed according to the channel types in the SEPA typology by a fieldwork reconnaissance survey. The second stage comprised map-based analysis and creation of digital maps in a GIS package, followed by derivation of catchment driver variables. Stage 3 consisted of using agglomerative HCA to identify catchment driver variables at the centroid of each cluster, and subsequently using theses variables in a second agglomerative HCA to generate a statistically derived channel typology. In the final stage, functional groupings were the product of quantitative and objective groupings of channel reaches, rather than a typology founded on subjective criteria, as adopted in most classification systems (Kondolf *et al.* 2003). This method is simple computationally, and requires relatively few materials. A good topographic map within a GIS package and OS maps of the study area are essential. When applied to other catchments in different regions, the HCA might generate a different number of clusters. The study stresses the importance of the methodology and the processes involved, rather than the number of clusters identified in this analysis. The number of clusters derived in the dendrogram in Figure 3-9 makes logical sense in terms of representing the fluvial processes in the Scottish landscape. The river typing approach developed here provides organisations with the opportunity of typing whole river systems at the national level within a GIS framework. Reliably mapping reaches at the national level will prove logistically impossible using the more traditional approach of visually classifying reaches using expert opinion, and it appears that many such reaches can be separated fairly reliably using GIS-derived predictors. The approach is also independent of variation in the opinions of experts. As such, the study advocates a simple approach to river typing, based on an *a priori* multivariate analysis, to underpin river management and restoration. Further work is required to test the multivariate typology outside of the area in which it was developed. The physical habitat characteristics, including the morphological and sedimentological traits also need to be examined and the biological relevance of the typology determined. These issues are addressed in Chapters 4 and 5.

The temporal stability of study reaches is also an important issue (Nanson and Croke, 1992; Schmitt *et al*. 2007), since this may lead to a shift in channel type within a reach. Channels may adjust due to siltation, incision or major flood events that cause channel avulsion. These channel adjustments are often linked to inherited geomorphic features, and may infer that some reference states are in dynamic dis-equilibrium (Bravard, 1989, 2002; Jacob, 2003; Brierley and Fryirs, 2005). Nanson and Croke (1992) devised a classification system focusing on equilibrium by dividing floodplain types into dis-equilibrium and dynamic equilibrium classes. Trimble (1995) also based a classification upon temporal change and thresholds. Five conceptual models of valley storage fluxes included a quasi steady state class and four classes exhibiting progressions from a steady state (Goodwin, 1999). Bull (1991) proposes that these two classifications could include variables, such as reaction times versus relaxation time, or alternatively use threshold ratio variables such as stream power to critical power (Bull, 1979). In the study, the temporal stability of reaches within the study was not addressed. Therefore, the typology may need to be reviewed in the future.

3.7.2 Limits of river classifications and typologies

River classifications and typologies have wide usage in fluvial stream management and restoration (Kondolf, 1995; Malavoi, 2000; Kondolf *et al.* 2003). However, it is paramount that managers avoid mistakenly using river typologies for purposes they were not intended (Schmitt *et al.* 2007). Classifications and typologies can generate broad generalisations for river systems and offer an insight into the linkages between channel networks and catchment scale processes (Montgomery and Buffington, 1998), but variability within groups is often still present. Hence, a typology only produces an indication of the spatio-temporal complexity of fluvial system dynamics (Kondolf, 1995; Kondolf *et al.* 2003). Typologies can be very appealing, particularly to non-geomorphologists, who may not fully understand the complex interactions of geomorphological processes and may feel a channel is fully described once "classified" (Kondolf *et al.* 2003), but this may result in major management errors (Miller and Ritter, 1996; Kondolf *et al.* 2001). Once a channel is designated, users of a classification system lacking a fluvial geomorphological background may consider characteristics "fully known", and abandon critical thinking in favour of the designated explanation for that stream class (Kondolf, 1995). River systems are ultimately a continuum in space and time, onto which types are imposed.

3.8 Conclusions

This chapter has presented an approach to reach-scale river typing using map-derived variables, supported by GIS procedures and a range of multivariate statistical techniques. The approach was applied to 67 near-natural river reaches within Scotland encompassing mainly upland and some lowland reaches. The multivariate typology in this study is applicable to reaches in near-natural condition.

Rivers are complex, dynamic systems that need to be interpreted within a local and historical context. Classifications and typologies are one of many tools that are applied to simplify and manage rivers, though they are not a panacea. Classifications can generate broad generalisations and offer an insight into the linkages between channel networks and catchment scale processes, but total dependence and misclassification by a surveyor can lead to damaging and costly mistakes. Attention must be given to bed morphology, valley confinement, position in the network and disturbance history. Inclusion of these variables within a spatial hierarchical framework can aid interpretation of field observations and assessment of channel conditions (Montgomery and Buffington, 1998). The approach given here uses widely available data and is simple computationally. GIS derived variables have proved useful in generating a broad characterisation of rivers in Scotland, but further work is needed for classifying rivers at finer scales and links to processes and associated biota need to be established.

4 Geomorphological typing of Scottish rivers using physical habitat variables

4.1 Introduction

The last chapter examined the efficacy of using catchment drivers to discriminate channel types in the SEPA typology based on map and GIS approaches. The catchment drivers failed to clearly identify the majority of channel types in the SEPA typology. The key aim of this chapter is to examine if multivariate methods using physical habitat variables derived from fieldwork procedures can generate a functional geomorphic typology based on measurements at the reach scale. The chapter also attempts to discriminate channel types in the SEPA typology using physical habitat variables. Additionally, the spatial extent and combinations of surface flow types (SFTs) within the study reaches are examined. Finally, the hydraulic and retention traits of the study reaches are investigated in order to determine whether channel types have a distinct hydraulic signature. The rationale, main aims of the chapter and related hypotheses are listed below.

4.2 Rationale

For any geomorphic classification system or typology to be ecologically relevant, channel types must have a distinct reach-scale morphology or physical habitat. Physical habitat at its most simple is the product of geomorphology and hydrology (Figure 4-1, Maddock; 1999). Structural features of river channels, such as channel size, channel shape, gradient, bank structure and substrate combined with a particular discharge generate a suite of hydraulic features with characteristic depths, velocities and shear stresses (Maddock, 1999). The combination of these structural features or geomorphology coupled with discharge regimes forms the physical habitat of river systems.

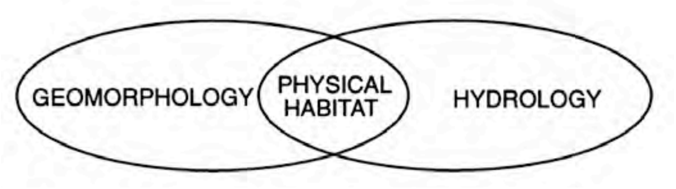


Figure 4-1: Physical habitat formed by the interaction of geomorphology and hydrology (from Maddock, 1999).

Physical habitat provides a logical basis to study the links between the environment and biota (Figure 4-2). Biota have been shown to respond to differences in physical habitat (reviewed in Giller and Malmqvist, 1998), such as substratum composition (Cobb *et al.* 1992; Quinn and Hickey, 1994; Lancaster and Mole, 1999; Thomson *et al.* 2004), hydrologic regime including flow magnitude, duration and timing of annual extreme conditions (Gibbins *et al.* 2001), frequency and duration of high and low flood pulses, the rate and frequency of variation in flow conditions (Maddock, 1999) depth (Mérigoux and Dolédec, 2004), cover (Kershner *et al.* 1992), and differences in streamwater chemistry that reflect variations in underlying geology (Clenaghan *et al.* 1998; Gibbins *et al.* 2001). Hence, a geomorphic classification system or typology with channel types possessing discrete physical habitat characteristics or a typology based on physical habitat traits is likely to be ecologically meaningful and highly useful for river management purposes.

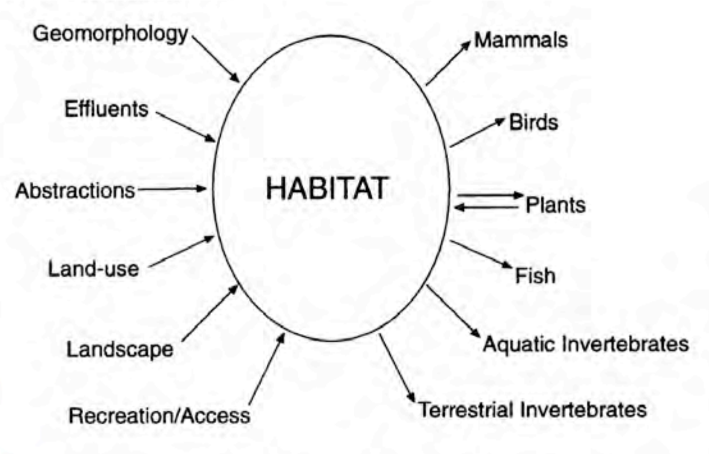


Figure 4-2: The concept of habitats as the natural link between the environment and its inhabitants (Harper *et al*. 1995).

4.3 Aims and hypotheses

The overall aim of the research presented in this chapter is to determine whether physical habitat variables can produce a functional geomorphic typology. A subsidiary aim is to investigate whether physical habitat variables can identify channel types in the SEPA and Catchment Driver typologies. Further aims include investigating the presence and combination of SFTs within the study reaches, and identifying if the SEPA channel types have a distinct hydraulic signature. The research hypotheses associated with these aims are:

a) Channel types in the SEPA and Catchment Driver typologies have significantly different depths, grain sizes and velocities.

b) Multivariate methods can discriminate channel types in the SEPA typology using physical habitat properties.

c) Catchment drivers can accurately predict channel types in the SEPA typology, and any groupings produced by multivariate methods using physical habitat properties in a Multiple Discriminant Analysis model.

d) Channel types in the SEPA typology are characterised by different surface flow types because of differing combinations of geomorphic units within reaches.

e) Channel types in the SEPA typology have varying hydraulic signatures due to variations in depth, grain size and velocity.

f) Retention decreases with distance downstream because of deeper depths, smaller grain sizes, higher velocities and wider channels.

4.4 Methods

4.4.1 Physical habitat characterisation

A preliminary study was carried out to trial the proposed fieldwork methodology in March 2007 on a pool-riffle and a plane-bed reach of the Dalveen Lane watercourse, a tributary of the River Nith in southern Scotland. A t-test indicated 100 measurements of water depth (*P* value 0.001), grain size (*P* value 0.009), and velocity (*P* value 0.052), across 20 channel widths showed a difference in most physical habitat properties between the two channel types. Thus, 100 measurements of water depth, grain size and velocity across 20 channel widths proved to provide a useful scale to link stream morphology to physical habitat characteristics. Montgomery and Buffington (1997) also found that 10 to 20 channel widths provided a useful scale to link stream morphology to channel processes and response potential in mountain drainage basins in the Pacific Northwest of the USA.

Morphological surveys of the study reaches took place in April-September 2007, and in April-August 2008. A detailed description of the study reaches used in the study can be found in Chapter 3, section 3.4.1. Surveys of the study reaches comprised measurements of channel bed slope, channel geometry, water depth, grain size and velocity. Channel bed slope was measured with an Electronic Distance Measure (EDM). Measurements of channel geometry were conducted at a riffle, a glide and a pool or at representative physical biotopes at each study reach. Water depth, grain size and velocity were measured at 100 equidistant points across the length of the channel using a 'zig-zag' procedure employed by Bevenger and King (1995). The three variables were sampled along a continuum as an integrated unit, incorporating a range of physical biotopes rather than sampling at individual cross-sections. Velocity (at 0.6 depth) was measured with a propeller current meter (Flo-mate, model 2000) for 20secs. A gravelometer incorporating the substrate categories of the Wentworth scale was used to measure grain size (Wentworth, 1922). Given that a significant number of bed material particles exceeded the Wentworth scale, three additional classes were added (256-512mm, 512-1048mm and >1048mm). Bedrock was recorded by the value one. Care was taken to minimise disturbance to the stream bed. The physical habitat variables obtained from fieldwork procedures are highlighted in Table 4-1.

Physical habitat variable	Code	Description
Bankfull width	Bank W	Horizontal level across the channel where the water initially flows onto the floodplain (m).
Water width	Water W	Horizontal level of the water surface (m).
Bank height (left and right banks)	Bank H	Vertical distance from the river bed to where water initially flows onto the floodplain (m).
Water Depth d_{10}	WD_{10}	Water depth of the 10th percentile.
Water Depth d_{25}	WD_{25}	Water depth of the 25th percentile (lower quartile).
Water Depth d_{50}	WD_{50}	Water depth of the 50th percentile (median value).
Water Depth d_{75}	WD_{75}	Water depth of the 75th percentile (upper quartile).
Water Depth d_{IQR}	WD_{IQR}	The inter-quartile range: the range in depth between the lower and upper quartile.
Water Depth d_{90}	WD_{90}	Water depth of the 90th percentile.
Water Depth d_{100}	WD_{100}	Water depth of the 100th percentile.
Grain Size gs_{10}	GS_{10}	Grain size of the 10th percentile.
Grain Size gs_{25}	GS_{25}	Grain size of the 25th percentile (lower quartile).
Grain Size gs_{50}	GS_{50}	Grain size of the 50th percentile (median value).
Grain Size gs_{75}	GS_{75}	Grain size of the 75th percentile (upper quartile).
Grain Size gs_{IQR}	GS_{IQR}	The inter-quartile range: the range in grain size between the lower and upper quartile.
Grain Size gs_{90}	GS_{90}	Grain size of the 90th percentile.
Grain Size gs_{100}	GS_{100}	Grain size of the 100th percentile.
Velocity v_{10}	Vel_{10}	Velocity of the 10th percentile.
Velocity v_{25}	Vel_{25}	Velocity of the 25th percentile (lower quartile).
Velocity v_{50}	Vel_{50}	Velocity of the 50th percentile (median value).
Velocity v_{75}	Vel_{75}	Velocity of the 75th percentile (upper quartile).
Velocity v_{IQR}	Vel_{IQR}	The inter-quartile range: the range in velocity between the lower and upper quartile.
Velocity v_{90}	Vel_{90}	Velocity of the 90th percentile.
Velocity v_{100}	Vel_{100}	Velocity of the 100th percentile.
Channel bed slope	C Slope	Average channel gradient of the reach (%).
Cross sectional area	CSA	Channel width multiplied by the sum of right and left bank top height and the water depth (m^2).
Discharge	Q	Cross sectional area multiplied by the averaged median velocity for the reach.
Total Stream Power Index	TSPI	Cross sectional area multiplied by slope.
Unit Stream Power Index	USPI	TSPI/width.
Width-depth ratio	WDR	Average channel width divided by average water depth at the 3 cross profiles.

Table 4-1: Physical habitat variables derived from fieldwork methods.

4.4.2 Surface flow types

The extent of SFTs (Table 4-2) in a study reach were recorded using modified terminology from the Environment Agency's (EA) River Habitat Survey (RHS) (Environment Agency, 2003). SFTs were recorded as rare, present or extensive (occupying <1%, 2-33% and >33% of the channel length respectively).

Surface flow type (Flow biotope)	Code	Description
Free fall	FF	Vertically-falling water that clearly separates from a vertical rock face.
Chute	CH	Low, curving flow with substantial water contact 'hugging' the substrate. Where multiple chutes occur over individual boulders or bedrock outcrops, a 'stepped' profile is created.
Broken standing waves	BW	Water appears to be flowing upstream. A white water wave must be present for the wave to be described as broken.
Unbroken standing waves	UW	Water has a disturbed 'dragon-back' surface, which has upstream facing wavelets that have not been broken.
Chaotic flow	CF	A mixture of several faster flow types (e.g. FF, CH, BW and UW) in no organised pattern.
Rippled	RP	Water surface with distinct, symmetrical, small ripples that are low and are moving downstream.
Upwelling	UP	Strong upward flow movements disturb the surface, creating an appearance of bubbling or boiling water.
Smooth	SM	Laminar flow where water does not produce a disturbed surface.
No perceptible flow	NP	In ponded reaches where it is difficult to perceive any surface water movement, or in pools where there is obvious rotational flow, but no net downstream movement of water at the surface.

Table 4-2: Description of surface flow types (modified from the Environment Agency, 2000 and Clifford *et al*. 2006).

4.4.3 Hydraulic diversity and retention

Hydraulic diversity and retention was measured through a short-term experiment of timing the speed of 100 plastic golf balls across a 100m section of a study reach. If the length of the study reach <100m, the extra distance was added proportionally to both ends of the reach. The plastic golf balls were chosen because of their consistent size, shape and density. The plastic golf balls were not intended to act as leaves or wood but as uniform, inexpensive, semi-buoyant material that could be readily monitored and used as an interpretive index of the hydraulic complexity and retention of a reach. The plastic golf balls will herein be referred to as ‘aqua-spheres’. The experiment finished 10mins after the last aqua-sphere had flowed 100m. Subsequently, a reconnaissance survey took place to retrieve any aqua-spheres trapped in the sedimentological and hydrological features within the reach. The number and location of aqua-spheres trapped in different sedimentological and hydrological features was noted. The variables derived from the hydraulic and retention experiments are shown in Table 4-3.

Hydraulic variable	Description
First aqua-sphere	Time of the first aqua-sphere to flow 100m
Last aqua-sphere	Time of the last aqua-sphere to flow 100m
Peak	Time of the peak number of aqua-spheres
Rising limb	Time between the first aqua-sphere and the peak number of aqua-spheres
Recessional limb	Time between the peak number of aqua-spheres and the last aqua-sphere
Number of peaks	Number of peaks in the response curve
Height of peak	The number of aqua-spheres at the height of the peak
Residence time	The base width of the response curve
Peakedness	Peak to base time ratio

Table 4-3: Variables derived from hydraulic and retention experiments.

The time of the first aqua-sphere to flow 100m is assumed to be indicative of the fastest velocity or the flow line along the thalweg. The median aqua-sphere reflects the average velocity and depth conditions of the 100m reach, and the recessional limb may represent aqua-spheres flowing in slower flows or aqua-spheres temporarily retained in storage, such as in backwaters or in a circulatory flow within an eddy.

Hydraulic diversity and retention experiments were also conducted on several SFTs: broken standing waves, unbroken standing waves, rippled flow and smooth flow. The aim of the hydraulic and diversity experiments was to identify how aqua-spheres responded to variations in flow associated with different SFTs. The time of 20 aqua-spheres across a 10m section of broken standing waves, unbroken standing waves, rippled and smooth flow was recorded. Each experiment was carried out three times on 10m sections of different SFTs. For example, the experiment was conducted on three 10m sections of broken standing waves, three 10m sections of unbroken standing waves, and so forth. In total twelve experiments were undertaken (4 SFTs x 3 experiments). The experiment ceased 10mins after the last aqua-sphere had flowed 10m. Similar to the above experiment, the number and location of aqua-spheres retained in any sedimentological and hydrological features was recorded. The hydraulic and diversity experiments were conducted on SFTs in the Allanwater, a tributary of the River Forth, in central Scotland.

4.5 Statistical analyses

In this chapter, data analysis consists of many of the descriptive and the multivariate statistical techniques used in Chapter 3. Initially, the frequency distributions of the physical habitat and hydraulic variables were tested for normality using the Shapiro-Wilk's (S-W) statistical test. Variables were transformed using log- or sqrt-transformations. In cases where the applied transformation produced even more skew than the original data, the untransformed data was used.

Agglomerative Hierarchical Cluster Analysis (HCA) was employed to group the study reaches based on their physical habitat characteristics, and identify any clusters. Subsequently, Principal Components Analysis (PCA) was performed to determine the extent by which different physical habitat variables dominated any clusters generated from the agglomerative HCA. A full description and explanation of HCA and PCA is given in the previous chapter in section 3.4.3

Multiple Discriminant Analysis (MDA, Tatsuoka, 1971) was also used to build a model to test the abilities of a range of catchment drivers to predict the SEPA channel types, and any groupings generated by the physical habitat dataset. MDA comprises a set of discriminant functions for predefined groups (i.e. channel types), based on linear combinations of the predictor variables (i.e. catchment drivers) that best segregate the groups (i.e. channel types). The discriminant functions can subsequently be used to classify new observations that have an unknown group membership.

Aqua-sphere data from the hydraulic diversity experiments for each study reach were grouped into 30sec time bands (i.e. 0-30, 31-60, 61-90secs). Data for each study reach were averaged according to channel type in the SEPA typology and plotted as hydrographs. Approaches dividing hydrographs into components are often based on the characteristics of the hydrograph shape (Gordon *et al.* 2008). The partition of the hydrograph is sometimes arbitrary; however, the consistent use of one approach is more important (Gordon *et al*. 2008). The base flow of the hydrograph was calculated by the use of a straight line from the point of rise on the hydrograph; to the recessional limb (an approach suggested by Linsley *et al.* 1975). The angle of the line is arbitrary and is based on the shape of the hydrograph. The base time (or residence time) was deemed the base width of the direct runoff segment of the hydrograph (Gordon *et al.* 2008). The 'flashiness' of the hydrograph was determined as the peak to base time ratio (Gregory and Walling, 1973). The components of the hydrograph are displayed in Figure 4-3. In this study, the hydrograph was re-named as a 'velocigraph' as the figure did not reflect changing discharge conditions, but reflected the velocity and depth characteristics in the 100m reach at the time of survey.

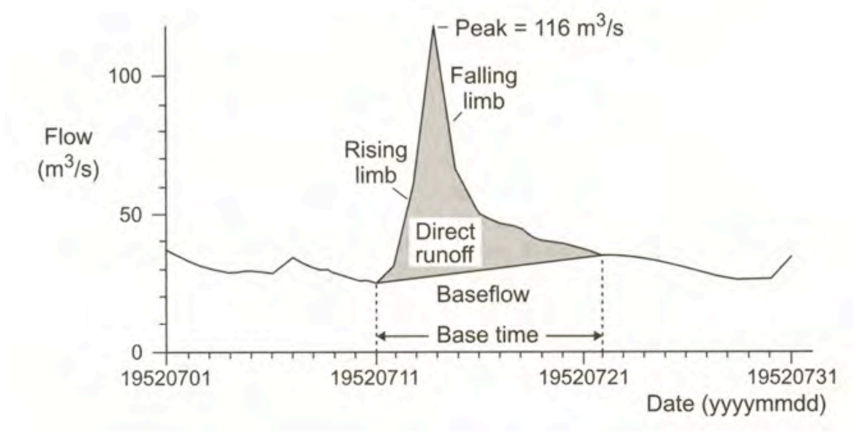


Figure 4-3: Components of a hydrograph (Gordon *et al.* 2008).

The hydraulic variables (in Table 4-3) were then entered into a PCA to identify the distinctiveness of the channel types. Subsequently, Kruskal-Wallis post-hoc tests were used to determine any significant differences between channel types based on PC1 axis scores. Finally, (simple) linear regression was employed to determine whether retention traits of the channel types vary with distance downstream.

Data obtained from the hydraulic and diversity experiments undertaken on different SFTs were plotted in Excel, and an average time for an aqua-sphere to flow 10m was determined. Subsequently, the average time per aqua-sphere from the 10m sections for each SFT was averaged, to produce an overall average time for an aqua-sphere to flow through a specific SFT. The average time for an aqua-sphere to flow through a SFT is expressed in metres per second. A summary of all statistical analyses in this chapter is shown in Table 4-4.

Factor of interest	Type of statistical technique	Input dataset	Typology used to group channel types
Identify SEPA channel types based on physical habitat characteristics	Boxplots	Physical habitat data	SEPA
Determine any significant differences between channel types	Kruskal Wallis tests	Physical habitat data	SEPA
Identify uncorrelated physical habitat variables	HCA	Physical habitat data	SEPA
Identify any physical habitat groups	HCA	Physical habitat data	SEPA
Identify percentage of data variability described by the physical habitat variables	PCA	Physical habitat data	SEPA
Determine any significant differences between channel types	ANOVA	PC1 axis scores	Physical habitat
Test catchment drivers ability to predict SEPA channel types and the physical habitat groups	MDA	Catchment-driver data	SEPA Physical habitat
Identify surface flow type of SEPA channel types	Bar chart	Surface flow type data	SEPA
Determine if channel types have a distinct hydraulic signature	Hydrographs	Aqua-sphere data	Physical habitat
Determine any distinct channel types based on hydraulic and retention characteristics	PCA	Aqua-sphere data	Physical habitat
Determine any significant differences between channel types	Kruskal Wallis tests	PC1 axis scores	Physical habitat

Table 4-4: Summary of statistical analyses employed in the chapter.

Descriptive statistics, including box and whisker plots, and agglomerative HCA were conducted in Minitab (version 15.1). PCA was applied in the Canoco software package (version 4.5, ter Braak and Šmilauer, 1998). MDA and ANOVA post-hoc tests were carried out in SPSS (version 16), and Kruskal-Wallis analyses were performed in the PAST (PAlaeontological STatistics) software package (version 1.94b, Hammer *et al.* 2001).

4.6 Results

4.6.1 Channel types in the SEPA and Catchment Driver typologies have significantly different depths, grain sizes and velocities.

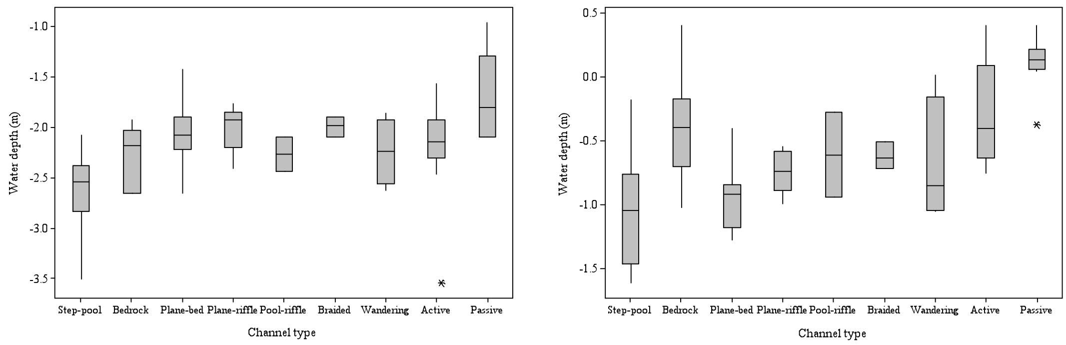
A statistical summary of water depth, grain size and velocity measurements is displayed in Table 4-5. The physical habitat characteristics of channel types in the SEPA and Catchment Driver typologies were explored by presenting box plots for the tenth and ninetieth percentile for water depth, grain size, and velocity (Figure 4-4 and 4-5). The tenth and ninetieth percentiles were chosen as it was assumed the values would reflect the presence of riffles and pools within a study reach. Also, the tenth and ninetieth percentiles were chosen as the values discriminated channel types more clearly compared to the twenty-fifth, median and seventy-fifth percentile.

Physical habitat variable	Min	Max	Med	Mean	SD	Skew	S-W (P)
WD_{10} (m)	0.03	0.38	0.12	0.12	0.06	1.84	<0.005
WD_{90} (m)	0.2	1.5	0.5	0.61	0.34	1.17	<0.005
GS_{10} (mm)	1	63	16	18.39	16.91	0.55	<0.005
GS_{90} (mm)	16	512	180	234.1	170.4	0.74	<0.005
Vel_{10} (m/s)	0.01	0.19	0.05	0.06	0.05	0.68	<0.005
Vel_{90} (m/s)	0.16	1.69	0.82	0.83	0.312	0.63	<0.005

Table 4-5: Summary of the physical habitat dataset. Physical habitat variable codes are shown in Table 4.1, and SD = Standard deviation and S-W = Shapiro-Wilk.

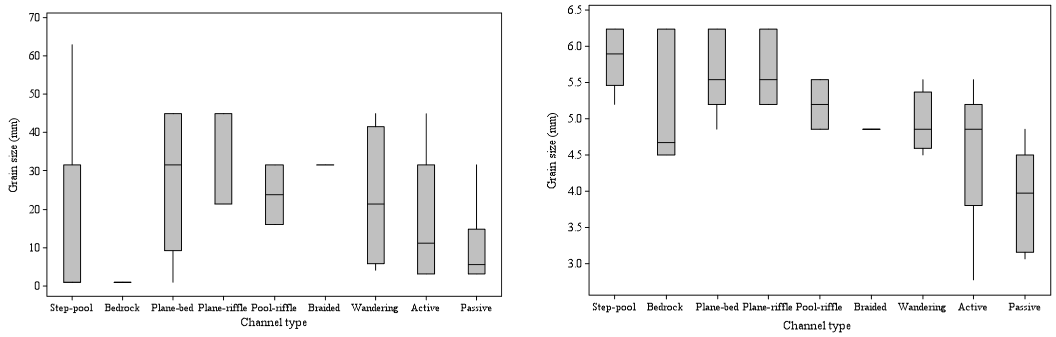
The distributions of channel types in both typologies clearly overlap, with few channel types possessing a discrete distribution based on any physical habitat property. For channel types in the SEPA typology (Figures 4-4a and 4-4b), there is an overall trend of increasing medians through from step-pool to passive meandering reaches based on WD_{10} and WD_{90} characteristics. A similar, but clearer trend is noted for channel types in the Catchment Driver typology (Figures 4-5a and 4-5b);

particularly meandering reaches as they possess a unique inter-quartile range based on WD_{90} values respectively. The difference in GS_{10} between channel types appears relatively small in both typologies. Similarly variations in GS_{90} appear slight, but an overall trend of decreasing medians across channel types is present in both typologies. In the SEPA typology, no pattern is apparent for Vel_{10} and Vel_{90} characteristics, excluding bedrock reaches, which have faster velocities (Figure 4-4b). In the Catchment Driver typology, variations in Vel_{10} are associated with a decrease in median values across channel types, excluding step-pool reaches. Channel types share similar median values for Vel_{90} values, with meandering reaches possessing lower median values.



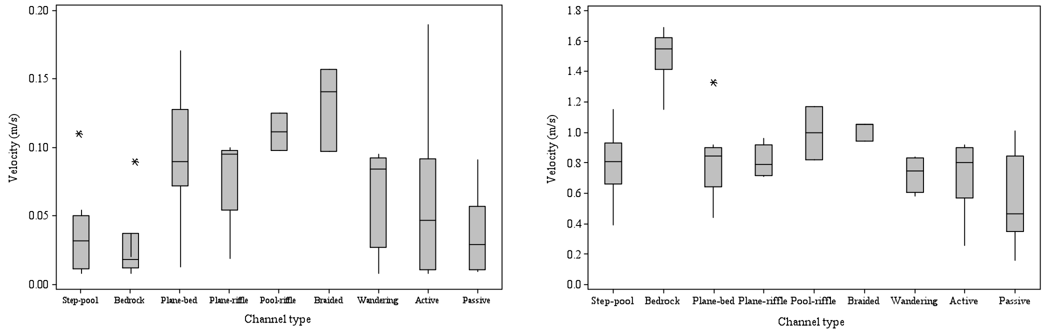
a) WD_{10} †

b) WD_{90}†



c) GS_{10}

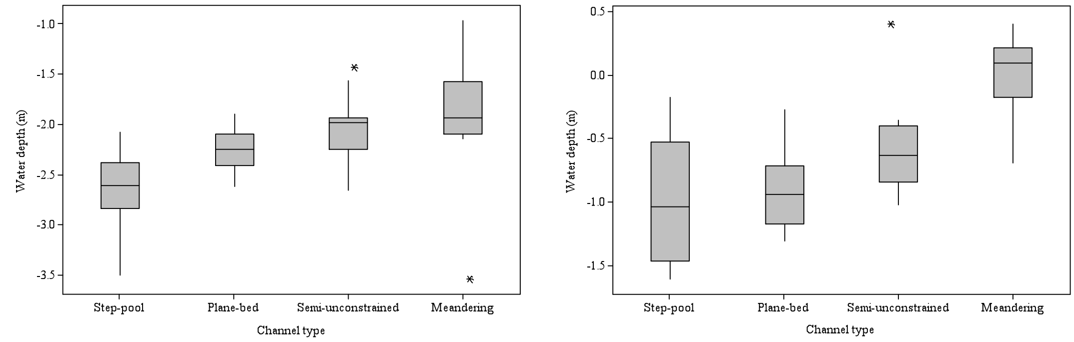
d) GS_{90}†



e) Vel_{10}

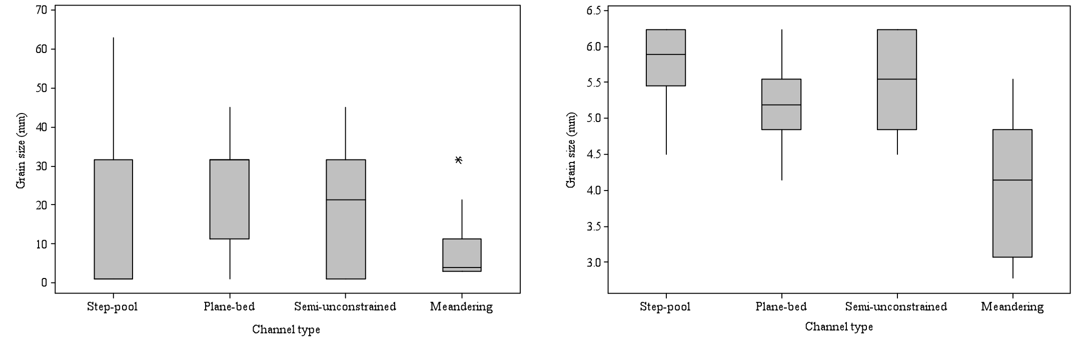
f) Vel_{90}

Figure 4-4: Boxplots of physical habitat variables grouped according to channel types in the SEPA typology; † indicates data has been transformed.



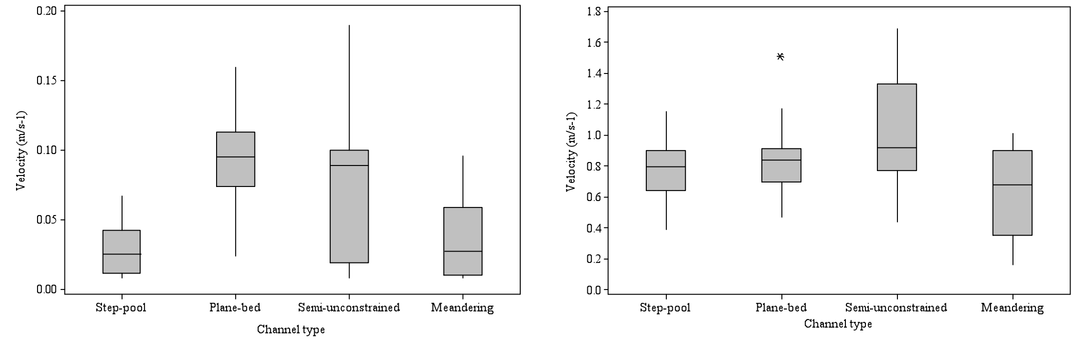
a) WD_{10}†

b) WD_{90}†



c) GS_{10}

d) GS_{90}†



e) Vel_{10}†

f) Vel_{90}†

Figure 4-5: Boxplots of physical habitat variables grouped according to channel types in the Catchment Driver typology; † indicates data has been transformed.

Kruskal Wallis tests identified some significant differences between channel types for most physical habitat properties (Table 4-6). In the SEPA typology, channel types were most clearly distinguished by their WD_{90}, GS_{90} and Vel_{90} characteristics. However, differences between channel types were less clear based on WD_{10} values, with several overlapping channel type groupings identified confirming that there is only a limited systematic difference in WD_{10} across the sample of reaches investigated. The Kruskal Wallis test identified step-pool reaches as shallower (a low WD_{10}), possessing a large number of boulders (a high GS_{90}), and having slower velocities (a low Vel_{10}).

In the Catchment Driver typology, the Kruskal-Wallis tests also revealed that meandering reaches were deeper (a high WD_{90}), had smaller grain sizes (a low GS_{90}), and slower velocities (a low Vel_{10}). In contrast, step-pool reaches were shallower (a low WD_{10} and WD_{90}), and contained coarser substrate material (a high GS_{90}).

Variable	*P* value	Channel type	Post-hoc test group
WD_{10}	<0.05	Step-pool	Plane-bed Passive
WD_{90}	<0.05	Step-pool	Active
	<0.01	Plane-bed	Active Passive
GS_{10}	<0.05	Bedrock	Active
GS_{90}	<0.05	Step-pool	Bedrock
	<0.000	Step-pool	Plane-bed Passive
	<0.001	Step-pool	Active
	<0.01	Plane-bed	Passive
Vel_{10}	<0.05	Step-pool	Plane-bed
Vel_{90}	<0.05	Bedrock	Step-pool Plane-bed Active

a) The SEPA typology

Variable	*P* value	Channel type	Post-hoc test group
WD_{10}	<0.001	Step-pool	Plane-bed Semi-constrained Meandering
	<0.01	Plane-bed	Meandering
WD_{90}	<0.05	Plane-bed	Semi-constrained
	<0.001	Meandering	Step-pool Plane-bed Semi-constrained
GS_{10}	<0.01	Plane-bed	Meandering
GS_{90}	<0.001	Meandering	Step-pool Plane-bed Semi-constrained
Vel_{10}	<0.001	Step-pool	Plane-bed
	<0.01	Plane-bed	Meandering
Vel_{90}	<0.05	Semi-unconstrained	Meandering

b) The Catchment Driver typology.

Table 4-6: Results of Kruskal-Wallis post-hoc tests performed on the channel types in a) the SEPA and b) the Catchment Driver typologies using several physical habitat variables. Variable codes are shown in Table 4-1.

The results of the box plots and Kruskal-Wallis tests reveal there is only a limited systematic difference in physical habitat characteristics between channel types in both typologies. Step-pool reaches in both typologies and meandering reaches in the

Catchment Driver typology are repeatedly distinguished by their physical habitat characteristics, but no other channel type is readily identifiable.

4.6.2 Multivariate methods can discriminate channel types in the SEPA typology using physical habitat properties.

An agglomerative HCA was performed on the physical habitat dataset in order to identify the best discriminating variables to segregate channel types in the SEPA typology. The output of the agglomerative HCA is shown by the dendrogram (in Figure 4-6), and the accompanying agglomeration schedule (in Table 4-7). The dendrogram (in Figure 4-6) visually shows the joining of different physical habitat variables through the clustering progress, and the agglomeration schedule (in Table 4-7) shows the steps during the clustering process: the number of clusters, the distance level and the distance between steps. The number of clusters in the dendrogram is decided upon by the first largest difference in distance level between each step. An appropriate number of clusters are before a large difference in distance level occurs. Hence, the agglomeration schedule shows the largest difference in distance level is between steps 18 and 19 (difference of 1.156), which relates to four clusters in the dendrogram (in Figure 4-6). Each cluster comprises four to seven variables. A variable was selected from each of the four clusters (WD_{IQR}, Q, GS_{IQR}, and Vel_{75}), and was entered into a second HCA to group the study reaches based on these physical habitat characteristics. One physical habitat variable was chosen from each cluster to decrease the co-linearity between variables.

Step	Number of clusters	Distance level	Distance between steps
1	21	0.018	
2	20	0.029	0.011
3	19	0.035	0.005
4	18	0.060	0.026
5	17	0.088	0.028
6	16	0.093	0.005
7	15	0.112	0.019
8	14	0.179	0.067
9	13	0.207	0.028
10	12	0.223	0.016
11	11	0.346	0.123
12	10	0.406	0.059
13	9	0.598	0.193
14	8	0.661	0.063
15	7	0.735	0.073
16	6	0.877	0.142
17	5	1.068	0.191
18	4	1.088	0.020
19	3	2.244	**1.156**
20	2	2.894	0.650
21	1	6.922	4.028

Table 4-7: Agglomeration schedule for HCA using physical habitat variables.

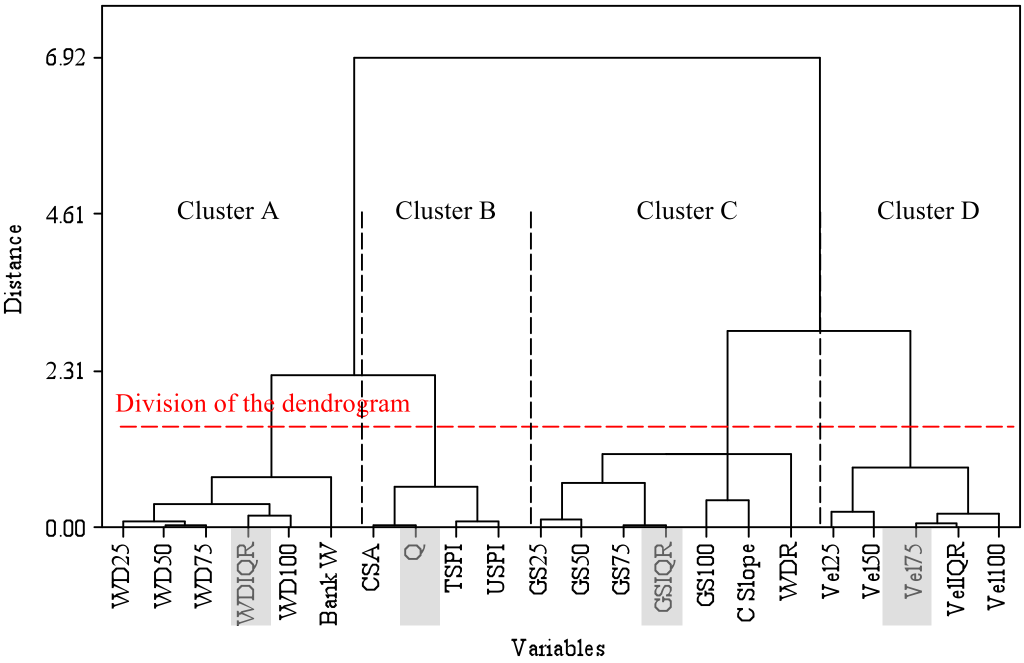


Figure 4-6: Dendrogram of the physical habitat variables generated in HCA. See Table 4-1 for variable codes. Variables highlighted in grey tone indicate centroid variables, which are used in subsequent analyses.

The agglomeration schedule (in Table 4-8) for the second agglomerative HCA shows the first substantial difference in distance level occurring between steps 61 and 62, suggesting the presence of six clusters in the dendrogram in Figure 4-7. Each cluster comprises between 6 to 23 study reaches. However, the agglomeration schedule also reveals several other large differences between steps. For example, a fairly considerable increase in distance level is present between steps 53 and 54, steps 56 and 57, and also steps 58 and 59. The division of the dendrogram according to these partitions relates to 14, 11 and 9 clusters respectively (shown in Figure 4-7).

Step	Number of clusters	Distance level	Distance between steps
1	66	0.222	
2	65	0.223	0.002
3	64	0.326	0.102
4	63	0.332	0.006
5	62	0.383	0.051
6	61	0.393	0.010
7	60	0.424	0.031
8	59	0.449	0.025
9	58	0.475	0.026
10	57	0.504	0.029
↓	↓	↓	↓
50	17	2.257	0.109
51	16	2.338	0.081
52	15	2.536	0.198
53	14	2.572	0.036
54	13	3.292	**0.720**
55	12	3.317	0.025
56	11	3.579	0.262
57	10	4.206	**0.627**
58	9	4.591	0.385
59	8	5.271	**0.681**
60	7	5.463	0.192
61	6	5.843	0.380
62	5	7.399	**1.556**
63	4	9.094	1.695
64	3	9.609	0.515
65	2	18.165	8.556
66	1	34.762	16.597

Table 4-8: Agglomeration schedule for HCA of the study reaches.

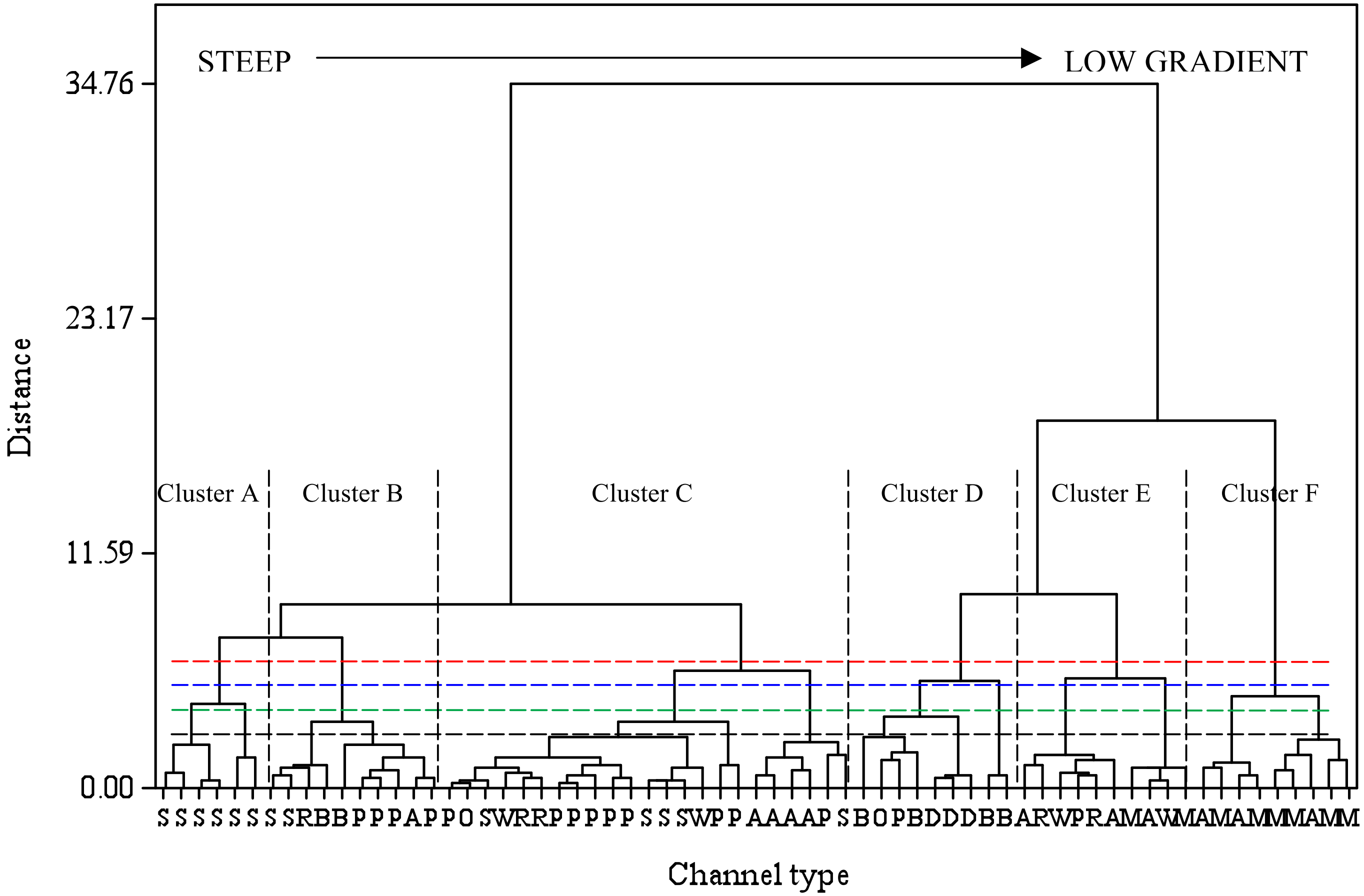


Figure 4-7: Ward-linkage dendrogram of the study reaches using the centroid physical habitat variables identified in Figure 4-6. See Table 4-9 for channel type codes. Dendrogram divisions are 1st = - - - , 2nd = - - -, 3rd = - - and 4th = - -

The physical habitat variables generated six clusters based on the first substantial difference in distance level (between steps 61 and 62) in the agglomeration schedule (in Table 4-8). The number and combination of SEPA channel types constituting each cluster are shown in Table 4-9. All the clusters are formed by a mixture of SEPA channel types; apart from “Cluster A”, which solely comprises step-pool reaches. Plane-bed reaches dominate both Clusters B and C, with the latter being the most heterogeneous cluster consisting of six SEPA channel types. Bedrock reaches are the most abundant channel type in Cluster D, with meandering types governing the final two clusters; active meandering reaches govern Cluster E and passive meandering reaches dominate Cluster F. The dominant channel type in each cluster was used to classify the cluster as a whole. Therefore, the clusters were identified as step-pool (Cluster A), plane-bed (Cluster B), plane-bed (Cluster C), bedrock (Cluster D), active meandering (Cluster E), and passive meandering (Cluster F) reaches. The predominance of plane-bed being the most common channel type in Clusters B and C indicates broad physical habitat characteristics within the ‘plane-bed’ category. Visual inspection of the photographs and examination of physical habitat data of the plane-bed reaches in Cluster B signifies the channels occur on moderately steep-gradients with a coarse bed, dominated by boulders and cobbles. In comparison, pebbles and gravels are the main sediment sizes within plane-bed reaches in Cluster C. Based on these morphological traits, Cluster B will be known as a coarse plane-boulder bed, and Cluster C will be named as plane-gravel bed. In further analysis and discussion, the clusters generated from the dendrogram (in Figure 4-7) will now be referred to by their given channel type labels. The six channel types will be known collectively as the “Physical Habitat Typology”.

		Cluster					
Channel type	Channel code	A	B	C	D	E	F
Active meandering	A		1	4		**3**	3
Bedrock	B		2		**4**		
Braided	D				3		
Passive meandering	M					2	**6**
Plane-bed	P		**4**	**8**	1	1	
Plane-riffle	R		1	2		2	
Pool-riffle	O			1	1		
Step-pool	S	**6**	2	6			
Wandering	W			2		2	
Total		6	10	23	9	10	9

Table 4-9: Number of SEPA channel types in each cluster of the dendrogram in Figure 4.6. Numbers in bold indicate the most common recurring channel type in each cluster.

PCA was conducted on the four physical habitat variables (WD_{IQR}, Q, GS_{IQR}, and Vel_{75}) identified from the dendrogram in Figure 4-6. The PCA biplot is shown in Figure 4-8. Table 4-10 shows the eigenvalues and percentage of variance accounted for by the four principal components (PCs) from the ordination. The vast majority of the variation in the PCA ordination is summarised in the first two axes, therefore, addition analysis will focus on these first two components. The ellipses of the six channel types clearly overlap. However, step-pool channels appear to be the most compact group, and only overlap with plane-gravel bed channels. Plane-boulder bed and plane-gravel bed channel types appear reasonably compact, and are distinct from bedrock and passive meandering reaches. Bedrock reaches have the largest ellipse; indicating members of the group have a diverse range of physical habitat characteristics.

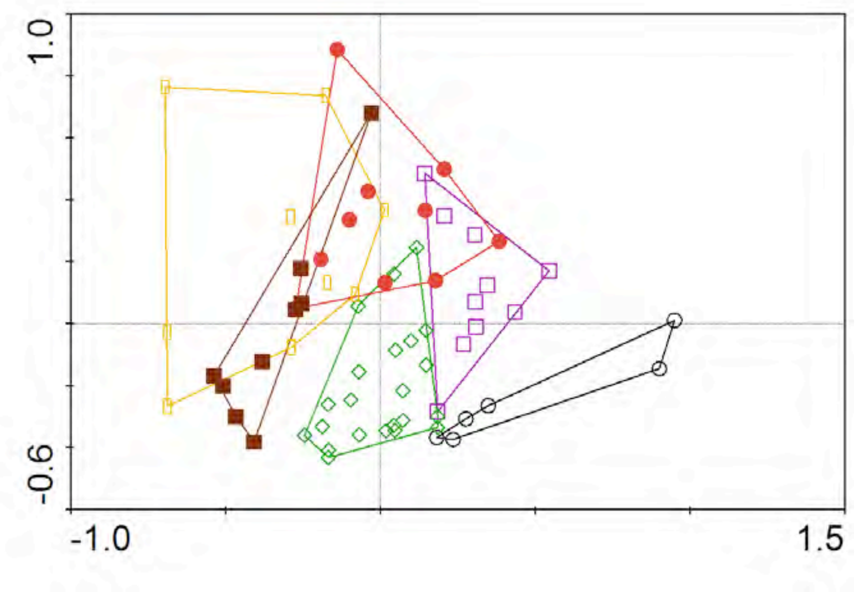


Figure 4-8: Distribution of samples based on a range of physical habitat variables in PCA space. Channel types are ○ step-pool, ☐ plane-boulder bed, ◊ plane-gravel bed, ▮ bedrock, ● active meandering, and ■ passive meandering.

Axes	1	2	3	4
Eigenvalues	0.97	0.028	0.001	0.001
Percentage variance	97	2.8	0.1	0.1
Cumulative percentage variance	97	99.8	99.9	100

Table 4-10: Eigenvalues, percentage and cumulative variance for physical habitat variables used in the PCA.

The spatial arrangement of physical habitat variables in PCA space is highlighted in Figure 4-9. PC1 was interpreted as a sedimentological gradient. Reaches located at the centre of the bi-plot have a very small inter-quartile range grain size (GS_{IQR}). Traversing horizontally across the positive axis of PC1, the GS_{IQR} values increase. Hence, samples located to the left and to the centre of the ordination will have small GS_{IQR}, and samples positioned towards the right side of the ordination will possess large values of GS_{IQR}. Plane-bed, plane-boulder bed, and step-pool reaches lie on this gradient of increasing GS_{IQR}. The second axis symbolises an index of discharge gradient. Reaches located to the upper centre of the PCA ordination will possess a high discharge and Vel_{75} values, compared to the reaches at the centre and bottom of the ordination.

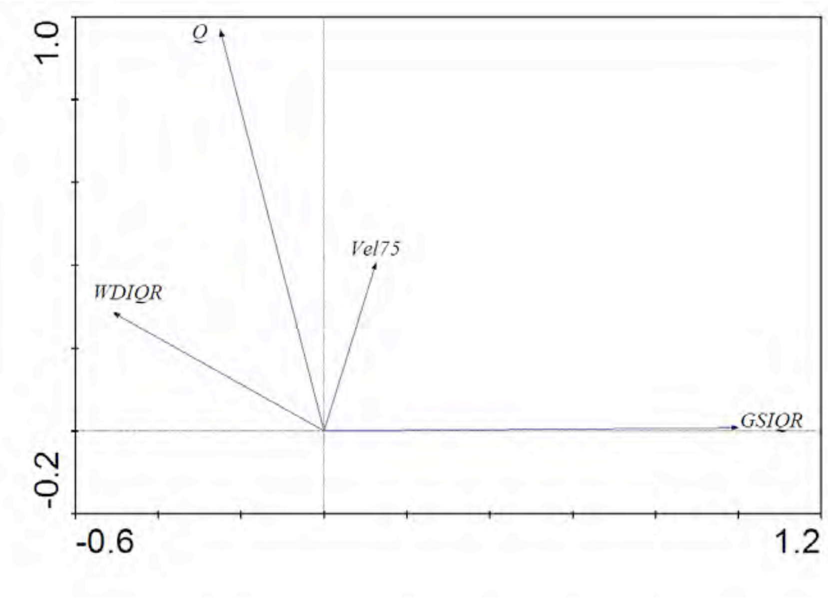
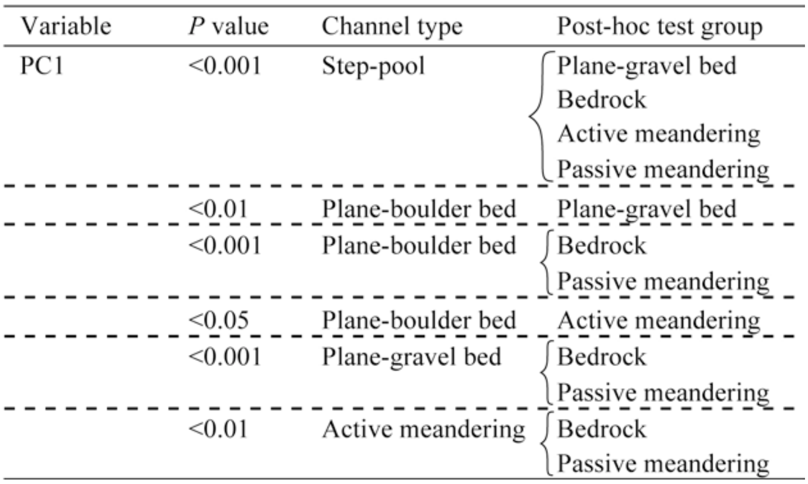


Figure 4-9: Distribution of physical habitat variables in PCA space. Variable codes are shown in Table 4-1.

The results of the post-hoc comparisons performed in a one-way ANOVA conducted on the PC1 axis scores are shown in Table 4-11. Samples are grouped according to the six main channel types in the Physical Habitat typology. The results from the PC1 axis scores indicate that most pair-wise comparisons are statistically significant at the 0.001 significance level. Step-pool channels are significantly different from all other channel types, excluding plane-boulder bed channels. The result is supported visually by the ellipse distributions in the PCA ordination (Figure 4-8). Similarly, plane-boulder bed channels are significantly different from all other channel types (excluding step-pool channels). Results from the PC1 axis scores also indicate that plane-gravel bed samples are significant from bedrock and passive meandering samples. This ANOVA post-hoc test is supported in the PCA ordination. The distribution of plane-gravel bed samples does not overlap the ellipses of bedrock and passive meandering samples. Finally, active meandering samples are different from bedrock and passive meandering channels.



Variable	P value	Channel type	Post-hoc test group
PC1	<0.001	Step-pool	Plane-gravel bed Bedrock Active meandering Passive meandering
	<0.01	Plane-boulder bed	Plane-gravel bed
	<0.001	Plane-boulder bed	Bedrock Passive meandering
	<0.05	Plane-boulder bed	Active meandering
	<0.001	Plane-gravel bed	Bedrock Passive meandering
	<0.01	Active meandering	Bedrock Passive meandering

Table 4-11: Results of the post-hoc comparisons performed in ANOVA conducted on the PC1 axis scores according to channel types in the Physical Habitat typology.

The results of the HCA and PCA have revealed that four physical habitat variables of WD_{IQR}, a surrogate index of discharge, GS_{IQR} and Vel_{75} have generated a river typology containing six channel types. Post-hoc ANOVA tests indicate the majority of channel types are significantly different from one another, especially step-pool, plane-gravel bed, bedrock and passive meandering channels.

4.6.3 Catchment drivers can accurately predict channel types in the SEPA typology, and any groupings produced by multivariate methods using physical habitat properties in a Multiple Discriminant Analysis model.

MDA was applied to identify the predictive capability of a suite of catchment drivers, such as valley slope, superficial and solid geology, valley width and altitude (see Chapter 3, Table 3-1 for catchment drivers used in analysis) to determine (i) the nine channel types in the SEPA typology, and (ii) the six channel types identified in the

Physical Habitat typology. MDA determines the relative contribution of each of the environmental variables (or in this case catchment drivers) to the partition among the groups (i.e. channel types) (McElarney and Rippey, 2009). For the SEPA typology, the first discriminant function explained 60.5% of the data variability, with the second discriminant function explaining an additional 23.5%. The first two discriminant functions therefore, account for 84% of the data variability in the MDA model. The main catchment driver variables for the first discriminant function were a surrogate measure of discharge, distance from source and valley slope (standardised canonical discriminant functions coefficients of 2.5, -1.6 and -0.5 respectively). A Wilks' lambda value of 0.011 shows the first discriminant function was significantly different ($P < 0.001$). Eigenvalues for the first three discriminant functions were 6.1, 2.4 and 0.7.

The MDA was re-run using the same catchment drivers, but the study reaches were classified according to channel types in the Physical Habitat typology. The dominant catchment drivers for the first discriminant analysis were again distance from source, a surrogate measure of discharge, and valley slope (standardised canonical discriminant function coefficients of 1.4, -0.1 and -0.7 respectively), and explained 69.4% of the variability in the MDA model. The discriminant functions (five used in the analysis) were significantly different (Wilks' lambda, 0.04, $P < 0.001$). The eigenvalues for the first three discriminant functions were 4.8, 1.5 and 0.4.

The results of the classification matrix within a MDA model provide the final test of discriminant analysis (Rock, 1988), and indicates the robustness of the tested typologies. A cross validation was used, whereby each case (i.e. study reach) is classified by the functions derived from all cases (i.e. study reaches) other than that case (i.e. study reach). Table 4-12 shows the different percentages of correct predictions per channel type for both typologies, and indicates the catchment drivers can assign a similar percentage of study reaches to the correct channel type for both typologies (55.2% for the SEPA typology and 56.7% for the Physical Habitat typology).

	SEPA channel type									
	S	B	P	R	O	D	W	A	M	
S	12	1								
B		4	2							
P	2		8	3						
R		1	3	1	1	1		2	2	
O			1					3		
D						2	3	1		
W					1			1		
A				1				4		
M							1		6	Total
N	14	6	14	5	2	3	4	11	8	67
n correct	12	4	8	1	0	2	0	4	6	37
Proportion	85.7	66.7	57.1	20	0	66.7	0	36.4	75	55.2

a) The SEPA typology.

	Physical habitat channel type						
	S	BB	GB	B	A	M	
S	5		4				
BB	1	4	4	1	2		
GB		1	12		1		
B		4		6	2		
A		1	3	2	3	1	
M					2	8	Total
N	6	10	23	9	10	9	67
n correct	5	4	12	6	3	8	38
Proportion	83.3	40	52.2	66.7	30	88.9	56.7

b) The Physical Habitat typology

Table 4-12: Classification matrix of channel types in a) the SEPA typology, and b) the Physical Habitat typology based on a cross-classification approach. See Table 4.9 for channel codes (BB = Plane-boulder bed and GB = Plane-gravel bed).

Prediction of individual channel types varies within each MDA model. In the SEPA typology, examination of the classification matrix shows a high classification accuracy of predicting step-pool (85.7%) and passive meandering (75%) reaches. Bedrock, plane-bed, and braided reaches have a lower classification accuracy of between 57-67%. Catchment drivers can only predict a low percentage of active meandering and plane-riffle reaches (36.4% and 20% respectively). Pool-riffle and wandering reaches are the most “ill-defined” group as they cannot be predicted.

Similar to the original MDA model, step-pool and passive meandering channel types in the Physical Habitat typology have the highest classification efficiency of the individual channel types (Table 4-12b). Active meandering reaches possess the lowest classification efficiency of 30%, losing a reach to plane-gravel bed, and two reaches to the plane-boulder bed, bedrock and passive meandering reaches. Bedrock reaches have a relatively high classification efficiency of 66.7%, relinquishing one reach to the plane-boulder bed channel type and two reaches to the active meandering channel type. Overall, catchment drivers can predict the number of study reaches to the correct channel types to a similar level of accuracy for both typologies.

4.6.4 Channel types in the SEPA typology are characterised by different surface flow types because of differing combinations of geomorphic units within reaches.

Figure 4-10 summarises the surface flow types (SFTs) or ‘flow biotopes’ for each channel type in the SEPA typology. No SFT is characteristic of one channel type. Channel types comprise a mixture of at least four SFTs. Smooth, rippled and unbroken standing waves are common to all channel types. Furthermore, bedrock and step-pool channel types were associated with all nine SFTs, albeit at highly varied frequencies.

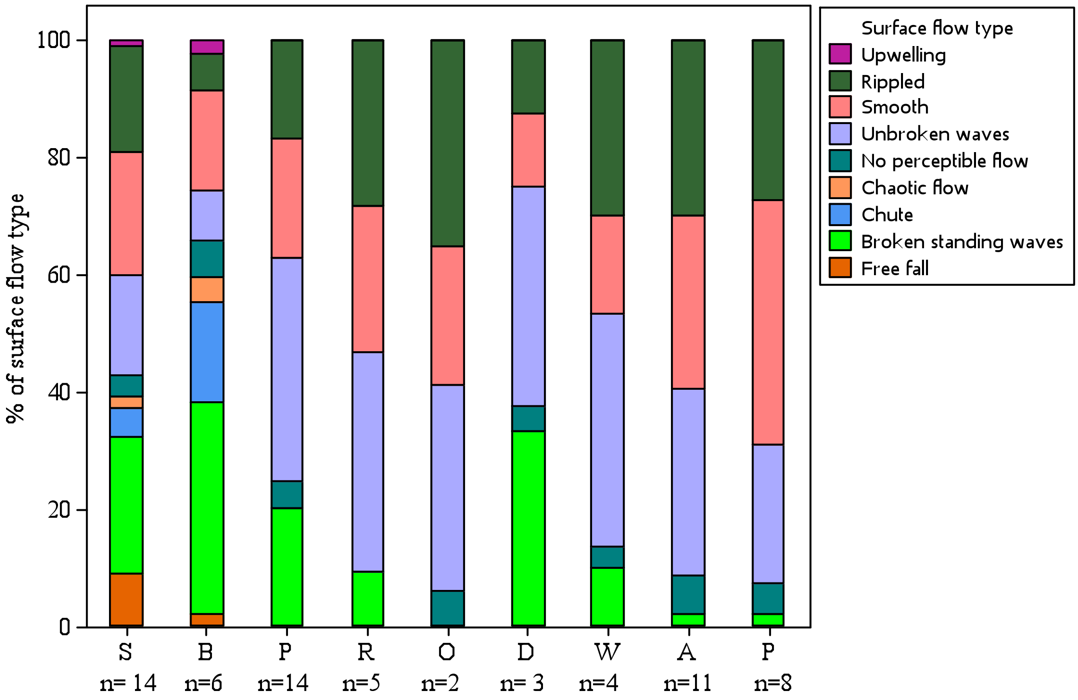


Figure 4-10: Changes in the dominance of SFTs channel types in the SEPA typology. See Table 4.9 for channel codes.

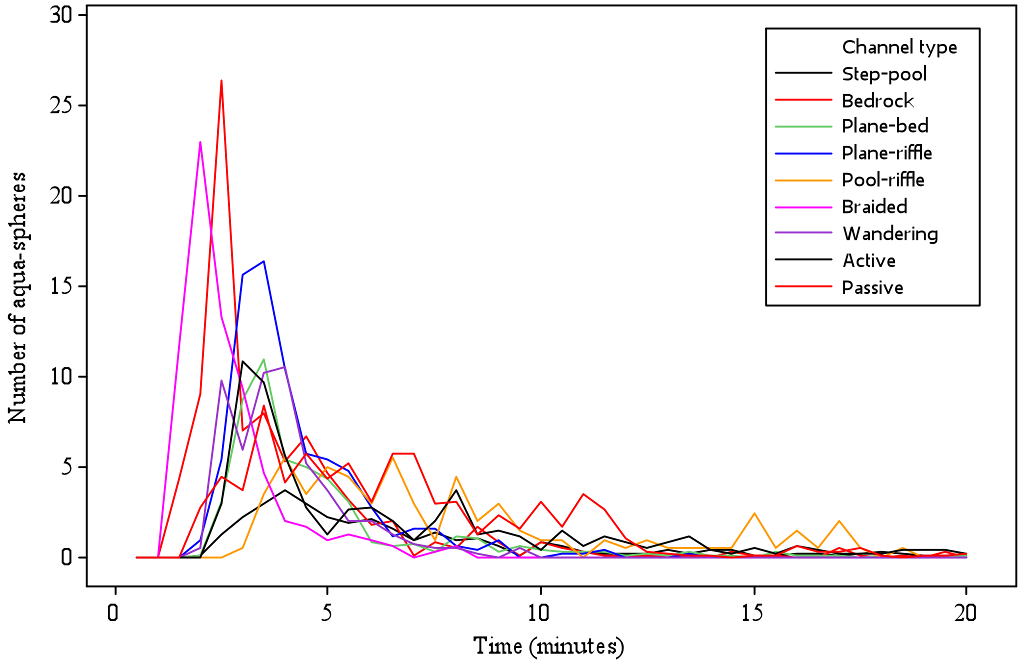
The pattern of SFTs initially appears quite complex, though most channel types are associated with three flow biotopes (Table 4-13). Three SFTs account for >90% of the flow variation in plane-riffle, pool-riffle, braided, active meandering and passive meandering channel types.

Channel type	N	Order of dominant flow type	Percentage variation account for 1 Flow Type	 2 Flow types	 3 Flow types
Step-pool	14	BW, UW, RP	26.59	49.71	70.52
Bedrock	6	BW, UW, CH	35.42	56.25	72.92
Plane-bed	14	UW, BW, RP	41.98	64.20	82.72
Plane-riffle	5	UW, RP, SM	37.50	65.63	90.63
Pool-riffle	2	UW=, RP=, SM	35.29	70.59	94.12
Braided	3	UW, BW, RP	42.86	80.95	95.24
Wandering	4	UW, RP, SM	40	70	86.67
Active	11	UW, SM=, RP=	31.91	61.70	91.49
Passive	8	SM, RP, UW	41.82	69.09	92.73

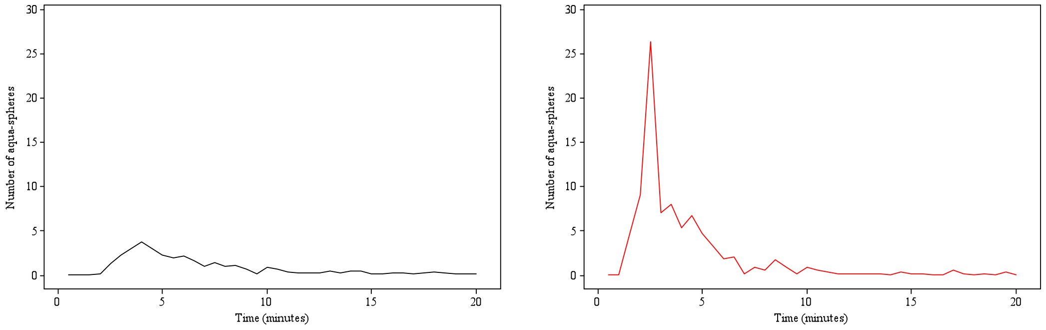
Table 4-13: Percentage occurrence of each channel type accounted for by one, two and three flow biotope categories. See Table 4.2 for SFT codes.

4.6.5 *Channel types in the SEPA typology have varying hydraulic signatures due to variations in depth, grain size and velocity.*

Figure 4-11 presents velocigraphs for channel types in the SEPA typology. Velocigraph shape was characterised by the timing of aqua-spheres, such as the time of the first aqua-sphere, the time to peak, the time of the last aqua-sphere, residence time, time of rising and recessional limb, and number and height of peaks (Table 4-14). The velocigraph shapes (and supported by the data in Table 4-14) reveal some differences between some channel types. Bedrock and braided reaches are characterised by a steep rising and recessional limb, and a tall peak, indicative of a flashy response. The peak of plane-riffles reaches is much smaller in comparison (10.93 aqua-spheres compared to 26.33 and 23 for bedrock and braided reaches respectively). Step-pool reaches have a very small peak (3.7 aqua-spheres) and possess a fairly uniform velocigraph shape. Passive meandering and pool-riffle reaches are characterised by several low sub-peaks, indicating groups of aqua-spheres maybe flowed through similar flow paths across the 100m reach. The velocigraph shape of plane-bed and active meandering are comparable, with both channel types possessing a small peak with a steep rising limb. Wandering reaches are distinct by having two peaks characterising the velocigraph, which maybe indicates the presence of separate anabranches.

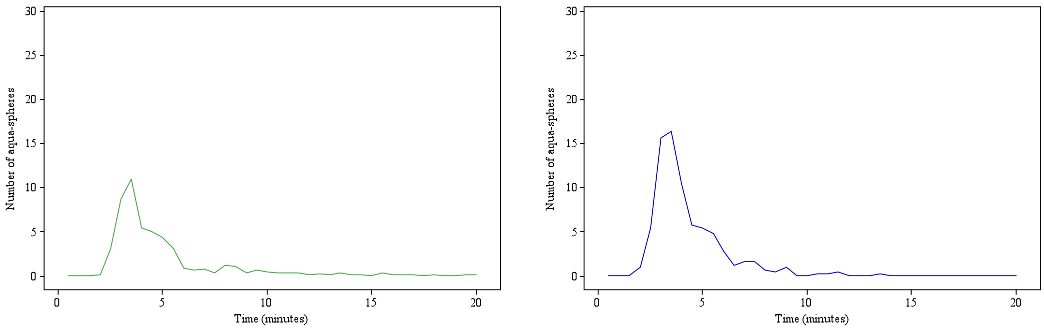


a) Velocigraph data for all channel types.



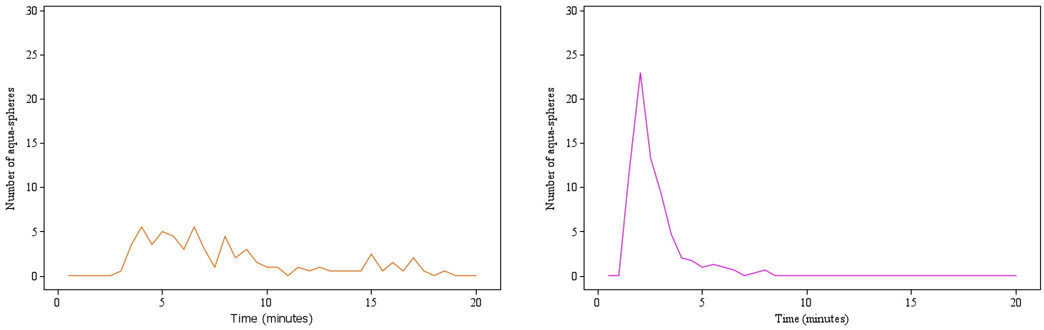
b) Step-pool (n=14)

c) Bedrock (n=6)



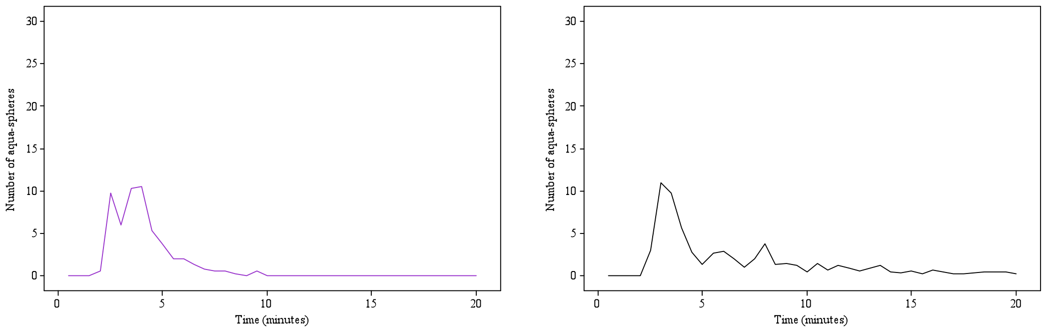
d) Plane-bed (n=14)

e) Plane-riffle (n=5)



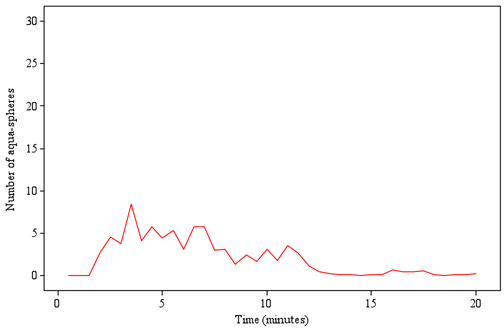
f) Pool-riffle (n=2)

g) Braided (n=3)



h) Wandering (n=4)

i) Active meandering (n=11)



j) Passive meandering (n=8)

Figure 4-11: Velocigraphs of channel types in the SEPA typology. (Data is an average of the study reaches within each channel type).

	Channel type								
Hydraulic variable	S n=14	B n=6	P n=14	R n=5	O n=2	D n=3	W n=4	A n=11	M n=8
Time of first aqua-sphere (secs)	105	75	105	105	165	75	105	135	105
Time of peak (secs)	225	195	195	195	225	465	225	165	195
Time of last aqua-sphere (secs)	1185	1155	1185	795	1095	465	555	1185	1185
Residence time (secs)	420	360	300	300	450	330	330	300	600
Time of rising limb (secs)	120	120	90	90	60	30	120	30	90
Time of falling limb (secs)	960	960	990	600	870	360	330	1020	990
Number of peaks	1	1	1	1	3+	1	2	1	3+
Height of peak	3.7	26.33	10.93	16.4	5.5	23	10.5	10.91	8.38
Peakedness	0.01	0.07	0.04	0.05	0.01	0.07	0.03	0.04	0.01

Table 4-14: Summary of hydrological variables.

The spatial arrangement of study reaches based on hydraulic variables is displayed in a PCA bi-plot in Figure 4-12. The ordination diagram clearly shows substantial overlapping of channel type ellipses. Step-pool and passive meandering samples have wide distributions and overlap with many other channel type ellipses. Braided, plane-riffle and wandering samples in comparison are tightly grouped, and the former channel type is distinct from step-pool, plane-bed, active and passive meandering samples. The ellipses of the remaining channel types: bedrock, plane-bed, and active meandering all severely overlap.

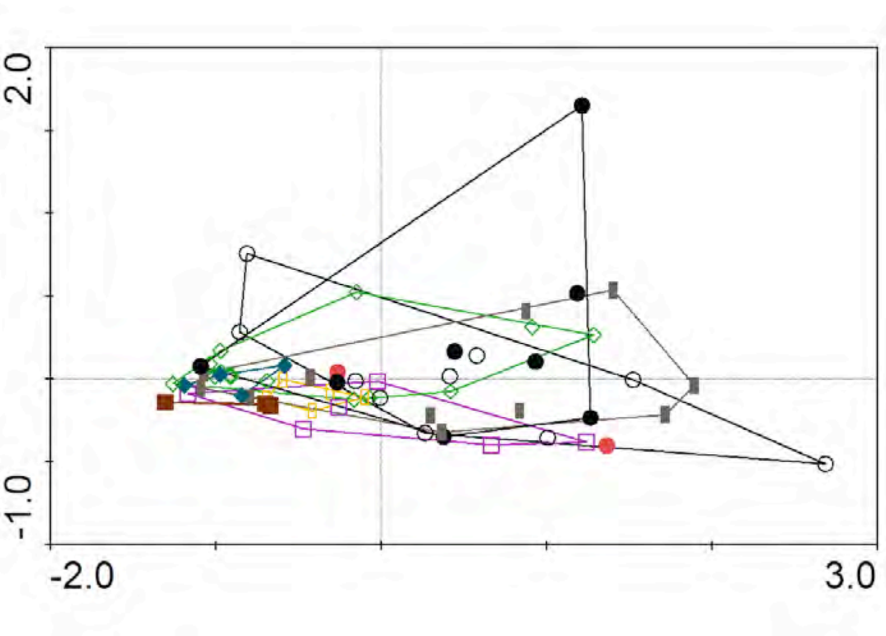


Figure 4-12: Distribution of study reaches in PCA space. Study reaches are classified according to channel types in the SEPA typology. Channel types are ○ step-pool, □ bedrock, ◊ plane-bed, ▮ plane-riffle, ● pool-riffle, ■ braided, ◆ wandering, ▮ active meandering, and ● passive meandering.

The PCA ordination produced four PC axes. The first two PC axes account for 98.9% of the data variability in the model (Table 4-15), with PC3 and PC4 contributing a further 1.1%. Hence, the majority of variability in the model is accounted for by the first two axes.

Axes	1	2	3	4
Eigenvalues	0.888	0.101	0.009	0.002
Percentage variance	88.8	10.1	0.8	0.3
Cumulative percentage variance	88.8	98.9	99.7	100

Table 4-15: Eigenvalues, percentage and cumulative variance for hydraulic and retention variables used in the PCA ordination.

The lengths and directions of arrows in Figure 4-13 represent the importance of each hydraulic variable in the model. Active meandering samples are located along the axis of PC1, and appear to be on a gradient of increasing time for the last aqua-sphere to flow 100m. The positioning of wandering samples on the negative axis of PC1 seems to correspond to a high number of peaks in the velocigraph. The wide distribution of step-pool and passive meandering samples implies a very diverse group with many hydraulic variables controlling the scatter. The latter channel type incorporates an outlier positioned in the upper, right side of the ordination, which indicates there was a long time for the aqua-spheres to peak, and for the first aqua-sphere to flow 100m.

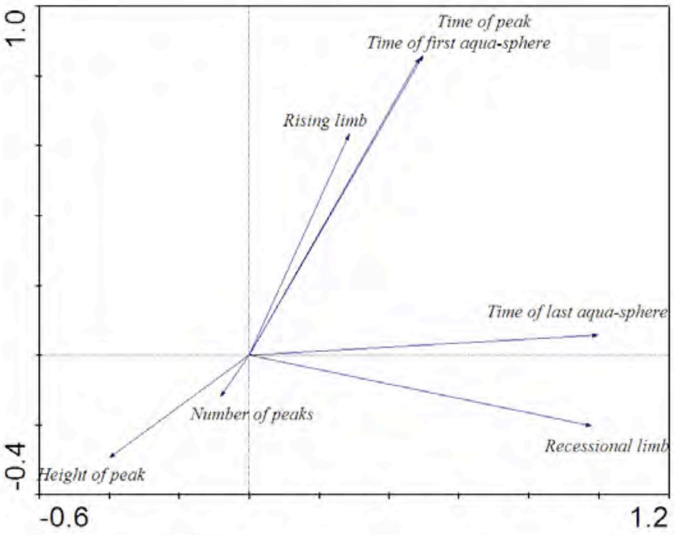


Figure 4-13: Distribution of hydraulic and retention variables in PCA ordination space.

Kruskal-Wallis post-hoc tests support the results of the PCA ordination (in Figure 4-12), in revealing no significant differences in hydraulic characteristics between channel types based on PC1 axis scores.

Table 4-16 provides a summary of hydraulic data obtained from the SFT experiments. Broken standing waves possess the fastest average time for an aqua-sphere to flow 10m, whereas smooth flow has the slowest average time for an aqua-sphere to flow 10m. Data (in Table 4-16) generated from the hydraulic experiments conducted on the four SFTs has been converted into a theoretical conceptual model to show the likely combination of SFT occupying different segments of the velocigraph (Figure 4-14). Based on the theoretical conceptual model, a reach containing a large proportion of broken standing waves and unbroken standing waves is likely to produce very flashy responses, whereas a reach comprising a large percentage of rippled and smooth flow is likely to generate a more subdued response curve.

		Experiment	Time of first aqua-sphere (ms^{-1})	Time of last aqua-sphere (ms^{-1})	Average aqua-sphere time (ms^{-1})	Time of average aqua-sphere per SFT (ms^{-1})
Surface flow type	Broken standing wave	1	1.67	0.59	0.78	
		2	2	0.71	0.90	
		3	1.25	0.67	0.90	**0.86**
	Unbroken standing wave	1	0.91	0.45	0.67	
		2	0.83	0.48	0.63	
		3	1.25	0.56	0.73	**0.68**
	Rippled flow	1	0.56	0.38	0.45	
		2	0.34	0.20	0.28	
		3	0.53	0.29	0.40	**0.37**
	Smooth flow	1	0.45	0.27	0.36	
		2	0.38	0.26	0.31	
		3	0.04	0.03	0.04	**0.24**

Table 4-16: Summary of hydraulic data for the SFT experiments.

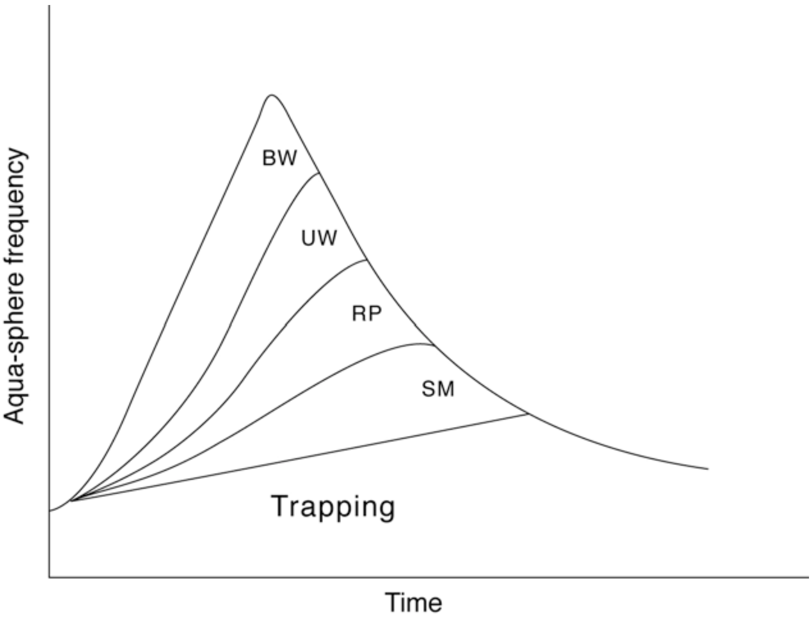


Figure 4-14: Order and combination of SFTs dominating different segments of the velocigraph. SFT codes can be found in Table 4-2.

4.6.6 Retention decreases with distance downstream because of deeper depths, smaller grain sizes, higher velocities and wider channels.

Table 4-17 shows the variation in retention of aqua-spheres for the SEPA channel types. Retention was highest in step-pool reaches and low in bedrock and braided reaches. A variety of hydrological features and substratum characteristics retained aqua-spheres, but most aqua-spheres were retained by boulders or cobbles. In pools, aqua-spheres were retained for long periods due to secondary circulatory eddies and/or in hydraulic jumps at the base of cascades. Slow flowing marginal features, such as embayments and backwaters also retained aqua-spheres (or the aqua-spheres flowed very slowly through these marginal features).

	Channel type								
Substratum / hydrological feature	A	B	D	M	P	R	O	S	W
	n=11	n=6	n=3	n= 8	n=14	n=5	n=2	n=14	n=4
Boulder	1.64		7		17.21	4.2	1	35.93	10
Cobble	3.91	2	10	8.38	14.07	5.8	7.5	20.29	13.5
Woody debris				1	2		8	6.5	
Blocks of soil in channel	21.5				1			2	
Bankside vegetation	2.75			3.5				2.5	
In-channel vegetation	3.5			1		1		2.67	
Undercut bank	1				8			16	
Pool	14.33	2		2.5	2.33	1	9	7.29	
Embayment	11.43	2.67		7	4.14	2.67	2	5	2.5
Side channel					1				
Backwater	8.5		10						14
Retained aqua-spheres (%)	25.55	3.67	9	12.88	35.86	12.2	22.5	67.86	28.25

Table 4-17: The percentage of aqua-spheres retained by hydrological and substratum features in the SEPA channel types. See Table 5.9 for channel codes.

The percentage of aqua-spheres retained in a study reach was explored in relation to distance downstream (Figure 4-15). Regression analysis revealed a significant trend (R square value of 36.5%, adjusted R Square value of 35.5%, and ANOVA *P* value of 0.000) of decreasing retention with increases in distance downstream.

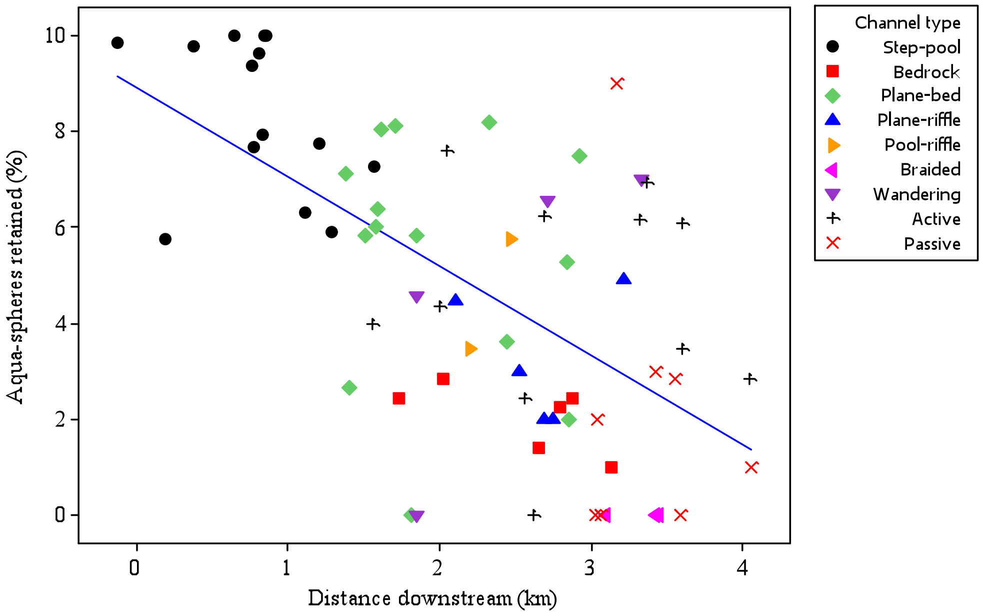


Figure 4-15: Retention characteristics of channel types in the SEPA typology with distance downstream.

The number of aqua-spheres retained by different hydraulic features and substratum characteristics was plotted against distance downstream (Table 4-17). The kite diagrams indicate that boulders and cobbles are the most efficient sedimentological characteristic in retaining aqua-spheres, particularly in headwater and upland environments. In contrast, bankside and in-channel vegetation retain a low number of aqua-spheres, but in reaches further downstream.

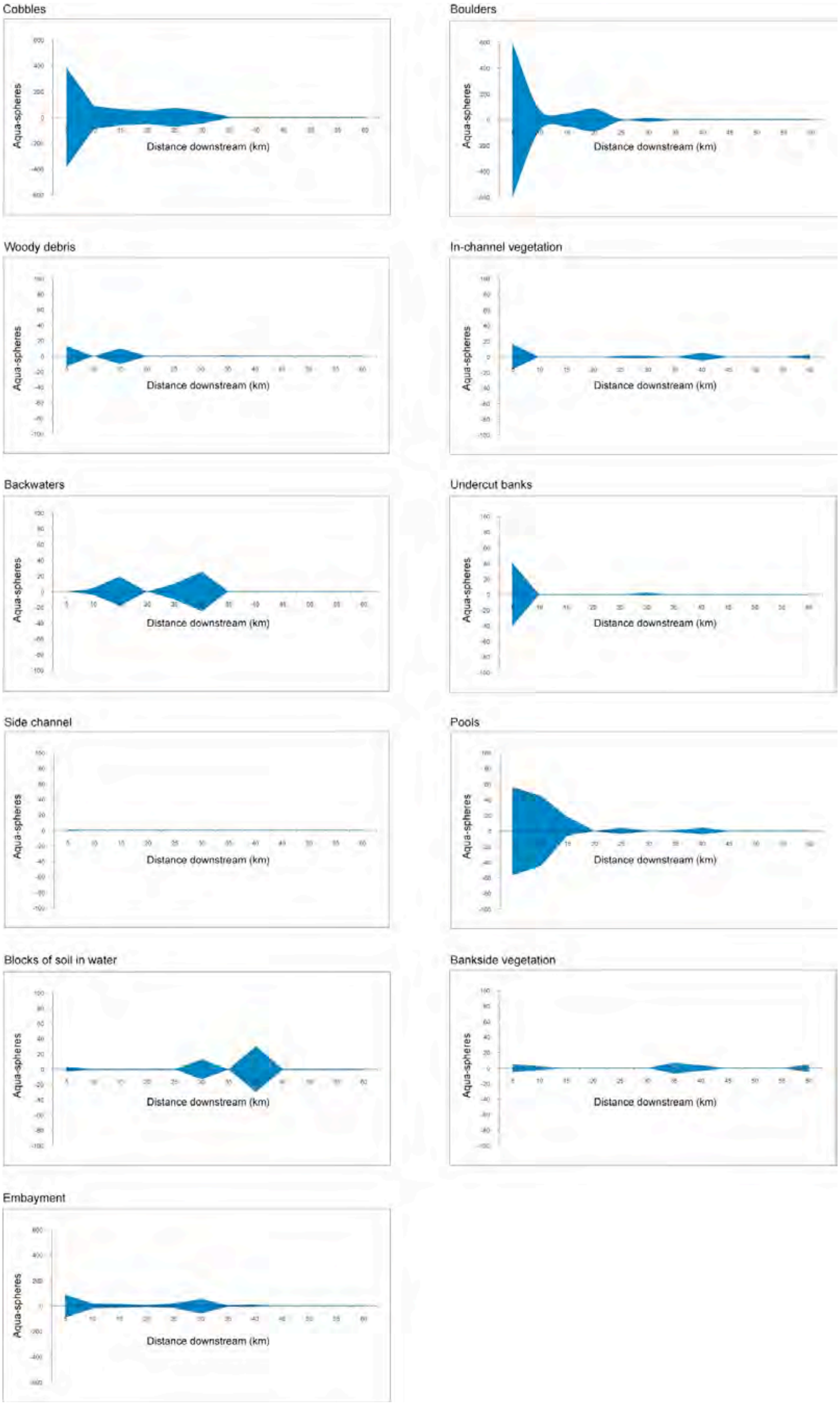


Figure 4-16: Downstream changes in aqua-sphere retention with different sedimentological and hydrological features.

4.7 *Discussion*

4.7.1 *Channel types in the SEPA and Catchment Driver typologies have significantly different depths, grain sizes and velocities.*

The physical habitat characteristics of channel types in the SEPA and Catchment Driver typologies were explored by presenting box plots for the tenth and percentile values for depth, grain size, and velocity traits. The tenth and ninetieth percentile was chosen as it was assumed the values would reflect the presence of riffles and pools within a study reach. For channel types in both typologies, there is an overall trend of increasing median values in WD_{10} and WD_{90} from step-pool through to passive meandering reaches. As the distribution of channel types in catchments follows a typical sequence of step-pool reaches in the headwaters, through to plane-bed and to meandering reaches in the lowlands (previous chapter, section 4.4.1). The relationship of increasing water depth with channel type equates to depth increasing with drainage area (α distance downstream^2; Schumm, 1977).

Bedrock reaches in the SEPA typology possess a very low median and range of GS_{10}. In the Wentworth scale, bedrock substrate is not included. However, the study incorporated additional size classes to include bedrock and large boulders. Bedrock substrate was classified as "1", and since most bedrock reaches are dominated by a bedrock substrate, the very low median and range of values appears reasonable. Variations in GS_{90} characteristics appear small, but an overall trend of decreasing median values across channel types is present in both typologies (apart from semi-constrained reaches in the Catchment Driver typology). As channel types tend to occupy similar geographical positions in the channel network, this relationship indicates that grain size decreases with increasing drainage area (α distance downstream^2). This broad pattern of gradual increases in channel depth coupled with reductions in grain size with drainage area (α distance downstream^2) was highlighted by Schumm (1977; see Chapter 2, Figure 2-2).

Mean flow velocity typically increases with drainage area (α distance downstream^2) (Schumm, 1977; Church, 1992), though this relationship is not clearly reflected in the study. The majority of reaches surveyed were located in upland environments. A higher number of study reaches surveyed in lowland and coastal environments may have revealed a clearer trend in velocity. In the SEPA typology, step-pool, active and passive meandering reaches possess slow velocities (indicated by Vel_{10} values). In comparison, plane-bed, plane-riffle, pool-riffle and braided reaches possess faster velocities (indicated by Vel_{10} values), and bedrock reaches possess the fastest velocities (based on Vel_{90} traits), which is confirmed statistically in the ANOVA post-hoc tests. In the Catchment Driver typology, variations in velocity (based on Vel_{10}) are associated with a decrease across channel types, excluding step-pool reaches. Overall, the results indicate much overlap between channel types using the tenth and ninetieth percentile for water depth, grain size and velocity. These physical habitat variables are not good indicators of describing channel types in either typology. Based on these results, the hypothesis that channel types in the SEPA typology have significantly different water depth, grain size and velocity values is rejected. An exception is step-pool reaches which can be defined on their shallower depths and coarser substrate. Based on the Kruskal-Wallis results (in Table 4-6), the hypothesis that channel types in the Catchment Driver typology have significantly different water depth, grain size and velocity values is also rejected as step-pool and meandering channel types can be discriminated by water depth characteristics (and grain size for meandering reaches), but plane-bed and semi-constrained types are not different.

In summary, the results broadly indicate that as drainage area (α distance downstream^2) increases, channel depth steadily increases, with bed material grain size systematically decreasing. The Kruskal-Wallis tests indicate few channel types in the SEPA and Catchment Driver typologies are different based on their physical habitat characteristics. Therefore, the hypothesis that channel types in the SEPA and Catchment Driver typologies have significantly different depths, grain sizes and velocities is rejected.

4.7.2 Multivariate methods can discriminate channel types in the SEPA typology using physical habitat properties.

The methodology in this chapter has employed a "top-down" approach to typing channel types based on a range of physical habitat variables obtained from fieldwork procedures. The output of the HCA produced six clusters based on WD_{IQR}, a surrogate index for discharge, GS_{IQR} and Vel_{75}. Each cluster comprised between one to six channel types in the SEPA typology, and contains six to twenty-three study reaches. Therefore, the number of study reaches within a cluster was uneven. One small and one very large group emerged, with the other four groups being approximately equal (containing nine or ten study reaches). Similar to the approach in Chapter 3, the most common recurring channel type in each cluster was used to classify the cluster as a whole. To reiterate the six clusters were known as step-pool, plane-boulder bed, plane-gravel bed, bedrock, active meandering and passive meandering. The analysis indicates that four of the nine channel types classified in the field according to the

SEPA typology can be identified based on range of physical habitat properties. Therefore, the above hypothesis has to be rejected as physical habitat properties can not discriminate all nine channel types. Physical habitat properties can only discriminate four of the nine channel types, with overlap among these groupings.

Clustering of the physical habitat variables produced six channel types, whereas using catchment drivers generated four channel types. Both methodological approaches have advantages and disadvantages. Measuring water depth, grain size and velocity for 100 repetitions at each study reach is time consuming and would necessitate substantial financial input for managers to employ surveyors. Maddock (1999) reports a key disadvantage of measuring physical habitat properties is the surveying time required. The importance of habitat assessment across many spatial and temporal scales is widely acknowledged, however, large scale mapping is very time consuming or not feasible if large regions need assessment (Maddock, 1999). Using variables derived from GIS software reduces the amount of time classifying reaches. Unlike the Catchment Driver typology that produced four functional channel types; channel types in the Physical Habitat typology overlap (Figure 4-8). Step-pool reaches appear the most clearly defined, but overlap exists between the remaining five channel types. The analysis indicates that channel types located at the headwaters of a catchment can be the most accurately distinguished.

4.7.3 Catchment drivers can accurately predict channel types in the SEPA typology, and any groupings produced by multivariate methods using physical habitat properties in a Multiple Discriminant Analysis model.

The catchment driver dataset assigned the study reaches into the correct channel types in both the SEPA and Physical Habitat typologies to a similar, but low level of accuracy (55.2% and 56.7% respectively). Therefore, the hypothesis that catchment drivers can predict the channel types in the SEPA and Physical Habitat typologies to a high level of accuracy is rejected. The classification matrices (in Table 4-12) indicate that channel types located at the extremity of the catchment are very accurately classified, such as step-pool and passive meandering reaches. The former channel type is typically found in headwaters, with the latter type commonly located in lowland environments. Classification accuracy appears reduced for channel types located in the mid sections of a catchment, such as plane-bed, plane-riffle and pool-riffle reaches. Hence, a high accuracy of assigning study reaches to the correct channel type occurs when study reaches are located at the extremity of a catchment (step-pool and passive meandering reaches) with classification accuracy diminishing among the transitional channel types, such as plane-riffle, and wandering reaches.

4.7.4 Channel types in the SEPA typology are characterised by different surface flow types because of differing combinations of geomorphic units within reaches.

The combination of SFTs characterising channel types in the SEPA typology initially appears quite complex. However, most channel types (plane-riffle, pool-riffle, braided, active and passive meandering channels) are associated with three principle

SFTs, which account for over 90% of the flow variability in the reach (Table 5.13). Three SFTs also explain in excess of 70% of the flow variability in step-pool, bedrock, and over 80% of the flow variability in plane-bed and wandering channels. Therefore, the study can accept the research hypothesis that channel types in the SEPA typology are governed by different SFTs.

Harvey *et al*. (2008b) investigated the linkages between SFTs, local channel morphology (physical biotopes) and biologically distinct vegetative and minerogenic habitat units (functional habitats). Their study found that most functional habitats, such as gravel, sand, floating leaved macrophytes (and others) are associated with two or three principal SFTs. Three SFTs account for over 90% of the flow variability in eight of the twelve functional habitats investigated (Harvey *et al*. 2008b). Although recorded at different frequencies and scales, both Harvey's *et al.* (2008b) work and the present study show three SFTs explain a very large percentage in flow variability for the spatial unit under examination (meso-habitat and reach scale respectively).

The present study indicates that bedrock, step-pool, and braided reaches are dominated by high energy flow types. For example, bedrock reaches mainly comprise broken standing waves, unbroken standing waves and chute flow, and step-pool and braided reaches contain broken standing waves, unbroken standing waves and rippled flow. In comparison, active and passive meandering channel types are associated with low energy flow types, such as unbroken standing waves, smooth and rippled flow. Two channel types, step-pool and bedrock reaches contain all nine SFTs, albeit at different frequencies. The varied frequencies may partly mirror the adopted recording methodology of the RHS. SFTs are recorded as rare, present or extensive (occupying

<1%, 2-33% and >33% of the channel length and score 1, 2 or 3 respectively). As a result, a SFT such as upwelling may have a spatial cover of <1% of the study reach and score 1, whereas rippled flow may possess a spatial coverage of 50% of the study reach and score 3. The former SFT occupies a very small spatial extent of the study reach, in comparison to the latter type, but the scores do not reflect this difference in coverage. However, the survey was intended to provide a rapid inventory to investigate the links between SFTs and channel types. In addition, the analysis excludes the more subordinate SFTs, such as free-fall by focusing on the three dominant SFTs constituting the study reach. Therefore, the relationships between the main SFTs and individual channel types are explored, and thus may partly alleviate inaccuracies caused by the field methodology. The three dominant SFTs associated with individual channel types are a reasonably accurate representation of their distribution within the study reaches.

Published works have linked SFTs at their low flow stage with physical biotopes (Table 5.17; Environment Agency, 1997; Newson *et al.* 1998b; Kemp *et al.* 1999; Newson and Newson, 2000). For example, the three main SFTs in wandering reaches are unbroken standing waves, smooth flow and rippled flow (Table 4-13), which relates to the physical biotopes of riffles, glides and runs. No SFT or their associated physical biotope is mutually exclusive to one channel type. Smooth, rippled flow and unbroken standing waves occur in all nine channel types. No perceptible flow is present in all channel types, apart from plane-riffle reaches. The flow type is associated with pools (Table 4-18), and indicates the physical biotope can occur in a variety of substrates and settings from bedrock plunge pools (e.g. in bedrock and step-pool reaches) to scour pools in alluvial channels (e.g. in pool-riffle, wandering, active and passive meandering reaches). Archetypal locations for pools include downstream from natural bedrock outcrops, such as downstream from waterfalls or chutes where plunge pools may form in bedrock channels or the outside of tight meanders in alluvial channels (Environment Agency, 2003).

Unbroken standing waves, smooth and rippled flow associated with riffles, pools and glides are the dominant SFTs and physical biotopes in pool-riffles, wandering, active meandering and passive meandering reaches. In the SEPA typology, pool-riffle channels are classified separately to active meandering and passive meandering channels based on sinuosity, with the former having a sinuous planform, and the latter two channel types possessing a meandering planform. Active meandering reaches are characterised by active erosion on the outside of meander bends and lateral movement across the floodplain, whereas passive meandering reaches typically have a stable planform. Despite, these differences in sinuosity, the three channel types share the same dominant SFTs and physical biotopes. The analysis implies that amalgamation of channel types based on SFTs may be appropriate. Pool-riffle reaches could be incorporated into the active or passive meandering category or these three channel types could be combined to form a ‘meandering’ channel type.

Surface flow type	Code	Associated river feature ('Physical biotope')
No perceptible Flow	NP	Pool, deadwater (margins, bends, downstream of point bars and other obstructions)
Smooth boundary turbulent	SM	Glide
Upwelling	UP	Boil
Rippled flow	RP	Run
Chaotic flow	CF	Any of the below physical biotopes
Unbroken standing waves	UW	Riffle
Broken standing waves	BW	Rapid, cascade
Chute flow	CH	Cascade (step)
Free fall	FF	Waterfall

Table 4-18: Flow biotopes and their low flow stage associations with physical biotopes (adapted from Newson *et al.* (1998b) and Kemp *et al.* (2000), and reproduced from Harvey *et al.* 2008b).

SFTs and physical biotopes are thought to reflect broad combinations of depth, velocity and substrate associated with the organisation of river bedforms and morphologies (Jowett, 1993; Wadeson, 1994; Wadeson and Rowntree, 1998). Figure 4-17 shows a conceptual model highlighting the likely combinations of velocity, grain size and depth associated with individual SFTs. For example, unbroken standing waves are associated with the physical biotope of riffles, which typically occurs on coarse substrates, possessing fast velocities and having shallow depths. A study by Hill *et al.* (2008) explored the distinctiveness of SFTs (NP, SM, RP, UW and UP) in six UK lowland rivers. They found overlap in the range of both depth and velocity between SFTs. However, Hill *et al.* (2008) showed significant differences ($P = <0.05$) in depth and velocity between all SFT combinations, except in velocity between upwelling and smooth boundary turbulent flow, and between upwelling and rippled flow. An earlier study by Newson *et al.* (1998b) into biotope research assessed the distinctiveness of physical conditions in relation to SFTs using variable discharge against Froude number on five rivers in the UK. The SFTs used were: scarcely perceptible unbroken standing waves, smooth boundary turbulent flow, chute flow, rippled flow and broken standing waves. The results indicated that scarcely perceptible flow and smooth boundary turbulent flow were present at Froude numbers lower than 0.2, and were dissimilar from the other four biotopes (Clifford *et al*. 2006). Rippled and unbroken standing waves possessed a Froude number between 0.2-0.5, and chute flow and broken standing waves were present at a Froude number >0.4. The degree of overlap in occurrence was 40%, for rippled flow and unbroken standing waves, and 30% for chute and broken standing waves (Clifford *et al*. 2006). Newson *et al.* (1998b) acknowledge the overlap of values between SFTs, but proposed that Froude was an ‘effective’ delimiter. Overall, published works into delimiting SFTs using physical habitat properties (i.e. velocity and depth) have had some success as demonstrated by the Hill *et al.* (2008) and Newson *et al.* (1998b) studies. However, Clifford *et al*. (2006) stress the large amounts of overlap often present in velocity, depth, Froude number and substrate between flow biotopes.

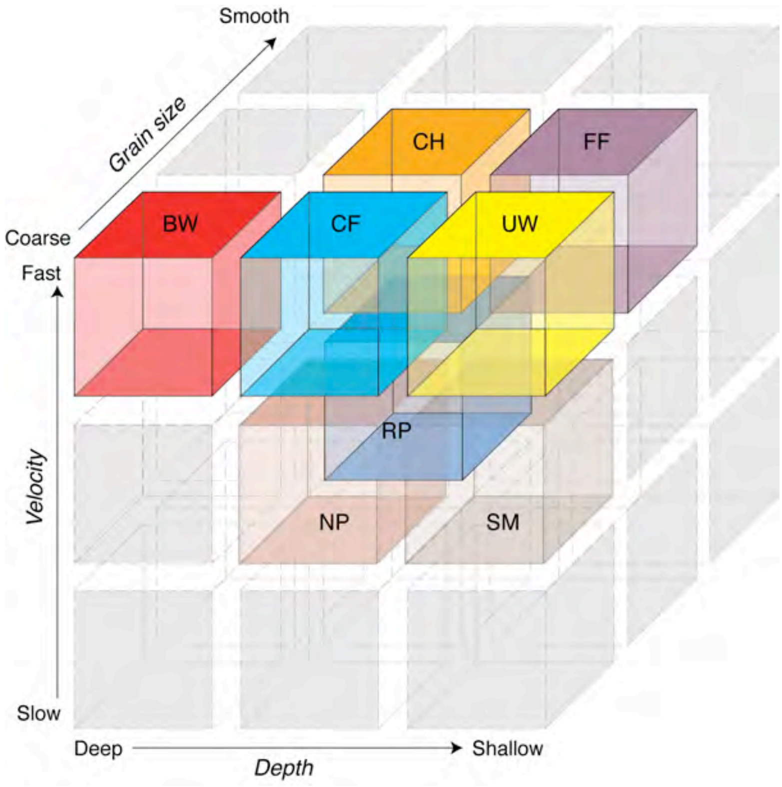


Figure 4-17: Conceptual model indicating the broad characteristics in velocity, grain size and depth associated with individual SFTs.

In summary, three SFTs account for a large percentage of the flow variability in the channel types examined. SFTs at their low flow stage have been related to physical biotopes (Environment Agency, 1997; Newson *et al.* 1998b; Kemp *et al.* 1999; Newson and Newson, 2000). The analysis indicates river systems are composed of differing SFTs and physical biotopes relating to a range of morphologic structures at a variety of scales, from pools, riffles and glides to rapids, cascades and waterfalls (Rayburg and Neave, 2008). The likely combination of SFTs and associated physical biotopes present in individual channel types is useful for river managers as this information maybe incorporated into guidelines to assist surveyors in the classification of reaches, and assessment of whether channel types are attaining good ecological status. Also, mesohabitat mapping based on SFTs has been demonstrated to be practical (Hill *et al.* 2008), and more cost effective compared to measuring physical habitat delimiters (i.e. depth, velocity and substrate).

4.7.5 Channel types in the SEPA typology have varying hydraulic signatures due to variations in depth, grain size and velocity.

A hydrograph shows the trends in water discharge or depth against time. Hydrographs can be produced for the pattern of streamflow occurring over a season, a year, or by a single runoff event caused by snowmelt, rainfall or both (Gordon *et al.* 2008). The latter hydrographs are commonly termed 'flood' hydrographs or 'storm' hydrographs. In this study, hydrographs have been re-named 'velocigraphs' to show the timing and distribution of aqua-spheres (plastic golf balls) flowing across 100m sections of reaches representing individual channel types. The velocigraphs (in Figure 4-11) demonstrate some distinct trends in the timing, frequency and distribution of aqua-spheres, related to in-channel hydraulics at one instance in time.

The shape of the majority of velocigraphs (bedrock, plane-bed, plane-riffle, braided, wandering and active meandering) are positively skewed, indicating most aqua-spheres flowed quickly across 100m. For example, bedrock and braided reaches are characterised by a flashy response (Figure 4-11c and 5-11g); in contrast to pool-riffle and passive meandering reaches that are characterised by a multi-peaked response (Figure 4-11f and 4-11j).

The main factors affecting the response curve are the characteristics of the channel, such as depth, grain size and velocity. The variations in physical habitat properties may be viewed in terms of differing combinations and abundances of SFTs and physical biotopes within a study reach (as demonstrated in Figure 4-9 and Table 4-13). In bedrock reaches, the three main SFTs are broken standing waves, unbroken standing waves and chute flow, which relate to the physical biotopes of rapids, cascades, chutes and riffles (Table 4-18). These flow features and physical biotopes tend to be associated with fast velocities (Table 4-16). For example, an aqua-sphere flowing through a reach dominated by broken standing waves has an average flow rate of 0.86ms^{-1}. Aqua-spheres are likely to flow through the 100m very quickly, primarily conditioned by the slope angle of bedrock reaches, and the lack of grain controlled roughness elements.

Wandering and active meandering reaches have a less steep rising limb, a smaller peak, and the latter channel type has two peaks in the recessional limb, compared to bedrock and braided reaches. The shape of these velocigraphs indicates most aqua-spheres flowed 100m quickly, but numerous aqua-spheres may have been temporarily retained in substratum or hydrological features, and subsequently released into the main thalweg of the channel accounting for the small peaks in the recessional limb. In pool-riffle and passive meandering reaches, numerous sub-peaks on the response curve occurred due to groups of aqua-spheres possessing similar travel rates (Figure 4-11f and 4-11j). This result may indicate a dominant flow pathway in the reach or denote groups of balls entered and exited an eddy at a similar flow rate. Pool-riffle, wandering, and active and passive meandering reaches share the same three dominant SFTs of unbroken standing waves, broken standing waves and rippled flow, albeit at different frequencies. The similar suite of SFTs may partly explain the similar response of pool-riffle and passive meandering reaches; and also wandering and active meandering.

Many channel types possess similar response curve durations as measured by the length of the residence time (Table 4-14). Plane-bed, plane-riffle and active meandering have the shortest response curve duration (300secs, equivalent to a flow rate of 0.33ms^{-1}), whereas passive meandering has the longest response curve duration (600secs, or a flow rate of 0.17ms^{-1}). All channel types are characterised by pools, eddies and embayments. These hydrological features often temporarily retain aqua-spheres, which are subsequently released into the main thalweg of the channel. Therefore, a channel type, such as a bedrock or braided reach may be characterised by predominantly fast flowing SFTs, but the presence of a slow flowing SFT or physical biotope (albeit a small spatial area of the 100m) may temporarily retain aqua-spheres. Hence, the presence of these hydrological features may partly explain the similarities and variations in residence time among channel types.

The Kruskal-Wallis post-hoc tests indicate no significant differences in hydraulic characteristics between channel types based on PC1 and PC2 axis scores. Therefore, the hypothesis that channel types in the SEPA typology possess a varying hydraulic signatures due to variations in depth, grain size and velocity must be rejected.

4.7.6 Retention decreases with distance downstream because of deeper depths, smaller grain sizes, higher velocities and wider channels.

Regression analysis indicates retention significantly decreases with distance downstream (Figure 5.14), related to a crude spatial geographical partitioning of channel types in a downstream pattern. Retention is highest in step-pool reaches, and low in bedrock, braided and passive meandering reaches. Lamberti *et al.* (1988) and Webster *et al.* (1994) also found low retention in bedrock reaches. The pattern of retention decreasing with distance downstream indicates a link to stream size (or channel width). Increases in stream size (or channel width) are accompanied with distance downstream (Robert, 2003), so retention decreases with increases in channel size. This is a similar conclusion to many other studies that have demonstrated that particulate organic matter (POM) is retained less in large streams and retained most in smaller streams (Wallace *et al.* 1982; Minshall *et al.* 1983; Naiman *et al.* 1987; Minshall *et al.* 1992). The decrease in retention with increasing stream size may also be due to the reduction in retention structures downstream (Wallace *et al.* 1982). Furthermore, increases in stream size are typically coupled with increases in channel depth and stream discharge (Robert, 2003). Streams with deep depths and high discharges typically have lower coarse particulate organic matter (CPOM) retention (Snaddon *et al.* 1992), and highlighted in this study, lower retention of aqua-spheres. Based on the results of the study, the hypothesis that aqua-sphere retention decreases with distance downstream must be accepted.

The outcome of the study implies that other factors may be more important in influencing retention, such as bed roughness. A study by Webster *et al.* (1994) investigating the retention of coarse particulate organic particles in streams in the southern Appalachian Mountains reached a similar conclusion, but concluded high retention in steep gradient reaches was due to high quantities of LWD trapping organic matter.

Many other studies have indicated that the retention of CPOM is related to the amount of LWD in streams (e.g. Smock *et al.* 1989; Trotter, 1990; Jones and Smock, 1991; Ehrman and Lambertti, 1992). In the UK, LWD is not very common and tends to be extremely localised and restricted to headwater streams (Mott, 2005). The effect of LWD was noted within a pool-riffle reach of the Derry Burn, a tributary of the Lui Water, in the upper River Dee catchment (Plate 4-1). During the short-term experiment, LWD trapped and retained many aqua-spheres, in a similar fashion to CPOM. Furthermore, the LWD created a forced pool via scouring processes near the channel bank, and had an effect of slowing the aqua-spheres.

Plate 4-1: LWD in a pool-riffle reach of the Derry Burn.

The study deduces that aqua-sphere retention is mainly related to the number of obstructions and depth of water. These two variables directly affect the likelihood that an aqua-sphere comes into contact with an obstruction (Webster *et al.* 1994). Obstructions in the study reaches include boulders and cobbles, LWD, bankside and in-channel vegetation and depositional bars (mid-channel, side and point bars). Boulders were the most effective sedimentological characteristic retaining aqua-spheres (Table 4-17), which is the same conclusion reached by Snaddon *et al.* (1992) in a study examining the effect of discharge of leaf retention in two headwater streams.

In summary, the hydraulic and retention diversity analyses indicate that the response curve is dependent on the depth, grain size, velocity and submergence of obstacles. Variations in depth, grain size and velocity characterise SFTs and associated physical biotopes. Bedrock reaches are typically dominated by high energy surface flow types, such as cascades, chutes and rapids. The majority of aqua-spheres tend to flow very quickly through these high energy flow types and produce very flashy responses. In contrast, glides, pools and riffles personify passive meandering and pool-riffle reaches. Glides and pools are slower flowing flow types compared to cascades, chutes and rapid. Resultantly, the response curve of passive and pool-riffle reaches have smaller, but numerous sub-peaks indicate groups of aqua-spheres flowed though similar flow pathways.

Retention decreases downstream with reductions in channel bed slope, and increases in stream size, discharges and depth. The retention of aqua-spheres is mainly due to the depth of water and the number of obstructions. Boulders are the most efficient sedimentological characteristic retaining aqua-spheres. Retention is lowest in bedrock and braided reaches; both channel types are associated with fast velocities. In contrast, retention is highest in step-pool channels with characteristically slow velocities, and a high number of obstacles, typically protruding boulders.

Further research may find it useful to investigate the seasonal pattern of retention. Seasonal patterns might relate to the annual pattern of discharge and depth. Increases in discharge with a corresponding increase in depth would decrease the number of flow obstructions within a reach, and cause less retention. Although, the short term experiment uses plastic golf balls, the trends and patterns of the study have similarities to the results of leaves and wooden dowel experiments by Webster *et al.* (1994).

4.8 Conclusions

The chapter has adopted a top-down approach to typing river systems at the reach scale, using variables obtained from fieldwork procedures. The measurement of physical habitat variables, such as depth, grain size and velocity per reach is very time consuming and necessitates a lot fieldwork from a surveyor. In the present study, using physical habitat variables failed to produce a functional geomorphic typology as all channel types overlapped. The agglomerative HCA analysis reveals that four of the nine channel types (step-pool, bedrock, active meandering and passive meandering) classified in the field can be identified based on range of physical habitat characteristics. Based on time required by a surveyor to measure the physical habitat variables, the failure to generate a functional typology, and the identification of only four of the nine SEPA channel types classified in the field, the study does not recommend using physical habitat variables to develop a geomorphic typology.

A channel type's response curve and retention characteristics are partly determined by the combination and abundances of different SFTs, and associated physical biotopes within a study reach. Fast flowing SFTs, such as broken standing waves, chaotic flow and chute flow typically relate to cascades and rapids, and tend to produce flashy responses, whereas reaches dominated by smooth and rippled flow are associated with pools and glides tend to generate a more subdued response with sub-peaks. Retention decreases with distance downstream mainly due to the number of obstacles and depth of water within the reach. Coarse substrate, such as boulders and cobbles are highly efficient at trapping aqua-spheres. Step-pool reaches possess the highest retention characteristics, with bedrock and braided reaches typically having low retention. Further research should maybe focus on retention characteristics under various discharge regimes.

5 The ecological significance of geomorphic typologies

5.1 Introduction

The two preceding chapters (Chapters 3 and 4) have adopted a top-down approach to the classification of channel types using catchment drivers and physical habitat variables to generate a geomorphic typology. This chapter employs a bottom-up, multivariate approach to produce a biological classification based on benthic macroinvertebrates. The chapter also examines the ecological relevance of channel types in the top-down typologies produced in the last two chapters: the Catchment Driver typology and Physical Habitat typology, and also the SEPA typology. Comparisons are made between the top-down approach and the bottom-up approach to the prediction of macroinvertebrates.

5.2 Rationale

In the last century, an increasing number of geomorphic classification systems and typologies have been developed in fluvial geomorphology (Kondolf *et al*. 2003). Over the last decade, this trend has been accentuated by the request of the EU WFD for Member States to assess surface waters, and to provide a standardised methodology for classification (Neale and Rippey, 2008). This task consists of setting ecological targets by using unimpacted water bodies grouped according to their environmental characteristics (see Chapter 2, section 2.4.3), and then assessing to what extent their water bodies deviate in terms of their ecology. The underlying rationale is that sites classified by their environmental characteristics, and belonging to the same group (i.e.

channel type), should harbour similar biological communities (Reynoldson *et al.* 1997). Thomson *et al.* (2004) propose that for any geomorphic typology to be useful in ecological applications, it is must be ecologically meaningful. At the very least, the relationships between geomorphic character, functional habitats (*sensu* Harper *et al.* 1992) and biological assemblages must be understood. Ideally, each geomorphic channel type should harbour a distinctive biological assemblage, showing similar ecological functioning and dynamics (Thomson *et al.* 2004). This scenario is unlikely across a wide variety of geomorphic features and scales. However, hierarchical geomorphic typologies may provide a tool to link ecological patterns and physical processes across a wide range of multiple spatial scales (Thomson *et al.* 2004). Excluding the work of Chessman *et al.* (2006) and Thomson *et al.* (2004) on the River Styles Framework in Australia, there have been few studies investigating the links between geomorphic typologies and aquatic biodiversity at the reach scale. Evidently, this is a field where further research is required.

5.3 Aims and hypotheses

The overall aim of the chapter is to identify the ecological relevance of several geomorphic typologies, and discover whether catchment drivers, physical habitat traits or water chemistry is more influential in determining macroinvertebrate community structure. The specific hypotheses are that:

a) Biotic indices can discriminate channel types in the SEPA typology.

b) A bottom-up, multivariate classification of macroinvertebrates can discriminate channel types in the SEPA typology.

c) Each geomorphic channel type in the SEPA, Catchment Driver and Physical Habitat typologies will harbour unique taxa.

d) The effect of geomorphic type will result in differences in macroinvertebrate communities that override the influences of water quality.

5.4 Methods

5.4.1 Biological surveys

Macroinvertebrate and water samples were collected at 43 study reaches in the upper River Dee (39) and Allt a'Ghlinne Bhig (4) catchment (Figure 4-1), representing eight channel types (Table 5-1). A spring survey and an autumn survey were conducted at each study reach. Sampling of macroinvertebrates occurred in April 2008 (43), and in September 2007 (40), and September 2008 (3). Macroinvertebrate samples were collected with a net (0.25-mm mesh) in the standard way by kicking the bed for a 3 minute duration. Macroinvertebrate samples were taken in all physical biotopes, but the duration of kick sampling was proportional to their spatial coverage within the study reach. For example, an active meandering reach containing 50% riffles, 25% pools, and 25% glides would comprise to 90s of kick sampling effort in a riffle, 45s in a pool, and 45s in a glide. Each 3 minute kick sample aimed to be representative of the physical biotopes constituting the reach. Specimens were preserved with methylated spirits and taken to a laboratory, where samples were sieved (500 µm mesh), counted and identified to family level. This level was chosen due to time constraints, and an assumption that differences in macroinvertebrate composition would be likely to exist between geomorphic channel types at this resolution. A water sample was collected simultaneously with each macroinvertebrate sample. Water samples were filtered in a laboratory and analysed for major determinants, such as pH, alkalinity, and major anions and cations. The pH of a sample was measured by a calibrated electrode. Calcium, sodium, magnesium and potassium were measured using atomic absorption spectrometry (AAS). The concentrations of chloride, nitrate, fluoride and sulphate were determined using dionex ion chromatography. Total alkalinity was calculated by titration of a sample with hydrochloric acid to a reaction end-point of pH 4.2. The total alkalinity for most stream water samples is largely due to bicarbonate (HCO_3) ion concentration in the stream. The colour of a stream samples was identified through measuring absorbance on a colorimetric spectrophotometer at 400nm wavelength.

SEPA channel type	Channel code	Frequency
Active meandering	A	7
Bedrock	B	5
Passive meandering	M	1
Plane-bed	P	8
Plane-riffle	R	5
Pool-riffle	O	2
Step-pool	S	12
Wandering	W	3
Total		43

Table 5-1: Frequency of study reaches per channel type in the SEPA typology.

5.5 Statistical analyses

Invertebrate biotic indices have been widely employed to evaluate river quality (Clews and Ormerod, 2009). Biotic indices have been developed for a variety of organisms; however, many use benthic macroinvertebrates in rapid assessment (Resh and Jackson, 1993; Metcalfe-Smith, 1994). Macroinvertebrates have benefits in biomonitoring, such as ubiquity, ease of collection, well-known taxonomy, sensitivity to pollutants, and known river conservation importance (Wallace and Webster, 1996; Chadd and Extence, 2004; Clews and Ormerod, 2009). In this study, simple combinations of biotic indices have been used to discriminate channel types in the SEPA typology. The biotic indices used are the Average Score Per Taxon (ASPT) score, that is typically used to detect organic effluents and or eutrophication (Hawkes, 1997), the Acid Waters Indicator Community Index (AWIC), an approach used to identify the affects of acidification (Davy-Bowker *et al*. 2005), the Lotic-invertebrate Index for Flow Evaluation (LIFE), believed to recognise low flow effects on assemblages (Extence *et al*. 1999), and finally abundance scores.

Ecological data is frequently complex, unbalanced and often includes missing values (De'ath and Fabricus, 2000). The interactions between biological and physico-chemical variables are often strongly correlated and linear. Standard exploratory data analysis, such as a histogram, median, standard deviation and inter-quartile range are often inadequate to identify meaningful ecological patterns (De'ath and Fabricus, 2000). Ordination methods and regression trees (Baker, 1993; Rejwan *et al*. 1999) are ideal statistical techniques to combine biological and physico-chemical variables into a meaningful and comprehensible output. Ordination methods are the 'tools of the trade', and have been widely employed by ecologists since the early 1950s, and during their development they have proliferated into a mixture of different techniques (Lepš and Šmilauer, 2003). The presence/absence and number of explanatory variables (predictors) is partly used to segregate ordination methods into types of statistical models (see Table 5-2). In cases where there is only a single response variable or no predictors, ordination methods represented by the techniques in indirect gradient analysis (namely principal components analysis (PCA), correspondence analysis (CA), detrended correspondence analysis (DCA) and non-metric multidimensional scaling (NMMS)) are used. Alternatively, many users adopt cluster analysis to group a set of samples; common methods include hierarchical or non-hierarchical techniques (Scott and Clarke, 2000). In situations where we have many predictors for a set of response variables, the interactions between multiple response variables (normally biological species), and several predictors can be summarised using methods of direct gradient analysis (most well-known are redundancy analysis (RDA) and canonical correspondence analysis (CCA)) (Lepš and Šmilauer, 2003).

	Predictor (s)	
Response variable	Absent	Present
One	Distribution summary	Regression models
Two +	Indirect gradient analysis (PCA, DCA, NMDS)	Direct gradient analysis (RDA, CCA)
	Cluster analysis	Discriminant analysis (CVA)

Table 5-2: Types of statistical model (modified from Lepš and Šmilauer, 2003).

Two-Way INdicator SPecies ANalysis (TWINSPAN, Hill, 1979) was used to derive a biological classification of macroinvertebrate communities. TWINSPAN is a complex, divisive clustering tool that was initially created for vegetation analysis, but is also suitable for other biological data. TWINSPAN uses the concepts of pseudo-species and pseudo-species cut levels to avoid losing information about the species abundances. Each species in a dataset can be represented by numerous pseudo-species, based on its abundance (Lepš and Šmilauer, 2003). A dichotomy (division) is created based on a correspondence analysis (CA) ordination. Subsequently, the samples are segregated on the negative (left) and positive (right) side of the ordination, depending on their score on the first CA axis (Lepš and Šmilauer, 2003).

The goal is to achieve a polarized ordination, i.e. where the samples are split clearly on the negative and positive side of the dichotomy, and ideally are not located near the centre of gravity (Lepš and Šmilauer, 2003). The classification is therefore, based on the species (or in this case family) characteristics of one part of the dichotomy, and not based on the species (or families) typical to both parts of the dichotomy.

TWINSPAN was performed on square-root transformed macroinvertebrate abundance data, using pseudo-species cut levels, which were: 0, 2, 5, 10 and 20. Within TWINSPAN, the user can select the number of samples per group size (Lepš and Šmilauer, 2003). A minimum of three samples per group was selected, as an aim of the classification was to produce a workable number of groups, and for these groups to have sufficient members for other forms of statistical analysis.

Multiple Discriminant Analysis (MDA) (Tatsuoka, 1971) was used to determine the capabilities of the catchment driver and physical habitat dataset to predict the groups of macroinvertebrates produced by TWINSPAN. The percentage of correct predictions per group for the model as a whole is presented. For a detailed description of MDA, see Chapter 4, section 4.5.

Ordinations were used to explore the similarity of macroinvertebrate assemblages between channel types in each of the three geomorphic typologies (the SEPA, the Catchment Driver and Physical Habitat typologies). A synopsis of all ordinations and statistical tests used in this chapter are outlined in Table 5-3. Detrended Correspondence Analysis (DCA, ter Braak, 1995) was initially used to examine the lengths of gradient that measure the beta diversity in community composition (the extent of species turnover) along the individual independent gradients (ordination axes) (Lepś and Šmilauer, 2003). When the longest gradient exceeds 4.0, unimodal methods should be employed, such as DCA, Correspondence Analysis (CA) or Canonical Correspondence Analysis (CCA). However, if the longest gradient is lower than 3.0, linear methods are more suitable, such as Principal Components Analysis (PCA) or Redundancy Analysis (RDA) (Lepś and Šmilauer, 2003). Alternatively, if the longest gradient is between 3.0-4.0, both linear and unimodal ordination methods are acceptable. DCA revealed linear ordinations were the best methods to employ in this study, there being relatively low species turnover between sites.

Variations in macroinvertebrate samples between channel types were analysed by a linear, unconstrained PCA (Hotelling, 1933). The ordination was conducted first to identify the variability that is related to species composition. Subsequently, RDA (van der Wollenberg, 1977), a constrained ordination was used to focus on the variability in macroinvertebrate patterns that is related to the measured geomorphic variables. Lepś and Šmilauer (2003) believe that by carrying out an unconstrained ordination first, the pattern of variability in species composition is not missed, even though most of this can be unrelated to the measured environmental variables.

The maximum number of macroinvertebrates for each family from spring and autumn were combined to form an overall abundance total for each study reach, and data from the two water chemistry samples (for a study reach in spring and autumn) were averaged. PCA was initially conducted on the macroinvertebrate dataset, and the study reaches were classified according to the channel types in the SEPA typology. Inspection of the location of the study reaches indicates that only two pool-riffle reaches and one passive meandering reach are located in the R.Dee and Allt a'Ghlinne Bhig catchments. These samples were excluded from this analysis due to their low frequency. Subsequently, PCA was re-run and the study reaches were re-classified based on the four channel types in the Catchment Driver typology. The final run of PCA was conducted with the study reaches re-assigned to five (of the six) channel types (step-pool, plane-boulder bed, plane-gravel bed, bedrock and active meandering) inherent within the Physical Habitat typology. The sixth channel type in the Physical Habitat typology, passive meandering reaches were excluded as there was only one reach in the R.Dee and Allt a'Ghlinne Bhig catchments. The re-naming of the study reaches were carried out to determine if channel types in the different geomorphic typologies possess a distinct macroinvertebrate assemblage.

Differences in macroinvertebrate assemblages between channel types in all typologies were tested for significance using a one-way Analysis of Similarity (ANOSIM, Clarke and Warwick, 1994). The statistical technique is a non-parametric test of significant difference between two or more groups (or in this case channel types), based on any distance measure (Clarke, 1993). In one-way ANOSIM, samples within a group (i.e. channel type) were classified as one sample and compared between different groups (i.e. between channel types) (Thomson *et al*. 2004). ANOSIM is usually employed for ecological taxa-in-samples data, where groups of samples are compared (Hammer *et al.*, 2001). ANOSIM produces a Global-*R* test statistic that contrasts the similarities among samples within groups (i.e. within a channel type) with the similarities between groups (i.e. between a channel type) (Clarke and Warwick, 1994). A total of 10,000 random permutations were used in deriving the significance of tests for differences between channel types. Significance levels were established at $P < 0.05$ for the analyses. ANOSIM was performed using a Euclidean similarity measure on principal component one (PC1) and principal component two (PC2) axis scores derived from PCA.

Indicator species analysis (Dufrêne and Legendre, 1997) was also employed to determine whether any individual taxa characterise channel types in the SEPA, Catchment Driver and Physical Habitat typologies. The test statistic amalgamates a species relative abundance with its relative frequency of occurrence in the different sites of each group (Dufrêne and Legendre, 1997). The output of the analysis produces an indicator value from 0 to 100. A value of 0 illustrates no discrimination among the groups (i.e. channel type), where a value of 100 denotes the taxon is exclusively associated to a single group (or channel type). The statistical significance of a species indicator value to a group is assessed using a randomisation procedure (Dufrêne and Legendre, 1997). As the approach gives ecological meaning to groups, the test can be very useful in comparing typologies, which is particularly useful for identifying if a geomorphic typology has ecological significance.

RDA was used to examine the relationships and interactions between macroinvertebrate samples and environmental variables. All environmental variables were range standardised (0-1) for use in RDA. In each RDA ordination, Monte-Carlo permutation tests identified significant variables that added to the explained variation in macroinvertebrate patterns (ter Braak, 1995). Initially, RDA was conducted using all variables in the catchment driver, physical habitat and physico-chemical datasets, and study reaches were classified according to channel types in the SEPA typology. Secondly, RDA was re-run using the significant environmental variables identified by the first RDA. Subsequently, RDA was performed using only the catchment drivers, and then using solely the physical habitat variables, and then using only physico-chemical variables.

Study reaches belonging to the same channel type tend to be geographically clustered (see Figure 3-2). Therefore, it is likely that biological similarities between study reaches of the same channel type may be due to physical proximity, rather than to their geomorphic characteristics (Chessman *et al.* 2006). This situation could partly be because short-range compared to long-range movement of organisms requires less expenditure of energy, and hence, organisms can move easily among sites that are geographically close. As a measure to disentangle the role of geographical distance as a confounding factor, the stream network geographic distance between all possible pairs of study reaches was determined in Arc View 3.2. A matrix of all the geographic distances between all possible pairs of study reaches was constructed, and entered into a DCA, with geographic distances as the species variables and the study reaches as the samples. The axis scores of the DCA ordination were then abstracted and entered into a RDA as co-variables, with macroinvertebrates entered as the species variables and catchment drivers, physical habitat and physicochemical variables entered as environmental variables. This RDA is a repeat of the first run of RDA, but with geographical distance axis scores added as covariables. Therefore, the stream network geographical distances acted as a distance matrix of independent sites. A summary of all statistical analyses used in this chapter are outline in Table 5-3.

Macroinvertebrate data were square-root transformed for all analyses. TWINSPAN was carried out in WinTwins (version 2.3, Hill 1979). MDA was applied in SPSS (version 16). DCA, PCA and RDA ordinations were all performed in the CANOCO (CANOnical Community Ordination) software package (version 4.5, ter Braak and Šmilauer, 1998). ANOSIM analyses were conducted in the PAST (PAlaeontological STatistics) software package (version 1.94b, Hammer *et al.*, 2001), and Indicator Species Analysis was performed in IndVal (Indicator Value of species, version 2.1, Dufrêne and Legendre, 1997).

Factor of interest	Type of ordination / statistical technique	Input dataset	Typology used to group channel types
Identify macroinvertebrate groups	Boxplots of abundance data and AWIC, ASPT and LIFE scores	Macroinvertebrate data	1. SEPA typology
Identify macroinvertebrate groups	TWINSPAN	Macroinvertebrate data	N/A
Test catchment drivers ability to predict TWINSPAN groups	MDA	Catchment driver data	TWINSPAN macro invertebrate groups
Examine lengths of gradient	DCA	Macroinvertebrate data	N/A
Compare macroinvertebrate communities in different channel types	PCA	Macroinvertebrate data	1. SEPA typology 2. Catchment driver 3. Physical habitat
Compare similarities among samples within channel types to similarities between channel types	ANOSIM	PC1 axis scores	1. SEPA typology 2. Catchment driver 3. Physical habitat
	ANOSIM	PC2 axis scores	1. SEPA typology 2. Catchment driver 3. Physical habitat
Identify any indicator species of channel types	Indicator species analysis	Macroinvertebrate data	1. SEPA typology 2. Catchment driver 3. Physical habitat
Factors affecting macroinvertebrate communities	RDA	a. Macroinvertebrate data b. Catchment driver physical habitat and Water chemistry data	1. SEPA typology
	RDA	a. Macroinvertebrate data b. Significant environmental variables	1. SEPA typology
	RDA	a. Macroinvertebrate data b. Physical habitat data	1. SEPA typology
	RDA	a. Macroinvertebrate data b. Water chemistry data	1. SEPA typology
	RDA	a. Macroinvertebrate data b. Physical habitat and physico-chemical data c. Catchment drivers as covariables	1. SEPA typology
Determine influence of geographical distances on macroinvertebrate patterns	DCA	Geographical distances	N/A
	RDA	a. Macroinvertebrate data b. Catchment driver, physical habitat and water chemistry data c. Geographical distances as covariables	1. SEPA typology

Table 5-3: Summary of ordinations and statistical techniques used in this chapter.

5.6 Results

Fifty-five taxa were recorded in the study reaches over the sampling period (Table 5-4). Samples were dominated by Baetidae, Heptageniidae, Chironomidae and Elmidae (mean > 64). Baetidae, Chironomidae, Leuctridae, Nemouridae, and Perlodidae occur in all 43 samples. In contrast, Athericidae, Beraeidae, Curculionidae, Dixidae, Gammaridae, Goeridae, Phryganeidae, planorbidae, Psychomyiidae, Siphlonuridae, Sphaeriidae and Veliidae only occur in one study reach.

Table 5-5 shows a statistical summary of macroinvertebrates for the study reaches. The maximum number of families recorded at one site was 27 (in the Corriemulzie Burn and the Allt a’choire Yaltie), and the lowest was 13 (in R.Dee 6). Total abundances in the study reaches vary from 65 taxa (in R.Dee 10) to 2239 (in Allt a'Mhaide 1).

Taxa	Code	Total reaches	Mean	Standard error
Baetidae	Bae	43	102.3	13.9
Caenidae	Cae	26	23.9	9.6
Ceratopogonidae	Cer	7	5.6	4.6
Chironomidae	Chi	43	69	17.5
Chloroperlidae	Chl	41	5.0	0.6
Dytiscidae	Dyt	18	2.7	0.6
Elmidae	Eli	40	63.7	17
Empididae	Emp	38	4.6	1.3
Ephemerellidae	Eph	8	1.8	0.3
Glossosomatidae	Glo	25	4.1	2.6
Heptageniidae	Hep	42	96.9	13.5
Hydraenidae	Hydr	17	1.7	0.2
Hydropsychidae	Hydpsy	29	7.3	1.5
Hydroptilidae	Hydtil	27	8.3	1.7
Lepidostomatidae	Lepi	10	2.8	0.8
Leptoceridae	Leptoc	6	7	4.1
Leptophlebiidae	Leptop	8	9.1	5.1
Leuctridae	Leu	43	54.3	9.3
Limnephilidae	Limn	20	3.2	1.1
Limoniidae	Limo	26	4.2	0.9
Nemouridae	Nem	43	36.5	9.8
Odontoceridae	Odo	10	3.8	1.5
Pediciidae	Ped	37	5.8	0.7
Perlidae	Perli	33	16.8	3.5
Perlodidae	Perlo	43	8.4	1.0
Philopotamidae	Phi	6	7	1.9
Polycentropodidae	Pol	32	6.3	1.1
Rhyacophilidae	Rhy	37	3.6	0.6
Sericostomatidae	Ser	15	2.4	0.5
Simuliidae	Sim	42	60.5	11.9
Taeniopterygidae	Tae	39	21.3	5.4
Tipulidae	Tip	13	2.2	0.4

Table 5-4: Abundance of taxa occurring in >10% of study reaches. Taxa are recorded in the study reaches across a spring (Apr. 2008) and an autumn sampling season (Sep. 2007 and 2008).

Study reach	Reach code	Sub-catchment	Family richness	Mean (per family)	Range	Total abundance
Cairnwell Burn	Cai	Clunie Water	18	6.0	226	346
Callater Burn 1	CB1	Callater Burn	23	19.4	239	1123
Callater Burn 2	CB2	Callater Burn	23	9.5	137	552
Coldrach Burn	Col	Clunie Water	24	15.7	186	908
Corriemulzie Burn	Cor	River Dee	27	16.5	199	956
Clunie Water 1	CW1	Clunie Water	20	11.0	216	639
Clunie Water 2	CW2	Clunie Water	20	9.2	216	535
Clunie Water 3	CW3	Clunie Water	29	14.7	192	853
Clunie Water 4	CW4	Clunie Water	22	11.4	240	661
Clunie Water 6	CW6	Clunie Water	30	13.7	157	792
Clunie Water 7	CW7	Clunie Water	17	10.7	265	620
Clunie Water 8	CW8	Clunie Water	23	13.1	199	758
Dalvorar Burn	Dal	River Dee	23	14.6	198	848
Allt Tòn na Gaoithe	Gao	River Dee	23	25.7	515	1490
Allt a'Ghlinne Bhig 1	GB1	Allt a'Ghlinne Bhig	17	10.7	289	620
Allt a'Ghlinne Bhig 2	GB2	Allt a'Ghlinne Bhig	24	11.5	188	668
Allt a'Ghlinne Bhig 3	GB3	Allt a'Ghlinne Bhig	21	12.2	222	707
Allt a'Ghlinne Bhig 4	GB4	Allt a'Ghlinne Bhig	27	21.5	466	1245
Allt a' Gharbh-choire	Gha	Clunie Water	20	20.1	313	1168
Lui Water 1	LW1	Lui Water	15	2.1	34	120
Lui Water 2	LW2	Lui Water	24	4.3	76	252
Lui Water 3	LW3	Lui Water	17	2.8	31	162
Lui Water 4	LW4	Lui Water	19	2.0	28	117
Allt a' Mhadaidh	Mhad	Lui Water	20	9.2	210	531
Allt a'Mhaide 1	Mhaide1	Clunie Water	24	38.6	430	2239
Allt a'Mhaide 2	Mhaide2	Clunie Water	24	12.8	196	742
Allt Creag Phadruig	Pha	River Dee	23	12.2	339	710
Quoich Water 1	QW1	Quoich Water	21	2.2	20	125
Quoich Water 2	QW2	Quoich Water	17	2.4	21	142
Quoich Water 3	QW3	Quoich Water	19	4.7	104	271
River Dee 1	RD1	River Dee	20	3.5	75	204
River Dee 2	RD2	River Dee	19	5.1	112	294
River Dee 3	RD3	River Dee	18	2.0	44	114
River Dee 4	RD4	River Dee	23	8.0	169	464
River Dee 5	RD5	River Dee	21	2.7	26	157
River Dee 6	RD6	River Dee	13	1.2	27	71
River Dee 8	RD8	River Dee	22	3.2	43	184
River Dee 9	RD9	River Dee	16	2.7	42	157
River Dee 10	RD10	River Dee	15	1.1	14	65
Allt a'Choire Yaltie	Yal	Clunie Water	27	10.6	139	616

Table 5-5: Summary of macroinvertebrate data for the study reaches.

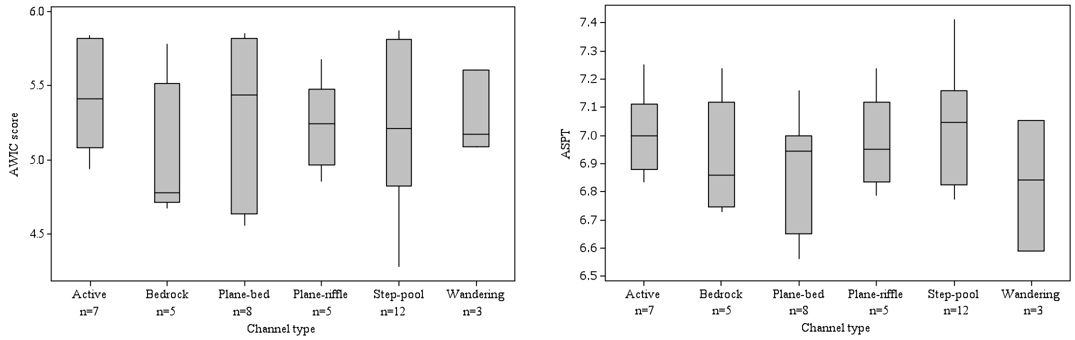
A statistical summary of the physico-chemical variables for the study reaches is shown in Table 5-6. In general, all the study reaches had low concentrations of nitrate, fluoride, potassium and absorbance. Chloride and calcium showed the greatest range in variability among the chemical determinands, reflecting geological differences within the catchments. The range in pH values denotes differences in stream acidity; some study reaches were fairly acidic (minimum value of pH 4.65), whereas others were alkaline (indicated by the maximum pH value of pH 7.9).

Physicochemical variable	Code	Min	Max	Med	Mean	SD	Skew	S-W (P)
pH	pH	4.65	7.9	5.65	6.01	0.82	0.51	0.007
Alkalinity	Alk	0.28	9.6	2.3	3.10	2.82	0.86	<0.005
Fluoride	F	0	0.27	0.11	0.10	0.10	0.2	<0.005
Chloride	C	2.36	16.45	4.22	5.54	3.54	2.08	<0.005
Nitrate	NO_3	0	0.58	0	0.08	0.16	1.91	<0.005
Sulphate	SO_4	1.12	4.29	2.06	2.38	0.95	0.31	<0.005
Calcium	Ca	0.78	11.26	3.26	4.29	2.75	0.89	<0.005
Sodium	Na	0.24	1.39	0.38	0.45	0.22	2.53	<0.005
Magnesium	Mg	0.21	2.02	0.53	0.70	0.42	0.87	<0.005
Potassium	K	0.12	0.82	0.30	0.39	0.20	0.45	<0.005
Colour	Abs	0.02	0.15	0.05	0.06	0.03	0.97	0.190

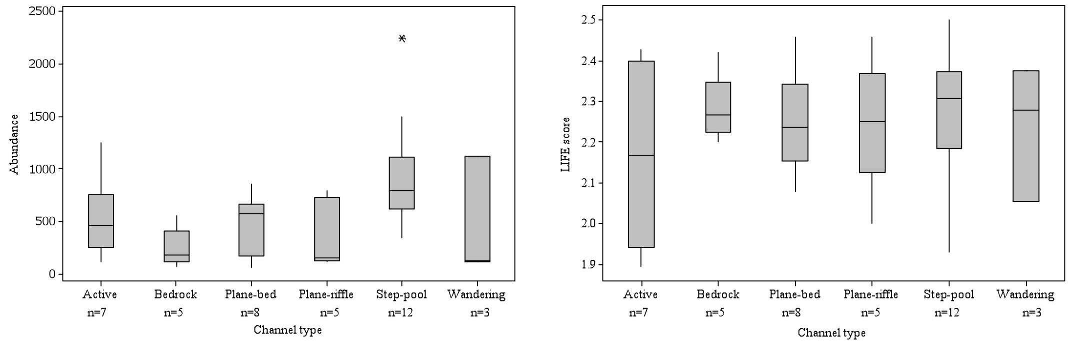
Table 5-6: Summary of physico-chemical dataset.

5.6.1 Biotic indices can discriminate channel types in the SEPA typology.

Figure 5-1 shows boxplots plotted for biotic indices and abundance data for channel types in the SEPA typology. Pool-riffle and passive meandering channel types were excluded from the statistical analysis, as there was only two and one study reach respectively. The output of the boxplots indicates no channel type has a discrete distribution based on AWIC, ASPT, LIFE scores or abundances. There is a large overlap in the distribution of values for the individual scores. For example, active meandering sites have a particularly large distribution in values based on LIFE scores (Figure 5.1d). One-way Analysis of Variance (ANOVA) post-hoc tests showed no statistical differences between any combinations of channel types based on any of the four scoring systems. The output of the boxplots and the one-way ANOVA post-hoc tests demonstrated that biotic scores and abundance data cannot discriminate the SEPA channel types.



a) AWIC score b) ASPT score



c) Abundance d) LIFE score

Figure 5-1: Boxplots for a range of metric scores (a-d) for channel types in the SEPA typology. Boxes represent the first and third quartiles, vertical lines signify upper and lower tenths, asterisks indicate outliers.

5.6.2 A bottom-up, multivariate classification of macroinvertebrates can discriminate channel types in the SEPA typology.

The TWINSPAN classification divided the study reaches into eight groups (Figure 5-2). The number of study reaches within each group varied between three and eleven. Small groups of study reaches consistently split off from the main body, for example, groups eight, eleven and thirteen. In contrast, group fifteen remained relatively large in comparison, consisting of eleven study reaches.

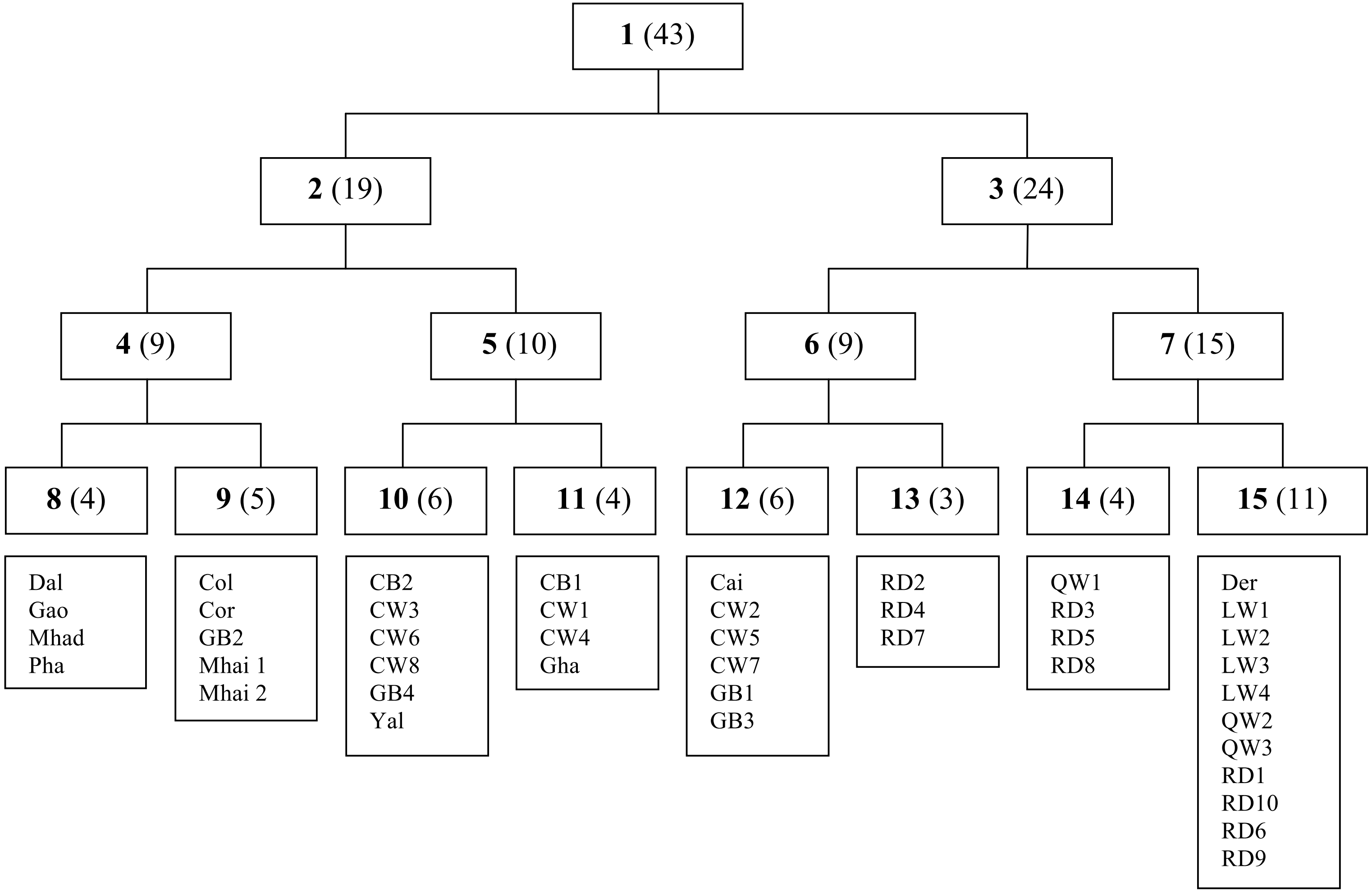


Figure 5-2: TWINSPAN classification of 43 minimally impacted study reaches based on macroinvertebrate family abundance data. Numbers in bold designate a group's number and numbers in brackets indicate the number of study reaches in that group. Study reach codes are shown in Table 5.5

Table 5-7 shows the combination of SEPA channel types forming each of the eight TWINSPAN groups. The majority of groups (6 out of 8) contain a mixture of SEPA channel types, with only groups 8 and 13 comprising solely of one channel type. The TWINSPAN results indicate that macroinvertebrate communities do not cluster into the SEPA channel types.

		TWINSPAN group							
SEPA channel type	Channel code	8	9	10	11	12	13	14	15
Active meandering	A			**2**		1	**3**		2
Bedrock	B			1				1	**3**
Plane-bed	P		1	1	1	**2**			**3**
Plane-riffle	R			1	1			1	2
Pool-riffle	O					1			1
Step-pool	S	**4**	**4**	1	1	**2**			
Wandering	W				1			**2**	
Total		4	5	6	4	6	3	4	11

Table 5-7: Number of SEPA channel types in the TWINSPAN groups. Numbers in bold indicate the most common SEPA channel type in each TWINSPAN group.

Tables 5-8 and 5-9 provide a summary of catchment and biological characteristics of the TWINSPAN groups. The study reaches in Group 8 (*n* = 4) are high in altitude (>400 m) with a steep gradient (6.4-19.6%), and are situated in the headwaters of catchments. Dominant macroinvertebrate families (occurring in 75% of samples) are Ceratopogonidae, Polycentropodidae and Simuliidae (Table 5-9). The group's water chemistry is characterised by acidic conditions (mean pH of 5.63), and low alkalinity (mean of 1.66). Group 9 (*n* = 5) is relatively species rich, with 11 macroinvertebrate taxa. Study reaches occupy a similar altitudinal range compared to Group 8, been located >390 m above sea level. The most abundant taxa are Baetidae, Odontoceridae, and Pediciidae, which are present in all samples (Table 5-9). Group 10 (*n* = 6) is the most diverse in the macroinvertebrate classification with the highest number of families. Macroinvertebrates occurring with the highest frequency are Chironomidae, Hydropsychidae and Hydroptilidae (occurring in 100% of samples). Group 11 is relatively species poor, only containing 7 families. Prominent taxa include Simuliidae, Taeniopterygidae and Tipulidae (present in 75% of samples). Baetidae, Caenidae and Pediciidae are the best indicator species of Group 12 (characterising 100% of samples). This group is dominated by circum-neutral pH, with the highest mean and median values for pH and alkalinity of the TWINSPAN groups. Study reaches in Group 13 are the lowest in altitude (mean of 334.33m), and have the highest upstream catchment area (mean of 311.9 km²) among the groups. The group's water chemistry is characterised by acidic conditions and low alkalinity values (mean of 5.7 and 1.5 respectively). Common occurring families of this group include Ceratopogonidae and Hydropsychidae. Group 14 is characterised by a relatively high species richness (14 families) in contrast to the other groups. Elmidae and Perlidae are the best indicators of the group, occurring in all four reaches (100% of samples). Water chemistry is similar to study reaches in Group 14 being dominated by acidic conditions and low alkalinity values (mean of 5.4 and 0.8 respectively). Group 15 has the lowest mean and median values for pH and alkalinity of all the groups. The study reaches are highly acidic occurring in a range between pH 4.7 to 5.5. Group 15 (n = 11) is also the most species poor of the TWINSPAN groups, supporting only five families. Empididae and Pediciidae are very good indicators of the group, present in eleven and ten samples. All study reaches from the Lui Water (4 in total) and the Derry Burn (1 in total, a tributary of the Lui Water), and four of the most upstream study reaches on the main stem of the R.Dee form this group. This clustering of study reaches by sub-catchment implies that geographical proximity is potentially exerting an influence on the composition of macroinvertebrate communities.

	Altitude (m)	Upstream catchment area (km²)	Distance from source (km)	Valley gradient (%)	pH	Alkalinity
Group 8 (*n* = 4)						
Mean	417	1.5	1.72	11.22	5.6	1.7
Median	411	1.6	1.85	9.46	5.6	1.7
Range	400 - 445	0.8 - 2	0.88 - 2.3	6.39 - 19.57	5.4 - 5.9	0.8 - 2.4
Group 9 (*n* = 5)						
Mean	419	3.6	2.83	9.62	6.6	4.8
Median	415	2	2.35	10.64	6.6	5.6
Range	390 - 445	1.8 - 8.8	2.18 - 3.98	2.61 - 13.05	5.6 - 7.7	1 - 7.9
Group 10 (*n* = 6)						
Mean	377	60.1	9.71	3.35	6.6	5.2
Median	369	66	9.68	1.06	6.8	4.5
Range	342 - 425	1.4 - 104	1.9 - 15.7	0.65 - 12.81	5.6 - 7.5	2.5 - 9.4
Group 11 (*n* = 4)						
Mean	463	26.8	5.75	1.91	6.5	4.4
Median	467	24.1	5.59	1.64	6.6	4.9
Range	394 - 525	8.3 - 50.8	3.63 - 8.2	0.66 - 3.71	5.9 - 6.9	2.4 - 5.5
Group 12 (*n* = 6)						
Mean	473	19.3	4.75	2.97	7.0	6.8
Median	458	13.5	4.41	2.46	6.8	6.6
Range	392 - 615	2 - 54.8	1.2 - 9.08	0.66 - 5.76	6.6 - 7.9	4.5 - 9.6
Group 13 (*n* = 3)						
Mean	334	311.9	29.13	0.22	5.7	1.5
Median	328	295	28.95	0.17	5.7	1.6
Range	325 - 350	285 - 355.8	27.65 - 30.78	0.17 - 0.33	5.7 - 5.8	1.5 - 1.6
Group 14 (*n* = 4)						
Mean	341	194.6	22.78	0.70	5.4	0.8
Median	340	215	23.99	0.66	5.5	0.7
Range	330 - 355	56 - 292.5	15.08 - 28.05	0.17 - 1.3	5.2 - 5.7	0.5 - 1.5
Group 15 (*n* = 11)						
Mean	396	59.8	15.33	1.67	5.2	0.5
Median	405	55.8	14.83	1.05	5.3	0.5
Range	335 - 426	25.8 - 137.5	11.83 - 18.7	0.37 - 4.36	4.7 - 5.5	0.3 - 0.8

Table 5-8: The physico-chemical characteristics of the TWINSPAN macroinvertebrate classification.

Taxa	Taxa code	Group 8 *N* = 4 *F* = 9	Group 9 *N* = 5 *F* = 11	Group 10 *N* = 6 *F* =16	Group 11 *N* = 4 *F* = 7	Group 12 *N* = 6 *F* =10	Group 13 *N* = 3 *F* =10	Group 14 *N* = 4 *F* =14	Group 15 *N* =11 *F* = 5
Ancylidae	Anc			33					
Baetidae	Bae		100			100			
Brachycentridae	Bra						2		
Caenidae	Cae		80			100			
Ceratopogonidae	Cer	75					100		
Chironomidae	Chi	25		100					27
Chloroperlidae	Chl		60						
Dytiscidae	Dyt			33.33		50		50	
Elmidae	Eli					33		100	
Empididae	Emp					83			100
Ephemerellidae	Eph		20	66.67					
Glossosomatidae	Glo		60	66.67			66.67		
Goeridae	Gor							25	
Heptageniidae	Hep		80			83		25	
Hydraenidae	Hydr					33			
Hydrophilidae	Hydo							25	
Hydropsychidae	Hydpsy			100			100	75	
Hydroptilidae	Hydtil			100			100		
Lepidostomatidae	Lepi	25		33			67	75	
Leptoceridae	Leptoc	50		33			67	50	
Leptophlebiidae	Leptop	50						25	
Leuctridae	Leu			50					
Limnephilidae	Limn				25				45
Limoniidae	Limo							75	
Lymnaeidae	Lym			33					
Nemouridae	Nem			50					
Odontoceridae	Odo		100			33			
Pediciidae	Ped		100			100			91
Perlidae	Perli		60		50			100	
Philopotamidae	Phi			33					
Phryganeidae	Phr							25	
Physidae	Phy			33					
Polycentropodidae	Pol	75		50		33.33			
Psychomyiidae	Psymy	25							
Rhagionidae	Rha						33	25	
Sericostomatidae	Ser		80	83			33	50	
Simuliidae	Sim	75			75		67		36
Siphlonuridae	Sip				25				
Sphaeriidae	Sph				25				
Taeniopterygidae	Tae		40		75				
Tipulidae	Tip				75				

Table 5-9: The frequency of occurrence (%) of macroinvertebrate families in each group generated by the TWINSPAN biological classification. *F* denotes number of families.

MDA was performed to explore the predictive power of the catchment driver and physical habitat datasets to identify the macroinvertebrate groups generated by the TWINSPAN classification. The discriminant functions generated from the test were used to assign the study reaches to the macroinvertebrate groups. MDA identifies the relative contribution of the environmental variables to the separation among the groups (McElarney and Rippey, 2009). The MDA eigenvalues for the first three discriminant functions were 8.04, 2.74 and 1.17 respectively, when using the catchment driver dataset to predict the a priori macroinvertebrate groups. The first discriminant function accounted for a reasonably high percentage of the variance (64.5%) in the macroinvertebrate groups, and was significantly different (Wilks' lamba = 0.009) at the 0.001 significance level. The key catchment drivers for the first function were distance from source, solid geology and superficial geology (standardised canonical discriminant functions of 2.051, -0.643 and 0.533 respectively). A classification matrix within a MDA model signifies the robustness of a tested typology. A cross validation method was employed, whereby each case (i.e. study reach) is classified by the functions derived from all cases (i.e. from all other study reaches) other than that case (i.e. study reach). Using catchment drivers to predict the macroinvertebrate groups, and the enter independents together method resulted in 41.9% of study reaches being correctly classified into their macroinvertebrate groups (Table 5-10).

The same process was repeated using the physical habitat dataset to predict the macroinvertebrate groups produced by the TWINSPAN classification. The principal variables of the first discriminant function were cross sectional-area, and a surrogate index of stream power and distance from source (standardised canonical discriminant function coefficients -7.832, 7.334 and 6.842 respectively), which accounted for 70.3%

of the data variability. The discriminant function was found to be significantly different (Wilks' lambda = 0.000) at the 0.001 significance level. Inspection of the classification matrix (Table 5-10) shows 18.6% of the study reaches been correctly allocated to the macroinvertebrate classification group. Therefore, examination of the two datasets from MDA analyses shows some clear trends in model performance. Using the physical habitat dataset compared to the catchment driver dataset resulted in a lower percentage of study reaches being assigned to the correct macroinvertebrate group.

	TWINSPAN group								
	8	9	10	11	12	13	14	15	
8	2	2	0	0	0	0	0	0	
9	1	3	0	0	1	0	0	0	
10	1	0	4	0	0	0	1	0	
11	0	0	1	0	3	0	0	0	
12	0	1	0	4	1	0	0	0	
13	0	0	0	0	0	0	3	0	
14	0	0	1	0	0	2	0	1	
15	0	0	0	0	0	1	2	8	Total
n	4	6	6	4	5	3	6	9	43
n correct	2	3	4	0	1	0	0	8	18
Proportion	50.55	50.55	66.67	0	20	0	0	88.89	41.86

a) Catchment driver dataset

	TWINSPAN group								
	8	9	10	11	12	13	14	15	
8	1	2	0	0	1	0	0	0	
9	2	0	1	1	1	0	0	0	
10	1	0	0	1	2	0	0	2	
11	0	1	1	0	1	0	1	0	
12	0	3	1	1	1	0	0	0	
13	0	0	0	0	0	1	2	0	
14	0	0	0	0	0	0	2	2	
15	0	0	3	2	2	0	1	3	Total
n	4	6	6	5	8	1	6	7	43
n correct	1	0	0	0	1	1	2	3	8
Proportion	25	0	0	0	12.50	100	33.33	42.86	18.60

b) Physical habitat dataset

Table 5-10: Classification matrix of the TWINSPAN groups using a) the catchment driver, and b) the physical habitat dataset.

5.6.3 Each geomorphic channel type in the SEPA, Catchment Driver and Physical Habitat typologies will harbour unique taxa.

The spatial arrangement of macroinvertebrate samples classified according to channel types in the SEPA typology is shown in Figure 5-3. The ordination diagram indicates severe overlapping of channel type ellipses. Step-pool samples are very widely scattered, and overlap with all other channel type ellipses. In contrast, bedrock and wandering samples tend to group tightly together in the ordination, and the former channel type is distinct from active meandering samples. The distributions of plane-bed, plane-riffle, and active meandering samples all substantially overlap.

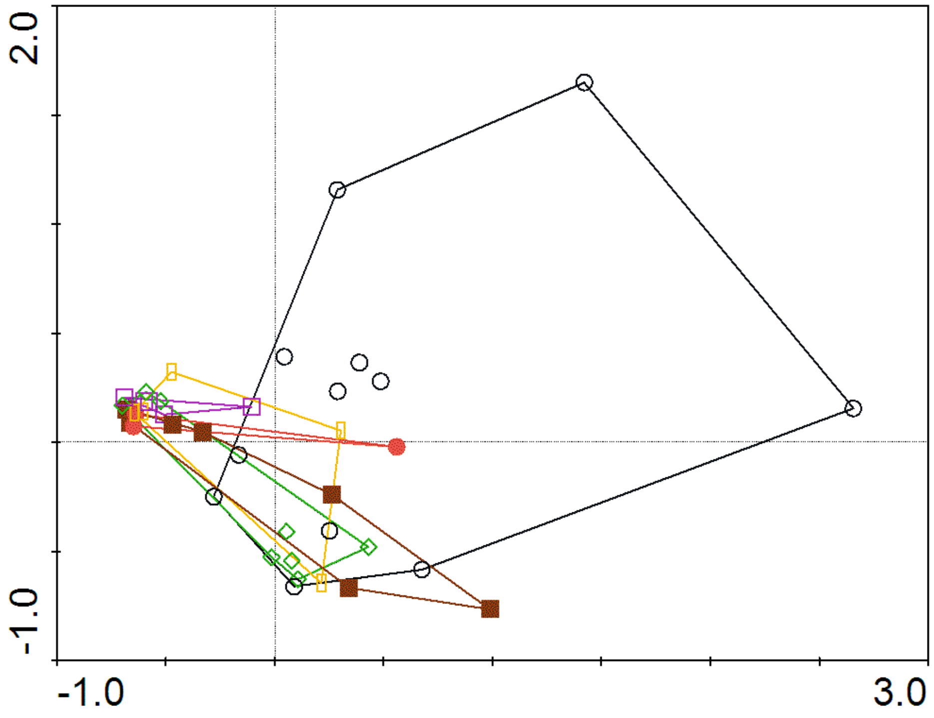


Figure 5-3: Distribution of macroinvertebrate samples in PCA space. Study reaches are classified according to channel types in the SEPA typology. Channel types are ○ step-pool, □ bedrock, ◊ plane-bed, ▮ plane-riffle, ● wandering, and ■ active meandering.

Axes	1	2	3	4
Eigenvalues	0.443	0.221	0.14	0.076
Percentage variance of family data	44.3	22.1	14	7.6
Cumulative percentage variance of family data	44.3	66.4	80.4	88

Table 5-11: Statistical summary of PCA of the biological data.

The first two PCA axes explain 66.4% of the variability in the family data (Table 5-11). The arrangement of the 55 macroinvertebrate taxa along the first two PC axes is presented in Figure 5-4. The lengths and directions of arrows signify the importance of the taxa in 'explaining' variation in macroinvertebrate patterns and direction of taxa compositional changes across samples (Thomson *et al*. 2004). The positioning of step-pool samples in the upper, right side of the ordination (in Figure 5-3) appear to on a gradient of increasing abundance of Chironomidae, Leptophlebiidae, Psychomyiidae, Leuctridae, Rhyacophilidae, and Nemouridae. In contrast, bedrock samples are located on the negative axis of PC1, and seem to be dominated by Haliplidae, Corixidae, Beraeidae, Curculionidae and Phryganeidae.

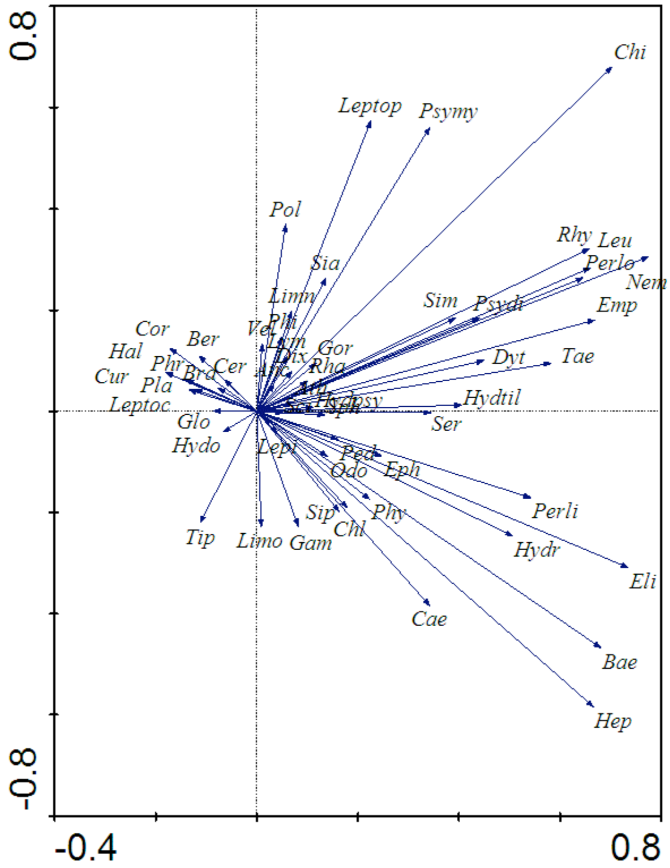


Figure 5-4: Distribution of macroinvertebrate families in PCA space. Family names are coded according to Table 5.4.

Ordination of channel types in the Catchment Driver typology reveals similar results to the ordination of channel types in the SEPA typology (Figure 5-5). Step-pool samples are widely scattered, and overlap with plane-bed and semi-constrained samples. In comparison, meandering samples occupy a small ordination space and have a tight distribution, indicative of low variability within the group. Furthermore, step-pool and meandering samples reaches are clearly separate from one another. As in the above ordination (Figure 5-3), plane-bed samples occupy similar ordination space.

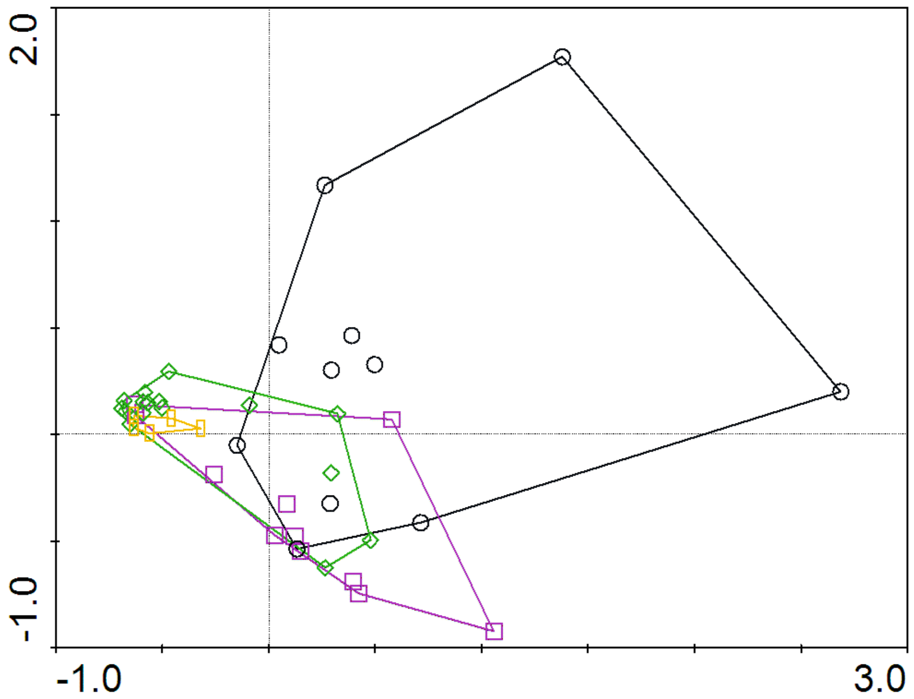


Figure 5-5: Distribution of macro-invertebrate samples in PDA space. Study reaches are classified according to channel types in the Catchment Driver typology. Channel types are ○ step-pool, □ plane-bed, ◊ semi-constrained, and ▮ meandering.

Axes	1	2	3	4
Eigenvalues	0.438	0.221	0.147	0.074
Percentage variance of family data	43.8	22.1	14.6	7.4
Cumulative percentage variance of family data	43.8	65.9	80.5	87.9

Table 5-12: Statistical summary of PCA of the biological data.

The first two PCA axes account for 65.9% of the variation in the family-environment relationship (Table 5-12). The positioning of step-pool samples in the upper, right side of the ordination (Figure 5-5) seems to be along a gradient of increasing Chironomidae, Leptophlebiidae, Psychomyiidae, Nemouridae, Rhyacophilidae, Empididae, Leuctridae and Perlodidae (Figure 5-6). Meandering samples are located on the negative axis of PC1 and seem to be dominated by Planorbidae, Brachycentridae, Leptoceridae, Haliplidae, Curculionidae, and Glossomatidae taxa.

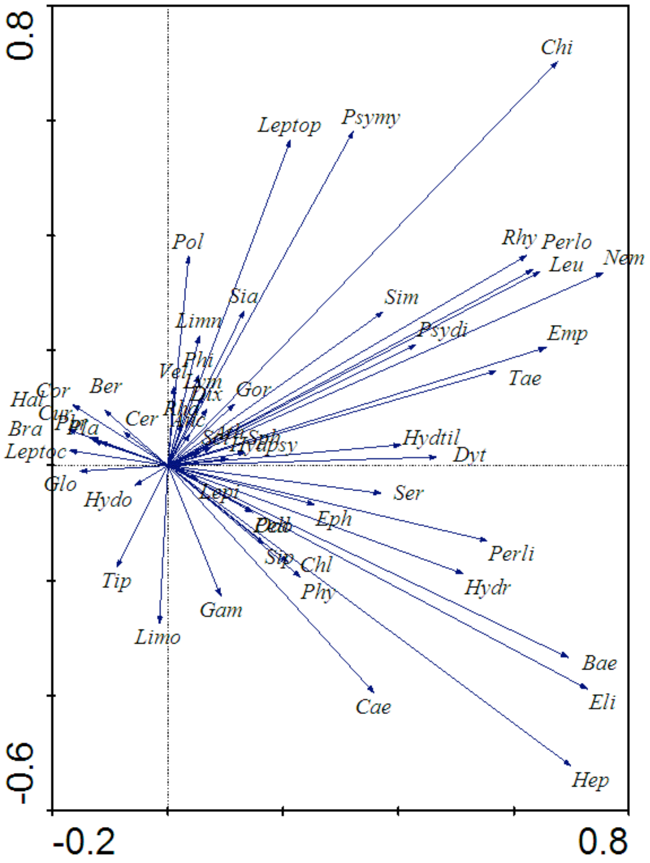


Figure 5-6: a) Distribution of macroinvertebrate families in PCA ordination space. See Table 5-4 for family names.

Similar to the other two typologies, the ellipses of channel types in the Physical Habitat typology occupy similar ordination space and their distributions strongly overlap (Figure 5-7). Plane-gravel bed samples are widely scattered, and their distribution overlaps with all other samples. Step-pool samples tend to group more tightly than plane-gravel bed samples, but the samples still possess a large distribution. Conversely, active meandering samples are grouped very tightly together, and are separate from step-pool samples; a similar pattern as in the Catchment Driver typology.

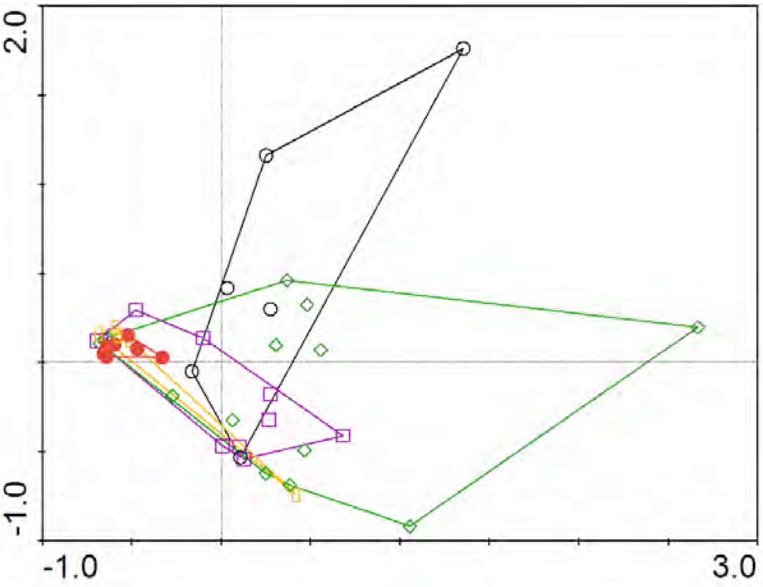


Figure 5-7: Distribution of macro-invertebrate samples in PCA space. Study reaches are classified according to channel types in the Physical Habitat typology. Channel types are ○ step-pool, □ plane-boulder bed, ◊ plane-gravel bed, and ▮ bedrock, and ● active meandering.

Axes	1	2	3	4
Eigenvalues	0.44	0.22	0.15	0.08
Percentage variance of family data	43.6	22.3	28.2	7.5
Cumulative percentage variance of family data	43.6	65.9	80.5	88

Table 5-13: Statistical summary of PCA of the biological data. (Passive meandering, RD7 is excluded from the analysis as there is only one sample).

Table 5-13Table 5-13 shows the first two PCs explain 65.9% of the data variability; a very similar pattern compared to the statistical summary output for the other two typologies. Similar to the other two typologies, step-pool samples appear on a gradient of increasing Leptophlebiidae and Psychomyiidae abundances (Figure 5-8). Bedrock samples appear on a gradient of increasing Haliplidae, Limoniidae, Gammaridae and Caenidae, whereas active meandering samples are on a gradient of increasing Leptoceridae and Glossosomatidae.

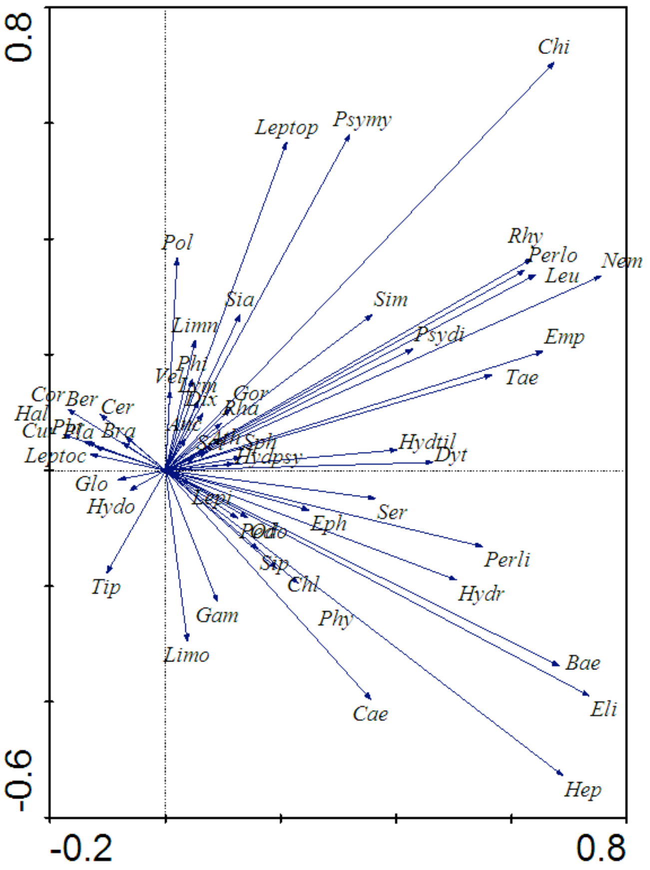


Figure 5-8: Distribution of macro-invertebrate families according to the physical habitat typology. Family names are coded according to Table 5.4

Analysis of Similarity

The results of the PCA ordination are supported by the Analysis of Similarity (ANOSIM) results (Table 5-14). When channel types in the SEPA typology were analysed together based on PC1 axis scores, no significant channel type effect was present (R = 0.05, P = 0.19). However, examination of individual channel types revealed a statistical difference between bedrock and step-pool samples (R = 0.33, P = 0.03). When channel types in the Catchment Driver typology were grouped together, the global R for the test of channel types was significant (R = 0.194, P = 0.001) for PC1, indicating greater biological differentiation at this level of typology. The greatest difference was between step-pool and semi-constrained sites (R = 0.358, P = 0.001), and then between step-pool and meandering sites (R = 0.479, P = 0.01), followed by plane-bed and semi-constrained sites (*R* = 0.227, *P* = 0.02). Step-pool and plane-bed (*R* = -0.018, *P* = >0.05), and semi-constrained and meandering sites (*R* = -0.128, *P* = >0.05) were not statistically different based on PC1 scores. A significant effect of channel type was seen for the Physical Habitat typology (*R* = 0.147, *P* = 0.01), with the greatest difference between step-pool and active meandering reaches (*R* = 0.78, *P* = 0.001). This result is visually apparent in the PCA ordination diagram (Figure 5-7). Active meandering samples are also statistically different from plane-boulder bed (*R* = 0.31, *P* = 0.012), and plane-gravel bed sites (*R* = 0.32, *P* = <0.001). Similarly, this result is also clear in the PCA ordination diagram as active meandering samples are tightly clustered together. Step-pool samples are also different from bedrock samples (*R* = 0.32, *P* = 0.042) based on PC1 scores.

Similar ANOSIM results occur based on PC2 scores. No significant (*R* = -0.06, *P* = 0.83) channel type effect was obtained for channel types in the SEPA typology, but a significant channel types effect was present for the Catchment Driver typology (*R* = 0.248, *P* = 0.000) and also the Physical Habitat typology (*R* = 0.071, *P* = 0.01). In the SEPA typology, bedrock samples were different from wandering samples (*R* = 0.539, *P* = <0.04). In the Catchment Driver typology, step-pool and semi-constrained samples (*R* = 0.272, *P* = <0.01), and step-pool and plane-bed samples (*R* = 0.152, *P* = <0.03) were statistically different. Plane-bed and semi-constrained samples were also different (*R* = 0.317, *P* = <0.01). When channel types in the Physical Habitat typology were analysed separately, the largest difference was between active meandering and step-pool samples (*R* = 0.518 = <0.001), followed by bedrock and active meandering samples (*R* = 0.418, *P* = <0.001). Step-pool and plane-boulder bed (*R* = 0.264, *P* =

<0.05), and also active meandering and plane gravel-bed samples (*R* = 0.226, *P* = <0.05) were different.

Typology	Channel type	R value	ANOSIM p-value	Post-hoc test group
SEPA	Step-pool	0.333	<0.05	Bedrock
Catchment driver	Step-pool	0.358	<0.001	Semi-constrained
		0.479	<0.01	Meandering
	Plane-bed	0.227	<0.05	Semi-constrained
Physical habitat	Step-pool	0.325	<0.05	Bedrock
		0.78	<0.001	Active meandering
	Active meandering	0.31	<0.05	Plane-boulder bed
		0.32	<0.001	Plane-gravel bed

a) PC1 axis scores

Typology	Channel type	R value	ANOSIM p-value	Post-hoc test group
SEPA	Bedrock	0.539	<0.05	Wandering
Catchment driver	Step-pool	0.152	<0.05	Plane-bed
		0.272	<0.01	Semi-constrained
	Plane-bed	0.317	<0.01	Semi-constrained
Physical habitat	Step-pool	0.264	<0.05	Plane-boulder bed
	Active meandering	0.518	<0.001	Step-pool
		0.226	<0.05	Plane-boulder bed
		0.418	<0.001	Bedrock

b) PC2 axis scores

Table 5-14: Results of ANOSIM comparing similarities of macroinvertebrate assemblages within and between channel types in the SEPA, Catchment Driver and Physical Habitat typologies for a) PC1 axis scores, and b) PC2 axis scores.

Indicator species analysis

Indicator species analysis showed six macroinvertebrate families (from a study total of 55 families) that differed significantly (*P* <0.05) among the SEPA channel types in relative abundance (Table 5-15). One significant taxon characterises bedrock reaches and wandering reaches, and four taxa are indicative of step-pool reaches. Bedrock reaches are characterised by Haliplidae (Table 5-15). Haliplidae are often in slow-running streams or stagnant water (Quigley, 1977). Typical characteristics of bedrock reaches are broken standing waves, unbroken standing waves and chute flow, which are indicative of fast velocities (Chapter 4, section 4.7.5). However, this channel type incorporates a range of flow environments from cascades and rapids to deep pools (Chapter 4, section 4.7.5). Haliplidae communities maybe clustered in the slow velocities associated with pools within this channel type. Taeniopterygidae, Chironomidae, Leptophlebiidae and Perlodidae are associated with step-pool channel types. This channel type typically occurs in steep headwaters, and is dominated by bedrock steps and plunge pools, and alternating velocities of critical and sub-critical flow. In contrast, wandering samples are exemplified with Limoniidae. Traits of this channel type include extensive gravel and sand sheets. Wandering channels are also characterised by their actively eroding banks and instability. No taxa are indicative of plane-bed, plane-riffle or active meandering channel types.

Channel type	Family	IndVal	t	Rank
B	Haliplidae	33.3	2.104	39
S	Taeniopterygidae	54.2	3.232	4
S	Chironomidae	51.9	2.902	9
S	Leptophlebiidae	42.9	2.225	34
S	Perlodidae	30.5	2.443	24
W	Limoniidae	52.7	3.583	9

Table 5-15: Taxa that differed significantly in abundance between channel types in indicator species analysis ($P < 0.05$), listed according to the channel types where each was most common. Channel codes are B = Bedrock, S = Step-pool and W = Wandering.

Indicator species analysis was also performed on the Catchment Driver typology, and revealed 19 macroinvertebrate families (from a study total of 55 families) that differed significantly ($P <0.05$) among the four channel types (Table 5-16). The majority of these significant taxa (12 macroinvertebrate families) characterise step-pool reaches. Highly indicative taxa of this channel type are Chironomidae, Taeniopterygidae, Empididae, Nemouridae and Simuliidae (indicator value of >50.0). In contrast, only one taxon is significantly associated with plane-bed and semi-constrained reaches; Caenidae (indicator value of 63.5) and Polycentropodidae (indicator value of 44.2) respectively. Finally, meandering samples are associated with Glossomatidae, Ceratopogonidae, Leptoceridae, Limoniidae and Brachycentridae (indicator value of >30.5). Glossomatidae are particularly indicative of meandering reaches, occurring in 91.9% of samples. The analysis indicates that the channel types with the most indicator species, step-pools reaches (12) and meandering reaches (5) occur at the extremities of the catchment. For examples, step-pool reaches typically occur in headwaters, whereas meandering reaches with pool-riffle sequences usually occupy in the lowlands.

Channel type	Taxa	IndVal	t	Rank
S	Chironomidae	71.3	4.417	2
S	Taeniopterygidae	66.5	3.984	2
S	Empididae	64.1	2.953	7
S	Nemouridae	61.7	2.78	6
S	Simuliidae	50.5	2.555	15
S	Perlidae	49.7	2.46	26
S	Perlodidae	49.1	5.23	1
S	Baetidae	45	3.167	8
S	Leuctridae	45	2.171	39
S	Rhyacophilidae	44.3	2.371	20
S	Leptophlebiidae	43.8	2.662	18
S	Odontoceridae	43.4	2.644	23
P	Caenidae	63.5	2.9	13
SU	Polycentropodidae	44.2	2.449	28
M	Glossosomatidae	91.9	4.223	1
M	Ceratopogonidae	56.2	4.136	6
M	Leptoceridae	54.6	4.853	3
M	Limoniidae	53.4	3.593	4
M	Brachycentridae	30.5	2.776	16

Table 5-16: Taxa that differed significantly in abundance between channel types in indicator species analysis ($P < 0.05$), listed according to the channel types where each was most common. Channel codes are S = Step-pool, P = Plane-bed, SU = Semi-constrained, and M = Meandering.

Of the macroinvertebrate families that differed significantly among channel types in the Physical Habitat typology (Table 5-17), the group related to step-pools consisted of Chironomidae, Simuliidae and Perlodidae (indicator value >41.0). These three taxa were also found to be significant indicators of step-pool reaches in the Catchment Driver typology. Furthermore, Chironomidae (indicator value of 54.3) is the most indicative macroinvertebrate family of step-pool reaches in the Physical Habitat typology, and also in the Catchment Driver typology. In contrast, plane-boulder bed reaches with a dominance of boulders, bedrock substrate, and cascades were associated with Heptageniidae (indicator value of 34.5). Plane-bed reaches were also characterised by a low number of indicator families, Baetidae and Ephemerellidae (indicator value of 34.3 and 32.2 respectively). Haliplidae were found to be symptomatic of bedrock reaches in the Physical Habitat typology, and the SEPA typology (with an indicator value of 40.0 and 33.3 respectively). Active meandering reaches with a low grain size, typically gravel and sand substrate, and with pool, riffle, glide flow conditions harboured Glossosomatidae (indicator value of 77.2), and Limoniidae (indicator value of 42.8) families. These two macroinvertebrate families were also indicative of meandering reaches in the Catchment Driver typology. Additionally, Glossosomatidae is the most indicative macroinvertebrate family in both typologies.

Channel type	Taxa	IndVal	t	Rank
S	Chironomidae	54.2	2.753	10
S	Perlodidae	41.4	4.861	1
S	Simuliidae	41.1	2.006	44
BB	Heptageniidae	34.4	2.014	38
GB	Baetidae	34.3	1.999	36
GB	Ephemerellidae	32.2	2.263	38
B	Haliplidae	40	4.085	15
A	Glossosomatidae	77.2	2.857	14
A	Limoniidae	42.8	2.394	29

Table 5-17: Taxa that differed significantly in abundance between channel types in indicator species analysis ($P < 0.05$), listed according to the channel types where each was most common. Channel codes are S = Step-pool, BB = Plane-boulder bed, GB = Plane-gravel bed, B = Bedrock and A = Active meandering.

Overall, the indicator species analysis indicates that certain macroinvertebrate families differ significantly among most channel types in all typologies, and show some consistent associations. Haliplidae appear to be indicative of bedrock reaches, whereas Glossosomatidae and Limoniidae inhabit meandering reaches. Furthermore, step-pool reaches appear to harbour the highest number of significant indicative macroinvertebrate families, perhaps implying the most specialised fauna, whilst plane-bed reaches have few indicator species, perhaps suggesting dominance by generalist. Step-pool reaches have distinct geomorphic features, of alternating bedrock steps separated by plunge pools. This repetitive sequence of geomorphic features seems to have a distinct macroinvertebrate community.

5.6.4 The effect of geomorphic type will result in differences in macroinvertebrate communities that override the influences of water quality.

Initially, a global analysis was performed using the macroinvertebrate data and all the measured environmental data (i.e. all catchment drivers, physical habitat and physicochemical variables) in a RDA ordination. In subsequent RDA analyses, the effect of the individual datasets (i.e. the catchment driver, physical habitat and physico-chemical datasets) was explored, to determine how important the different subsets explain the influence of macroinvertebrate abundances. The spatial arrangement of the 43 macroinvertebrate samples and all the environmental variables along the first two RDA axes are shown in Figure 5-9. The lengths and directions of environmental arrows signify their relative importance in ‘explaining’ variation in macroinvertebrate taxa. The first two axes explain 25.9% and 28.6% of the variation in family data and family-environment relationship respectively (Table 5-18). The distributions of the majority of channel types are severely overlapping. However, step-pool samples tend to group together in the bottom right side of the ordination, and appear to be along a gradient of increasing channel gradient, superficial geology, potassium and altitude.

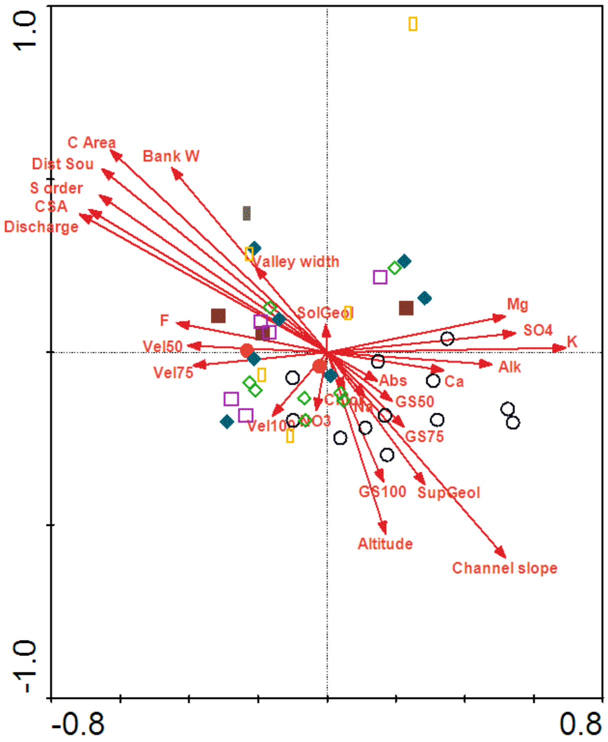


Figure 5-9: Distribution of macro-invertebrate samples and catchment driver, physical habitat and water chemistry data in RDA space. Channel types are ○ step-pool, □ bedrock, ◊ plane-bed, ▮ plane-riffle, ● pool-riffle, ■ wandering, ◆ active meandering, and ▮ passive meandering.

Axes	1	2	3	4
Eigenvalues	0.167	0.092	0.075	0.058
Family-environment correlations	0.993	0.967	0.993	0.994
Cumulative percentage variance of family data	16.7	25.9	33.4	39.2
Cumulative percentage variance of family-environment relationship	18.5	28.6	37.0	43.4

Table 5-18: Statistical summary of RDA using the catchment driver, physical habitat and physico-chemical variables.

Table 5-19 highlights the order of inclusion of environmental variables entered into the RDA ordination, plus the additional variance each environmental variable explains at the time it was included (lambda), and the significance of the environmental variable at that time (*P* value) (ter Braak and Šmilauer, 1998). Forward step-wise regression identified seven environmental variables that significantly ‘explained’ biological variation using RDA, and a further environmental variable (valley slope), which was marginally significant (Table 5-19). Two of these seven significant variables were catchment drivers (catchment area and stream order), two variables were physical habitat characteristics (a surrogate index of discharge and cross sectional area), and three variables relate to water chemistry (Mg, C and alkalinity). These initial results indicate that a combination of catchment drivers, physical habitat characteristics and geology (directly or via water chemistry) influence macroinvertebrate communities.

	Conditional Effects			
Variable	Var.N	Lambda	P	F
Discharge	24	0.11	0.002	4.9
Mg	35	0.06	0.002	2.83
Chloride	30	0.04	0.004	2.33
Stream order	3	0.04	0.002	1.9
Catchment area	5	0.04	0.002	2.17
CSA	23	0.04	0.04	1.83
Alkalinity	28	0.03	0.012	1.77
K	36	0.03	0.066	1.64
Valley slope	10	0.03	0.016	1.63
Solid geology	2	0.02	0.072	1.62
Altitude	1	0.03	0.058	1.46
Vel$_{50}$	20	0.02	0.102	1.39
Ca	33	0.02	0.206	1.25
GS$_{25}$	15	0.02	0.198	1.23
GS$_{75}$	17	0.03	0.004	1.87
Vel$_{100}$	22	0.03	0.028	1.71
Distance from source	6	0.02	0.118	1.33
Fluoride	29	0.03	0.056	1.49
Stream power	7	0.01	0.168	1.31
WD$_{75}$	13	0.02	0.184	1.27
Bankfull width	26	0.02	0.176	1.34
WD$_{50}$	12	0.02	0.176	1.29
Superficial Geology	4	0.02	0.222	1.26
GS$_{50}$	16	0.02	0.162	1.28
Channel Slope	25	0.02	0.208	1.28
Valley width	8	0.01	0.37	1.12
WD$_{100}$	14	0.02	0.288	1.13
Vel$_{75}$	21	0.01	0.384	1.05
Colour	37	0.01	0.49	0.97
GS$_{100}$	18	0.02	0.526	0.96
Sulphate	32	0.01	0.422	1.03
Na	34	0.01	0.536	0.94
WD$_{25}$	11	0.01	0.68	0.72
Vel$_{25}$	19	0.01	0.68	0.71
Nitrate	31	0.01	0.73	0.67
pH	27	0.01	0.714	0.66
Sinuosity	9	0.01	0.95	0.25

Table 5-19: Summary of the automatic forward selection procedure highlighting the conditional effects of the environmental variables.

The seven environmental variables identified in Table 5-19 as significantly ‘explaining’ biological variation were entered into a second RDA (Figure 5-10). The first two axes of the RDA ordination using only these variables cumulatively account for 60.5% of the family-environment relationship (Table 5-20). The pattern of macroinvertebrate samples in the ordination is similar to the original RDA ordination as the distribution of many channel types overlap. However, step-pool samples appear more clustered together, located along the positive part of RDA1 and along the negative part of RDA2. Bedrock samples tend to be located towards the negative part of RDA1 and RDA2 of the ordination. However, the remaining channel types retain a widely scattered distribution.

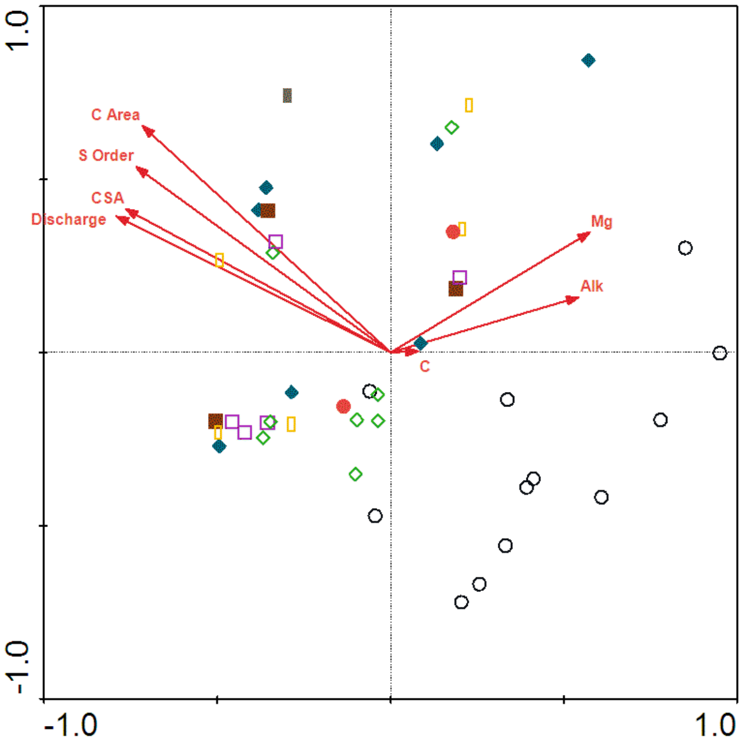


Figure 5-10: Distribution of macroinvertebrate samples and significant (P <0.05) environmental variables identified in Table 5-19. Channel types are ○ step-pool, ☐ bedrock, ◊ plane-bed, ▮ plane-riffle, ● pool-riffle, ■ wandering, ◆ active meandering, and ▮ passive meandering.

Axes	1	2	3	4
Eigenvalues	0.145	0.072	0.048	0.037
Family-environment correlations	0.937	0.903	0.881	0.853
Cumulative percentage variance of family data	14.5	21.7	26.5	30.2
Cumulative percentage variance of family-environment relationship	40.5	60.5	739.0	84.2

Table 5-20: Statistical summary of RDA using only the significant (P < 0.05) environmental variables identified in Table 5-19.

The ordering of the seven environmental variables in the model (Table 5-21) remains the same as in the first RDA ordination (Table 5-19). The significance of environmental variables contributing to the macroinvertebrate variation in the ordination also remains constant.

	Conditional Effects			
Variable	Var.N	Lambda	P	F
Discharge	3	0.11	0.002	4.9
Mg	7	0.06	0.002	2.83
Chloride	6	0.04	0.004	2.33
Stream order	1	0.04	0.002	1.9
Catchment area	2	0.04	0.002	2.17
CSA	4	0.04	0.04	1.83
Alkalinity	5	0.03	0.012	1.77

Table 5-21: Summary of the automatic forward selection procedure highlighting the conditional effects of the significant environmental variables identified in Table 5.19.

RDA was re-run using solely the catchment driver variables. Figure 5-11 shows the lengths and directions of catchment drivers and their relationship to macroinvertebrate samples. The first two axes of the RDA ordination explain 17.3% and 52.3% of the family data and family-environment relationship respectively (Table 5-22). Thus, over the first two axes, catchment drivers alone explain 67% (17.3/25.9) of the family level variation explained using the full environmental dataset.

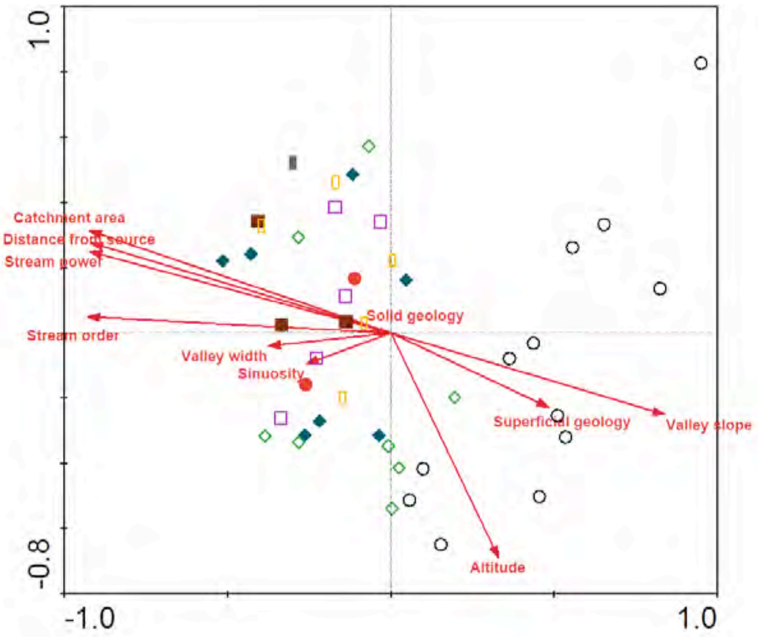


Figure 5-11: Distribution of macroinvertebrate samples and catchment driver variables in RDA space. Channel types are ○ step-pool, ☐ bedrock, ◊ plane-bed, ▮ plane-riffle, ● pool-riffle, ■ wandering, ◆ active meandering, and ▮ passive meandering.

Axes	1	2	3	4
Eigenvalues	0.12	0.06	0.05	0.03
Family-environment correlations	0.89	0.81	0.83	0.85
Cumulative percentage variance of family data	11.8	17.3	21.8	24.6
Cumulative percentage variance of family-environment relationship	35.6	52.3	65.9	74.5

Table 5-22: Statistical summary of RDA using the catchment driver variables.

Forward stepwise regression recognised four catchment drivers (catchment area, distance from source, stream power and stream order) that significantly ‘explained’ biological variation using RDA (Table 5-23). Stream order and catchment area were also identified as significant in the initial RDA ordination using all environmental variables (Table 5-19).

	Conditional Effects			
Variable	Var.N	Lambda	P	F
Catchment area	5	0.11	0.002	4.88
Distance from source	3	0.04	0.006	2.14
Stream power	6	0.03	0.042	1.59
Stream order	1	0.04	0.02	1.59
Valley slope	2	0.03	0.16	1.39
Altitude	7	0.02	0.188	1.38
Superficial geology	9	0.03	0.374	1.07
Valley width	4	0.01	0.556	0.93
Solid geology	8	0.02	0.428	0.97
Sinuosity	10	0.02	0.792	0.76

Table 5-23: Summary of the automatic forward selection procedure highlighting the conditional effects of the catchment driver variables.

The spatial arrangement of physical habitat characteristics of the study reaches, and their importance in explaining variation in macroinvertebrate taxa and direction of compositional changes across samples is presented in Figure 5-12. The statistical summary of the RDA ordination (in Table 5-24) shows similar results to RDA ordination using catchment drivers. In this RDA ordination, 18.1% of the variability is macroinvertebrate data is explained by the first two axes compared to 17.3% in the RDA ordination using purely catchment drivers. Thus, physical habitat characteristics are only slightly better predictors of composition at family level compared to catchment drivers.

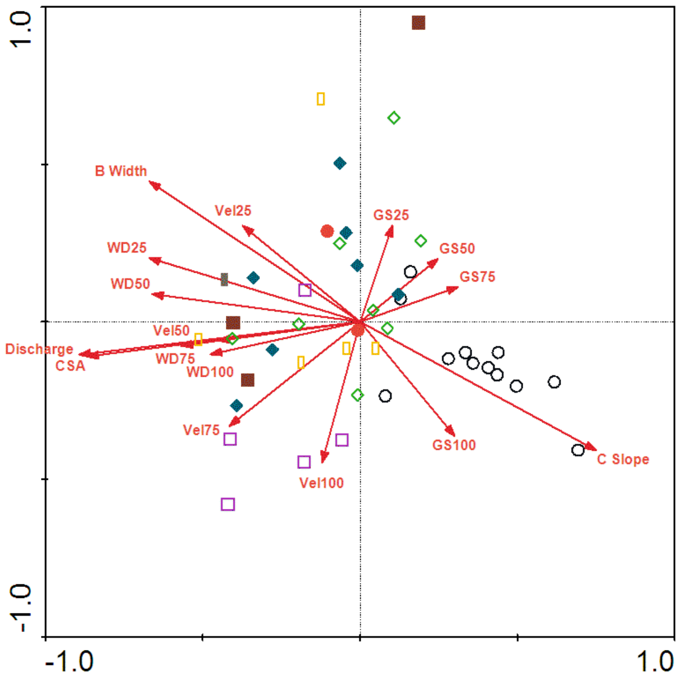


Figure 5-12: Distribution of macro-invertebrate samples and physical habitat variables in RDA space. Channel types are ○ step-pool, ☐ bedrock, ◊ plane-bed, ▮ plane-riffle, ● pool-riffle, ■ wandering, ◆ active meandering, and ▮ passive meandering.

Axes	1	2	3	4
Eigenvalues	0.13	0.05	0.05	0.04
Family-environment correlations	0.92	0.79	0.90	0.87
Cumulative percentage variance of family data	12.9	18.1	23.1	26.9
Cumulative percentage variance of family-environment relationship	27.0	37.9	48.3	56.1

Table 5-24: Statistical summary of RDA using the physical habitat variables.

Table 5-25 reveals three physical habitat variables of discharge, cross-sectional area and channel slope significantly influence macroinvertebrate communities. Discharge and CSA were also identified by the first RDA as significantly explaining variation in macroinvertebrate communities (Table 5-19).

	Conditional Effects			
Variable	Var.N	Lambda	P	F
Discharge	14	0.11	0.002	4.9
CSA	13	0.04	0.036	1.86
Channel slope	15	0.04	0.006	1.88
Bank W	16	0.02	0.15	1.3
WD_{25}	1	0.03	0.17	1.28
GS_{25}	5	0.02	0.34	1.07
Vel_{75}	11	0.03	0.17	1.26
WD_{100}	4	0.02	0.21	1.18
GS_{75}	7	0.03	0.22	1.23
WD_{75}	3	0.02	0.20	1.23
WD_{50}	2	0.02	0.47	1.01
Vel_{25}	9	0.02	0.48	0.97
GS_{50}	6	0.02	0.59	0.91
GS_{100}	8	0.02	0.47	0.97
Vel_{100}	12	0.02	0.42	1.03
Vel_{50}	10	0.02	0.41	1.04

Table 5-25: Summary of the automatic forward selection procedure highlighting the conditional effects of the physical habitat variables.

The composition of the 41 macroinvertebrate sites and physico-chemical variables along the first two RDA axes are shown in Figure 5-13. Step-pool samples tend to congregate in the positive area of RDA1, along a gradient of increasing base-status, and the negative area of RDA2 of the ordination, along a gradient of increasing colour. The majority of bedrock reaches are clustered in the negative part of RDA1 and RDA2, along a gradient reflecting decreasing base status. Plane-bed, plane-riffle, and wandering samples appear widely scattered, especially active meandering samples. The statistical output for the RDA ordination is summarised in Table 5-26. The RDA ordination using physico-chemical variables explained 19.3% of the variation in invertebrate composition over the first two axes, and was thus, slightly superior to the use of either physical habitat or catchment driver variables in isolation.

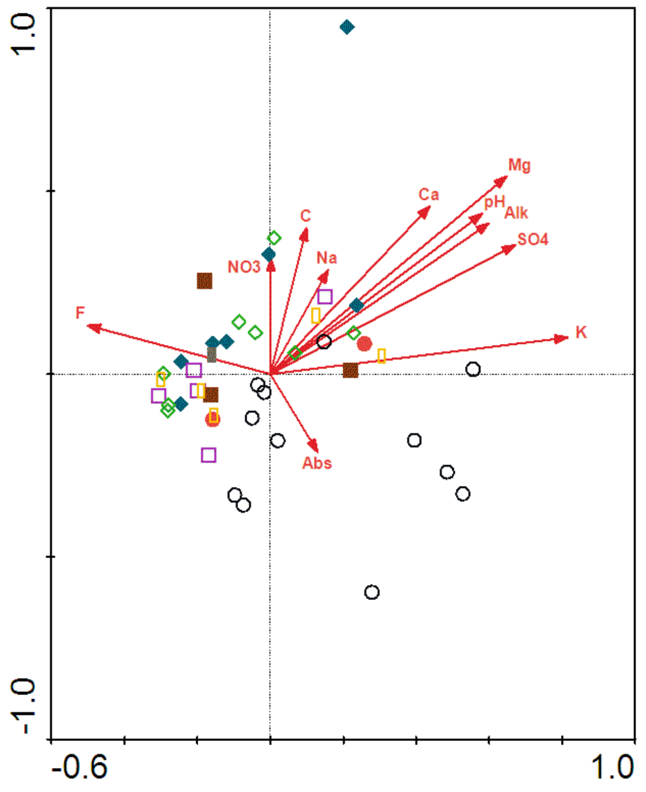


Figure 5-13: Distribution of macroinvertebrate samples and physico-chemical variables in RDA space. Channel types are ○ step-pool, □ bedrock, ◊ plane-bed, ▮ plane-riffle, ● pool-riffle, ■ wandering, ◆ active meandering, and ▮ passive meandering.

Axes	1	2	3	4
Eigenvalues	0.13	0.06	0.04	0.03
Family-environment correlations	0.90	0.90	0.84	0.76
Cumulative percentage variance of family data	13.2	19.3	23.5	26.8
Cumulative percentage variance of family-environment relationship	34.5	50.3	61.2	69.9

Table 5-26: Statistical summary of RDA using the physico-chemical variables.

Forward stepwise regression revealed four physio-chemical variables that significantly ‘explained’ macroinvertebrate variation using RDA (Table 5-27). The variables are potassium, magnesium, chloride and alkalinity.

	Conditional Effects			
Variable	Var.N	Lambda	P	F
K	10	0.1	0.002	4.47
Mg	9	0.05	0.008	2.2
C	4	0.03	0.02	1.89
Alkalinity	2	0.05	0.002	2.13
Absorbance	11	0.03	0.094	1.43
Ca	7	0.02	0.184	1.38
F	3	0.03	0.218	1.16
pH	1	0.02	0.294	1.14
SO_4	6	0.02	0.236	1.22
NO_3	5	0.02	0.77	0.77
Na	8	0.01	0.774	0.74

Table 5-27: Summary of the automatic forward selection procedure highlighting the conditional effects of the physico-chemical variables.

A matrix of all the geographic distances between all possible pairs of study reaches was constructed, and entered into a DCA, with geographic distances as the species variables and the study reaches as the samples. The axes scores of the DCA ordination were abstracted and entered into a RDA as a geographical co-variable, with macroinvertebrate and environmental data as the species and environmental variables (Figure 5-14). This analysis serves to identify how much variation in biology can be explained by environmental factors, once the geographical relatedness of sites has been taken into account. The first two axes of the RDA ordination using environmental variables with geographical distances as a co-variable describe 24.6% and 30.6% of the family data and family-environment relationship respectively (Table 5-28). The ordination of macroinvertebrate samples constrained only by these environmental variables and co-variables was very similar to the original RDA ordination with the first two axes describing 25.9% and 28.6% of the family and family-environment of variation in macroinvertebrate data (Table 5-18), which indicates that the spatial auto-correlation of sites is of very little importance.

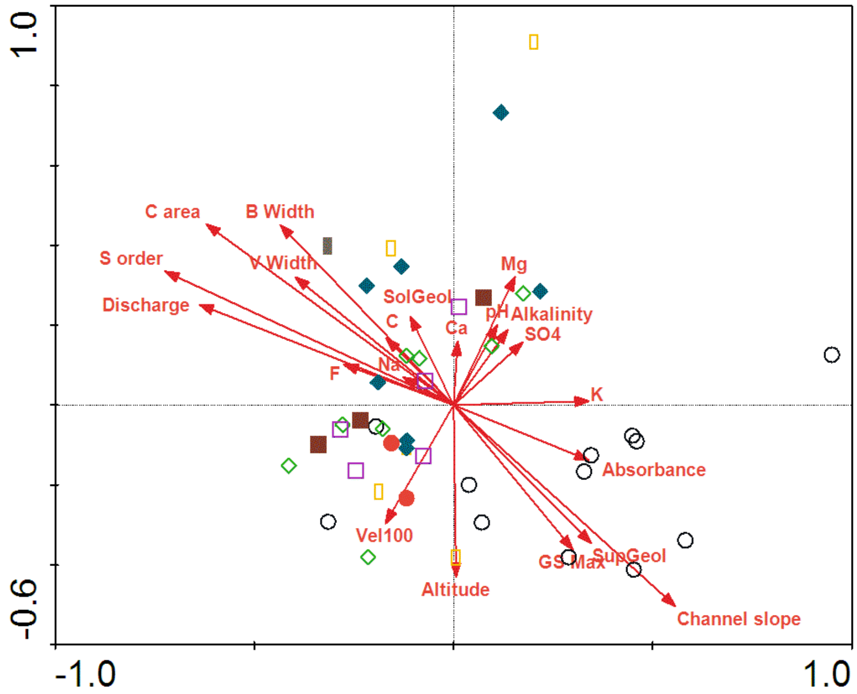


Figure 5-14: Distribution of macroinvertebrate samples, catchment drivers, physical habitat characteristics and physico-chemical variables, with geographical distances as co-variables in RDA space. Channel types are ○ step-pool, ☐ bedrock, ◊ plane-bed, ▮ plane-riffle, ● wandering, and ■ active meandering.

Axes	1	2	3	4
Eigenvalues	0.13	0.08	0.06	0.05
Family-environment correlations	0.98	0.97	0.95	0.94
Cumulative percentage variance of family data	15.6	24.6	31.4	37
Cumulative percentage variance of family-environment relationship	19.5	30.6	39.0	46.1

Table 5-28: Statistical summary of RDA using environmental variables and geographical distances as co-variables in RDA space.

The effect of using geographical distances as a co-variable only slightly changes the significant environmental variables effecting macroinvertebrate communities. Forward stepwise regression has identified three significant environmental variables (compared to seven without using geographical distances as a co-variable) that explain variation in macroinvertebrate assemblages (Figure 5-29). Two of these are catchment drivers (stream order and catchment area), and one is a physio-chemical variable (Mg).

	Conditional Effects			
Variable	Var.N	Lambda	P	F
Stream order	3	0.1	0.002	4.79
Mg	35	0.06	0.002	3.03
Catchment area	5	0.03	0.006	1.91
Solid geology	2	0.04	0.054	1.75
Na	34	0.03	0.10	1.62
Alkalinity	28	0.03	0.05	1.72
Valley slope	10	0.02	0.03	1.57
F	29	0.03	0.08	1.42
Distance from source	6	0.03	0.04	1.59
Absorbance	37	0.03	0.01	1.79
K	36	0.02	0.05	1.53
WD_{100}	14	0.02	0.12	1.35
Vel_{100}	22	0.02	0.10	1.44
Bankfull width	26	0.02	0.18	1.25
C	30	0.02	0.16	1.31
Altitude	1	0.03	0.13	1.39
Superficial geology	4	0.01	0.28	1.18
SO_4	32	0.02	0.26	1.21
pH	27	0.02	0.30	1.13
Ca	33	0.02	0.18	1.35
NO_3	31	0.01	0.45	1.01
Stream power	7	0.02	0.43	0.97
CSA	23	0.01	0.51	0.93
Discharge	24	0.02	0.14	1.42
Valley width	8	0.01	0.42	1.06
Channel slope	25	0.01	0.93	0.48
WD_{100}	18	0.01	0.90	0.51
Sinuosity	9	0.01	0.97	0.34

Table 5-29: Summary of the automatic forward selection procedure highlighting the conditional effects of the environmental variables with geographical distances as co-variables.

5.7 Discussion

There have been numerous geomorphic classification systems and typologies developed, with many claiming to be useful for ecological applications (e.g. Frissell *et al.* 1986; Rosgen, 1994). However, few have explicitly linked biological assemblages to different geomorphic channel types at the reach scale (Thomson *et al.* 2004; Chessman *et al.* 2006). This void is starting to be partly addressed by the EU WFD since Member States are required to generate a standardised methodology to assess the ecological status of water bodies. This necessitates the derivation of ecological targets using reference water bodies classified on their environmental characteristics (Neale and Rippey, 2008). The underlying principle supporting this approach is that sites which share similar environmental characteristics should also share similar biological communities (Reynoldson *et al.* 1997). However, recent findings have suggested that this approach has had poor success in predicting macroinvertebrate communities in river systems (Heino *et al.* 2002; Parsons *et al.* 2003). The EU WFD approach is the reverse of many conventional methods of classifying stream biota. Traditionally, a multivariate approach is initially used to classify biological communities, and the environmental variables are studied in relation to the generated biological groups. The discussion in this chapter concentrates on the traditional method of classifying biota, and subsequently explores the consequences of classifying the environmental variables first, and subsequently predicting the macroinvertebrate communities within the defined environmental groups.

5.7.1 Biotic indices can discriminate channel types in the SEPA typology.

The ecological status of rivers is often determined by using biological indicators (e.g. Camargo *et al*. 2004; Padisak *et al*. 2006). Biotic indices for rivers have been related to pollution, acidification, eutrophication and metals (Rosenberg and Resh, 1993). Effective bioassessment methods not only identify, but also assess the ecological success of restoration or management that cannot be shown solely by physico-chemical data (Kowalik *et al*. 2007; Clews and Ormerod, 2009). In the study, biotic indices: AWIC, ASPT, LIFE scores, and abundance data were used to discriminate channel types in the SEPA typology. The boxplots (in Figure 5-1) showed considerable overlap in abundance data and values of AWIC, ASPT, LIFE between the SEPA channel types. Therefore, the results show that the study reaches have similar macroinvertebrate abundances, acidity (indicated by AWIC scores), family richness (indicated by ASPT scores), and have responded in a similar manner to low flow effects (indicated by LIFE scores). One-way Analysis of Variance (ANOVA) post-hoc tests showed no statistical differences between any combinations of channel types based on any of the four scoring systems. The output of the boxplots and the one-way ANOVA post-hoc tests demonstrated that biotic scores and abundance data cannot discriminate the SEPA channel types, and therefore, the above hypothesis is rejected.

5.7.2 A bottom-up multivariate classification of macroinvertebrates can discriminate channel types in the SEPA typology.

The classification of macroinvertebrate abundances using a multivariate approach in TWINSPAN failed to segregate channel types in the SEPA typology, and therefore, the above hypothesis is rejected. The TWINSPAN classification produced uneven group sizes (Figure 5-2), as the number of study reaches within each group varied between three and eleven. Small groups of study reaches consistently split off from the main body, for example, groups eight, eleven and thirteen. In contrast, group fifteen remained relatively large in comparison, consisting of eleven study reaches. The study reaches appeared to cluster partly due to channel type and also due to geographical proximity in a catchment. Examination of Table 5-7 shows the combinations of SEPA channel types forming each of the TWINSPAN groups. Group eight solely consists of step-pool reaches and group thirteen comprises of active meandering reaches. Furthermore, group nine contains 80 per cent of step-pool reaches. However, the remaining five groups contain a heterogeneous mix of SEPA channel types, which implies other factors are influencing the pattern of macroinvertebrates other than channel type. Inspection of the study reaches in group fifteen in Figure 5-2 shows that some study reaches are clustering based on their position in the catchment. All four study reaches on the main stem of the Lui Water (LW1 to LW4), and a study reach on the Derry Burn (a tributary of the Lui Water) fall into this group. Additionally, two study reaches on the Quoich Water (QW1 and QW2) that are in close geographical proximity (0.475km) are also in group fifteen. Lastly, the four most upstream study reaches (RD1, RD6, RD9 and RD10) on the main stem of the River Dee are in group fifteen. The results indicate that some study reaches are clustering partly on a sub-catchment basis. This may reflect physical similarities in geographically adjacent sites or natural similarities in fauna associated with dispersion from a regional species pool.

The study divided one catchment (the upper River Dee and Allt a'Ghlinne Bhig) biologically, and subsequently tried to predict the groups using Multiple Discriminant Analysis (MDA). The MDA classification tables (5-10) show low percentages of correct predictions for the TWINSPAN groups from the catchment driver and physical habitat dataset, 42% and 19% in overall accuracy. At this spatial scale, the distinction between groups is subtle and hard to explain. The result may have been better if biological data from unimpacted rivers across Scotland had been used. A study by Holmes *et al.* (1998) grouped 1514 riverine sites based on macrophyte data using TWINSPAN. The highest level of the TWINSPAN classification identified four broad groups (A-D) representing an environmental gradient from lowland, eutrophic rivers to upland, torrential and oligotrophic rivers (Holmes *et al.* 1998). These four broad groups were further split into 10 River Community Types (RCTs) with additional sub-divisions into 38 sub-types. Subsequently, MDA was used to predict the classification of these TWINSPAN groups. A re-classification success of 45% was achieved. The Holmes *et al.* (1998) study is very different in scale to the work presented in this thesis.

The biological distinction between types in this study was very subtle, but may have been more apparent if using the RIVPACS approach.

5.7.3 Each geomorphic type in the SEPA, Catchment Driver and Physical Habitat typologies will harbour unique taxa.

The results of the analysis indicate that a few of the investigated geomorphic typologies have some ecological relevance. The ANOSIM results show that when channel types in the SEPA typology were analysed together based on PC1 and PC2 axis scores; no significant channel type effect was present. Hence, the hypothesis that each geomorphic type in the SEPA typology possesses a unique fauna is rejected. Indeed, a R value of -0.032 for the PC2 axis scores indicates that sites within a channel type can be more biologically different to one another, compared to study reaches in other channel types. However, when channel types were analysed individually based on PC1 axis scores, a significant difference between bedrock and step-pool samples was present. However, there was large within-river biotic variability within the other channel types. The macroinvertebrate communities of bedrock channels were also different from wandering reaches based on PC2 scores. Hawkins *et al.* (2000) propose that often the poor performance in environmental classifications in predicting macroinvertebrate communities may be partly because physical habitat heterogeneity present within the sites is not included, within the broad partitions of the classification. Thus, the clustering focuses on average values from a site, and not the variability if these values. The channel types within the SEPA typology have large biological variation within each type. A study by Hawkins *et al.* (2000) found that landscape classifications used in isolation can result in inaccurate predictions of the expected biota at sites. The ordinations in PCA and the ANOSIM results performed on the channel types in the SEPA typology supports this conclusion.

In the Catchment Driver typology, channel types separated more clearly based on their macroinvertebrate communities compared to channel types in the SEPA typology (Figure 5-5). When channel types were analysed together, a significant channel type influence was present based for both PC1 and PC2 axis scores ($R = 0.19$, $P = 0.002$ for PC1 scores, and R = 0.248, $P = 0.000$ for PC2 scores respectively). In contrast to the SEPA typology, channel types in the Catchment Driver typology contain a distinct macroinvertebrate community, and the hypothesis can be accepted. Inspection of the results for the individual channel types shows considerable between-river biotic variability between step-pool and meandering reaches based on PC1 scores.

Examination of the macroinvertebrate communities of channel types in the Physical Habitat typology reveals some strong overlapping in the polygons occupied by some channel types (Figure 5-7). However, when channel types were analysed together, a significant channel type effect was present for both PCA and PC2 axis scores ($R = 0.147$, $P = 0.01$, and $R = 0.071$, $P = 0.01$). Therefore, the hypothesis that geomorphic types in the Physical Habitat typology possess unique taxa is accepted. Analysis of individual channel types reveals that step-pool channels are significantly different from bedrock channels based on PC1 axis scores. Active meandering reaches are also different from step-pool, plane-boulder bed and bedrock channels. The results of the PCA ordination diagrams indicate that none of the three typologies have a functional typology (as the distributions all overlap). The ANOSIM analysis reveals that overall geomorphic channel types in the SEPA typology do not have a distinct macroinvertebrate community. However, channel type significantly influences macroinvertebrate communities in the Catchment Driver and Physical Habitat typologies. An overall trend recurring through all typologies is that step-pool and meandering channels frequently have a distinct macroinvertebrate community compared to the other channel types. The weak and variable distinctiveness of macroinvertebrate faunas between the three investigated typologies implies that geomorphic channel typologies are inadequate to classify the biotic assemblages of fluvial systems to a high accuracy.

The findings of the study concur with a similar study conducted by Chessman *et al.* (2006) who investigated the aquatic biota of River Styles (i.e. channel types) in the River Styles Framework (a top-down typology), in the Bega River basin in New South Wales, Australia. The study examined four biological assemblages: diatoms, aquatic and semi-aquatic macrophytes, macro-invertebrates and fish, and found that River Style (i.e. channel type) appeared to directly affect macrophyte and macroinvertebrate assemblages (at the taxonomic family level), probably through differences in physical habitat, but not diatoms and fish. This finding is similar to channel types in the Catchment Driver typology possessing a distinct macroinvertebrate community. Although, the study by Chessman *et al.* (2006) found an overall difference between macroinvertebrates and macrophytes and River Styles, the study did not specify which of the nine River Styles was different from one another. Thomson *et al.* (2004) also compared macroinvertebrate assemblages (at the taxonomic family level) and habitat characteristics of pool and run geomorphic units for three different River styles: a Gorge (a confined style), a Bedrock-Controlled Discontinuous Floodplain (BCDF, a partly confined style), and a Meandering Gravel Bed (MGB, an alluvial style), on the north coast of New South Wales, Australia. The study found significant differences for pools (although not for those associated with runs) between BCDF rivers, Gorge rivers and MGB rivers (Thomson *et al.* 2004), but the influence of geographic separation and proximity was not addressed (Chessman *et al*. 2006).

A study by Parsons *et al*. (2003) investigated differences of macroinvertebrates (mostly identified to the genus and species level) in riffles in the Upper Murrumbidgee in south-east Australia. Parsons *et al*. (2003) applied their study to a hierarchical arrangement of different spatial scales from catchments and zones to reaches and riffles. These spatial zones were identified via a combination of both hydrological and geomorphological criteria (Chessman *et al.* 2006). More specifically the study defined three zones on the basis of channel confinement: confined, unconfined and broad. The study identified that riffle assemblages were more similar to one another with close geographical proximity within the same reach, compared to being classified by zone type. Although the geomorphic classification used by Parsons *et al.* (2003) is less complex than the Catchment driver, Physical habitat typologies and River Styles Framework, since it is founded only on confinement, the study portrays a prevailing influence of geographical proximity on macroinvertebrate assemblages, and an evident pattern associated with geomorphic zone or type. The studies by Parsons *et al.* (2003) and Chessman *et al.* (2006) both demonstrate that geomorphic river typologies can partly explain variations in macroinvertebrate assemblages, though most can be attributed to the spatial patterning of other environmental variables, such as altitude and water temperature, and to biological processes such as colonisation and extinction.

5.7.4 The effect of geomorphic type will result in differences in macroinvertebrate communities that override the influences of water quality.

Many catchment drivers have been shown to influence macroinvertebrate community composition, such as catchment area, distance from source, mean annual discharge (all substitutes of stream size), conductivity, alkalinity (a surrogate of geology), and altitude (broadly indicative of temperature regime) (Wright *et al.* 1984; Moss *et al.* 1987; Marchant *et al.* 1997; Newson and Newson, 2000). When all variables from each of the three datasets (catchment driver, physical habitat and water chemistry datasets) were entered into a RDA, the multi-response permutation procedure (MRPP, Table 5-16) reveals similar patterns to those identified in previous studies, namely that a surrogate index of discharge, catchment area, and stream order (surrogates for stream size), are strong influences on macroinvertebrate community composition within channel types in the SEPA typology. Channel dimensions, such as cross sectional area was also significantly correlated with variations in the macroinvertebrate data. The results imply that macroinvertebrate communities are responding to a combination of large scale and local factors rather than to solely local factors, which is consistent with many other studies (e.g. Robson and Barmuta, 1998; Robson and Chester, 1999; Thomson *et al.* 2004). Physicochemical variables: magnesium, chloride and alkalinity were also significant in determining the macroinvertebrate community of channel types, although in reference sites these are a direct reflection of the weatherability of the underlying geology. Many other studies have identified stream chemistry as affecting macroinvertebrates (Clenaghan *et al.* 1998; Gibbins *et al.* 2001). Therefore, geomorphic, hierarchical classifications that use catchment drivers, physical habitat characteristics and water chemistry variables in combination may be highly useful in predicting the biotic assemblages. The use of physical habitat variables may be more relevant to fish and other biota that migrates over larger spatial areas, and have a more specific habitat requirement (Thomson *et al*. 2004). Different geomorphic units may provide different functions. For example, runs may act as a feeding source, backwaters and pools as resting areas and gravel bars as spawning sites (Thomson *et al*. 2004). Hence, a reach scale classification of geomorphic units may provide a useful suitable base to classify fish assemblages.

The similarity of macroinvertebrate samples in the SEPA typology implies that other factors may be equally or more influential in affecting biota than fluvial geomorphology. The lack of a strong pattern may be due to confounding by other factors that spatially vary in a similar manner to channel type. Channel types in the upper River Dee and Allt a'Ghlinne Bhig catchment tend to be geographically clustered, instead of being distributed at random. Potential confounding factors maybe biological dispersal and migration as movement by biota is energetically less costly between sites that are closer together than sites that are further apart (Chessman *et al.* 2006). Additionally, hostile environments, biogeographic or physical barriers, such as naturally, steep bedrock waterfalls or cascades may restrict movement. Confounding factors could also have occurred though if biological mechanisms are governed by physical variables, such as water temperature. Study reaches that are close together are likely to have similar water temperature regimes, or comparable altitudes. However, results of the RDA and MRPP analyses (Figure 5-14, Table 5-28 and Table 5-29) indicate that accounting for geographical distances between study reaches only slightly changes the results. For example, when all variables from the three datasets were entered into a RDA, 25.3% of the cumulative percentage of family data was accounted for by the first two RDA axes (Table 5-18), compared to 24.3% after extracting the influence of geographical distances between sites (Table 5-28). Thus, this analysis suggests that geographical distance between sites is not a confounding factor in the present study. This is a similar result to the study by Chessman *et al.* (2006) who found that the geographical clustering of sites in the same River Style did not affect macrophytes and macroinvertebrates.

The study highlights the multitude of factors influencing the presence and composition of macroinvertebrates within river systems, and the problems of disentangling these variables. The hypothesis that the effect of geomorphic type will result in differences in macroinvertebrate communities that override the influences of water quality has to be rejected as catchment drivers, physical habitat characteristics and water quality all have significant and overlapping effects on macroinvertebrate communities that are difficult to isolate.

5.8 General discussions and conclusions

The approach adopted in this study uses a bottom-up approach to develop a biological classification of macroinvertebrates, and examines the ecological significance of several top-down typologies based on geomorphic variables. The methodology of using geomorphic variables to develop a typology, and subsequently identifying if the channel types within the typology have any significance is a similar approach adopted by Brierley and Fryirs (2002) in relation to River Styles in the Australian River Styles Framework. The approach also has similarities to the EU WFD, which requires Member States to ecologically assess water bodies through the initial development of a geomorphic typology founded on environmental variables. The approach within the Directive is founded on the ecoregion concept of Omernik (1995) and further expanded upon by Barber *et al.* (1995). The underlying rationale is that sites classified by their environmental characteristics, and belonging to the same groups should harbour similar macroinvertebrate communities under unimpacted conditions. This theory is dependent on the assumption that classification of sites based on environmental variables will produce a meaningful partitioning of the biota, namely, in rivers, diatoms, benthic macroinvertebrates, aquatic macrophytes and fish (Neale and Rippey, 2008). Many past approaches to biological classifications have used data on the biological distribution, and subsequently focussed on the driving variables (Owen, 2001). However, the WFD has reversed this approach by describing habitat types or channel types by environmental attributes and then investigating the biota that is indicative of these types (Neale and Rippey, 2008). Owen (2001) warns of the potential problems of this approach, chiefly of the failure to have biological meaningful communities within a classification. The statistical analyses in the study show weak correspondence between geomorphic types and macroinvertebrate communities for the SEPA typology. The findings are very similar to a study by Neale and Rippey (2008) who examined the performance of the relative efficiency of multimetric and multivariate classification approaches in segregating the biological variation of macroinvertebrate communities of 22 minimally disturbed lakes in Northern Ireland. Their study found that the three investigated typologies divided the macroinvertebrate variation poorly in contrast to a multivariate biological site classification. The results of this study supported by other findings from the literature raises important questions as to the value of classifications and typologies that have been promoted as being useful in ecological applications, in particular the WFD typology approach of using environmental variables to predict macroinvertebrate communities, and also to establish type-specific biological reference conditions (Neale and Rippey, 2008).

The adoption of classifications and typologies as a tool for the biological assessment of rivers has attracted much debate and criticism, especially outside Europe (Neale and Rippey, 2008). For example, Hawkins and Vinson (2000) believe that no classification presently exists to reliably predict invertebrate fauna, and Reynoldson *et al*. (1997) has urged caution over the present use of multimetric approaches due to their 'imprecision and inaccuracy' contrasted to multivariate approaches. This study advocates a multivariate approach that initially starts with a biological classification of reference sites for the setting of biological targets as preferential compared to multimetric approaches, as no groups need to be specified. Gerritsen *et al.* (2000) highlight that a key advantage of biological classifications is that they do not make restrictive, untested or false assumptions about variation in biota.

The work presented in this chapter indicates the varying success of typologies to predict macroinvertebrate communities. Not all typologies have distinct fauna within their channel types. This has ramifications for the implementation of environmental classifications specified in the EU WFD. An alternative multivariate approach using a biological classification maybe more appropriate, such as using TWINSPAN or a RIVPACS-type approach (Wright *et al.* 2000), in which a site-specific fauna is predicted via MDA using measured unimpacted environmental variables as predictors. These tools are viewed as providing a standard method of biological assessment that can be applied universally, and not just limited to Europe as in the WFD (Hawkins *et al.* 2000). A biological classification and prediction tools have been proposed for lake littoral macroinvertebrate sets within the three ecoregions of Sweden by Johnson and Sandin (2001). Neale and Rippey (2008) highlight that the UK Technical Advisory

Group (2008) have proposed that this methodology could offer a standard framework for establishing biological objectives throughout Europe, and the obligatory EU WFD environmental typology could subsequently be used as a pan European standard administration tool to assess the ecological quality of water bodies.

The relationships between macroinvertebrates and other biota and reach scale geomorphic typologies are important for river management purposes, in particular river restoration. Traditionally, there was a consensus that different channel types would engender predictable differences in stream biota. However, this study has highlighted that macroinvertebrate communities do not differ between most channel types (excluding step-pool reaches) within a catchment, which may suggest that the classification of reaches into channel types is less useful. The study was undertaken on reaches in good-high morphological condition. Further work is needed to explore the macroinvertebrate communities of channel types in moderate and poor morphological condition. For example, potentially there may be type-specific trajectories in response to a given type of degradation.

The present study only found that two of the three geomorphic typologies had biological relevance. Macroinvertebrates were identified to family level in this study, and also in the study by Chessman *et al.* (2006). Identifying macroinvertebrates to a higher taxonomic resolution, such as genus or species level may have shown more distinction between channel types, but the differences would probably have been less ecologically significant, but purely taxonomically significant. The lack of biological distinction between types may also be due to several physical biotopes being present within all study reaches (Chapter 4, Figure 4-10). Rippled, smooth flow and unbroken standing waves, symptomatic of riffles, glides, pools and marginal deadwater are present in all channel types (Chapter 4, Table 4-18). Hence, channel types will share some communal macroinvertebrates.

Macroinvertebrate samples were collected from all dominant physical biotopes within a study reach, with the duration of kick sampling being proportional to their spatial coverage within the study reach. Each 3 minute kick sample aimed to be representative of the physical biotopes constituting the reach. However, in some study reaches, such as bedrock channels, it was difficult to kick sample representative physical biotopes. Many bedrock reaches possess an abundance of exposed boulders, which are difficult to sample. Furthermore, high velocities ($>2.3 m/s^{-1}$) characterising cascades and rapids in bedrock reaches also make sampling hard. The difficulty of sampling specific physical biotopes partly explains the lack of difference between channel types.

All study reaches in the upper River Dee and Allt a'Ghlinne Bhig catchment are subject to common stresses, such as through flashy flood regimes, high water velocities and low productivity. This study is trying to see the differences between channel types within these constraints. The combination of taxonomic resolution, the presence of some physical biotopes occurring across channel types, the difficulty of kick sampling specific micro-habitat, and common stresses partly accounts for the lack of biological distinction between types.

5.9 Conclusions

This chapter has developed a biological classification of macroinvertebrates using a multivariate predictive model approach, and also examined the macroinvertebrate communities of channel types in three typologies (the SEPA, Catchment Driver and Physical Habitat typologies) using a variety of multivariate statistical methods. The analysis has demonstrated that a multivariate predictive model approach is preferable to an environmental classification for the assessment of rivers using macroinvertebrates. This result is very similar to the conclusions of Neale and Rippey (2008) who favoured a multivariate approach compared to an environmental classification approach for the ecological assessment of 22 minimally disturbed lakes in Northern Ireland using macroinvertebrates. The work also mirrors the work conducted using stream communities by Van Sickle *et al*. (2005) and Davy-Bowker *et al*. (2006), and reveals that classifications are an unreliable tool for establishing type-specific biological reference targets in the UK (Neale and Rippey, 2008).

6 An assessment of variation in professional judgement of geomorphologically-based channel types

6.1 Introduction

The identification of channel types in many classification systems relies on a field surveyor's judgement of channel characteristics, such as channel planform, valley confinement, typical bed material and geomorphic units. Notable examples of classification systems and typologies requiring a surveyor's judgement of channel characteristics in the field include the classification systems of Kellerhals *et al.* (1972, 1976), Galay *et al.* (1973), Mollard (1973), the Montgomery and Buffington (1997, 1998) typology, and the River Styles Framework of Brierley and Fryirs (2000, 2005). Examples of these classification systems and typologies have been extensively reviewed in Chapter 2.

This chapter explores human perception of channel types in the SEPA typology across a range of disciplines, varying levels of involvement in typologies and from different geographic regions. Channel types in the SEPA typology should be identifiable based on a combination of channel planform, typical bed material, bedform pattern, dominant roughness elements, valley confinement and geomorphic units.

6.2 Rationale

The assessment of landscape perception in riverine environments using photographs is a well known approach (Brown and Daniel, 1991; Gregory and Davis, 1993), and is preferable to directly showing large numbers of participants a wide range of sites separated by large geographical distances (Shuttleworth, 1980). Several studies have explored the perception of observers in the field to ground photos, and have revealed no statistical difference between the two methods (Shuttleworth 1980; Vining and Orland, 1989). As such, using photographs in a web-based questionnaire was viewed as an acceptable method to identify the perception of channel types in the SEPA typology by a range of participants. Accurate classification of channel types using photographs would be beneficial for river managers as the approach would reduce the amount of fieldwork and decrease costs.

6.3 Aims and hypotheses

The aim of the chapter is to compare the perception of channel types in the SEPA typology by scientists with different backgrounds, varying levels of involvement in classification systems, and from different geographic regions using a photo-questionnaire. The research hypotheses associated with this overall aim are:

a) Natural scientists (with geomorphological or geological training) have a lower level of disagreement in the identification of individual channel types compared to biologists and environmental practitioners.

b) A high level of involvement in classification systems will translate to a lower level of disagreement in the identification of individual channel types.

c) No difference exists in the level of disagreement regarding the identification of individual channel types between European and North American respondents.

6.4 Methods

A questionnaire with photographs of nineteen river reaches (see Plate 6-1 for photographs) was advertised and circulated at a workshop, 'Defining hydromorphological condition and links to ecology', in Ballater, Scotland in March 2009, and at the 'First Triennial Symposium for the International Society of River Science (ISRS)', in St Petersberg, Florida, USA in July 2009. The photo-questionnaire was available online on the website http://www.sbes.stir.ac.uk/people/postgrads milner/questionnaire. The photo-questionnaire contained four background questions relating to a respondent's discipline, affiliated organisation, level of involvement in classification systems, and geographic region. A wide range of disciplines and job titles were specified from the respondents who conducted the questionnaire. These were categorised as natural sciences, ecological sciences and environmental practitioners for simplicity. Similarly, categories relating to a respondent's level of involvement in classification systems was amalgamated from extensive, significant, moderate, limited and none into three broad categories of high (extensive or significant), moderate and low (limited or none).

A respondent was requested to classify each reach into one of eleven channel types inherent within the SEPA typology (Table 6-1). A description of each channel type was also included in the photo-questionnaire (see Chapter 1, Table 1-1). The classification of reaches into channel types was also determined by the averaged expert opinion of three professional fluvial geomorphologists: Dr Richard Jeffries, SEPA, Professor David Gilvear, the University of Stirling and myself. All three fluvial geomorphologists have been involved with testing and applying the SEPA typology to the Scottish fluvial environment, and are familiar with the river systems used.

Channel type	Channel code
Active meandering	A
Bedrock	B
Braided	D
Cascade	C
Groundwater	G
Passive meandering	M
Plane-bed	P
Plane-riffle	R
Pool-riffle	O
Step-pool	S
Wandering	W

Table 6-1: Channel types in the SEPA typology.

In addition to the main study, a short experiment was carried out to investigate if a short training programme could reduce the diversity of opinion among respondents when classifying a reach. Fifteen MSc students, studying for an MSc in Environmental Management at the University of Stirling, were asked to conduct the photo-questionnaire. Subsequently, the students attended a three hour presentation relating to the background of classification systems, fluvial forms and processes. This "training programme" also included a discussion of how to classify the channel types in the SEPA typology using a channel typology flow diagram (See Appendix D). Post training, the students were asked to re-take the questionnaire.

The photographs used in the questionnaire were obtained from the wider study presented in this thesis, which assesses the performance of morphologically-based typing in Scotland using a geomorphological and ecological approach. Of the 134 pictures of reaches used in the mentioned study (67 reaches were surveyed in the study and two photographs recorded the character of each reach), 50 were downloaded for a final selection by the professional geomorphologists. Pictures were removed from the selection if scenes were deemed inappropriate for the survey (e.g. containing people or man-made structures, or views that were too scenic beyond the channel itself). Finally, 19 pictures were agreed upon by the professional geomorphologists in the group. For some channel types, such as for braided or wandering reaches, a single photograph was judged to be insufficient to portray the full range of characteristics of the channel type, so a second photograph was included. One photograph aimed to show an overview of the planform of the reach, and a second photograph focused on the geomorphic attributes and/or the hydraulics within the reach, such as the presence of depositional bars or the occurrence of pools and riffles. In contrast, the characteristics of a plane-bed reach, for example, may be encapsulated in one photograph. Plane-bed reaches are single channels with a planar gravel and cobble-bed (Florsheim, 1985), which lack discrete bars that are often related to low width to depth ratios (Sukegawa, 1973; Ikeda, 1975, 1977). This range of characteristics can be easily captured by one photograph.

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O

Plate 6-1: Photographs of streams and rivers used in the photo-questionnaire.

6.5 Statistical analyses

Data from the photo-questionnaire was downloaded and checked randomly for errors. The data was added to a single Excel sheet with the respondents raw data tabulated. A second error-checking was performed systematically by identifying the number of channel types chosen per reach. If a value exceeded 12 (the maximum number of channel types is 11, and 'other' was specified as an additional category), the responses were identified and the correction was conducted. The Shapiro-Wilk's (S-W) statistical test was applied to test the data's frequency distribution for normality. A log transformation was used where necessary. A paired *t*-test was performed to test if the mean number of channel types chosen per reach was statistically different, between respondents from different disciplines, respondents with different amounts of experience in classification systems, and respondents from Europe and North America. A paired *t*-test was also performed on the average percentage of respondents selecting the most common channel types per reach, between disciplines, respondents with different levels of experience in classification systems, and respondents from different geographic regions. Lastly, a paired *t*-test was performed on the results of the photo-questionnaire undertaken by the group of students, pre and post training.

Principal Components Analysis (PCA) was carried out on the probability of a channel type being selected by a respondent. For a full description of PCA see Chapter 3, section 3.4.3. The kappa statistic was also used in this chapter as a method to determine the level of agreement among respondents, regarding the number and range of channel types selected per reach. The kappa statistic is a technique that measures agreement between categorical variables after correction that is expected to occur due to chance (Siegel and Castellan, 1988). The kappa statistic can be used on any number of cases (i.e. study reaches), categories (i.e. channel types) or raters (i.e. number of respondents). A value of kappa ranges from -1.0 to 1.0, with -1.0 denoting perfect disagreement below chance, 0 denoting agreement equal to chance, and 1.0 denoting perfect agreement above chance (Randolph, 2008). A kappa of >0.7 indicates adequate agreement among the raters (i.e. respondents; Randolph, 2008). In this study, the free-marginal kappa of Brennan and Prediger (1982) was used, as this version of the statistic allows raters (i.e. respondents) to select any category (i.e. channel type) for any case (i.e. study reach).

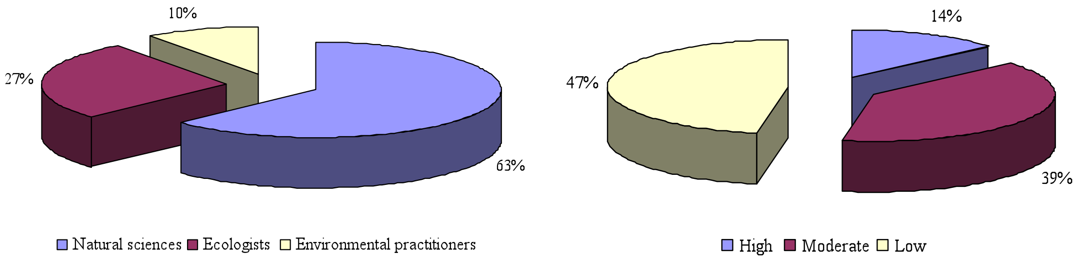
A summary of all statistical techniques conducted in this chapter is shown in Table 6-2. Paired *t*-tests were conducted in Minitab (version 15.1), PCA was performed in the CANOCO (CANOnical Community Ordination) software package (version 4.5, ter Braak and Šmilauer, 1998), and the Kappa statistic was determined using the 'Online Kappa Calculator' of Randolph (2008).

Factor of interest	Type of statistical technique
Identify the level of agreement among respondents	Kappa statistic
Determine the position of reaches compare to channel types in ordination space	PCA
Identify any significant differences between the mean number of channel types chosen per reach between natural scientists, ecological scientists and environmental practitioners	t-test
Identify any significant differences between the percentage of respondents selecting the most common channel type per reach, between natural scientists, ecological scientists and ecological scientists and environmental practitioners	t-test
Identify any significant differences between the mean number of channel types chosen per reach between respondents with high, moderate and low levels of experience	t-test
Identify any significant differences between the percentage of respondents selecting the most common channel type per reach, between respondents with high, moderate and low levels of experience	t-test
Identify any significant differences between the mean number of channel types chosen per reach among students, pre and post a training programme	t-test
Identify any significant differences between the mean number of channel types chosen per reach between North American and European respondents	t-test
Identify any significant differences between the percentage of respondents selecting the most common channel type per reach, between North American and European respondents	t-test

Table 6-2: Summary of statistical techniques conducted in this chapter.

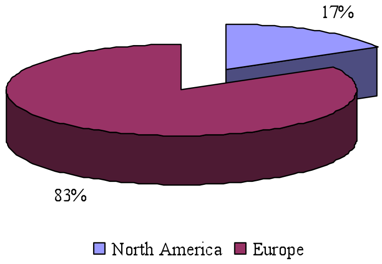
6.6 Results

A total of 131 scientists responded to the photo-questionnaire. Figure 6-1 shows the respondents demographics. The majority of respondents were from Europe (83%), and possessed a natural science background (63%). A large proportion of respondents had a moderate or low level of experience in classification systems (86%), with few respondents possessing a high amount of experience in classification systems (14%).



a) Discipline

b) Involvement in classification systems.



c) Geographic regions

Figure 6-1: Respondent demographics.

The percentage of channel types chosen per reach, and the probability of a respondent choosing a channel type is illustrated in Table 6-3 and 6.4. The channel type with the highest percentage of respondents per reach represents as the most common channel type chosen, and is regarded as the “global view” of the respondents. For example, the most common channel type chosen for Photograph A is an active meandering channel. Therefore, Photograph A will now be designated as an active meandering channel. The Kappa statistic was performed on the data in Table 6-3, and generated a free-marginal kappa value of 0.26. This statistic is below the critical value of 0.7, which indicates adequate agreement among the respondents. Instead, the kappa value is closer to 0, which denotes agreement equal to chance. The output of the kappa technique indicates a large variation in responses regarding the selection of channel types per reach. A kappa value of 0.26 would nominally indicate a moderate-poor level of agreement in classification between raters.

	Channel type												
Photo-graph	A	B	D	C	G	M	P	R	O	S	W	Other	Didn't specify	Total
A	**65.65**	0	1.53	0	0.76	10.69	2.29	2.29	10.69	0	4.58	0	1.53	100
B	0	7.63	0	12.98	0.76	0	3.05	9.16	19.85	**45.04**	0	0.76	0.76	100
C	3.82	0	**74.81**	0	0	2.29	1.53	1.53	0.76	0.76	13.74	0.76	0	100
D	**41.22**	0	0.76	0	0	38.17	3.05	0.76	5.34	0.00	9.92	0.76	0	100
E	0.76	3.82	0	2.29	0.76	0.76	14.50	30.53	**40.46**	5.34	0	0.76	0	100
F	0.76	24.43	0	12.21	0.76	0	3.82	10.69	18.32	**25.19**	0	3.05	0.76	100
G	0	**73.28**	0	19.08	0	0	1.53	0.76	1.53	3.82	0	0	0	100
H	1.53	1.53	1.53	4.58	1.53	4.58	**38.93**	36.64	1.53	0	1.53	4.58	1.53	100
I	5.34	2.29	**56.49**	0	0	3.05	2.29	7.63	1.53	0	16.79	3.05	1.53	100
J	3.82	15.27	3.05	3.05	1.53	7.63	22.90	**24.43**	0.76	1.53	6.87	6.11	3.05	100
K	0	13.74	0	33.59	0	0	0	0	1.53	**50.38**	0	0.76	0	100
L	12.98	0	**42.75**	0	0.76	4.58	1.53	2.29	6.11	0	22.90	4.58	1.53	100
M	19.08	0	1.53	0	1.53	17.56	7.63	**27.48**	12.21	0	7.63	3.82	1.53	100
N	6.11	0	0	0.76	3.05	30.53	**41.98**	1.53	0.76	0	3.82	11.45	0	100
O	0.76	**66.41**	0	17.56	0	0.76	1.53	1.53	3.05	7.63	0	0.76	0	100
P	0	9.16	0.76	**35.88**	0.76	0	0.76	4.58	13.74	30.53	0	3.05	0.76	100
Q	19.85	7.63	2.29	0.76	5.34	9.92	17.56	**25.95**	3.82	0	3.82	2.29	0.76	100
R	**54.96**	0	0	0.76	0.76	19.08	0.76	7.63	7.63	0.76	6.11	0.76	0.76	100
S	0	8.40	0	32.82	0	0.76	0.76	0	6.11	**47.33**	0	3.82	0	100

Table 6-3: Percentage of respondents selecting a channel type per photograph. Numbers in bold indicate the most common channel type chosen per photograph. See Table 6-1 for channel codes.

	Channel type												
Photo-graph	A	B	D	C	G	M	P	R	O	S	W	Other	Didn't specify	Total
A	**0.66**	0	0.02	0	0.01	0.11	0.02	0.02	0.11	0	0.05	0	0.02	1
B	0	0.08	0	0.13	0.01	0	0.03	0.09	0.20	**0.45**	0	0.01	0.01	1
C	0.04	0	**0.75**	0	0	0.02	0.02	0.02	0.01	0.01	0.14	0.01	0	1
D	**0.41**	0	0.01	0	0	0.38	0.03	0.01	0.05	0	0.10	0.01	0	1
E	0.01	0.04	0	0.02	0.01	0.01	0.15	0.31	**0.40**	0.05	0	0.01	0	1
F	0.01	0.24	0	0.12	0.01	0	0.04	0.11	0.18	**0.25**	0	0.03	0.01	1
G	0.00	**0.73**	0	0.19	0	0	0.02	0.01	0.02	0.04	0	0	0	1
H	0.02	0.02	0.02	0.05	0.02	0.05	**0.39**	0.37	0.02	0	0.02	0.05	0.02	1
I	0.05	0.02	**0.56**	0	0	0.03	0.02	0.08	0.02	0	0.17	0.03	0.02	1
J	0.04	0.15	0.03	0.03	0.02	0.08	0.23	**0.24**	0.01	0.02	0.07	0.06	0.03	1
K	0	0.14	0	0.34	0	0	0	0	0.02	**0.50**	0	0.01	0	1
L	0.13	0	**0.43**	0	0.01	0.05	0.02	0.02	0.06	0	0.23	0.05	0.02	1
M	0.19	0	0.02	0	0.02	0.18	0.08	**0.27**	0.12	0	0.08	0.04	0.02	1
N	0.06	0	0	0.01	0.03	0.31	**0.42**	0.02	0.01	0	0.04	0.11	0	1
O	0.01	**0.66**	0	0.18	0	0.01	0.02	0.02	0.03	0.08	0	0.01	0	1
P	0	0.09	0.01	**0.36**	0.01	0	0.01	0.05	0.14	0.31	0	0.03	0.01	1
Q	0.20	0.08	0.02	0.01	0.05	0.10	0.18	**0.26**	0.04	0	0.04	0.02	0.01	1
R	**0.55**	0	0	0.01	0.01	0.19	0.01	0.08	0.08	0.01	0.06	0.01	0.01	1
S	0	0.08	0	0.33	0	0.01	0.01	0	0.06	**0.47**	0	0.04	0	1

Table 6-4: Probability of a respondent selecting a channel type. Numbers in bold denote the most likely channel type chosen by respondents. See Table 6-1 for channel codes.

The range in the percentage of respondents choosing the most common channel type varies from 24.43% for photograph J, a plane-riffle channel to 74.81% for photograph C, a braided channel (Table 6-3). The results imply that some individual channel types may be easier to identify than others. However, taking account of both the first and second most commonly voted types in each photograph, only four of the nineteen pictures showed >50% of the votes split across more than two possible channel types. Based on the results in Table 6-3, an average percentage of respondents choosing a specific channel type was calculated (Table 6-5). Bedrock channels, particularly the reach in Photograph G appear the most readily identifiable. Similarly, braided channels are also identifiable, especially the reach in Photograph C. Plane-riffle reaches seem to be the most difficult channel type to classify, indicated by a low average of respondents (25.95%).

Channel type	Mean percentage of respondents
Bedrock	61.58
Braided	58.02
Active	53.94
Step-pool	40.97
Pool-riffle	40.46
Plane-bed	39.31
Cascade	35.88
Plane-riffle	25.95

Table 6-5: Mean percentage of respondents per channel type.

The probability data (in Table 6-4) indicates the likelihood of a respondent choosing a channel type, and is useful in indicating the diversity of the respondents' opinion, regarding the classification of a channel type per reach. The probability of a respondent choosing the most common channel type is lowest for the reach in photograph J, a plane-riffle channel (0.24 probability). The channel type with the second highest probability of being chosen for the reach is a plane-bed reach (0.23

probability). The small difference in probability between the first and second most common channel type being chosen indicates respondents maybe confused regarding the characteristics of a plane-bed and a plane-riffle channel. Furthermore, photograph J cannot be reliably classified as either a plane-bed or plane-riffle channel as there is only a very small difference in the proportion of respondents choosing either channel types. A similar pattern is present for the reach in photograph H. There is a very low probability (0.2 probability) between a respondent opting for a plane-bed (0.39 probability) or a plane-riffle (0.37 probability) channel type. The trend reinforces the earlier statement that many respondents maybe confused regarding the characteristics of a plane-bed and a plane-riffle channel, and consequently find classification difficult.

In contrast, the reaches in photographs A, C, G, I, O and R all have relatively high probabilities of being chosen by a respondent. Furthermore, there is a considerable difference in probability between the first and second most common channel type being selected (Table 6-4). For example, the probability of a respondent opting for a braided channel for the reach in photograph C is 0.75. The channel type with the next highest probability of being chosen is a wandering reach (0.14). Thus, there is a substantial difference in the proportion of respondents choosing the first and second most common channel type. Therefore, the reach in photograph C can be classified as a braided reach with a high level of confidence.

The majority of reaches (in photographs B, D, E, H, J, K, L, N, P and S) have reasonably high probabilities of two channel types being selected. However, the reaches in photographs F, M and Q have a relatively uniform probability of three channel types being chosen. For example, for the reach in photograph F, 25% of respondents opted for a step-pool channel, 24% selected a bedrock channel, and 18% chose a pool-riffle channel. The diversity of opinions regarding the classification of reach in photograph F (and also in photograph M and Q) indicates improved training of geomorphological processes and associated forms is maybe required. Overall, the results indicate that specific channel types, such as active meandering and bedrock channel types have high probabilities of being chosen, whereas other channel types, namely plane-bed and plane-riffle reaches possess lower probabilities.

A Principal Components Analysis (PCA) was conducted on the probability of a channel type been chosen by the respondents. Table 6-6 reveals the eigenvalues and cumulative percentage of variance accounted for by four principal components (PCs) from the ordination. The majority of the variation in the PCA model is accounted for by the first two PCs, and therefore, further analysis will focus on these two PC axes. An accompanying PCA bi-plot for these two PC axes is shown in Figure 6-2. The arrows denote the channel types, and the circles indicate the position of the nineteen photographs (A to S). The arrows denote increasing probabilities of a respondent selecting a channel type. Thus, photographs positioned near the arrowhead will have a high probability of being selected, compared to a photograph located near the centre of the bi-plot. The positioning of a photograph also reveals the diversity of opinions among the respondents regarding the classification of a reach. A high percentage of respondents (74.81%, Table 6-3) classified the river in photograph C as a braided reach. The river in photograph L was also classified as a braided reach, but fewer respondents (42.75%, Table 6-3) opted for this channel type. A substantial number of respondents (22.9%, Table 6-3) also selected a wandering channel type for the reach in photograph L. The difference in the agreement between the reaches in photographs C and L is reflected in the positioning of the circles in the PCA bi-plot.

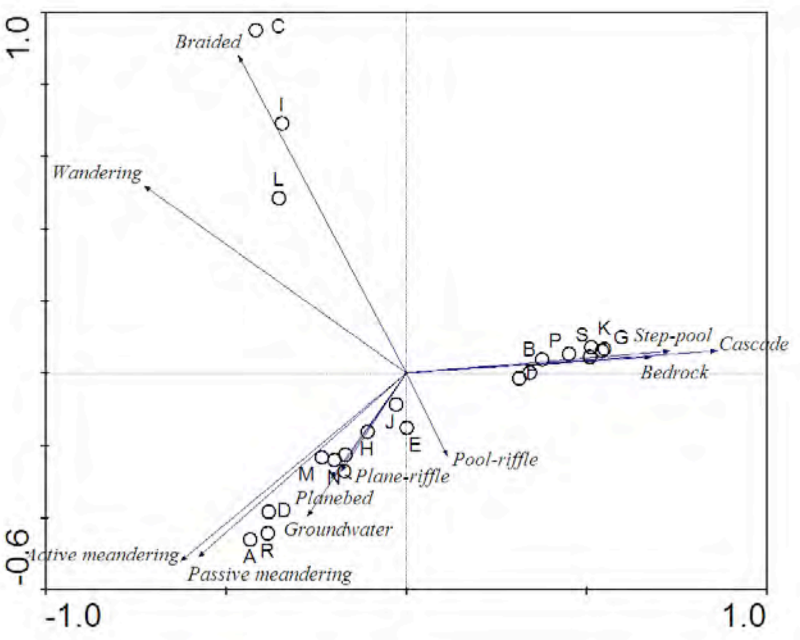


Figure 6-2: Principal component bi-plot of the distribution of photographs (labelled A to S) and channel types in the SEPA typology.

Axes	1	2	3	4
Eigenvalues	0.351	0.234	0.163	0.148
Percentage variance	35.1	23.4	16.3	14.9
Cumulative percentage variance	35.1	58.5	74.8	89.7

Table 6-6: Statistical summary of PCA of the channel type data.

The responses of the participants who conducted the questionnaire were compared to the channel types chosen by the three professional geomorphologists (Table 6-7). The respondents agree with the professional geomorphologists for eleven of the nineteen reaches. The two groups tend to agree regarding the characteristics of an active meandering channel (both classified photographs A, D and R as active meandering reaches), and a step-pool channel (both groups selected step-pool channel for photographs B, K and S). Disagreement exists concerning the classification of braided and wandering reaches. The professional geomorphologists classified the reaches in photographs C, I and L as wandering channels, whereas the majority of respondents believed the reaches are braided.

Photo-graph	Professional judgement	Global view	Agreement
A	A	A	=
B	S	B	=
C	W	D	x
D	A	A	=
E	R	O	x
F	B	S	x
G	B	B	=
H	P	P	=
I	W	D	x
J	P	R	x
K	S	S	=
L	W	D	x
M	R	R	=
N	M	P	x
O	B	B	=
P	S	C	x
Q	R	R	=
R	A	A	=
S	S	S	=

Table 6-7: The combined view of three professional geomorphologists and the global view of respondents. See Table 6-1 for channel codes.

6.6.1 Natural scientists (with geomorphological or geological training) have a lower level of disagreement in the identification of individual channel types, compared to ecological scientists and environmental practitioners.

The level of disagreement among natural scientists, ecological scientists and environmental practitioners has been measured by the number of channel types selected per reach, and the percentage of respondents agreeing with the common channel type per reach. Table 6-8 illustrates the number of channel types chosen per reach by respondents from different disciplines. Overall, the lowest number of channel types chosen is for the reach in Photograph K, a step-pool channel, and the highest number of channel types selected is for the reach in Photograph J, a plane-riffle channel. Clear statistical differences were present between natural scientists and environmental practitioners (paired *t*-test *P*-value of <0.000), and also between ecological scientists and environmental practitioners (paired *t*-test of *P*-value <0.005). No statistical difference was apparent in the number of channel types selected per photograph between natural and ecological scientists (paired *t*-test *P*-value of <0.094).

	Discipline		
Photograph	Natural sciences	Ecological sciences	Environmental practitioners
A	7	6	3
B	6	7	5
C	8	6	4
D	7	5	6
E	8	5	7
F	7	6	8
G	3	4	4
H	8	9	6
I	9	9	6
J	12	10	8
K	4	4	2
L	7	9	6
M	9	7	5
N	8	7	5
O	8	7	3
P	6	5	7
Q	9	10	8
R	6	7	6
S	7	5	3
Mean	7.32	6.74	5.37
Std dev	1.95	1.91	1.83

Table 6-8: Number of channel types chosen by respondents from different disciplines.

Although, natural scientists selected a statistically higher number of channel types per reach compared to environmental practitioners, the former group had a statistically higher percentage of respondents agreeing with the most common channel type per reach (paired *t*-test *P*-value of <0.033; Table 6-9) selected by that group. No statistical difference existed between the mean numbers (48.89 and 45.11) of natural scientists and ecological scientists choosing the dominant channel type (paired *t*-test *P*-value of <0.139), or between the mean numbers (45.11 and 44.13) of ecological scientists or environmental practitioners (paired *t*-test *P*-value of <0.695).

	Discipline					
	Physical sciences		Ecological sciences		Environmental practitioners	
Photo-graph	% of respondents	Dominant channel type	% of respondents	Dominant channel type	% of respondents	Dominant channel type
A	66.27	A	68.57	A	53.85	A
B	51.81	S	31.43	O	46.15	S
C	74.70	I	74.29	I	76.92	I
D	44.58	A	42.86	M	53.85	A
E	46.99	O	40	R	30.77	P
F	26.51	B	28.57	S	23.08	B
G	79.52	B	65.71	B	53.85	B
H	43.37	P	45.71	R	38.46	P
I	63.86	I	37.14	I	61.54	I
J	27.71	R	22.86	I and P	23.08	P and R
K	46.99	S	57.14	S	53.85	S
L	46.99	I	42.86	I	30.77	O
M	22.89	R	37.14	R	30.77	R
N	40.96	P	51.43	P	38.46	M
O	72.29	B	54.29	B	61.54	B
P	36.14	C	34.29	C	38.46	C
Q	26.51	R	25.71	R	23.08	R
R	56.63	A	54.29	A	46.15	A
S	54.22	S	42.86	C	53.85	S
Mean	48.89		45.11		44.13	
Std dev	16.97		14.52		15.13	

Table 6-9: The most common channel type chosen by respondents of different disciplinary backgrounds. See Table 6-1 for channel codes.

6.6.2 A high level of involvement in classification systems corresponds to a lower level of disagreement in the identification of individual channel types.

The number of channel types chosen per reach by respondents with different levels of experience in classification systems is shown in Table 6-10. Respondents possessing a high level of experience in classification systems have the lowest overall average for the number of channel types selected per reach. Respondents possessing moderate and low levels of experience in classification systems have a higher average for the number of channel types chosen per stream or river. A paired t-test highlighted the means were statistically different between all three groups (*P*-value for all combinations of groups <0.000).

		Level of experience		
Photo-graph	Channel type (global view)	High	Moderate	Low
A	Active meandering	3	7	8
B	Bedrock	4	7	8
C	Braided	3	5	7
D	Active meandering	5	5	6
E	Pool-riffle	7	5	8
F	Step-pool	5	8	8
G	Bedrock	3	5	4
H	Plane-bed	5	6	10
I	Braided	6	8	9
J	Plane-riffle	8	10	11
K	Step-pool	3	5	3
L	Braided	5	7	9
M	Plane-riffle	7	9	9
N	Plane-bed	5	6	7
O	Bedrock	5	6	7
P	Cascade	5	5	7
Q	Plane-riffle	6	10	10
R	Active meandering	4	6	8
S	Step-pool	4	5	6
	Mean	4.89	6.58	7.63
	Standard deviation	1.45	1.71	1.98

Table 6-10: Number of channel types chosen per photograph by respondents with different levels of experience in classification systems.

Table 6-11 shows the most common channel type chosen per photograph by respondents with different levels of experience in classification systems. The three groups of respondents (based on level of experience: high, moderate and low) selected the same channel type for ten of the nineteen rivers and streams (photographs A, B, C, E, G, H, L, O, R and S). No reach has more than two different dominant channel types. A paired t-test identified no statistical difference in mean values between any of the groups of respondents (*P*-value for all combinations of groups >0.05).

	Level of experience in classification systems					
	High		Moderate		Low	
Photograph	% of respondents	Dominant channel type	% of respondents	Dominant channel type	% of respondents	Dominant channel type
A	66.67	A	58.82	A	70.97	A
B	66.67	S	47.06	S	40.32	S
C	66.67	D	74.51	D	77.42	D
D	44.44	A	47.06	M	41.94	A
E	38.89	O	43.14	O	38.71	O
F	44.44	B	25.49	B	27.42	S
G	83.33	B	66.67	B	75.81	B
H	33.33	P	41.18	P	37.10	P and R
I	38.89	W	56.86	D	66.13	D
J	33.33	P	29.41	P	27.42	R
K	38.89	S	47.06	S	56.45	S
L	38.89	D	49.02	D	37.10	D
M	33.33	A	29.41	R	27.42	R
N	55.56	M	50.98	P	40.32	P
O	61.11	B	74.51	B	61.29	B
P	38.89	S	41.18	C	37.10	C
Q	44.44	A	27.45	R	24.19	R
R	72.22	A	52.94	A	51.61	A
S	61.11	S	54.90	S	38.71	S
Mean	50.58		48.30		46.18	
Std dev	15.37		14.47		17.02	

Table 6-11: The most common chosen channel type by respondents of different levels of experience in classification systems. See Table 6-1 for channel codes.

The results show a high level of experience in classification systems corresponds to a statistically lower number of channel types chosen per reach. This statement is supported by the results of the short experiment undertaken on a group of students to identify if a training programme could improve the level of agreement among respondents when classifying reaches. A group of students at the University of Stirling were asked to conduct the photo-questionnaire, pre and post training. A paired t-test (*P*-value of 0.005) revealed a statistically lower number of channel types per reach were chosen post-completion of a training programme (Table 6-12). The short experiment indicates how a simple training programme can increase the accuracy of classifying reaches.

		Training	
Photo-graph	Channel type (global view)	Pre-training	Post-training
A	Active meandering	5	3
B	Bedrock	4	4
C	Braided	2	2
D	Active meandering	4	4
E	Pool-riffle	3	3
F	Step-pool	6	5
G	Bedrock	5	1
H	Plane-bed	5	5
I	Braided	3	3
J	Plane-riffle	8	6
K	Step-pool	3	3
L	Braided	4	3
M	Plane-riffle	7	6
N	Plane-bed	4	2
O	Bedrock	6	3
P	Cascade	6	1
Q	Plane-riffle	5	6
R	Active meandering	4	4
S	Step-pool	4	2
	Mean	4.63	3.47
	Std dev	1.50	1.58

Table 6-12: Number of channel types chosen by respondents pre- and post-training.

In summary, the results show a high level of experience in classification systems corresponds to a statistically lower number of channel types chose per reach. No statistical difference existed in the percentage of respondents choosing the dominant channel type between the different groups of respondents.

6.6.3 *No difference exists in the level of disagreement regarding the identification of individual channel types between European and North American respondents.*

Respondents from North America have a lower overall level of disagreement regarding the number of channel types per reach, compared to European respondents, as indicated by the lower average number of channel types chosen per reach (Table 6-13). A paired t-test (*P*-value of <0.000) shows this result is statistically different.

		Geographic region	
Photo-graph	Channel type (global view)	Europe	North America
A	Active meandering	8	4
B	Bedrock	7	6
C	Braided	9	2
D	Active meandering	7	5
E	Pool-riffle	9	5
F	Step-pool	9	7
G	Bedrock	6	3
H	Plane-bed	11	7
I	Braided	9	5
J	Plane-riffle	12	7
K	Step-pool	5	3
L	Braided	9	6
M	Plane-riffle	9	7
N	Plane-bed	9	5
O	Bedrock	8	5
P	Cascade	9	5
Q	Plane-riffle	11	8
R	Active meandering	10	4
S	Step-pool	7	3
	Mean	8.63	5.11
	Std dev	1.74	1.66

Table 6-13: Number of channel types chosen by respondents in different geographic regions.

Table 6-14 shows the most common channel type chosen per reach from European and North American respondents, and the percentage of respondents selecting this channel type. The means indicate there is statistically less disagreement among North American respondents (*P*-value paired *t*-test of <0.018) compared to European correspondent regarding the dominant channel type selected.

	Geographic region			
	Europe		North America	
Photo-graph	% of respondents	Dominant channel type	% of respondents	Dominant channel type
A	68.81	A	50	A
B	42.20	S	59.09	S
C	73.39	I	81.82	I
D	42.20	A	50	M
E	38.53	O	50	O
F	28.44	S	36.36	B
G	71.56	B	81.82	B
H	39.45	P	36.36	P and R
I	56.88	I	54.55	I
J	23.85	P	40.91	R
K	49.54	S	54.55	S
L	43.12	I	40.91	I
M	30.28	R	27.27	M
N	43.12	P	36.36	M and P
O	65.14	B	72.73	B
P	28.44	S	40.91	S
Q	25.69	P	31.82	A
R	51.38	A	72.73	A
S	42.20	S	72.73	S
Mean	45.49	Mean	52.15	
Std dev	15.58	Std dev	17.10	

Table 6-14: The most common channel type select by respondents from different geographic regions. See Table 6-1 for channel codes.

6.7 Discussion

The approach used in this chapter uses photographs in a web-based questionnaire to identify the perception of channel types in the SEPA typology by scientists from a range of disciplines, with varying levels of involvement in classification systems, and from different geographic regions. Photographs have often been used in questionnaires or surveys to gauge public or scientific perception. For example, Piégay *et al.* (2005) and Le Lay *et al.* (2008) used a photo-questionnaire to assess variations in public perception as a barrier to introducing wood in rivers for restoration purposes. Mosley (1989) also used photographs to obtain views of New Zealand river scenery from different groups of respondents, such as canoeists, anglers, landscape architects and government staff. However, a photo-questionnaire has not been used to assess the perception of channel types across disciplines, levels of involvement in classification systems and across geographic regions.

The percentage of respondents selecting the most common channel type per reach varies from 24.43% to 74.81% (Table 6-3), which implies the difficulty of classifying a reach into a specific channel types varies depending on the characteristics of the reach. The percentage of the most common channel type chosen per reach was averaged according to channel type (i.e. into bedrock, plane-bed; Table 6-5). The results revealed that bedrock reaches (possessing an average of 61.58%, Table 6-5) emerge as the single most identifiable channel type. Bedrock channels are characterised by either a predominance of exposed bedrock or have a thin, sporadic accumulation of alluvium (Montgomery and Buffington, 1998). Bedrock channels tend to lack an alluvial bed due to high transport capacities associated with steep channel gradients and deep flow (Montgomery and Buffington, 1997). The fast velocities generally associated with a high transport capacity are indicative of a combination of surface flow types (SFTs), particularly chute flow, broken standing and unbroken standing waves (Chapter 4, section 4.7.4). The dominance of exposed bedrock, lack of alluvium and high energy SFTs contribute to bedrock channels possessing distinct characteristics, and thus, are relatively easy to identify for surveyors or respondents. Braided reaches also have a relatively high percentage of correct identification (58.02%, Table 6-5). Braided reaches are characterised by having numerous alluvial channels with bars or islands, repeatedly joining and dividing (Leopold and Wolman, 1957; Lane, 1957). This distinct morphology aids respondents to easily recognise a braided channel. Active meandering channels also have a relatively high rate of correct identification (53.94%; Table 6-5). Meandering reaches are single channelled systems with a low width-depth ratio occurring on low-moderate slopes (Brierley and Fryirs, 2005), and are characterised by a sinuosity index of >1.5 (Gordon *et al*. 2004). A notable trait of active meandering reaches is exposed banks, which are indicative of the ongoing bed and bank deformation in self-forming channels (Brierley and Fryirs, 2005). Reaches often contain pool-riffle topography that is linked to the pattern of pools at bends and crossings in the meandering channel alignment, with pools located at bends and riffles at crossings (Brierley and Fryirs, 2005). The combination of these distinctive features produces a set of characteristics that should make active meandering channels relatively easily identifiable.

In contrast, plane-riffle channels have a very low rate of correct identification (25.95%, Table 6-5). A plane-riffle channel is a transitional reach between a plane-bed and a pool-riffle channel, possessing attributes of both types (Greig *et al*. 2006). Plane-riffle reaches tend to be on gentler gradients have a greater range of velocities compared to plane-bed reaches, and have less defined pools, coarser (armoured) substrate, and less extensive bar features compared to pool-riffle reaches. The transitional characteristics of this channel type may explain why respondents may misclassify a plane-riffle reach as a plane-bed or a pool-riffle channel. A distinguishing feature of plane-riffle reaches is the sequence of a smooth flow and unbroken standing waves, symptomatic of glides and riffles. The identification of these SFTs is difficult to identify from a photograph, and is more apparent in the field. This may partly account for the low percentage of respondents classifying reaches as a plane-riffle channel.

The respondents and professional geomorphologists matched the same channel type for eleven of the nineteen photographs. Two of the professional geomorphologists (Professor David Gilvear and Victoria Milner) have extensively visited and surveyed all the reaches in the photographs. Consequently, their choice of type may be influenced by their field visits. Both geomorphologists have the advantage of viewing the reaches in relation to the valley setting, and observing the reaches' surface flow patterns and geomorphic units. Valley confinement, width of floodplain, and differing and repeating combinations of SFTs and geomorphic units all aid a surveyor in classifying a reach to a channel type. The professional geomorphologists' field visits may partly explain the difference in opinion between their view of a channel types and the view of respondents with high levels of experience in classification. It is also likely in some cases that the professional view was arrived at discussion, whereas (it is assumed) web-based respondents must achieve their choice independently.

6.7.1 Natural scientists (with geomorphological and geological training) have a lower level of disagreement in the identification of individual channel types compared to ecological scientists and environmental practitioners

The channel types in the SEPA typology are partly based on the morphological response to the relative ratio of sediment supply to transport capacity, and also on channel pattern and characteristics. Channel types should be distinguished by typical bed material, bedform pattern, dominant roughness elements, primary sediment sources and sediment storage elements, typical confinement, and typical pool spacing (channel widths) (Montgomery and Buffington, 1997). The underlying principle of classification is that channel morphology is the collective product of a number of interacting variables (Kellerhals *et al.* 1976; Kellerhals and Church, 1989; Thorne, 1997; Eaton *et al.* 2004), such as the volume and time distribution of water from upstream, the volume, timing and character of sediment transported to the channel, the materials through which the river flows, the local geological history and the topographic gradient of the landscape (Church, 1992). Natural scientists, such as hydrologists and particularly fluvial geomorphologists ought to have a more extensive knowledge and understanding of these independent variables controlling channel morphology and form, compared to ecological scientists and other disciplines. Therefore, in theory, natural scientists should have less diversity of opinion regarding the number of channel types per reach compared to ecological scientists and environmental practitioners. However, the results indicate that natural scientists actually select a higher overall number of channel types per reach in contrast to environmental practitioners. This may reflect a greater awareness of the range of possible channel types among natural scientists and a familiarity with key terminology, even if this is interpreted to produce a large number of types per channel.

The number of channel types chosen per reach is statistically higher for natural scientists compared to environmental practitioners. However, there are a statistically higher percentage of natural scientists choosing the most common channel type per reach compared to environmental practitioners. The results imply that there are a relatively uniform number of environmental practitioners choosing a few channel types per reach, whereas for natural scientists, a greater number of channel types per reach are chosen, but most of the respondents choose the same channel type. Therefore, the hypothesis that natural scientists have a lower level of disagreement in the identification of individual channel types compared to environmental practitioners can be accepted, but natural scientists do not have a lower level of disagreement compared to ecological scientists.

6.7.2 A high level of involvement in classification systems corresponds to a lower level of disagreement in the identification of individual channel types.

The level of involvement in classification systems corresponds to the number of channel types selected per reach (Table 6-10). Respondents with a high level of experience in classification systems possessed a statistically lower average for the number of channel types chosen per reach, compared to respondents with a moderate or low level of expertise in classification systems. Therefore, the more experience an individual possesses regarding working with classification systems, the less confusion exists about selecting a channel type. The results of a short experiment conducted on the perception of channel types on a group of students pre and post training supports this conclusion. The number of channel types chosen per reach, by a group of students was statistically lower post training. However, there was no statistical difference in mean values between respondents with high, moderate and low levels of experience, regarding the percentage of respondents choosing the dominant channel type.

The hypothesis that a high level of involvement in classification systems corresponds to a lower level of disagreement in the identification of individual channel types is tested by the number of channel types selected per reach, and the percentage of respondents agreeing with the common channel type per reach. Therefore, part of the hypothesis that a high level of involvement in classification systems relates to a low number of channel types per reach can be accepted, but the hypothesis that an increasing level of experience in classification systems results in a higher percentage of respondents selecting the same channel must be rejected. The results indicate the importance of training, knowledge and experience. The more experience a respondent possesses in fluvial systems, the greater their understanding of the processes and resulting forms of rivers and streams.

A training programme focussing on the dominant characteristics of the channel types in the SEPA typology (or channel types in any classification or typology) may improve a respondent's accuracy of classifying reaches. The reaches in photographs A, C, G, I, O and R all have relatively high probabilities of being chosen by a respondent (Table 6-4). Therefore, the reaches could possibly be used as a benchmark for the channel type they most represent. A high percentage of respondents (75.8%, Table 6-3) classified the reach in photograph C as a braided reach. Thus, this reach could be used as an example of a braided reach, and be included in training documentation. The reach in photograph L was also classified as a braided reach, but fewer respondents (42.8%, Table 6-3) opted for this channel type. A notable number of respondents (22.9%, Table 6-3) selected a wandering reach. The difference in the agreement between reaches being classified as braided or a wandering reach may reflect a change in the specific characteristics of a reach been viewed as typical of a braided or wandering reach. The higher percentage of respondents opting for a wandering reach for photograph L suggests the reach signifies a transition between the two channel types. The change in the characteristics of a reach from a typical braided reach to possessing attributes of a wandering reach is shown in Figure 6-3. A braided index (BI, proposed by Howard *et al.* 1970) was calculated for each reach as a measure of network complexity. This braided index provides a simple count of the total number of links (or segments, $<N_L>$) in the measured reach (Egozi and Ashmore, 2008). Photograph C has a BI of 18, Photograph I possess a BI of 4, and Photograph L has a BI of 3. The braided index scores for the three reaches support the earlier statement that the photographs show a continuum of changes in the key characteristics from one channel type (braided) to another channel type (wandering). This continuum of key characteristics may be highly useful for educating and training scientists in classifying reaches, and this type of training programme may lead to greater accuracy in field surveys.

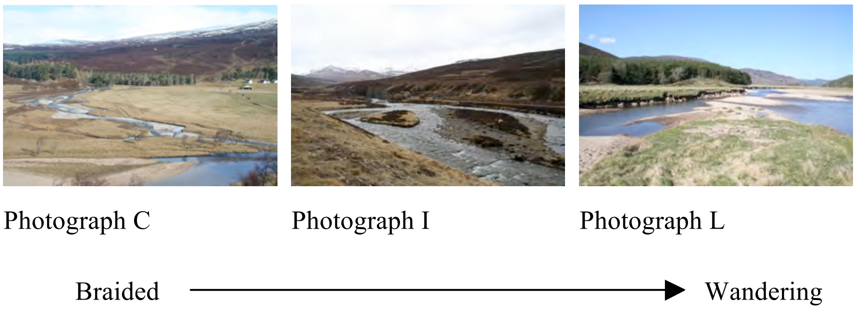

Photograph C Photograph I Photograph L

Figure 6-3: Changes in the continuum of characteristics for braided and wandering channel types (based on data from Table 6-4).

6.7.3 No difference exists in the level of disagreement regarding the identification of individual channel types between European and North American respondents.

The average number of channel types chosen per reach was lower from North American compared to European respondents. Additionally, North American respondents have a higher percentage of scientists agreeing on the most common channel type. Therefore, the hypothesis that no difference exists in the level of disagreement in the identification of individual channel types between European and North American respondents must be rejected.

This aspect of the results of the photo-questionnaire is unexpected. The SEPA typology is a modification of the Montgomery and Buffington typology (1997, 1998) developed in the Pacific Northwest of the USA. The mountainous Pacific Northwest region is similar in character to many upland regions in Scotland. Therefore, channel types found in the Pacific Northwest were expected to be found in Scotland and other mountainous regions in Europe. The study anticipated that respondents from both regions would have a similar level of disagreement concerning the classification of channel types.

The difference in opinion may be due to the range and availability of training courses in fluvial geomorphology offered in the two regions. For example, the USA has a vast array of training courses in fluvial geomorphology in comparison to the UK. Wildland Hydrology based in Fort Collins, Colorado offers short courses in basic survey skills, applied fluvial geomorphology, river morphology and applications, river assessment and monitoring, river restoration, river restoration and design implementation and fluvial geomorphology for engineers. The courses aim to provide individuals with the knowledge and skills needed for successful, integrated catchment management (Wildland Hydrology, 2010). Furthermore, the courses train scientists to classify reaches into channel types inherent in the Rosgen (1996) classification. The Rosgen classification (Rosgen, 1996) has been very widely employed by hydrologists, ecologists, engineers and managers in federal, state and local government agencies in the USA as a tool to assess the physical characteristics of stream reaches and to guide restoration and rehabilitation plans (Juracek and Fitzpatrick, 2003). Hence, there is an opportunity for scientists to learn how to classify types into a classification, and the techniques are widely employed. There is currently no equivalent training course in

Europe to classify reaches into types. In the UK, the Environment Agency (EA) offers a training course to assess the character and habitat quality of rivers based on their physical structure (Raven *et al.* 1997, 1998b). The survey is the well known River Habitat Survey (RHS). Although, an important output of the RHS is the generation of a semi-natural river typology based on a subset of reference sites (Jeffers, 1998), this is not taught in the training course. Other possibilities are that North American respondents have an intrinsically greater familiarity with unimpacted stream systems, spend more time in the field, or are naturally exposed to a greater range of possible stream types within a similar geographical area compared to European respondents.

6.8 Conclusions

In summary, 131 scientists from a range of backgrounds, varying levels of involvement in classification systems, and from different geographic regions undertook the questionnaire. Natural scientists and ecological scientists selected a higher number of channel types per reach compared to environmental practitioners. However, natural scientists had a higher percentage of respondents choosing the dominant channel type, compared to the other two groups of respondents. A high level of experience in classification systems translated to a lower number of channel types being chosen per reach, which implies training, and knowledge of fluvial systems is important. This conclusion is supported by the output of a short training programme, which examined the number of channel types chosen per reach, by a group of students pre and post training. A statistically lower number of channel types per reach were selected by the students post completion of the training programme. Lastly, North American respondents selected a much lower number of channel types per reach, and had a higher percentage of respondents choosing the dominant channel type, compared to European respondents.

To conclude, the results of the photo-questionnaire indicate a diversity of opinion among scientists from different disciplines, varying levels of experience and from different geographic regions. Good training is needed to improve knowledge of fluvial processes and forms which may lead to greater accuracy and less disagreement. In the future, the subjective approach of classifying reaches into channel types using photo-questionnaires or field surveys maybe replaced or compared to more objective, quantitative, statistical approaches, such as using GIS variables to predict channel types (assessed in Chapter 3) or using quantitative techniques such as cluster analysis and ordination techniques (explored in Chapters 3 to 6). These approaches may prove less time consuming, more accurate and robust compared to subjective judgements of channel types based on photographs or field surveys.

7 Conclusions

7.1 Introduction

This chapter presents a summary of the scientific key findings within this thesis. The rationale for the project is restated, and the conclusions of the four main aims of the thesis are addressed. The implication of these findings for the use of geomorphic typologies in predicting macroinvertebrate communities is also discussed, especially in regard to the EU WFD (2000/60/EC). This chapter and thesis then concludes with the identification of the future direction of geomorphic typologies, and priorities for further research and development.

7.2 Rationale

As stated earlier, the link between physical habitat and aquatic biodiversity has been widely acknowledged, but poorly quantified (Orr *et al.* 2008). However, this link is receiving increasing impetus from developments in environmental policy, such as the EU WFD (Clarke *et al.* 2003), which stresses the importance of hydromorphological condition (physical structure) in significantly supporting the ecological status of water bodies (Raven *et al*. 2002). Tools are needed to combine and reflect the interactions between hydrology, fluvial geomorphology (via physical habitat) and ecology. Ideally, these tools need to show where changes in physical habitat result in improvements and deterioration in ecological status (Orr *et al*. 2008).

The nature of physical habitat strongly influences the structure and organisation of biological communities (Southwood, 1975; Meffe and Sheldon, 1988; Maddock, 1999). However, the development of assessment methods characterising the physical habitat are not as well developed as methods examining attributes of river health, such as water quality, water quantity and biotic integrity (Maddock, 1999). Many habitat assessment methods that have been developed tend to be uniscalar, and do not relate habitat to physical processes (Maddock, 1999; Davies *et al*. 2000). Hence, there is the need for effective characterisation of physical habitat at a range of spatial scales, and to relate habitat to physical processes. This would potentially further our knowledge of ecological response to variations in physical habitat (Orr *et al.* 2008). Hierarchical geomorphic classification systems and typologies provide a tool to link physical habitat and aquatic biodiversity. As geomorphic processes operate across a range of spatial scales, controlling the physical structure of a river, geomorphological principles form a logical base for characterising and assessing physical habitat (Thomson *et al*. 2001). This scientific need has underpinned the work described in this thesis.

To understand the links between physical habitat and aquatic biodiversity, a geomorphic classification system or typology must be ecologically meaningful, if used in ecological applications (Thomson *et al.* 2004). Hence, an understanding of ecosystem patterns, dynamics and interactions across a variety of spatial and temporal scales is crucial (Ward *et al*. 2001; Frothingham *et al*. 2002). In theory, each geomorphic channel type would ideally possess discrete biota, showing similar ecological functioning and dynamics (Thomson *et al*. 2004). Although this scenario is unlikely across a variety of geomorphic features and scales, hierarchical geomorphic typologies may offer a logical base to study the relationships among aquatic biodiversity through the medium of physical habitat (Chessman *et al.* 2006).

This research project focussed initially on a geomorphic channel typology developed by SEPA, which forms part of the MImAS tool that assesses the impact of engineering activities required by the Water Environment (Controlled Activities) Scotland Regulations 2005 (commonly known as CAR). Despite some initial testing of the approach by CRESS (2006), no in-depth research had been undertaken to test the typology's validity. Furthermore, there has been limited work studying the ecological significance of geomorphic types and typologies. There are currently no published works on the ecological relevance of geomorphic channel types and typologies in Scotland. Therefore, an opportunity exists to investigate this identified research gap in linking physical habitat and aquatic biodiversity, through testing the ecological relevance of a geomorphic typology.

7.3 Summary of findings

The overarching aim of this research project was to assess the performance of morphologically-based river typing in Scotland using a geomorphological and ecological approach. The overarching aim was split into four main research aims that are addressed in Chapters 3 to 6. This section presents a synthesis of the findings of these four main aims.

7.3.1 Geomorphological typing of Scottish rivers using catchment driver variables.

The overriding aim of Chapter 3 was to identify the efficiency of catchment drivers to classify channel types in the SEPA typology. The main conclusions derived from this chapter are:

- The overall downstream pattern in the spatial arrangement of channel types from headwaters to lowland environments typically change in a sequence of step-pool, plane-bed, plane-riffle through to active and passive meandering channel types. The results indicate that channel types have some predictable geographically positioning in the landscape. However, few catchments will possess this exact downstream sequence or have all possible channel types due to a collective number of interacting environmental variables, geological discontinuities, and the geographic complexity of a river system.
- No combination of catchment drivers clearly separated the nine channel types in the SEPA typology, apart from step-pool reaches that possess smaller catchment areas, lower stream orders and stream powers, are nearer to the river source, and occur on steep slopes. An overall trend of increasing values of catchment area, distance from source, sinuosity, stream order, a surrogate index of stream power, and valley width is present from step-pool through to passive meandering channels.
- An agglomerative HCA using catchment drivers produced four clusters. Each cluster was formed of three to six channel types in the SEPA typology. The four clusters could be assigned to the most common recurring channel type within the cluster or defined on the characteristics that best represented the majority of channel types. The four clusters were thus classified as step-pool, plane-bed, semi-constrained, and meandering channel types.

7.3.2 Geomorphological typing of Scottish rivers using physical habitat variables.

In Chapter 4, a major research aim was to examine if multivariate methods using physical habitat variables can produce a functional geomorphic typology. A subsidiary aim was to determine whether channel types in the SEPA and Catchment Driver typologies can be identified based on physical habitat alone. Another key aim of the chapter was to identify the spatial extent, and arrangement of SFTs within the SEPA channel types. The final aim of the chapter investigated the hydraulic and retention characteristics of the SEPA channel types. The key conclusions generated from this work are:

- Channel types in the SEPA and Catchment Driver typologies do not have significantly different depths, grain sizes and velocities based on values of the tenth and ninetieth percentiles, with the exception of step-pool reaches that could be clearly discriminated based on shallower depths and coarser substrate.
- An agglomerative HCA generated six clusters based on WD_{IQR}, a surrogate index for discharge, GS_{IQR} and $Vel_{75.}$ The first cluster contained all step-pool reaches, whereas the remaining five clusters comprised two to six channel types in the SEPA typology. The most common recurring channel type in each cluster and/or the key characteristics of the majority of reaches was used to classify the cluster. The six clusters were thus identified as step-pool, plane-boulder bed, plane-gravel bed, bedrock, active meandering and passive meandering. The results indicate that multivariate methods can discriminate four of the nine channel types in the SEPA typology, but significant overlap is present among these types.
- The majority of channel types (plane-riffle, pool-riffle, braided, active and passive meandering channels) in the SEPA typology are characterised by three dominant surface flow types (SFTs) that explain over 90% of flow variability

in the reach. Three SFTs also explain in excess of 70% of the flow variability in step-pool, bedrock, plane-bed and wandering channels.

- The velocigraphs of bedrock and braided reaches signify flashy responses; in comparison to pool-riffle and passive meandering reaches that generated a multi-peaked response. The study revealed that the main variables influencing the response curve are the channel characteristics, namely depth, grain size and velocity. Kruskal-Wallis post-hoc tests based on hydraulic indices indicated no significant differences in hydraulic characteristics between channel types based on PC1 and PC2 axis scores.
- The findings of the aqua-sphere experiments reveal that retention significantly decreases with distance downstream, related to reductions in channel bed slope, and increases in stream size, discharge and depth. Aqua-sphere retention is largely due to the depth of water and the number of obstructions within the reach.

7.3.3 The ecological significance of geomorphic typologies

The aim of Chapter 5 was to determine the ecological significance of the SEPA, Catchment Driver and Physical Habitat typologies, and also discover whether geomorphic type results in differences in macroinvertebrate communities that override the influences of water quality. Listed below are the principal conclusions derived from the respective analyses:

- A classification of macroinvertebrate abundances using TWINSPAN generated eight groups. One group contained step-pool reaches, and another group consisted of active meandering reaches. The remaining six groups contained a mix of SEPA channel types. Therefore, a bottom-up, multivariate classification based on macroinvertebrate composition cannot discriminate most of the SEPA channel types.

- The ANOSIM analyses revealed that no significant channel type effect was present in the SEPA typology based on PC1 and PC2 axis scores. However, analysis of individual channel types showed a statistical difference between bedrock and step-pool samples based on PC2 axis scores. For the Catchment Driver typology, channel types had a distinct macroinvertebrate community, between step-pool and semi-constrained reaches, between step-pool and meandering reaches, and between plane-bed and semi-constrained reaches. Channel types in the Physical Habitat typology also have a significantly different macroinvertebrate assemblage.
- Findings of the RDA and MRPP reveal not surprisingly, a combination of catchment drivers, physical habitat characteristics and physico-chemical variables effect macroinvertebrate abundances within river systems. The similarity of macroinvertebrate samples between channel types in the SEPA typology implies that other factors besides fluvial geomorphology may be more important determinants of invertebrate distributions, such as dispersal limitation, resource availability and water temperature.

7.3.4 An assessment of variation in professional judgement of geomorphically-based channel types.

The final results chapter, Chapter 6 compared human perception of channel types in the SEPA typology by scientists with different backgrounds, varying levels of involvement in classification systems, and from different geographic regions using a photo-questionnaire. The conclusions of the chapter are:

- Natural scientists and ecological scientists selected a higher number of channel types per reach in contrast to environmental practitioners, but a statistically higher percentage of natural scientists chose the most common channel type per reach compared to environmental practitioners.
- A high level of experience in classification systems corresponds to a greater accuracy in selection of the correct channel type. This finding suggests that training, experience and knowledge of fluvial systems is important, and this results in a lower diversity of opinion regarding the classification of channel types. This result is supported by the output of the MSc student experiment. Post geomorphic training of a group of MSc students showed a statistically lower number of channel types selected per reach.
- North American respondents picked a lower number of channel types per reach, and possessed a higher percentage of respondents choosing the most common channel type compared to European respondents. The results may be due to North American respondents possessing a greater familiarity with natural river systems, spending more time in the field or being exposed to a wider range of channel types within a similar geographical area in comparison to European respondents.

7.4 Recommendations on the use of the SEPA typology

The study used a wide range of catchment drivers and physical habitat variables to discriminate channel types in the SEPA typology. Statistical analyses were unable to discriminate between all channel types in the SEPA typology, as indicated by the overlap in the range of values of catchment drivers and physical habitat variables. The finding does not necessarily invalidate the typology, but highlights the difficulty in quantifying the complexity and subtleties of morphological differences present in the types. The data analyses also implies that naturally occurring channel types merge from one type to an adjacent type, and fuzzy boundaries are present.

The output of the data analysis implies that the amalgamation of some channel types in the SEPA typology may be appropriate. Catchment drivers and physical habitat variables clearly identified step-pool reaches based on their distinctively lower catchment area, lower distance from source, smaller stream orders, occurring on steep slopes, shallower water depths and slower velocities. Bedrock reaches have a predominance of bedrock substrate, and have faster velocities. Plane-bed, plane-riffle and pool-riffle reaches have a large overlap in catchment drivers and physical habitat variable values. Plane-riffle reaches are a transitional channel type between plane-bed and pool-riffle. The study recommends merging these three channel types based on catchment drivers and physical habitat characteristics. The study recommends that the remaining channel types: braided, wandering, active meandering and passive meandering types should remain as individual channel types.

7.5 Geomorphic typologies and the EU WFD

The EU WFD (2000/66/EC) was implemented on 22nd December 2000, with the overall aim of providing an integrated framework to the protection and improvement of Europe's inland surface waters, transitional waters, coastal waters, groundwaters and wetlands. The Directive requires Member States to develop a geomorphic typology based on environmental variables (see Chapter 2, section 2.4.3). The theory underpinning this methodology is that the classification of reaches based on their environmental characteristics ought to harbour comparable aquatic biota (Reynoldson *et al.* 1997).

In this study, the methodological approach initially classified study reaches based on their catchment drivers and physical habitat characteristics to generate a geomorphic typology (i.e. the Catchment Driver and Physical Habitat typologies), and subsequently examined macroinvertebrate abundances within the geomorphic channel types of these typologies (and also channel types in the SEPA typology). The statistical analyses indicate weak correlations between channel types in the SEPA and typology and macroinvertebrate composition. The results reveal the problem of promoting geomorphic typologies as being useful in ecological applications (as in the EU WFD), in that discrete channel types fail to have distinctive biological communities (Owen, 2001). Other studies have also indicted this approach has had poor success in predicting macroinvertebrate and macrophyte communities in river systems (e.g. Heino *et al.* 2002; Parsons *et al.* 2003; Neale and Rippey, 2008). In summary, the output of this study highlights that geomorphic types in the SEPA typology does not have distinct macroinvertebrate communities. This finding therefore, questions whether the application of specific geomorphic classifications and typologies can be argued to have direct and useful ecological relevance.

7.6 Future work and recommendations

Most of the geomorphic surveys and all of the biological sampling were conducted in upland environments. The study recommends replicating the geomorphic and biological surveys in a greater number of catchments that encompass a range of environments, in particular lowland and coastal rivers. Efforts linking geomorphic channel types (or River Styles) to aquatic biodiversity have been largely focussed in Australia, and the present study undertaken in Scotland. Testing the ecological relevance of existing typologies in other geographic regions would be highly useful in examining the links between physical habitat and aquatic biodiversity.

The study also advocates that the biota of channel types is further investigated through sampling for aquatic and semi-aquatic macrophytes, fish, and diatoms. Sampling a greater range of biota, rather than simply macroinvertebrates, may elucidate any links between geomorphic channel type and aquatic biodiversity at a more holistic level. Chessman *et al*. (2006) surveyed various River Styles for diatoms, aquatic and semi-aquatic macrophytes, macroinvertebrates and fish. Their study identified geomorphic type (i.e. River Style) directly affected the aquatic and semi-aquatic macrophytes and macroinvertebrates through differences in physical habitat traits.

In the present study, geomorphic surveys and macroinvertebrate sampling were conducted on reaches of good-high geomorphic condition. However, the study recommends geomorphic surveys and biological sampling are carried out on reaches in moderate and poor geomorphic condition, as a large percentage of river systems in many countries are heavily modified and/or contain degraded reaches. For example, surveys of river systems in Denmark reveal that 97.8% of channels have been artificially straightened, and only 2.2% (880km) have natural morphological characteristics (Brookes, 1987). In the UK, 60% of river systems were appraised by RHS (a stratified random sample of 3.5% of UK channels), and were identified as been modified (Orr *et al.* 2008). Geomorphic surveys and biological sampling of reaches in moderate and poor condition may yield useful results regarding the links between geomorphic condition, physical habitat and aquatic biodiversity, and may help to determine if trajectories of biological communities change in response to physical habitat degradation are type-specific.

This study found that broad-scale patterns of macroinvertebrates have been found to be associated with a combination of geographical location, large-scale catchment drivers, physical habitat characteristics and physicochemical variables (Chapter 5, section 5.6.3). Many studies have particularly stressed the importance of physical habitat on aquatic organisms (e.g. Maddock, 1999; Urban and Daniels, 2006), and this is reflected in the development of conceptual models linking biotic and ecological integrity (Karr, 1981; Francis *et al.* 1993) and Ecological Health (Simon, 1999). Some aquatic organisms, such as fish, favour specific habitat types, which are well defined in terms of hydrological and hydraulic habitats and to some extent micro-morphological habitats (e.g. Heggenes and Saltvei, 1990; Schiemer *et al.* 2003; Moir *et al.* 2004). A study by Moir *et al.* (2004) investigated whether the spatial pattern of spawning by Atlantic salmon (*Salmo salar* L.) related to reach type and if discharge use changes between reach types. Their study found that during spawning events, Atlantic salmon favoured pool-riffle and transitional pool-riffle/plane-bed reaches, and avoided plane-bed and step-pool reaches. At a smaller scale, within reaches (or channel types) different physical biotopes have been shown to fulfil different habitat requirements of fish. For example, runs maybe used for feeding, backwaters for resting, and gravel bars for spawning (Thomson *et al.* 2004; Barlaup *et* al. 2008; Louhi *et al.* 2008). Therefore, studies at a smaller spatial extent and at a finer spatial grain (in contrast to the present one, across 20 channel widths) may better elucidate the links between physical habitat and aquatic biodiversity. For instance, a study in a smaller spatial extent, such as within narrow bands of altitude and within physical biotopes, such as pools, riffles and glides would provide insights for fish, macroinvertebrates and macrophytes by permitting the interactions of geomorphology to be clear from the large-scale biogeographic background (Chessman *et al*. 2006). A study at a finer scale may make clearer the links between fluvial geomorphology via physical habitat on aquatic biodiversity, as the influence of biogeographic variables would be better controlled. Within individual physical biotopes, differences in altitude, temperature and water quality would also be fairly constant.

This study also proposes that further research is conducted into the response of aqua-spheres under varying discharge regimes, so the sensitivity of the technique can be assessed to different flow conditions at the time of the experiment. Using aqua-spheres is a method to quantify habitat according to bed topography, channel slope, discharge, meso-habitat pattern, and bed and marginal features, such as living vegetation and dead wood. In the current study, aqua-sphere experiments were carried out under similar discharges. However, increases in discharge with an equivalent increase in depth would reduce the number of flow obstructions within a reach, which are known to influence retention. The present study proposes repeating the experiment multiple times in designated reaches as discharge increases change (e.g. on a flood hydrograph falling limb).

7.7 Final conclusions

Rivers and streams are individually unique, patchy, discontinuous systems (Folt *et al.* 1998), changing across spatial and temporal scales (Thorp, 2009). Hierarchical geomorphic typologies are a tool to capture, simplify and understand this variability in river systems. Typologies can provide an initial starting point to identify functionally similar sites, and investigate the linkages between channel networks and catchment scale processes, but total dependence and misclassification by a surveyor can lead to deterioration in geomorphic condition of reaches and potentially costly mistakes (Kondolf *et al.* 2003). Typologies are not a panacea for river managers, and do not solve all the problems associated with maintaining and restoring the morphological and ecological status of river systems, but can be a useful research tool for researchers and managers.

This thesis has moved forward the subject of river classification and typing from a subjective, mainly qualitative approach to a fully quantitative, repeatable, statistical methodology. A key advantage of generating typologies through clustering techniques is their repeatability and defensibility. The approach also overcomes the subjectivity of professional judgement, and provides a common framework for geomorphologists, ecologists and biologists. In the present study, the majority of the geomorphic surveys and all of the biological sampling were conducted in upland catchments. In the future, further work encompassing a more even spread of reaches in each geomorphic type and across larger catchments is recommended, as the extent of clustering is partially a reflection of the relative number of reaches in each geomorphic type.

To conclude, many geomorphic classification systems and typologies have been developed, and have been argued as being useful for ecological applications (Frissell *et al.* 1986; Rosgen, 1994). However, few have explicitly linked channel types to biological communities at the reach scale. This study has shown that highly defined boundaries between geomorphic types do not occur. Instead, boundaries between types are transitional in nature, reflecting shifts in instream hydraulic habitat. The majority of channel types (i.e. plane-bed and plane-riffle) do not have specialised fauna. However, step-pool, bedrock and meandering reaches do harbour a distinct macroinvertebrate fauna. Chironomidae and Perlidae are indicative of step-pool reaches, Haliplidae appear characteristic of bedrock reaches, whereas Glossosomatidae and Limoniidae inhabit meandering reaches. Fluvial geomorphology can be used as a base to manipulate aquatic biodiversity through the medium of physical habitat (Brussock *et al.* 1985; Sear, 1994; Harper and Everard, 1998; Newson, 2002). However, fluvial geomorphology is not the sole influence on aquatic biodiversity. Geomorphic typologies are a useful tool and can explain some variability in aquatic biodiversity, such as in macroinvertebrate assemblages, but most variability appears attributable to other environmental variables, and to biogeographic and evolutionary constraints such as dispersal, colonisation and local extinction (Chessman *et al.* 2006). Typologies may need to be one of a collective number of interacting tools to predict biological condition. For example, they may need to be coupled with the development of hydrological and water quality classifications and condition ratings (Thomson *et al.* 2004). Only a full appreciation of all variables influencing aquatic biodiversity will ensure that effective management strategies that maintain or improve river structure functioning.

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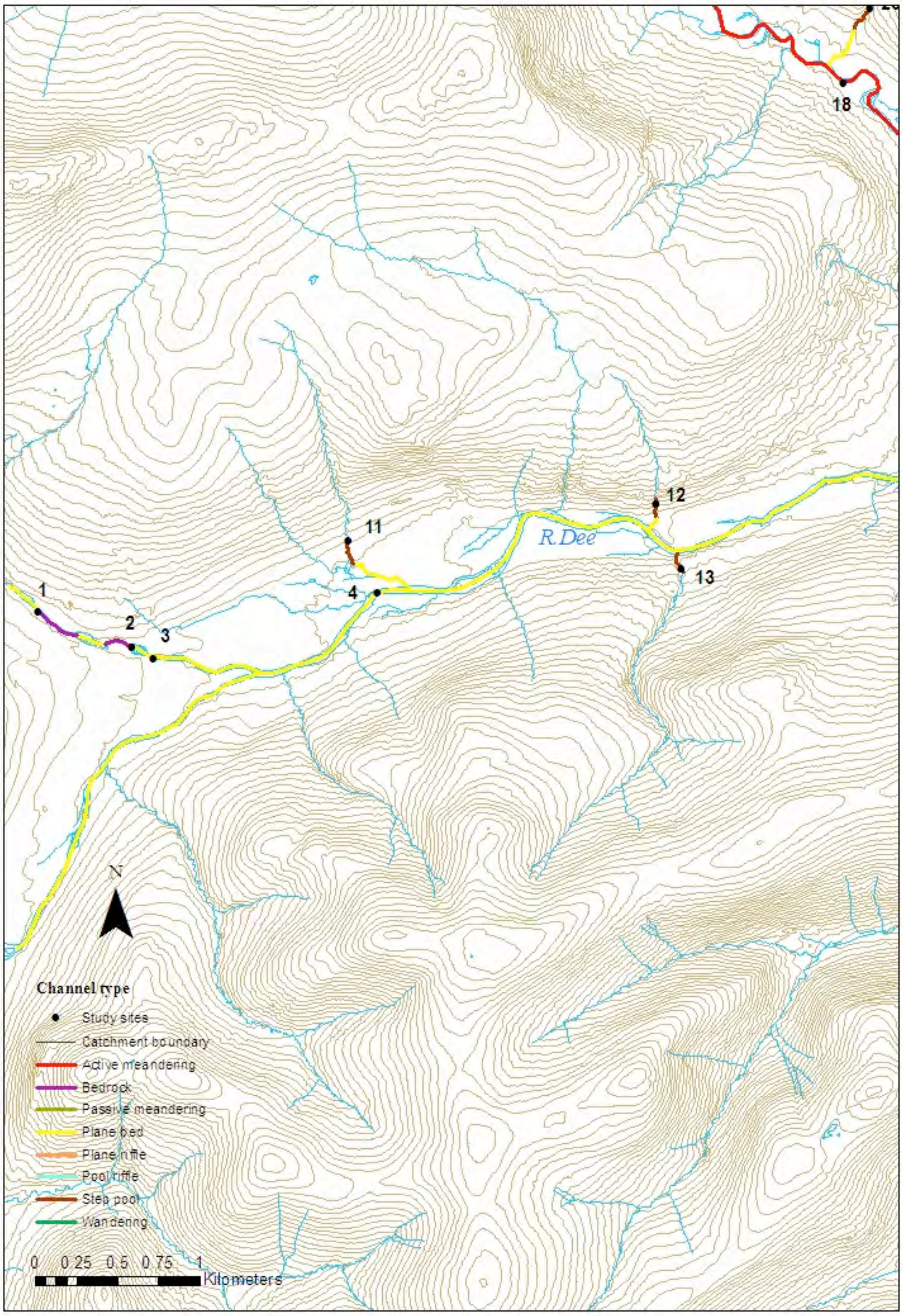
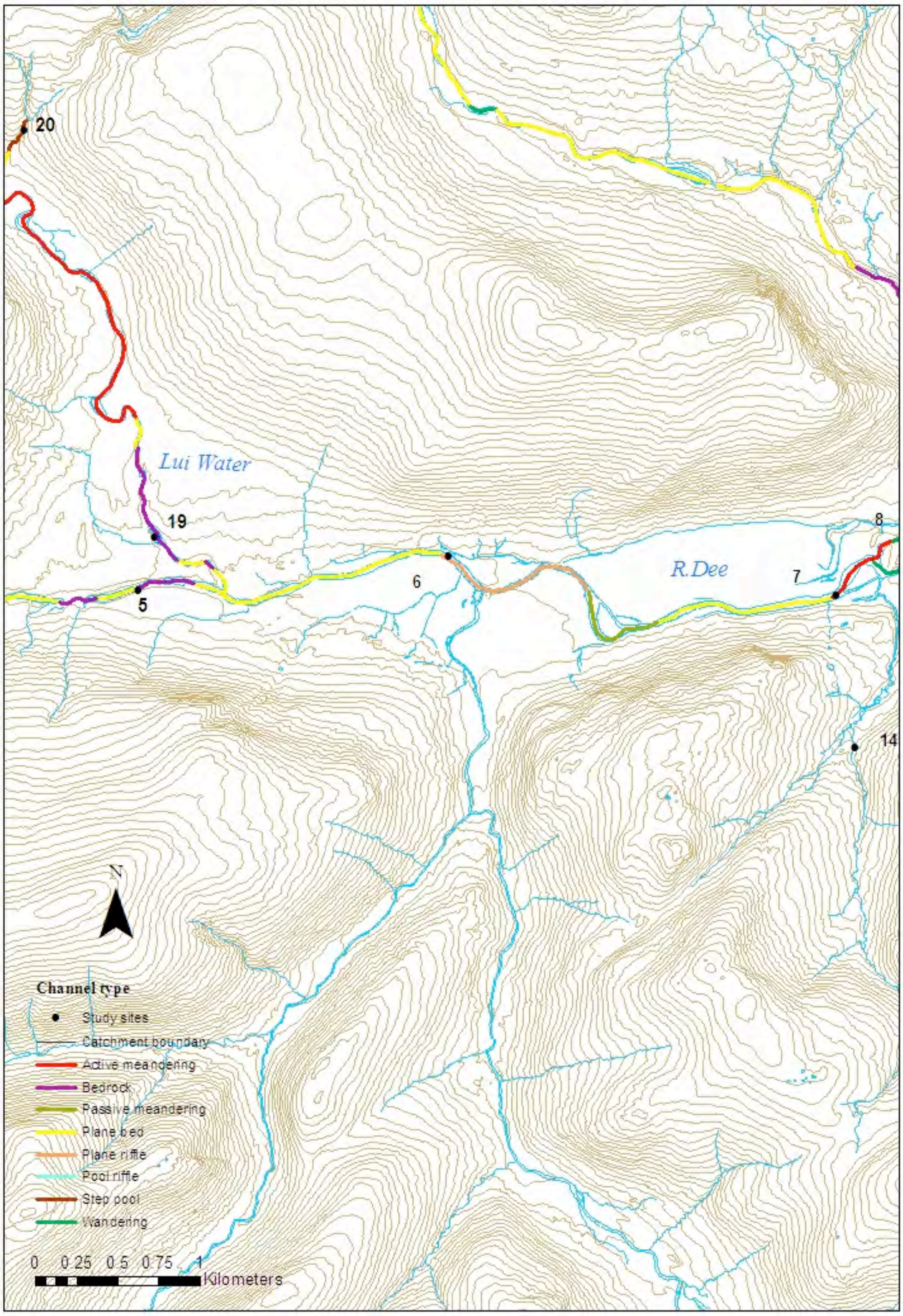
APPENDIX A

Plate A-2: Topographic setting of the study reaches in the R.Dee and Allt a'Ghlinne Bhig catchments.

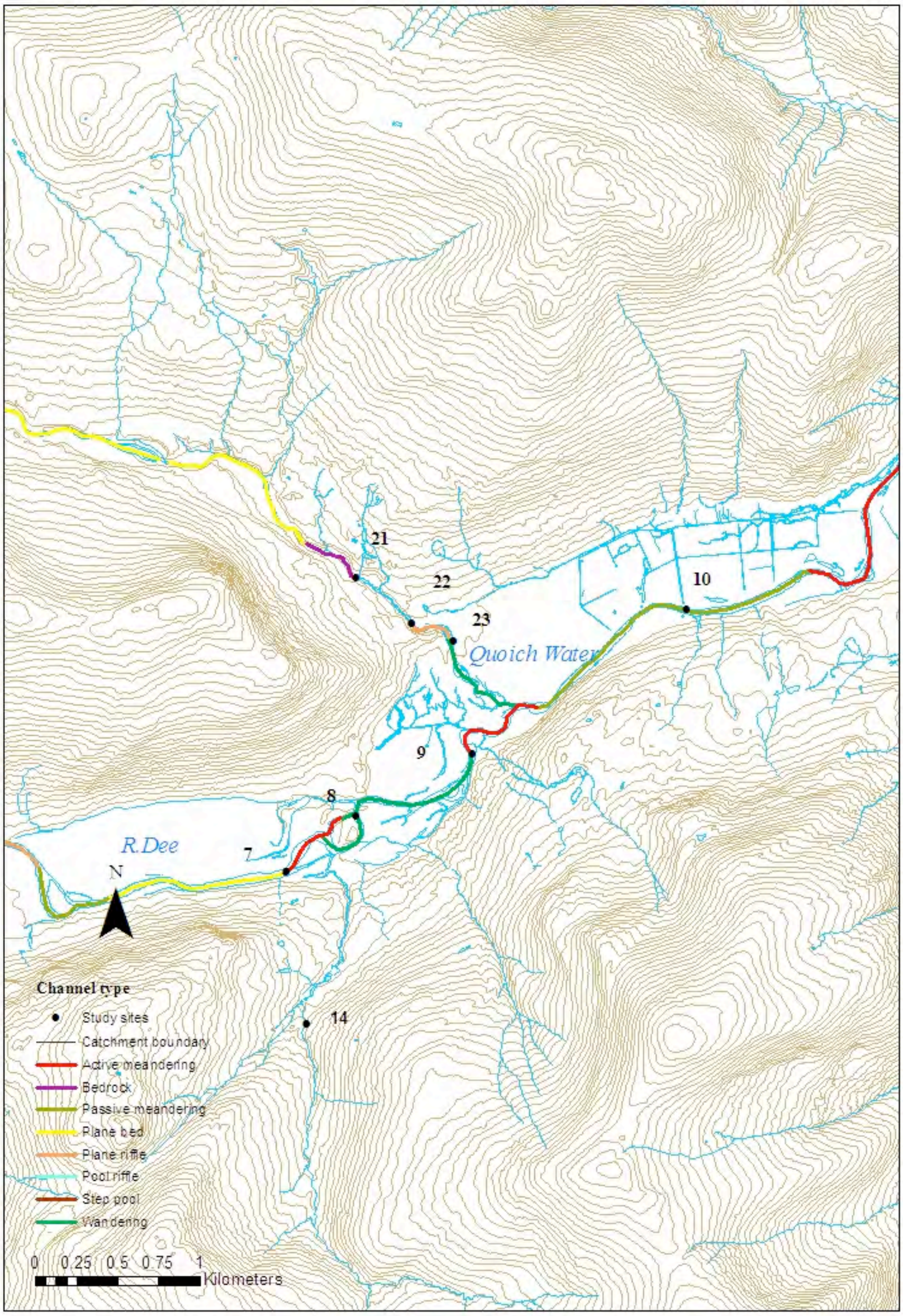
The upper River Dee (study sites 1-4 and 11-12). Please see Table A-1 for names of study reaches.



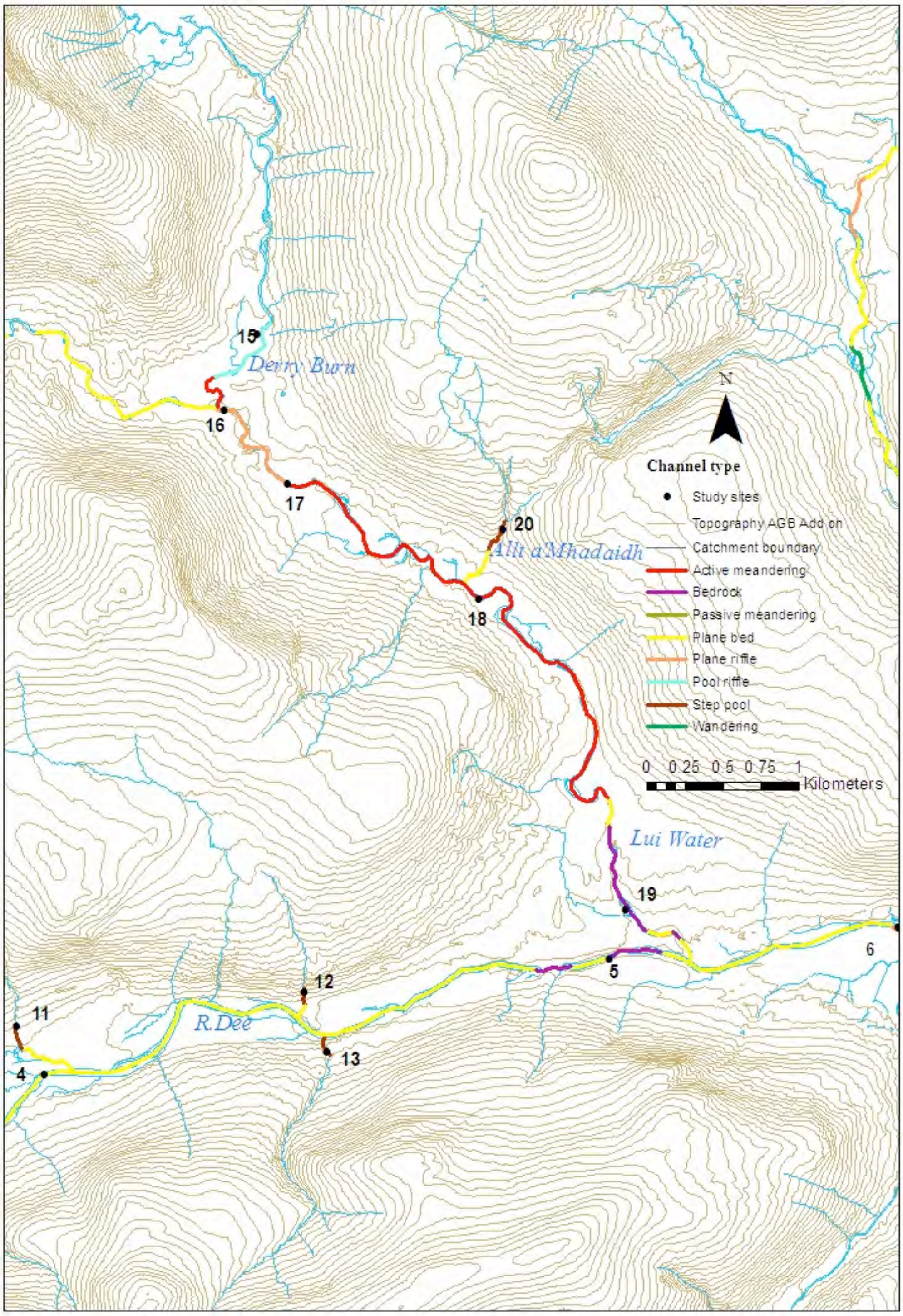
The middle River Dee (study sites 5-7).



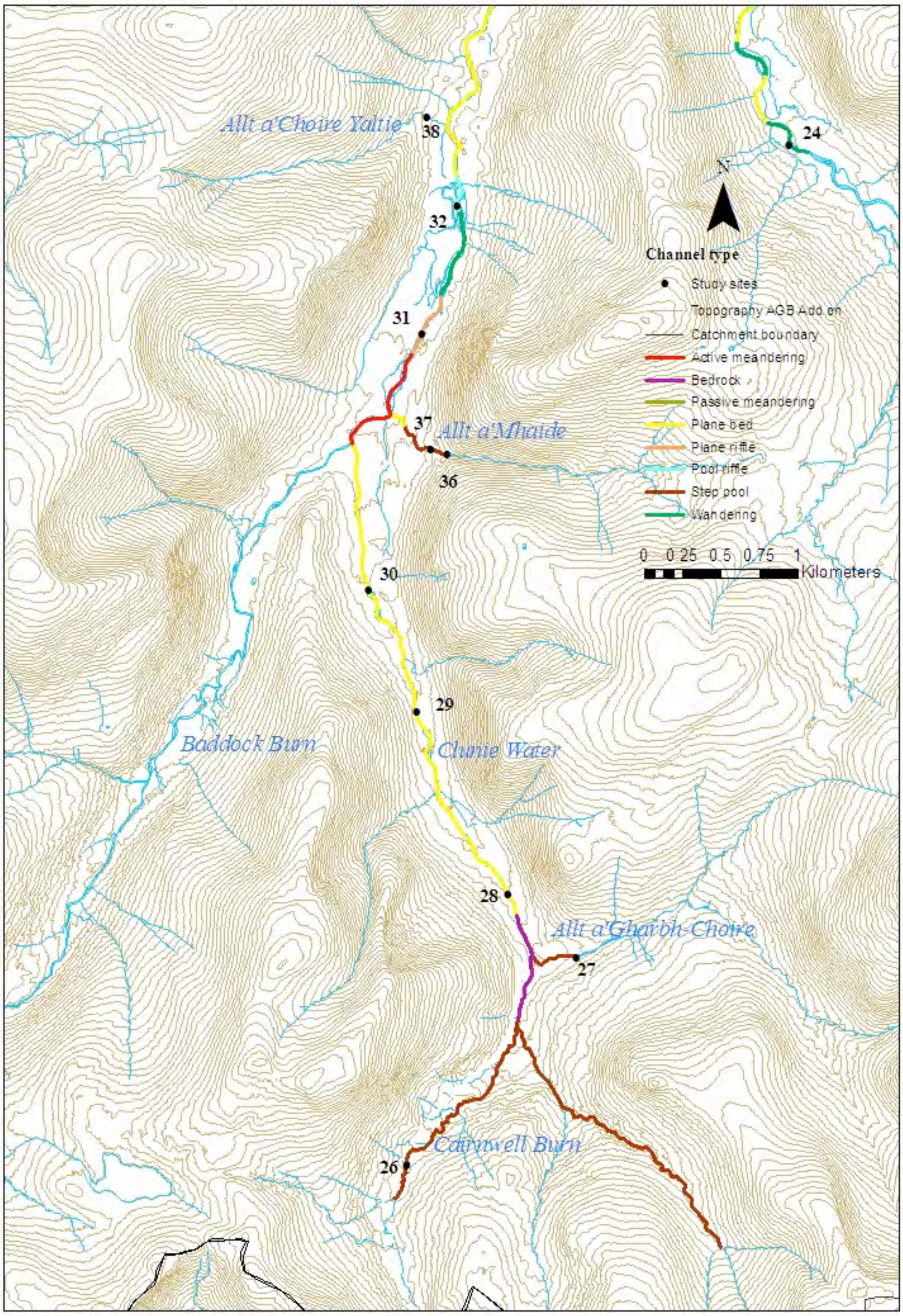
The lower River Dee (study sites 7-9) and Quoich Water (study sites 21-22).



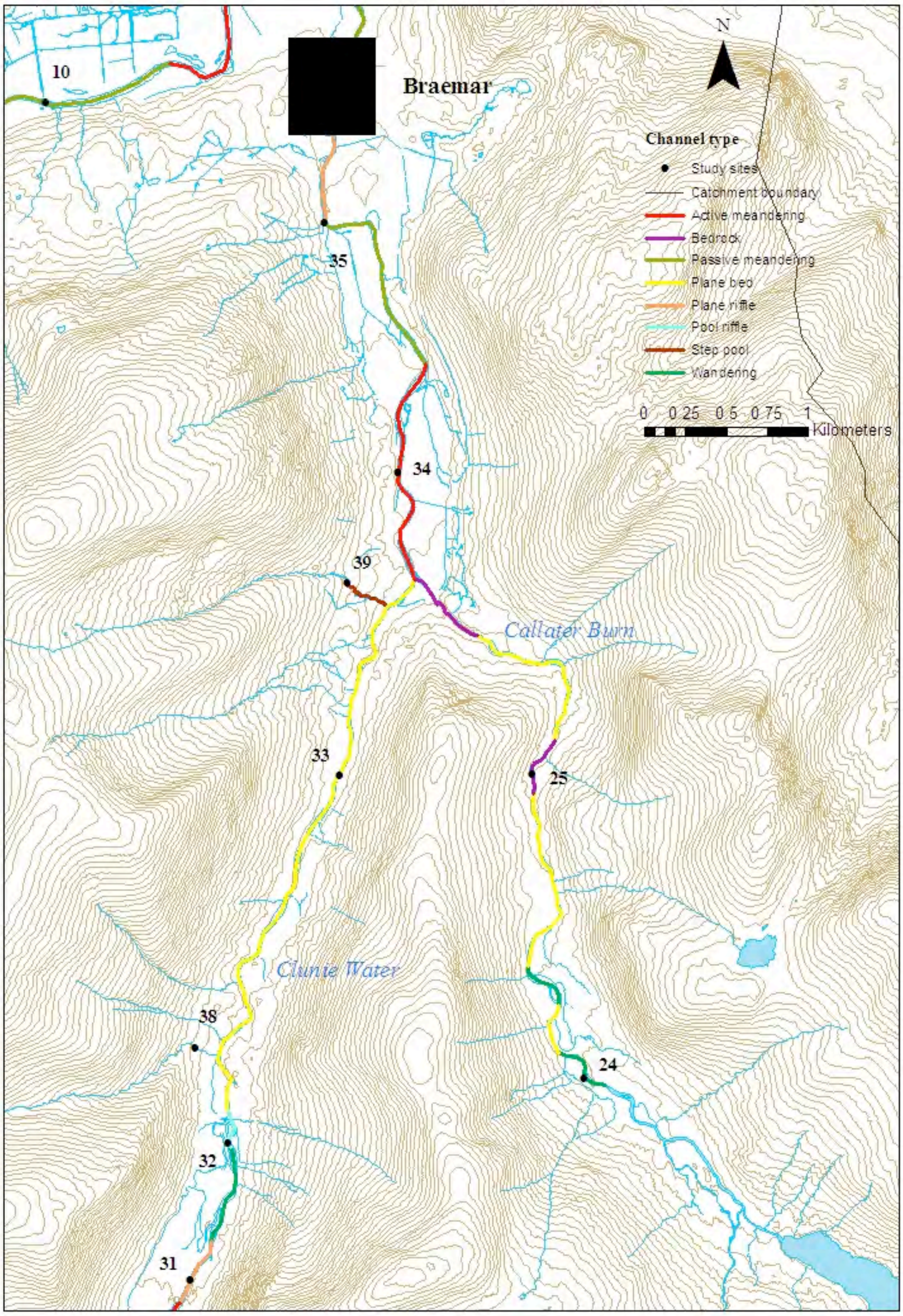
The Lui Water (study sites 16-19), the Derry Burn (study site 15) and the Allt a'Mhadaidh (study site 20).



The upper Clunie Water (study sites 28-32 and 36-38).



The lower Clunie Water (study reaches 31-35, 38 and 39) and the Callater Burn (study reaches 24 and 25).



[redacted]

The Allt a'Ghlinne Bhig catchment (study reaches 40-43).

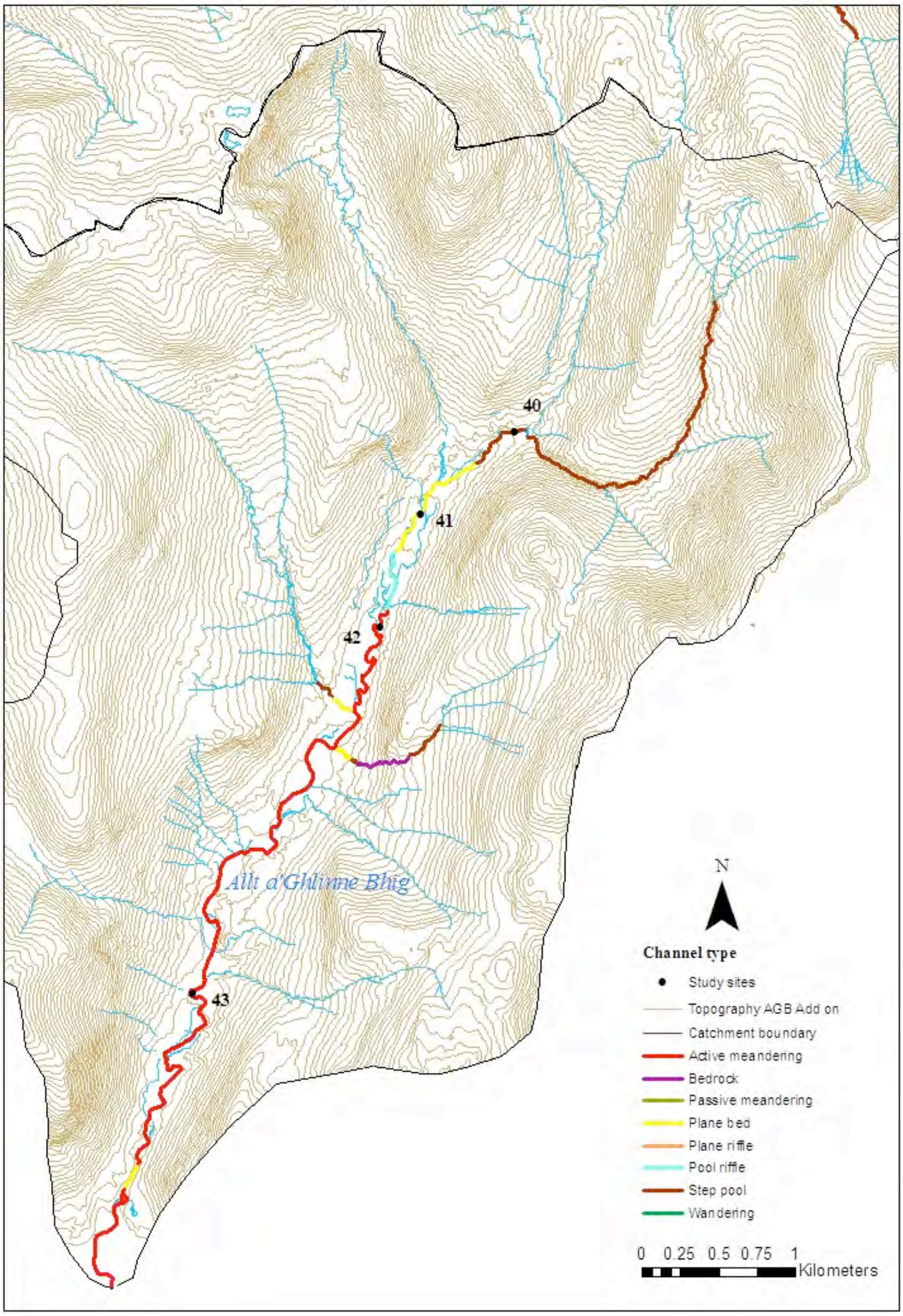


Table A-15: Name and number of study reaches

Study reach	Number	Channel type
Allt a' Choire Yaltie	38	Step-pool
Allt a' Gharbh-Choire	27	Step-pool
Allt a' Ghlinne Bhig 1	40	Step-pool
Allt a 'Ghlinne Bhig 2	41	Plane-bed
Allt a' Ghlinne Bhig 3	42	Active meandering
Allt a' Ghlinne Bhig 4	43	Active meandering
Allt a' Mhadaidh	20	Step-pool
Allt a'Mhaide 1	36	Step-pool
Allt a'Mhaide 2	37	Step-pool
Allt Creag Phadruig	12	Step-pool
Allt Tòn na Gaoithe	11	Step-pool
Cairnwell Burn	26	Step-pool
Callater Burn 1	24	Wandering
Callater Burn 2	25	Bedrock
Clunie Water 1	29	Step-pool
Clunie Water 2	30	Step-pool
Clunie Water 3	33	Step-pool
Clunie Water 4	31	Plane-riffle
Clunie Water 5	32	Pool-riffle
Clunie Water 6	35	Plane-riffle
Clunie Water 7	28	Step-pool
Clunie Water 8	34	Active meandering
Coldrach Burn	39	Step-pool
Corriemulzie Burn	14	Step-pool
Dalvorar Burn	13	Step-pool
Derry Burn	15	Pool-riffle
Lui Water 1	16	Active meandering
Lui Water 2	17	Plane-riffle
Lui Water 3	18	Bedrock
Lui Water 4	19	Active meandering
Quoich Water 1	21	Wandering
Quoich Water 2	22	Plane-riffle
Quoich Water 3	23	Bedrock
R.Dee 1	4	Plane-bed
R.Dee 2	7	Active meandering
R.Dee 3	8	Wandering
R.Dee 4	9	Active meandering
R.Dee 5	6	Plane-riffle
R.Dee 6	1	Bedrock
R.Dee 7	10	Passive meandering
R.Dee 8	5	Bedrock
R.Dee 9	2	Plane-bed
R.Dee 10	3	Plane-bed

APPENDIX B

Plate A-3: Photographic database of study reaches.

Allt a'Choire Yaltie

Allt a'Gharbh-Choire

Allt a'Ghlinne Bhig 1

Allt a'Ghlinne Bhig 2

Allt a'Ghlinne Bhig 3

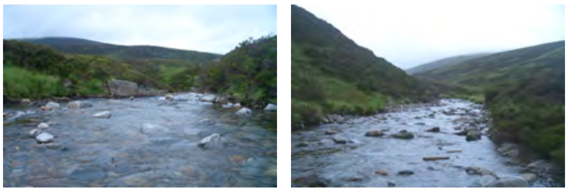
Allt a'Ghlinne Bhig 4

Allt a'Mhadaidh

Allt a'Mhaide 1

Allt a'Mhaide 2

Allt Coire Dhomhain 1



Allt Coire Dhomhain 2

Allt Coire Dhomhain 3

Allt Creag Phadruig

Allt Dubhaig 1

Allt Dubhaig 2

Allt Dubhaig 3

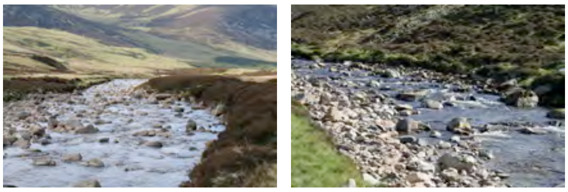
Cairnwell Burn

Calair Burn

Callater Burn 1

Callater Burn 2

Clunie Water 1



Clunie Water 2


Clunie Water 3


Clunie Water 4


Clunie Water 5

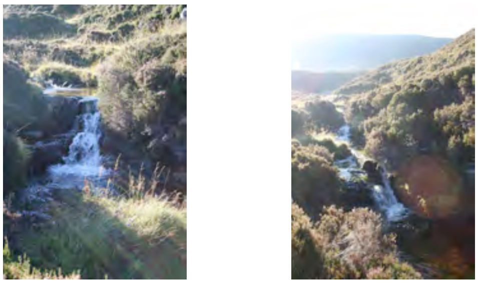

Clunie Water 6


Clunie Water 7


Clunie Water 8


Coldrach Burn


Corriemulzie Burn


Dalvorar Burn


Derry Burn

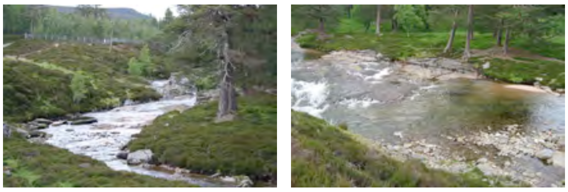

Endrick Water 1


Endrick Water 2

Endrick Water 3

Lui Water 1

Lui Water 2



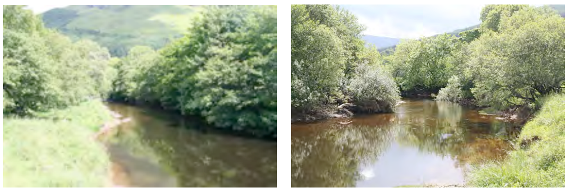
Lui Water 3

Lui Water 4

Quoich Water 1

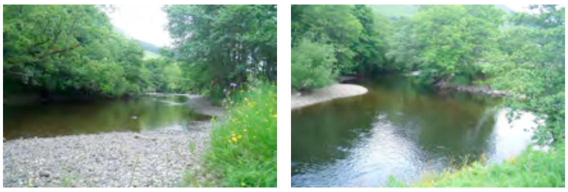
Quoich Water 2

Quoich Water 3



R.Balvag 1

R.Balvag 2



R.Balvag 3

R.Dee 1

R.Dee 2

R.Dee 3


R.Dee 4


R.Dee 5


R.Dee 6


R.Dee 7


R.Dee 8


R.Dee 9


R.Dee 10


R.Feshie 1


R.Feshie 2


R.Feshie 3


Wharry Burn 1


Wharry Burn 2


Wharry Burn 3


Wharry Burn 4

APPENDIX C

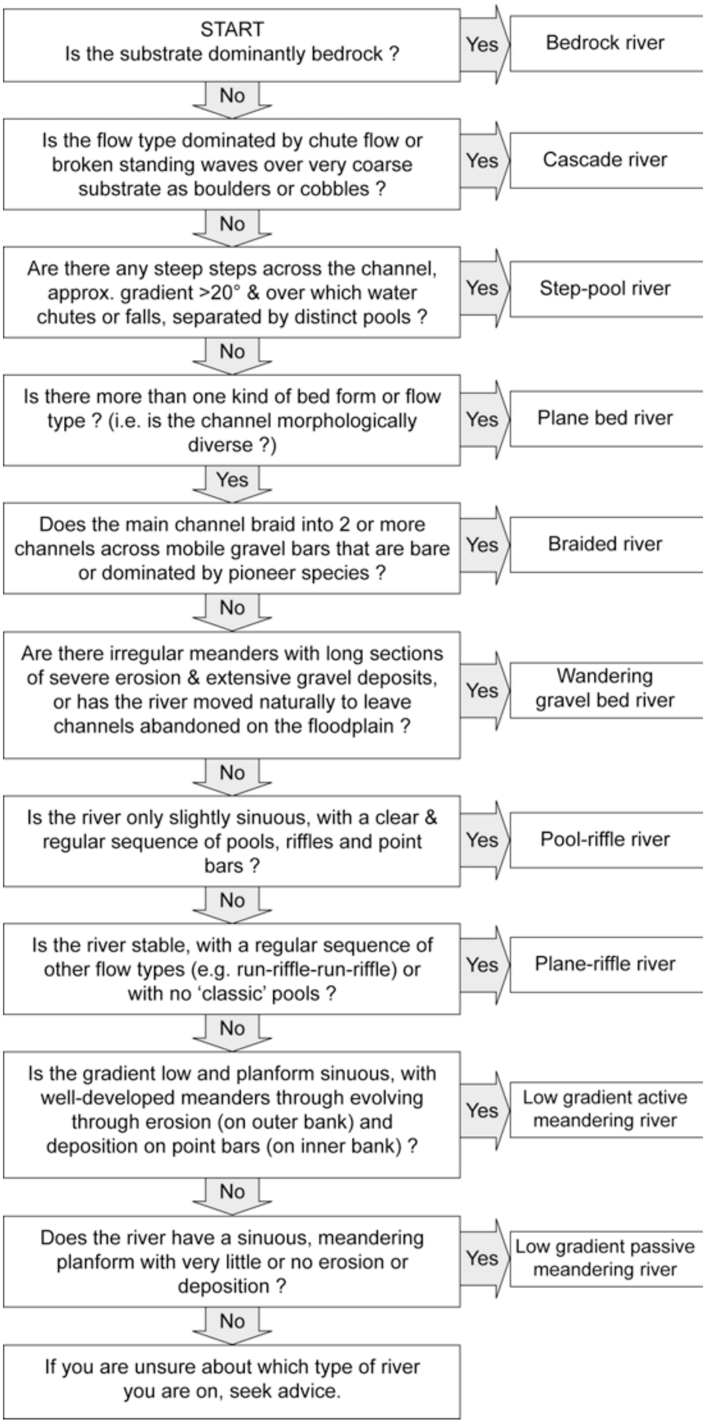
Table A-16: GPS co-ordinates of the study reaches. Channel type codes are A = Active meandering, B = Bedrock, D = Braided, M = Passive meandering, O = Pool-riffle, P = Plane-bed, R= Plane-riffle, S = Step-pool and W = Wandering.

	GPS Co-ordinates				Channel type
Study reach	Start of reach		End of reach		
Allt a' Choire Yaltie	NO 314183	BNG 785486	NO 314225	BNG 785469	S
Allt a' Gharbh-Choire	NO 315167	BNG 779985	NO 315062	BNG 780000	S
Allt a' Ghlinne Bhig 1	NO 313860	BNG 775523	NO 313771	BNG 775520	S
Allt a 'Ghlinne Bhig 2	NO 313250	BNG 774978	NO 313166	BNG 774871	P
Allt a' Ghlinne Bhig 3	NO 312983	BNG 774246	NO 312962	BNG 774202	A
Allt a' Ghlinne Bhig 4	NO 311760	BNG 771846	NO 311830	BNG 771800	A
Allt a' Mhadaidh	NO 305874	BNG 792498	NO 305872	BNG 792473	S
Allt a'Mhaide 1	NO 314214	BNG 783314	NO 314154	BNG 783307	S
Allt a'Mhaide 2	NO 314301	BNG 783237	NO 314281	BNG 783299	S
Allt Coire Dhomhain 1	NN 262845	BNG 775261	NN 262900	BNG 775289	B
Allt Coire Dhomhain 2	NN 262680	BNG 775228	NN 262774	BNG 775251	P
Allt Coire Dhomhain 3	NN 259491	BNG 774217	NN 259560	BNG 774255	S
Allt Creag Phadruig	NO 304574	BNG 789470	NO 304564	BNG 789420	S
Allt Dubhaig 1	NN 263143	BNG 775236	NN 263232	BNG 775091	P
Allt Dubhaig 2	NN 263248	BNG 774912	NN 263256	BNG 774766	W
Allt Dubhaig 3	NN 263445	BNG 774009	NN 263543	BNG 773970	A
Allt Tòn na Gaoithe	NO 302692	BNG 789250	NO 302683	BNG 789208	S
Cairnwell Burn	NO 314054	BNG 778624	NO 314058	BNG 778674	S
Calair Burn	NN 253633	BNG 720390	NN 253770	BNG 720454	R
Callater Burn 1	NO 316556	BNG 785303	NO 316437	BNG 785444	W
Callater Burn 2	NO 316237	BNG 787156	NO 316322	BNG 787284	B
Clunie Water 1	NO 314116	BNG 781599	NO 314086	BNG 781793	S
Clunie Water 2	NO 313801	BNG 782394	NO 313783	BNG 782634	S
Clunie Water 3	NO 315064	BNG 787148	NO 315144	BNG 787399	S
Clunie Water 4	NO 314149	BNG 784070	NO 314266	BNG 784262	R
Clunie Water 5	NO 314381	BNG 784907	NO 314407	BNG 785029	O
Clunie Water 6	NO 314972	BNG 790523	NO 314983	BNG 790929	R
Clunie Water 7	NO 314720	BNG 780402	NO 314644	BNG 780540	S
Clunie Water 8	NO 315419	BNG 788995	NO 315450	BNG 789459	A
Coldrach Burn	NO 315110	BNG 788328	NO 315115	BNG 788308	S
Corriemulzie Burn	NO 310951	BNG 788731	NO 310932	BNG 788800	S
Dalvorar Burn	NO 304722	BNG 789079	NO 304660	BNG 789134	S
Derry Burn	NO 304267	BNG 793777	NO 304235	BNG 793634	O
Endrick Water 1	NS 246874	BNG 687345	NS 246831	BNG 687519	A
Endrick Water 2	NS 246861	BNG 687559	NS 246948	BNG 687667	A
Endrick Water 3	NS 247225	BNG 687308	NS 247015	BNG 687259	A
Lui Water 1	NO 305713	BNG 792041	NO 305930	BNG 792004	A
Lui Water 2	NO 304051	BNG 793276	NO 304167	BNG 793097	R
Lui Water 3	NO 206674	BNG 790010	NO 206081	BNG 789874	B
Lui Water 4	NO 304463	BNG 792800	NO 304668	BNG 792811	A
Quoich Water 1	NO 311847	BNG 791064	NO 312047	BNG 790754	W
Quoich Water 2	NO 311598	BNG 791173	NO 311841	BNG 791109	R
Quoich Water 3	NO 311252	BNG 791452	NO 311482	BNG 793284	B

R.Balvag 1	NN 254190	BNG 720628	NN 254306	BNG 820406	M
R.Balvag 2	NN 254327	BNG 720556	NN 254564	BNG 820523	M
R.Balvag 3	NN 254000	BNG 720568	NN 254185	BNG 820632	M
R.Dee 1	NO 302868	BNG 788933	NO 303232	BNG 788951	P
R.Dee 2	NO 310798	BNG 789744	NO 311183	BNG 789949	A
R.Dee 3	NO 311240	BNG 789948	NO 311598	BNG 790070	W
R.Dee 4	NO 311964	BNG 790378	NO 312112	BNG 790513	A
R.Dee 5	NO 385960	BNG 789801	NO 308521	BNG 789867	R
R.Dee 6	NO 300796	BNG 788818	NO 301036	BNG 788662	B
R.Dee 7	NO 313278	BNG 791224	NO 313926	BNG 791402	M
R.Dee 8	NO 306568	BNG 789690	NO 306917	BNG 789746	B
R.Dee 9	NO 301373	BNG 788595	NO 301486	BNG 788540	P
R.Dee 10	NO 301502	BNG 788527	NO 301888	BNG 788439	P
R.Feshie 1	NH 384546	BNG 800783	NH 384448	BNG 800913	D
R.Feshie 2	NH 384412	BNG 801250	NH 384573	BNG 801458	D
R.Feshie 3	NN 284458	BNG 792906	NN 284385	BNG 793264	D
R.Glass 1	NH 240045	BNG 839498	NH 240731	BNG 839881	M
R.Glass 2	NH 236645	BNG 834100	NH 237194	BNG 834842	M
R.Teith 1	NS 276222	BNG 697171	NS 276052	BNG 696818	A
R.Teith 2	NS 275569	BNG 697815	NS 276197	BNG 697316	M
Wharry Burn 1	NN 282635	BNG 701496	NN 282624	BNG 701455	P
Wharry Burn 2	NN 282416	BNG 701467	NN 282389	BNG 701432	S
Wharry Burn 3	NN 282314	BNG 701382	NN 282288	BNG 701370	M
Wharry Burn 4	NN 282277	BNG 701310	NN 282240	BNG 701281	M

APPENDIX D

Figure A-1: Channel typology flow diagram (Jeffries, 2009).



START
Is the substrate dominantly bedrock ?

Is the flow type dominated by chute flow or broken standing waves over very coarse substrate as boulders or cobbles ?

Are there any steep steps across the channel, approx. gradient >20° & over which water chutes or falls, separated by distinct pools ?

Is there more than one kind of bed form or flow type ? (i.e. is the channel morphologically diverse ?)

Does the main channel braid into 2 or more channels across mobile gravel bars that are bare or dominated by pioneer species ?

Are there irregular meanders with long sections of severe erosion & extensive gravel deposits, or has the river moved naturally to leave channels abandoned on the floodplain ?

Is the river only slightly sinuous, with a clear & regular sequence of pools, riffles and point bars ?

Is the river stable, with a regular sequence of other flow types (e.g. run-riffle-run-riffle) or with no ‘classic’ pools ?

Is the gradient low and planform sinuous, with well-developed meanders through evolving through erosion (on outer bank) and deposition on point bars (on inner bank) ?

Does the river have a sinuous, meandering planform with very little or no erosion or deposition ?

If you are unsure about which type of river you are on, seek advice.